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A First-Order Nutrient Budget for the Tropical Moresby Estuary and Catchment, North Queensland, Australia

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ABSTRACT

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Dry and wet season phosphorus and nitrogen budgets for the Moresby Estuary and catchment are constructed to interpret cause-effect relationships between catchment landuse and nutrient loads in the coastal waterways of the Great Barrier Reef region. Samples were collected during seasonal extremes to reflect as wide a range of conditions as possible. Smaller scale processes cannot be resolved at this level of nutrient balance due to large budget uncertainties. However, the nutrient budget does give an insight into catchment scale processes. Fertilizer application on cane land in the catchment is the dominant source of phosphorus (about 3,566 ± 735 × 10^3 moles) and nitrogen (about 79,330 ± 11,338 × 10^3 moles), contributing 88 times more phosphorus and nitrogen to the catchment than is supplied by other sources (*e.g.*, septic tanks, atmospheric fallout, natural runoff and natural springs). However, only about 4 ± 2% of the phosphorus and about 11 ± 7% of the nitrogen added to the catchment is transferred to the estuary. About 82% of the phosphorus and about 90% of the nitrogen flux from the catchment occurs during the wet season. Once in the estuary, only small amounts of phosphorus and nitrogen are retained with most of the phosphorus being transferred to the ocean and it is suggested that most of the nitrogen may be used biologically. The fact that the Moresby Estuary is not a strong sink for nutrients (*i.e.*, it is not becoming eutrophic with time) suggests that current levels of agricultural activity in the catchment can be maintained without adverse effects on ecological components of the estuary and catchment.

ADDITIONAL INDEX WORDS: *Nitrogen budget, phosphorus budget, Great Barrier Reef, fertilizer, catchment.*

INTRODUCTION

Mass balance budgets are relatively simple models that simulate natural systems and thus provide an insight into the complex processes that occur in these systems. Mass balance budgets also have some advantages over the more complex multi-equation numerical models in that the detailed data sets required for accurate definition of equations and coefficients in numerical models are not needed. The conceptual nature of mass balance budgets also makes them a useful organizational tool and their generality makes them easy to apply to other similar systems (GROTH *et al.*, 1978).

Construction of nutrient budgets for estuarine systems provide an insight into the controls on biogeochemical and ecological processes (SMITH and VEEH, 1989), define constraints on internal functions (SMITH *et al.*, 1987), identify biogeochemical pathways and help predict the effects of likely future changes in these systems. However, although there are many published nutrient budgets for estuarine systems (*e.g.*, CORRELL, 1981; SMULLEN *et al.*, 1982; KAUL and FROELICH, 1984; NIXON and PILSON, 1984; LUKATELICH *et al.*, 1987; NIXON, 1987; SMITH *et al.*, 1987; LUCOTTE, 1988; BAIRD and WINTER, 1990; VAN RAAPHORST and VAN DER VEER, 1990; JORDAN *et al.*, 1991), studies that consider in detail the mass balance of nutrients in the catchment of the receiving estuary are rare and there have been no such studies in tropical regions.

This paper constructs a mass balance nutrient budget for the Moresby Estuary and catchment to interpret cause-effect relationships between catchment landuse and enhanced nutrient loads in the coastal waterways of the Great Barrier Reef region. The aims of this study are to (1) establish a quantitative inventory of the sources of nutri-

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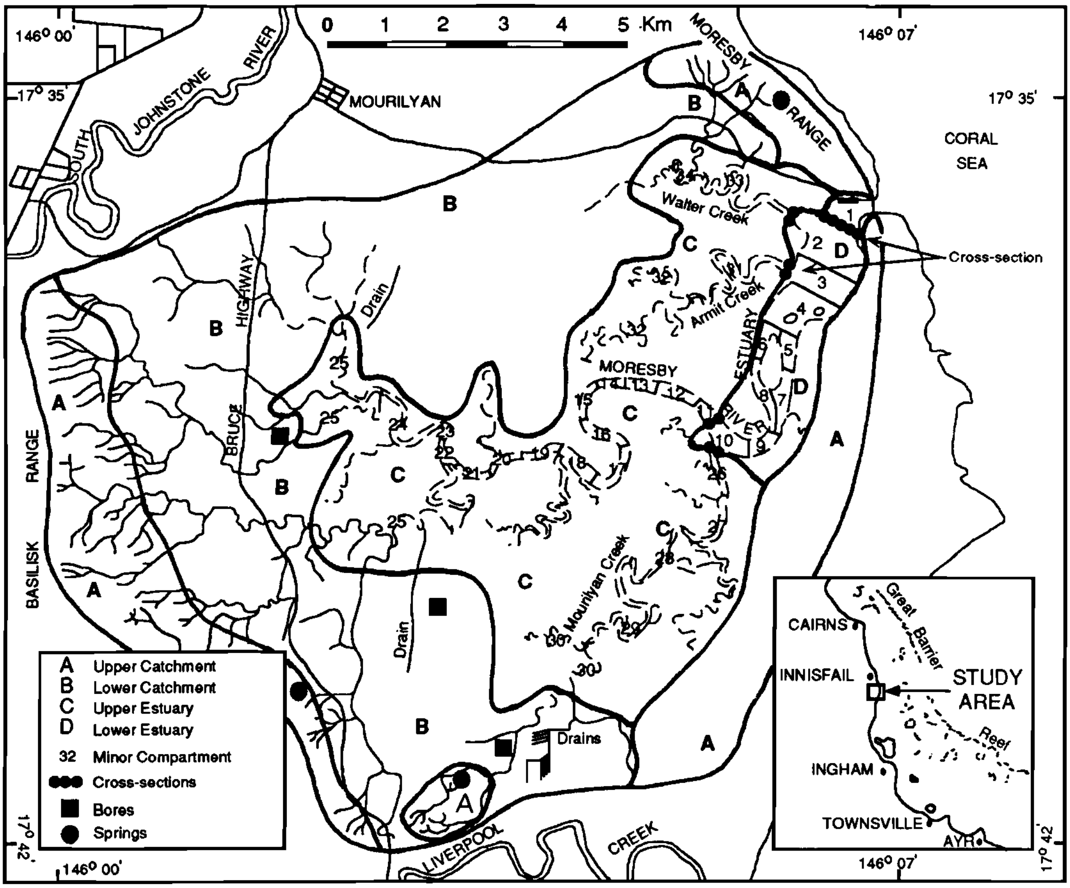

Figure 1. Location and extent of the compartments used for calculation of a nutrient budget for the Moresby Estuary and catchment. Letters represent the four major compartments (A) upper catchment, (B) lower catchment, (C) upper estuary, and (D) lower estuary. Numbers represent the minor compartments. Also shown are the locations of cross-sections taken in the wet and dry seasons and catchment bores and springs.

ents in the catchment, (2) determine the fluxes of these nutrients from the catchment to the estuary, within the estuary, and out of the estuary, (3) evaluate seasonal change in these nutrient fluxes, and (4) evaluate the implications of these nutrient fluxes. Although a simple approach is used in this study, it should be remembered "... that nutrient budgets are simple only in concept. In practice, they add up and balance all of our uncertainty and ignorance as well as our knowledge" (NIXON, 1987).

STUDY AREA

The Moresby Estuary is on the northeastern coast of Australia 15 kilometers south of Innisfail (Figure 1). Its catchment covers approximately 125 km^2 of which 52% is used for sugarcane crops, 30% is naturally vegetated by mangroves and 18% naturally vegetated by rain forest. The catchment has a population of approximately 300 people in scattered residential areas. The region has two pronounced seasons, with a dry season from April to November having moderate temperatures (24–28 °C) and an average monthly rainfall of 200 mm, and a wet season, from December to March with high temperatures (30–34 °C) and a monthly average rainfall of 800 mm (Commonwealth Bureau of Meteorology). The seasonal difference in rainfall results in intermittent stream flow which significantly affects the physical characteristics of the estuary. During the period of this study, the Moresby system changed from a vertically homogeneous saline embayment (11‰ to 35‰ salinity) in the dry season to a highly stratified salt-wedge estuary (fresh to 35‰ salinity) in the wet season.

The Moresby Estuary has developed in a topographic depression between a Pleistocene and a Holocene beach barrier system which formed in the protected environment behind the Moresby Range. The upper part of the catchment drains Lower Palaeozoic metamorphic rocks that form the Moresby and Basilisk Ranges (Figure 1). The main channel (Moresby River) is 20 km long and averages 3 meters in depth at low tide. This narrow (20 m to 100 m) meandering channel broadens out into a wide (1 km) funnel shape just downstream of Mourilyan Creek (main tributary) and flows north-east, sub-parallel to the coastline. It then abruptly turns east and flows out through a deep, narrow restricted entrance (9 m by 90 m) cutting across a rocky sill between two headlands of the Moresby Range (Figure 1). A rocky sill at the estuary mouth produces abnormal flow conditions near the entrance, resulting in natural scouring of a deep (25 m) hole, immediately landward of the sill. This natural hole provides an excellent low maintenance deep-water port (Mourilyan Harbour) for the local sugar industry, and provides berthing for vessels up to 21,000 gross tons.

METHODS

The nutrient budget is calculated from data obtained during the dry season, July 1990 through December 1990 and April 1991 through June 1991, and the wet season, January 1991 through March 1991. For budget calculations, the estuary system is sub-divided into four major compartments, (A) upper catchment, (B) lower catchment, (C), upper estuary, and (D) lower estuary (Figure 1). The upper catchment is above the area of agricultural influence and is treated as a separate compartment to give an estimate of the nutrient flux from natural areas. The lower catchment is extensively affected by agricultural activities (dominantly sugarcane farming) which involve the application of fertilizers and are the major source of nutrients to the system. The upper estuary includes the upper part of the Moresby Estuary and Mourilyan, Armit and Walter Creeks (Figure 1) and is defined to establish the relationship between fluxes in the catchment and the estuary. The lower estuary is defined to establish the relationship between fluxes in the estuary and the ocean and internal fluxes within estuary. Surface areas of each compartment were calculated by counting 0.12 ha squares on grid overlays of 1:25,000 aerial photographs.

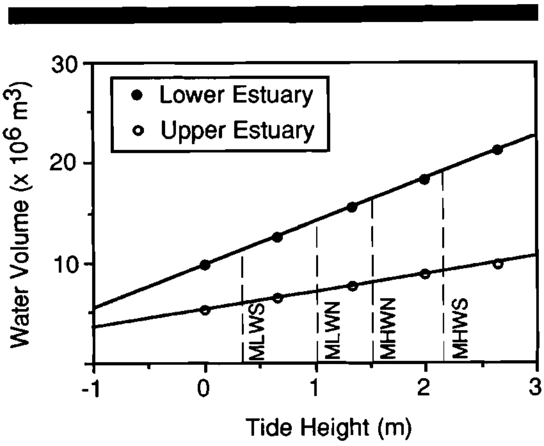

Figure 2. Hypsographic curve for the upper and lower Moresby Estuary showing the volume of water contained within the tidal areas as a function of tide height.

Ocean-Estuary and Lower Estuary-Upper Estuary Fluxes

Tidal water flux between the estuary and the ocean and the upper and lower estuary is calculated using a hypsographic curve and yearly tidal records. Thirty nine cross-sections were measured in the estuary using an echo sounder, to sub-divide the estuary into thirty four minor compartments (Figure 1). The volume in each of these compartments at low water datum (0.00 m) is calculated using the average of the two boundary cross-sections multiplied by the distance between them obtained from aerial photographs. The volume in each compartment is then calculated at 66 cm tide height intervals from zero to 266 cm corrected linearly for the 10% attenuation of the tide in the upper reaches. Compartment volumes at the various tide heights were summed to give the volume of water in the lower estuary and the upper estuary at 5 tide heights; these volumes were plotted as a function of tide height and a hypsographic curve was constructed (Figure 2). The hypsographic curve was combined with daily tide height data (Department of Harbours and

Marine, Brisbane) from a tide gauge at the estuary entrance to calculate flood tide water fluxes for the wet and dry seasons. Ebb tide water flux is calculated by adding the freshwater input minus evaporation in the estuary to the flood tide flux.

Nutrient fluxes between the estuary and the ocean and the upper and lower estuary were established by measuring nutrient concentrations in samples collected over one ebb/flood tidal cycle in the wet season (March) following a small flood event, and dry season (December) following a prolonged dry period. Samples were collected during seasonal extremes to reflect as wide a range of conditions as possible. Cross-sections were established between the estuary and the ocean (*i.e.*, estuary entrance: 5 stations, 3 sampling depths; Figure 1) and between the upper and lower estuary (*i.e.*, mid-Moresby Estuary: 3 stations, 2 depths; Mourilyan Creek entrance: 1 station, 2 depths; Armit and Walter Creeks entrances: 2 stations, 2 depths; Figure 1). Water and suspended particulate samples were collected by hand pumping water to the surface at each sampling point approximately every hour. Samples were then filtered through pre-washed, pre-dried, and pre-weighed 0.45 μm membrane filters into HCl-washed and sample-rinsed polyethylene bottles. Water and particulate samples were kept in the dark on ice until they were frozen (-20 °C) within 8 hours at base camp. Nutrient concentrations are averaged for the ebb and flood tides. These averaged nutrient concentrations were multiplied by the water fluxes to calculate nutrient fluxes for the wet and dry seasons.

Dissolved nutrients were determined by standard colourmetric methods (PARSONS *et al.*, 1984): phosphate (PO_4^{3-}), molybdate blue and ascorbic acid (analytical error ± 10% at 0.1 $\mu mol \cdot L^{-1}$, ± 2% at 1.0 $\mu mol \cdot L^{-1}$); nitrate + nitrite (hereinafter referred to as nitrate (NO_3^-)), sulfanilamide and N-(1-naphthyl)-ethylenediamine following cadmium reduction (analytical error ± 5% at 1.0 $\mu mol \cdot L^{-1}$). Analytical errors were determined by running 10 replicate standards at the given concentration. The effects of salt concentrations on colour development were corrected for by using standard additions. Particulate-bound phosphate was determined colourmetrically following digestion of filters in 10 ml of 2 molar HCl. Particulate-bound nitrate was extracted by shaking filters for 1 minute in 100 ml of 0.02 molar ammonium chloride; the nitrate was determined colourmetrically following cadmium reduction.

Upper Catchment-Lower Catchment and Lower Catchment-Upper Estuary Fluxes

Water flux in the catchment is calculated using the formula:

$$P = R + Gf + Et \pm Gs \pm Sm$$

where P is precipitation, R is runoff, Gf is groundwater flow, Et is evapotranspiration, Gs is change in groundwater storage, and Sm is change in soil moisture.

Daily precipitation records (Commonwealth Bureau of Meteorology) for the Innisfail rain gauge 10 km north of the study site were examined to obtain a total value of precipitation for the wet and dry seasons. The percentage of this precipitation that occurs as runoff is calculated using the formula:

$$\%R = (Sf/Pd \cdot Sa) \cdot 100\%$$

where Sf is the volume of stream flow (m^3) in the catchment for one day, Pd is the preceding day's precipitation (m), and Sa is the surface area of the catchment (m^2).

Stream flow (hand current meter at 0.4 total depth) and cross-sections (tape measure) in all the major creeks in the catchment were measured and summed to give a total volume of stream flow for one day. Monthly evaporation records (Commonwealth Bureau of Meteorology) for the Innisfail Class A pan 10 km north of the study site were examined and a correction value of 0.75 (FETTER, 1988) applied to calculate annual evapotranspiration (MANNING, 1992; DINGMAN, 1994). Groundwater flow was calculated by difference assuming that groundwater storage and change in soil moisture approximated zero over the period of one year (CHANG, 1982).

Dissolved nutrient flux (Dnf; moles), particulate nutrient flux (Pnf; moles), and groundwater nutrient flux (Gnf; moles) in the catchment were calculated using the formulae:

$$Dnf = (R \cdot Ad)/10^6$$

$$Pnf = (R \cdot Ap \cdot As)/10^6$$

$$Gnf = (R \cdot Ag)/10^6$$

where R (L) is runoff, Ad ($\mu mol \cdot L^{-1}$) is the average dissolved nutrient concentration of the surface waters, Ap ($\mu mol \cdot g^{-1}$) is the average particulate nutrient concentration of the surface waters, As ($g \cdot L^{-1}$) is the average suspended sediment concentration of the surface waters, and Ag ($\mu mol \cdot$

L^{-1}) is the average nutrient concentration of the groundwaters.

Groundwater samples for the upper catchment were taken from natural springs above the farmland, and from farm bores for the lower catchment. Surface water sample sites are given in EYRE (1994) and groundwater sample sites are shown in Figure 1.

Inventory of Total Nutrient Input to the Catchment

A survey was conducted to assess the total anthropogenic nutrient input to the catchment by interviewing 70% of the farmers and the local authorities. The aim of interviewing the farmers is to establish the types of crops and the types of chemicals, amounts applied, time of application, method of application and the ratoon plant cycle. The aim of interviewing the local authorities is to establish if there were any significant nutrient inputs other than farming (*e.g.*, industrial, *etc.*).

The contribution of nutrients from fertilizers and removal of nutrients by crops exported from the farms is calculated by multiplying the average amount applied per hectare and the amount removed per hectare by the number of hectares of farmland. The amount of nutrients removed (Nr; kg) by crops per hectare was calculated using the formula:

$$Nr = (Cc \cdot Rn + Pc)/Rn + 1$$

where Cc ($kg \cdot ha^{-1}$) is the amount of nutrients removed by cane, Rn is the average number of ratoon cycles in the Moresby catchment, and Pc ($kg \cdot ha^{-1}$) is the amount of nutrients removed as cane + tops + trash.

The contribution of nutrients from domestic septic tanks is calculated by multiplying the catchment population by the average per capita nutrient excretion rate (PORTNOY, 1990). The contribution of nutrients from precipitation (Pn) (moles) is calculated using the formula:

$$Pn = (Sa \cdot P \cdot Ad)/10^6$$

where Sa is the surface area of the catchment (m^2), P is precipitation (m), and Ad is the average nutrient concentration of the precipitation ($\mu mol \cdot L^{-1}$).

A sample of precipitation was collected during the wet season by catching rainwater in a plastic beaker.

Long Term and Short Term Sedimentation Fluxes

Long term (Sl) and short term (Ss) sedimentation fluxes (moles) were calculated using the formulae:

$$Slf = Sl \cdot Sa \cdot Bd \cdot An/1 \times 10^6$$

$$Ssf = Ss \cdot Sa \cdot Bd \cdot An/1 \times 10^6$$

where Sl ($m \cdot yr^{-1}$) is the long term sedimentation rate, Ss is the short term sedimentation rate ($m \cdot yr^{-1}$), Sa (m^2) is the surface area of active deposition, Bd is the bulk density ($g \cdot cm^{-3}$), and An ($\mu mol \cdot g^{-1}$) is the average nutrient concentration.

The area of active deposition is defined as the channel of the estuary and is estimated from aerial photographs using 0.12 ha grid overlays. Bulk density is the ratio between total mass (g) and total volume (cm^3) and is obtained by drying a known volume of sample at 65 °C for 48 hours and weighing. Long term sedimentation rates were determined using ^{14}C dating of organic material from the bottom of two 1 m cores from the upper and lower estuary. Annual rates were multiplied by 0.75 (9 months) for the dry season and by 0.25 (3 months) for the wet season. Short term sedimentation rates were determined using brick dust marker horizons. Brick dust horizons were placed in 100 × 100 cm plots in the upper estuary, lower estuary, Mourilyan Creek, and Armit Creek and marked with a 2 m orange stake. The brick dust horizon was cored using 5 × 30 cm PVC cores at the end of the dry season and the end of the wet season. Three cores were taken at each site, frozen and later split to measure the depth of sediment accumulated on top of the marker horizon; an average for the three cores was used. Where erosion occurred the term resuspension is used in place of short term sedimentation.

Error Estimates

Error estimates (emphasised in this study) are critical to nutrient budget calculations, particularly when dealing with surpluses and deficits, as these terms also contain the sum of all the errors of the measured fluxes. Nutrient budget errors can be classified into water flux and nutrient flux measurement errors and interpolation errors. Water flux measurement errors result from measuring a quantity at a point using imperfect procedures (WINTER, 1981). Nutrient flux errors result from applying a given nutrient concentration with errors to a water flux with errors. It is important

Table 1. *Surface area of the 4 main estuary compartments.*

Compartment	Sub-Compartment	Surface Area ($\times 10^6$ m^2)	% of Total Area
Upper catchment		22.28 ± 1.11	17.73
Lower catchment		64.98 ± 3.25	51.72
Upper estuary	Mangrove	28.19 ± 1.41	22.44
	Channel	1.68 ± 0.08	1.34
Lower estuary	Mangrove	4.88 ± 0.24	3.88
	Channel	3.64 ± 0.18	2.89
Total surface area		125.65 ± 3.73	

to note that the variance associated with these fluxes propagates additively (DEVITO and DILLON, 1993). Interpolation errors result from applying spatially and temporally limited data over a broader area or time frame.

Water budget errors (E) were calculated using the formula (modified from WINTER, 1981):

$$E_P^2 + E_R^2 + E_{Et}^2 + E_{Gs}^2 + E_{Sm}^2 = E_{Gf}^2$$

Errors associated with precipitation range from 5 to 15% (WINTER, 1981); based on the type of instrument used, topography, and gauge density a ± 10% error has been adopted for this study. Evapotranspiration errors based on Class A pan evaporation data range from 10 to 15% (DINGMAN, 1994); an error of ± 12.5% has been adopted for this study. Measurement of streamflow using a current meter involves an error of about ± 5% (WINTER, 1981). The error associated with measuring surface areas from airphotos and cross-sectional areas from echo sounding profiles was estimated to be ± 5%. This estimate is based on a comparison of a measured distance on the ground with a distance obtained from airphotos. Errors associated with tide height readings using a stilling well over a 2.5 meter range are ± 1% (PURG, 1987). Where water flux estimates involved more than one component, errors were calculated from the sums of the squared component errors (WINTER, 1981).

Nutrient flux errors (E) were calculated using the formula (modified from MOOD *et al.*, 1974):

$$V_{nf} = u_{wf}^2 V_{nc} + u_{nc}^2 V_{wf} + V_{wf} V_{nc}$$

where V_{nf} is the variance of the nutrient flux, u_{wf} is the mean of the water flux, u_{nc} is the mean of the nutrient concentration, V_{nc} is the variance of the nutrient concentration, and V_{wf} is the variance of the water flux. The variance associated with surpluses and deficits was determined by summing the individual variances of the fluxes used to calculate the annual values.

Interpolation errors are estimated by comparing nutrient retention calculated by the input-output method adopted in this study to the approach used by NIXON (1987) based on nutrient and sediment input combined with the chemical composition of the sediment. Interpolation errors have been minimised by collecting samples during seasonal extremes to reflect as wide a range of conditions as possible, using all available data, and by estimating only seasonal fluxes since long term averages have smaller errors of estimation than short term averages (WINTER, 1981).

Significant Figures

Two decimal places are carried in all calculations and terms, even though the accuracy this suggests is much greater than can be justified by the methods used. This is to avoid progressive accumulation of rounding errors and to avoid the loss of some of the smaller fluxes (*e.g.*, natural input, particulate bound nitrate, *etc.*) which are less than the rounding errors of the larger fluxes (*e.g.*, fertilizer application).

RESULTS

Water Budget

The surface areas of the 4 main estuary compartments are summarised in Table 1. The catchment is clearly dominated by sugarcane farmland (lower catchment) with mangroves (upper estuary) and rain forest (upper catchment) evenly distributed over the remaining areas. Precipitation for the area totalled 1,141 ± 114 mm for the dry season and 2,816 ± 282 mm for the wet season (Commonwealth Bureau of Meteorology). Total flow in all the major creeks in the catchment on the 23rd of June 1991 was 47,447 ± 2,372 m^3 and the preceding day's precipitation was 87,260 ± 9,599 m^3. Assuming all the precipitation found its way to the creeks by the next day, which is a reasonable assumption based on the size of the catchment, runoff accounts for 54% of precipitation. This value is in good agreement with the 59% value given for the nearest flow-gauged catchment (Johnstone River), 10 km north of the study area, and is also in good agreement to several other North Queensland streams (Mossman 57%; Hinchinbrook 56%) with similar sized catchments (HAUSLER, 1991). Annual Class A pan evaporation for the area equalled 1,548 ± 194 mm

Table 2. *Water budget for the Moresby River-estuary, 1st July 1990 to the 30th June 1991.*

Compartment	Flux Type	Wet Season ($\times 10^6$ m^3)	Dry Season ($\times 10^6$ m^3)
Upper catchment	Precipitation	62.74 ± 6.90	25.42 ± 2.80
	Surface flow	33.88 ± 4.07	13.73 ± 1.65
	Sub-surface flow	10.67 ± 2.24	4.32 ± 0.91
Lower catchment	Precipitation	182.98 ± 20.13	74.14 ± 8.16
	Surface flow	132.69 ± 15.92	53.77 ± 6.45
	Sub-surface flow	41.78 ± 8.77	16.92 ± 3.55
Upper estuary	Ebb tide	744.98 ± 52.15	1,248.72 ± 87.41
	Flood tide	495.07 ± 34.65	1,169.96 ± 81.90
	Evaporation	8.67 ± 1.13	26.01 ± 3.38
	Precipitation	84.11 ± 9.25	34.08 ± 3.75
Lower estuary	Ebb tide	1,430.00 ± 100.10	3,037.00 ± 212.59
	Flood tide	1,158.57 ± 81.10	2,955.94 ± 206.92
	Evaporation	2.47 ± 0.32	7.42 ± 0.96
	Precipitation	23.99 ± 2.64	9.72 ± 1.07

giving an annual evapotranspiration of 1,161 ± 145 mm or 29% of the precipitation. By difference groundwater flow equals 17% of precipitation. The water budget summarised in Table 2 is clearly dominated by tidal exchange. During the dry and wet seasons, fresh water input to the estuary measured only 4% and 18%, respectively, of the tidal input of ocean water.

Nutrient Inventory in the Catchment

A survey of local authorities revealed that there are no major industrial or commercial nutrient inputs to the Moresby catchment and that the catchment population use domestic septic tanks. Aerial photographs show only a minor percentage of the catchment is urbanised, therefore, nutrients derived from urban runoff are also insignificant. Farmer surveys revealed that there are very few livestock or crops other than sugarcane in the catchment. Sugarcane in the Moresby catchment is planted July to September (dry season) and harvested July to November (dry season) and on average has a 4 ratoon (*i.e.*, only cane is harvested) 1 plant (*i.e.*, cane, tops, and trash harvested) cycle.

The major nutrient inputs and outputs for the wet and dry seasons in the lower catchment are summarised in Table 3. Nitrogen and phosphorus inputs are clearly dominated by fertilizers which account for 99% and 98% respectively of the total annual input. Outputs of nitrogen and phosphorus are dominated by removal in crops which accounts for 36% and 57% respectively of the total annual input. The upper catchment, septic tanks and atmospheric fallout were the second most important sources of phosphorus all supplying similar amounts, but these inputs are about $^1/_{88}$ of the input from fertilizers. Atmospheric fallout and the upper catchment are the second most important sources of nitrogen supplying significantly more than septic tanks, but these inputs are also small compared to fertilizers. Removal of particulate material in runoff during the wet season is the second most important output of phosphorus. In contrast, the second most important output of nitrogen is dissolved nitrate in runoff during the wet season. Only about 4 ± 2% of the phosphorus and about 11 ± 7% of the nitrogen added to the lower catchment (dominantly fertilizers) reaches the estuary; this transfer equates to a loss of approximately 0.70 ± 0.35 kg·ha^{-1} phosphorus and 17.89 ± 11.76 kg+ha^{-1} nitrogen.

Nutrient Inventory in the Upper Estuary

The major nutrient inputs and outputs for the wet and dry seasons in the upper estuary are summarised in Table 4. During the wet season phosphorus inputs to the upper estuary are dominated by particulate-bound phosphorus, with the lower estuary and the catchment supplying similar amounts. Particulate material remains the dominant input of phosphorus to the upper estuary in the dry season, but very little is supplied by the catchment; most of the supply comes from the lower estuary and from the resuspension of sediments. Other sources of phosphorus include dissolved fluxes from the catchment and lower estuary and atmospheric fallout. The input of nitrogen to the upper estuary in the wet season

Table 3. *Major nutrient inputs and outputs for the lower Moresby Catchment.*

	Phosphate Concentration		Phosphate Flux (× 10^3 moles)	
Nutrient Source/Sink	Wet Season	Dry Season	Wet Season	Dry Season
Fertilizers[1]	—	17.00 ± 3.40 kg·ha^{-1}	—	+3,566.44 ± 735.25
Septic tanks[2]	0.36 kg·capita^{-1}	1.10 kg·capita^{-1}	+3.49	+10.65
Upper catchment (dissolved)[3]	0.18 ± 0.06 μmol·L^{-1}	0.07 ± 0.05 μmol·L^{-1}	+6.10 ± 2.21	+0.96 ± 0.75
Upper catchment (particulate)[3]	30.00 ± 10.12 μmol·g^{-1}	14.90 ± 6.58 μmol·g^{-1}	+8.13 ± 2.91	+0.20 ± 0.09
Natural springs[4]	0.10 ± 0.02 μmol·L^{-1}	0.06 ± 0.02 μmol·L^{-1}	+1.07 ± 0.37	+0.26 ± 0.17
Atmospheric fallout[5]	0.04 ± 0.00 μmol·L^{-1}	0.04 ± 0.00 μmol·L^{-1}	+7.32 ± 0.28	+2.97 ± 0.11
Crops[6]		9.80 ± 0.98 kg·ha^{-1}	—	−2,055.94 ± 229.87
Runoff (dissolved)[7]	0.15 ± 0.14 μmol·L^{-1}	0.39 ± 0.39 μmol·L^{-1}	−19.90 ± 18.79	−20.97 ± 21.18
Runoff (particulate)[8]	79.16 ± 41.49 μmol·g^{-1}	14.90 ± 6.55 μmol·g^{-1}	−84.03 ± 45.18	−0.80 ± 0.12
Sub-surface flow[9]	0.46 ± 0.10 μmol·L^{-1}	0.32 ± 0.09 μmol·L^{-1}	−19.22 ± 5.88	5.41 ± 1.98
Annual difference			+1,401.32 ± 772.22	

Positive values = inputs, negative values = outputs

[1] Survey of 70% of farmers in the catchment

[2] Yearly values form PORTNOY (1990) multiplied by 0.25 for the wet season and 0.75 for the dry season

[3] N = 3

[4] N = 3

[5] N = 1

[6] MOODY and CHAPMAN (1991)

[7] N = 21 (wet), N = 17 (dry)

[8] N = 5 (wet), N = 6 (dry)

[9] N = 3

is clearly dominated by dissolved nitrate from the catchment. However, during the dry season nitrogen input to the upper estuary is dominated by resuspension of sediments, sediment/water fluxes, groundwater and the lower estuary. Other sources of nitrogen include particulate nitrate flux from the catchment and lower estuary and atmospheric fallout.

Table 4. *Major nutrient inputs and outputs for the upper Moresby Estuary.*

	Phosphate Concentration		Phosphate Flux (× 10^3 moles)	
Nutrient Source/Sink	Wet Season	Dry Season	Wet Season	Dry Season
Catchment runoff (dissolved)[1]	0.15 ± 0.14 μmol·L^{-1}	0.39 ± 0.39 μmol·L^{-1}	+19.89 ± 18.79	+20.97 ± 21.18
Catchment runoff (particulate)[2]	79.16 ± 41.49 μmol·g^{-1}	14.90 ± 6.55 μmol·g^{-1}	+84.03 ± 45.18	+0.80 ± 0.12
Catchment sub-surface flow[3]	0.46 ± 0.1 μmol·L^{-1}	0.32 ± 0.09 μmol·L^{-1}	+19.22 ± 5.88	+5.41 ± 1.98
Atmospheric fallout[4]	0.04 ± 0.00 μmol·L^{-1}	0.04 ± 0.00 μmol·L^{-1}	+3.36 ± 0.81	+1.36 ± 0.33
Lower estuary (dissolved)[5]	0.05 ± 0.02 μmol·L^{-1}	0.03 ± 0.01 μmol·L^{-1}	+24.75 ± 10.09	+35.10 ± 11.99
Lower estuary (particulate)[5]	8.65 ± 1.41 μmol·g^{-1}	5.62 ± 0.90 μmol·g^{-1}	+107.06 ± 18.99	+164.38 ± 28.73
Resuspension[6]	—	2.65 ± 0.65 μmol·g^{-1}	—	+118.20 ± 36.01
Lower estuary (dissolved)[5]	0.06 ± 0.02 μmol·L^{-1}	0.03 ± 0.01 μmol·L^{-1}	−44.70 ± 15.26	−37.46 ± 12.79
Lower estuary (particulate)[5]	10.68 ± 1.50 μmol·g^{-1}	5.62 ± 0.89 μmol·g^{-1}	−198.90 ± 31.21	−175.45 ± 21.10
Long term sedimentation[7]	1.65 ± 0.36 μmol·g^{-1}	2.56 ± 0.65 μmol·g^{-1}	−0.17 ± 0.06	−0.83 ± 0.21
Short term sedimentation[8]	1.65 ± 0.36 μmol·g^{-1}	—	−123.44 ± 68.57	—
Total annual difference			+23.59 ± 110.13	

[1] N = 21 (wet), N = 17 (dry)

[2] N = 5 (wet), N = 6 (dry)

[3] N = 3

[4] N = 1

[5] Ebb N = 58 (wet), N = 40 (dry), flood N = 46 (wet), N = 62 (dry)

[6] Sedimentation rate (resuspension) −45.00 ± 7.90 mm·dry season^{-1}, bulk density 0.59 g·cm$^{3\ -1}$

[7] Sedimentation rate 0.24 mm·yr^{-1}, bulk density 1.04 g·cm$^{3\ -1}$, N = 8

[8] Sedimentation rate 73.00 ± 38.00 mm·wet season^{-1}, bulk density 0.61 g·cm$^{3\ -1}$

Table 3. *Extended.*

Nitrogen Concentration		Nitrogen Flux (×10³ moles)	
Wet Season	Dry Season	Wet Season	Dry Season
—	171.00 ± 63.00 kg·ha⁻¹	—	+79,330.46 ± 11,338.04
0.56 kg·capita⁻¹	1.67 kg·capita⁻¹	+11.99	+35.77
13.40 ± 6.81 μmol·L⁻¹	1.61 ± 0.58 μmol·L⁻¹	+453.99 ± 237.14	+22.11 ± 8.45
16.16 ± 5.42 μmol·g⁻¹	13.70 ± 5.44 μmol·g⁻¹	+4.38 ± 1.56	+0.19 ± 0.08
8.71 ± 3.50 μmol·L⁻¹	6.71 ± 1.17 μmol·L⁻¹	+92.94 ± 42.23	+28.99 ± 7.99
1.14 ± 0.00 μmol·L⁻¹	1.14 ± 0.00 μmol·L⁻¹	+208.60 ± 7.86	+84.52 ± 3.19
—	63.00 ± 6.30 kg·ha⁻¹	—	−29,227.01 ± 2,922.74
31.20 ± 26.25 μmol·L⁻¹	2.80 ± 2.77 μmol·L⁻¹	−4,139.93 ± 3,518.41	−121.52 ± 150.09
58.12 ± 55.48 μmol·g⁻¹	13.70 ± 3.70 μmol·L⁻¹	−61.70 ± 59.36	−0.74 ± 0.08
76.30 ± 33.04 μmol·L⁻¹	52.34 ± 10.50 μmol·L⁻¹	−3,187.81 ± 1,534.14	−885.59 ± 257.15
		+42,649.64 ± 12,327.88	

Most phosphorus is transported from the upper estuary in both the wet and dry seasons as particulate phosphorus flux to the lower estuary. Appreciable amounts are also removed by short term sedimentation in the dry season. Some phosphorus is also removed as dissolved phosphorus flux to the lower estuary and through long term sedimentation.

Table 4. *Extended.*

Nitrogen Concentration		Nitrogen Flux (×10³ moles)	
Wet Season	Dry Season	Wet Season	Dry Season
31.20 ± 26.25 μmol·L⁻¹	2.80 ± 2.77 μmol·L⁻¹	+4,139.93 ± 3,518.41	+121.52 ± 150.09
58.12 ± 55.48 μmol·g⁻¹	13.70 ± 3.70 μmol·g⁻¹	+61.70 ± 59.36	+0.74 ± 0.08
76.30 ± 33.04 μmol·L⁻¹	52.34 ± 10.50 μmol·L⁻¹	+3,187.81 ± 1,534.14	+885.59 ± 257.15
1.14 ± 0.00 μmol·L⁻¹	1.14 ± 0.00 μmol·L⁻¹	+95.89 ± 22.95	+38.85 ± 9.30
2.95 ± 1.44 μmol·L⁻¹	0.66 ± 0.35 μmol·L⁻¹	+1,460.46 ± 720.22	+772.17 ± 413.07
0.74 ± 0.55 μmol·g⁻¹	8.46 ± 3.60 μmol·g⁻¹	+9.16 ± 6.84	+247.45 ± 106.71
—	20.93 ± 8.98 μmol·g⁻¹	—	+933.56 ± 434.00
7.12 ± 1.15 μmol·L⁻¹	0.66 ± 0.34 μmol·L⁻¹	−5,304.26 ± 933.76	−824.16 ± 428.50
0.72 ± 0.67 μmol·g⁻¹	8.46 ± 3.70 μmol·g⁻¹	−13.41 ± 12.51	−264.10 ± 116.98
19.71 ± 9.29 μmol·g⁻¹	20.93 ± 8.98 μmol·g⁻¹	−2.06 ± 1.01	−6.58 ± 2.85
19.71 ± 9.29 μmol·g⁻¹	—	−1,474.51 ± 1,024.09	—
		+4,066.01 ± 4,222.89	

Table 5. *Major nutrient inputs and outputs for the lower Moresby Estuary.*

	Phosphate Concentration		Phosphate Flux ($\times 10^3$ moles)	
Nutrient Source	Wet Season	Dry Season	Wet Season	Dry Season
Upper estuary (dissolved)[1]	$0.06 \pm 0.02\ \mu mol \cdot L^{-1}$	$0.03 \pm 0.01\ \mu mol \cdot L^{-1}$	$+44.70 \pm 15.26$	$+37.46 \pm 12.79$
Upper estuary (particulate)[1]	$10.68 \pm 1.50\ \mu mol \cdot g^{-1}$	$5.62 \pm 0.89\ \mu mol \cdot g^{-1}$	$+198.90 \pm 31.21$	$+175.45 \pm 0.67$
Atmospheric fallout[2]	$0.04 \pm 0.00\ \mu mol \cdot L^{-1}$	$0.04 \pm 0.00\ \mu mol \cdot L^{-1}$	$+0.95 \pm 0.10$	$+0.39 \pm 0.04$
Ocean (dissolved)[1]	$0.08 \pm 0.02\ \mu mol \cdot L^{-1}$	$0.10 \pm 0.02\ \mu mol \cdot L^{-1}$	$+104.27 \pm 24.10$	$+295.59 \pm 62.69$
Ocean (particulate)[1]	$12.95 \pm 0.27\ \mu mol \cdot g^{-1}$	$5.14 \pm 0.14\ \mu mol \cdot g^{-1}$	$+375.09 \pm 27.40$	$+379.84 \pm 28.53$
Upper estuary (dissolved)[1]	$0.05 \pm 0.02\ \mu mol \cdot L^{-1}$	$0.03 \pm 0.01\ \mu mol \cdot L^{-1}$	-24.75 ± 10.09	-35.10 ± 11.99
Upper estuary (particulate)[1]	$8.65 \pm 1.41\ \mu mol \cdot g^{-1}$	$5.62 \pm 0.90\ \mu mol \cdot g^{-1}$	-107.06 ± 18.99	-164.38 ± 28.73
Ocean (dissolved)[1]	$0.11 \pm 0.02\ \mu mol \cdot L^{-1}$	$0.10 \pm 0.01\ \mu mol \cdot L^{-1}$	-157.30 ± 30.70	-303.70 ± 37.10
Ocean (particulate)[1]	$12.60 \pm 0.54\ \mu mol \cdot g^{-1}$	$5.05 \pm 0.30\ \mu mol \cdot g^{-1}$	-450.45 ± 36.97	-383.42 ± 35.20
Long term sedimentation[3]	$4.48 \pm 1.24\ \mu mol \cdot g^{-1}$	$8.47 \pm 2.10\ \mu mol \cdot g^{-1}$	-2.04 ± 0.61	-11.56 ± 3.06
Total annual difference			-27.12 ± 119.40	

Positive values = inputs, negative values = outputs

[1] Ebb N = 58 (wet), N = 40 (dry), flood N = 46 (wet), N = 62 (dry)

[2] N = 1

[3] Sedimentation rate 0.5 $mm \cdot yr^{-1}$

During the wet season, nitrogen is mainly transported from the upper estuary as dissolved nitrate flux to the lower estuary. An appreciable amount of nitrogen is also removed through short term sedimentation. In contrast, during the dry season nitrogen is transported from the upper estuary dominantly as dissolved and particulate-bound flux to the lower estuary. Nitrogen is also removed through long term sedimentation.

Nutrient Inventory in the Lower Estuary

The major nutrient inputs and outputs for the wet and dry seasons in the lower estuary are summarised in Table 5. Phosphorus inputs to, and outputs from, the lower estuary for both seasons are dominated by the particulate phosphorus flux to and from the ocean and upper estuary. An appreciable amount of phosphorus is also supplied to and removed from the lower estuary in the dry season as dissolved flux to and from the ocean. Other phosphorus inputs to the lower estuary include dissolved phosphorus flux from the upper estuary and atmospheric fallout. Phosphorus is also removed through long term sedimentation.

In both the dry and wet seasons most of the nitrogen input to the lower estuary is supplied by dissolved nitrate flux from the upper estuary. Nitrogen output from the lower estuary is dominated by dissolved nitrate flux to the ocean and upper estuary. Other sources of nitrogen include the particulate-bound nitrate flux from the upper estuary and the ocean, dissolved nitrate flux from the ocean and atmospheric fallout. Nitrogen is also removed as particulate-bound nitrate flux to the upper estuary and ocean and through long term sedimentation.

DISCUSSION

Balancing the Overall Budget

Calculation of a nutrient budget for the Moresby Estuary and catchment revealed discrepancies for phosphorus and nitrogen in each compartment (Tables 3, 4, 5). Some discrepancies such as nitrogen in the upper estuary and phosphorus in the upper and lower estuary are clearly less than budget uncertainties. This suggests that processes in the upper estuary may have reached a steady state, or simply that smaller scale processes cannot be resolved at this level of nutrient balance. However, larger discrepancies such as nitrogen and phosphorus in the lower catchment and nitrogen in the lower estuary are larger than budget uncertainties and suggest the existence of a major sink or source other than those considered. Although inputs and outputs for individual seasons are calculated, the budget is balanced on an annual basis because of the better agreement between annual fluxes than seasonal fluxes. The disparity between seasonal budget estimates is due to nutrients being accumulated during the dry season and transported during the wet season.

The extra 1,401.32 × 10^3 moles of phosphorus in the lower catchment (Table 3) can be accounted for as an increase in the soil phosphorus concentration. The difference between the average soil

Table 5. *Extended.*

Nitrogen Concentration		Nitrogen Flux (× 10^3 moles)	
Wet Season	Dry Season	Wet Season	Dry Season
7.12 ± 1.15 μmol·L^{-1}	0.66 ± 0.31 μmol·L^{-1}	+5,304.26 ± 933.76	+824.16 ± 428.50
0.72 ± 0.67 μmol·g^{-1}	8.46 ± 3.70 μmol·g^{-1}	+13.41 ± 12.51	+264.10 ± 116.98
1.14 ± 0.00 μmol·L^{-1}	1.14 ± 0.00 μmol·L^{-1}	+27.35 ± 3.01	+11.09 ± 1.22
0.10 ± 0.12 μmol·L^{-1}	0.27 ± 0.27 μmol·L^{-1}	+115.86 ± 139.29	+798.10 ± 130.80
1.96 ± 0.14 μmol·g^{-1}	4.49 ± 0.30 μmol·g^{-1}	+56.77 ± 5.68	+331.80 ± 32.10
2.95 ± 1.44 μmol·L^{-1}	0.66 ± 0.35 μmol·L^{-1}	−1,460.46 ± 720.22	−772.17 ± 413.07
0.74 ± 0.55 μmol·g^{-1}	8.46 ± 3.70 μmol·g^{-1}	−9.16 ± 6.84	−247.45 ± 106.71
0.32 ± 0.14 μmol·L^{-1}	0.27 ± 0.03 μmol·L^{-1}	−457.60 ± 202.78	−819.99 ± 107.71
1.96 ± 0.18 μmol·g^{-1}	4.49 ± 0.27 μmol·g^{-1}	−70.07 ± 4.95	−340.90 ± 23.86
14.43 ± 2.69 μmol·g^{-1}	24.26 ± 7.94 μmol·g^{-1}	−6.57 ± 1.32	−33.11 ± 11.43
		3,529.42 ± 1,364.25	

phosphorus concentration in the upper catchment (5.18 μmol·g^{-1}; Eyre, 1993) and the lower catchment (16.10 μmol·g^{-1}; Eyre, 1993) is 10.92 μmol·g^{-1}. If it is assumed that the concentration increased consistently over the last 100 years (the approximate period over which there has been intense farming in the catchment), it would require an addition of 0.1092 μmol of phosphorus per gram of catchment soil per year. Using a bulk density of 1.0 g·cm^{-3} (N = 5) and a surface area of 64.98 × 10^6 m^2 (Table 1) excess phosphorus in the lower catchment can be accounted for in the top 20 cm of the soil profile. However, such an increase in soil phosphorus concentrations can only continue until the phosphorus adsorption capacity of the soil is reached (Moody and Chapman, 1991). This suggests that once the phosphorus adsorption capacity of the soil is reached, more phosphorus may be removed in runoff than is currently occurring.

Large amounts of nitrogen fertilizer (urea) can be lost through volatilization of ammonia (Moody and Chapman, 1991) and by increasing the soil nitrogen concentration. The difference between the average soil nitrogen concentration in the upper catchment (40.50 μmol·g^{-1}; Eyre, 1993) and the lower catchment (109.00 μmol·g^{-1}; Eyre, 1993) is 68.50 μmol·g^{-1}. Assuming that this increase has occurred consistently over the last 100 years in the top 20 cm of soil in the lower catchment it would account for 8,902 × 10^3 moles of nitrogen per year. The soil depth value of 20 cm is a reasonable figure based on the study conducted by Gillman and Bristow (1990), who found that nitrogen fertilizer applied to the surface as ammonium sulphate and urea was retained in the top 20 cm. Taking the value of 8,902 × 10^3 moles away from the value of 42,649.64 × 10^3 moles for extra nitrogen in the lower catchment budget (Table 3) suggests that 33,747.64 × 10^3 moles of nitrogen per year is lost through volatilization. This value is about 43% of the total amount of nitrogen fertilizer applied and agrees well with the values of Moody and Chapman (1991; up to 60%) and Denmead *et al.* (1990; 30–40%) for nitrogen fertilizer loss through volatilization in wet tropical areas. However, 43% probably represents a maximum value, because some on the nitrogen surplus may be removed as dissolved and particulate organic nitrogen.

Eyre (1994) suggests that nitrate is removed from the Moresby Estuary water column by biological uptake, which may explain the nitrogen surplus in the lower estuary. Using the method outlined in Fisher *et al.* (1988) based on departures from conservative mixing on a nutrient/salinity plot (given in Eyre, 1994) and the estuary water volume, the amount of nitrogen removed in the lower estuary was calculated. This value of 4,618 × 10^3 moles easily accounts for the nitrogen surplus in the lower estuary. If a similar calculation is performed for the upper estuary 3,432 × 10^3 moles of nitrogen are removed from the water column by biological uptake. Other possible removal processes for this excess nitrogen are exchange with the atmosphere as gaseous nitrogen after denitrification, or alternatively it may be converted to forms of nitrogen that were not measured (*e.g.*, organic nitrogen).

Seasonal Fluxes

Although the budget has been balanced on an annual basis, seasonal fluxes illustrate the influence of catchment hydrology. The wet season lasts for 25% of the year, but accounts for about 82% of the phosphorus and about 90% of the nitrogen flux from the catchment. This observation is not unexpected, however, what is interesting is the effect seasonal rainfall has on nutrient fluxes out of the estuary. The average nutrient composition of the water measured at the estuary mouth shows little variation between ebb and flood tides in the dry season. This situation would remain the same all year round with very little net phosphorus and nitrogen flux to the ocean without the high wet season rainfall. The wet season accounts for about 92% of the annual phosphorus and nitrogen flux out of the estuary. Thus, the wet season has a significant impact on nutrient fluxes in the estuary as well as in the catchment.

Estimation of Interpolation Error

The amount of phosphorus and nitrogen remaining in the estuary can be calculated as the difference between inputs and outputs. These fluxes were calculated from the study of 2 days of nutrient transport averaged over an annual water budget. The problems of using such an approach where small instantaneous net fluxes are measured against a large background transport of water have been discussed by NIXON (1987). NIXON (1987) found that such an approach, even where extensive data sets (*e.g.*, 38 days) are available, can lead to large errors. He suggests that a more accurate estimate of nutrient retention can be obtained using nutrient and sediment input combined with the chemical composition of the accumulated sediment. Such a calculation should provide a simple check on the accuracy of the estimate obtained using the input-output approach.

Total P input = 156.39 × 10^3 moles·yr^{-1} (4,843.99 kg·yr^{-1})
Total N input = 8,339.03 × 10^3 moles·yr^{-1} (116,802.29 kg·yr^{-1})
Total sediment input = 1,112,200 kg·yr^{-1}

If all the phosphorus and nitrogen remain in the estuary, the average sediment composition should equal 0.44% P and 10.5% N. The average composition of sediments in the Moresby Estuary is 4.64 μmol·g^{-1} (0.014%) phosphorus and 20.0 μmol·g^{-1} (0.028%) nitrogen (EYRE, 1993) suggesting that only about 3% of the phosphorus and < 1% of the nitrogen actually remains in the estuary. Using the input-output approach, nearly all of the phosphorus (82%) added to the water column in the estuary is transferred to the ocean (Tables 3, 4, 5). In contrast, only about 4% of the nitrogen that is added to the water column in the estuary is transferred to the ocean (Tables 3, 4, 5) and it is suggested that about 87% used biologically (calculated using the method of FISHER *et al.*, 1988). Therefore, about 18% of the phosphorus and about 9% of the nitrogen that enters the estuary remains in the estuary.

The differences between the two estimates of nutrient retention may be explained by the fact that the input-output approach does not consider the day-to-day variability of nutrient fluxes (*e.g.*, a storm event). One such high energy event may transport some nutrients out of the estuary. A record of this nutrient loss would be recorded in the sediments, but missed by the temporally limited input-output approach. Further evidence of this flushing of some nutrients and sediments during high energy events is illustrated by the difference between short term and long term sedimentation (Tables 4 and 5). Short term sedimentation shows a greater burial of nutrients suggesting more material is trapped in the estuary through sedimentation than shown by long term sedimentation. The long term sedimentation records account for high energy events being averaged over the last 1,800 to 3,500 years but, such events may be missed by short term sedimentation which accounts for only a few months of accumulation. Although calculations by both approaches can only be considered as rough approximations because of budget uncertainties, both approaches reach the same general conclusion that very little of the nutrients that enter the estuary are retained in the estuary.

Unpublished data (TED LODER, *personal communication*, 1993) show that ammonium concentrations in the Moresby catchment and estuary are on average about 5% of the nitrate concentrations suggesting that ammonium will not affect budget calculations. However, as no dissolved or particulate organic phosphorus and nitrogen analyses were undertaken in this study, the contribution of these nutrient forms to the nutrient

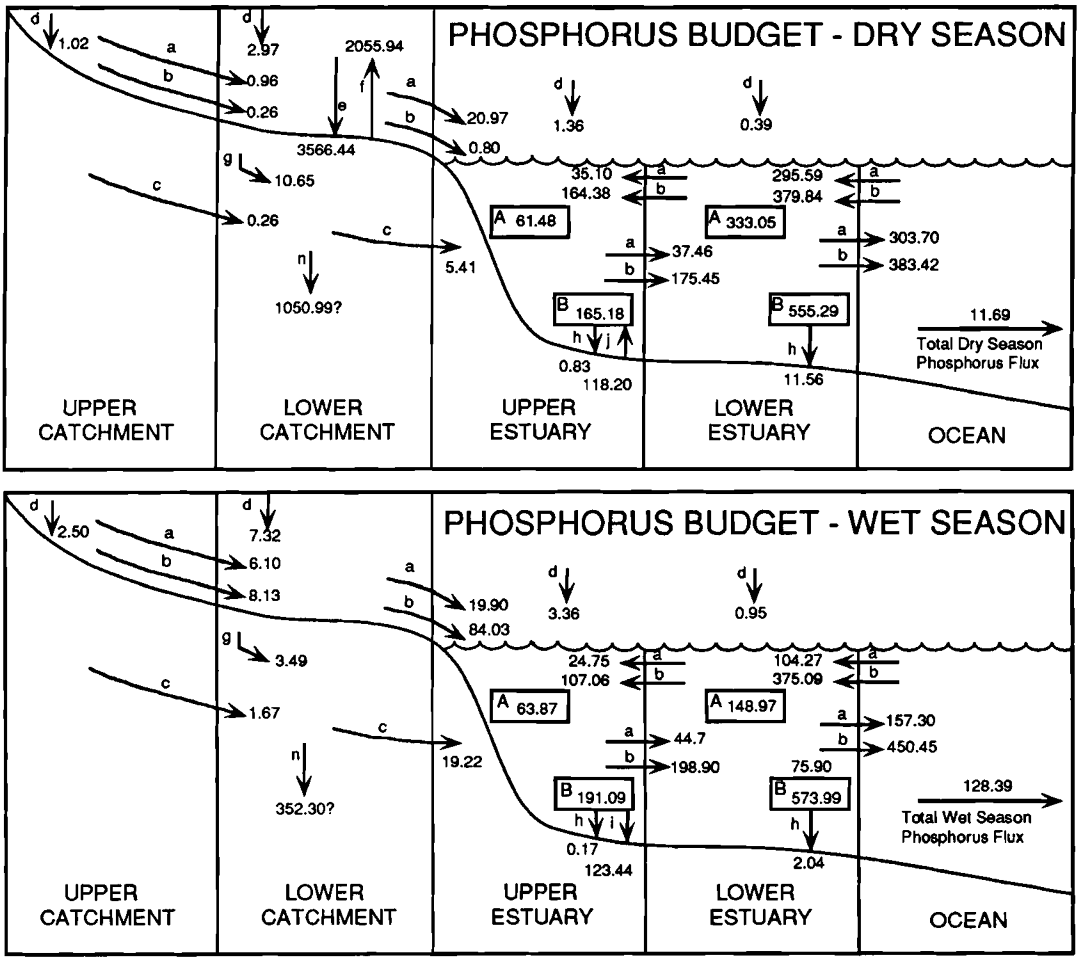

Figure 3. Schematic model of phosphorus budgets for the dry and wet seasons in the Moresby Estuary and catchment. *Reservoirs* ($\times 10^3$ moles): A, dissolved load; B, particulate-bound load. *Fluxes* ($\times 10^3$ moles): a, dissolved; b, particulate; c, groundwater; d, precipitation; e, fertilizers; f, crop removal; g, septic tanks; h, long term sedimentation; i, short term sedimentation; j, resuspension; n, soil uptake. ? = terms added to balance the budget.

budgets cannot be quantified. No comparison could be made with published work because of the lack of studies in tropical regions that include dissolved and particulate inorganic and organic forms of phosphorus and nitrogen in both the catchment and estuary. This is clearly an area that urgently needs some pioneer work.

The lack of organic nutrient data suggests that the budget probably under-estimates total nutrient flux. To illustrate the effect this may have on budget calculations, it will be assumed that inorganic phosphorus and nitrogen only account for 50% of the total phosphorus and nitrogen flux. Combining these new fluxes with the chemical composition of the sediments which include inorganic and organic forms of phosphorus and nitrogen would suggest that only about 2% of the phosphorus and < 1% of the nitrogen remains in the estuary. The same overall conclusion is reached, that very little of the nutrients that enter the estuary are retained.

Budget Implications

The dry and wet season phosphorus and nitrogen budgets (Figures 2 and 3) developed here may be used as a predictive tool. To assess the impact

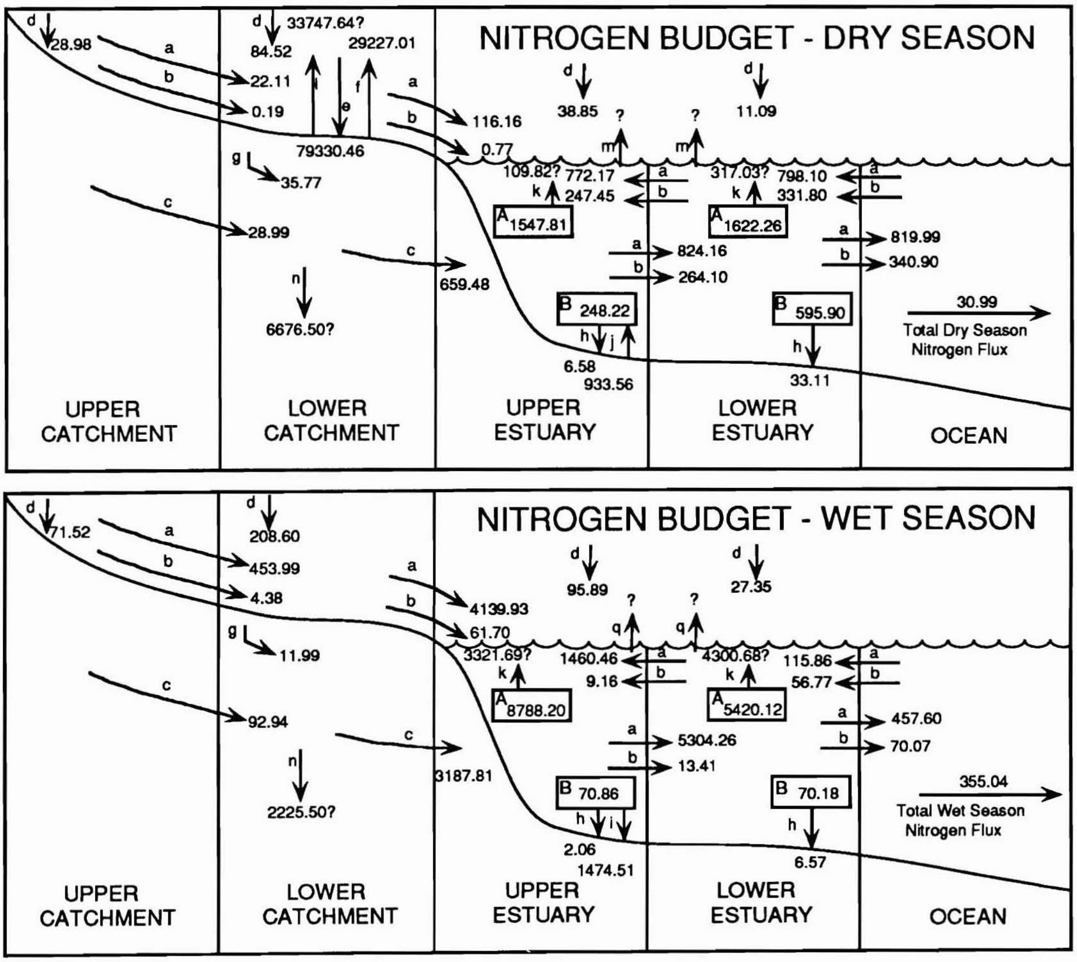

Figure 4. Schematic model of nitrogen budgets for the dry and wet seasons in the Moresby Estuary and catchment. *Reservoirs* ($\times 10^3$ moles): A, dissolved load; B, particulate-bound load. *Fluxes* ($\times 10^3$ moles): a, dissolved; b, particulate; c, groundwater; d, precipitation; e, fertilizers; f, crop removal; g, septic tanks; h, long term sedimentation; i, short term sedimentation; j, resuspension; k, biological uptake; l, volatilization; m, atmospheric exchange; n, soil uptake. ? = terms added to balance the budget.

of anthropogenic inputs on a natural system any natural background signals must be removed. Assuming fluxes from the upper catchment can be extrapolated over the whole catchment if there are no anthropogenic perturbations (*e.g.*, humans, fertilizers, septic tanks), natural input from Moresby catchment to the upper estuary will approximate 61.30 × 10^3 mol·yr^{-1} phosphorus and 1,996.04 × 10^3 mol·yr^{-1} nitrogen. Comparing these values to current inputs of 150.55 × 10^3 mol·yr^{-1} phosphorus and 8,165.85 × 10^3 mol·yr^{-1} nitrogen shows that humans have caused a 2.5 fold increase in phosphorus and a 4 fold increase in nitrogen flux from the catchment to the upper estuary.

Although agricultural activities in the catchment have increased nutrient flux to the Moresby Estuary, the increased nutrient flux appears to be having no visible ecological impact (*e.g.*, eutrophication) on the system. The low retention of nutrients in the estuary sediments suggests that current levels of agricultural activity can be maintained in the Moresby catchment without adverse effect on the river-estuary system. The fact that Moresby Estuary sediments are not a strong sink for nutrients refutes suggestions (MITCHELL *et al.*, 1991) that estuaries in the Great Barrier Reef region may act as temporary sinks for large quantities of nutrients which are then discharged during large episodic flood events. A sudden release of large quantities of stored nutrients over a period of hours (*e.g.*, cyclone) may have a much more damaging effect on coastal ecosystems than a gradual release during normal runoff events.

SUMMARY AND CONCLUSIONS

Dry and wet season phosphorus and nitrogen budgets for the Moresby Estuary and catchment are summarised in Figures 3 and 4. Because of uncertainties involved in any mass balance calculation, this study emphasises detailed error analysis to allow any meaningful interpretation of budget components, particularly surpluses and deficits. Smaller scale processes cannot be resolved at this level of nutrient balance due to large budget uncertainties. However, the nutrient budget does give an insight into the catchment scale processes. Clearly fertilizer application on caneland in the Moresby Estuary catchment is the dominant source of nutrients to the system, however, only a relatively small proportion of these nutrients is transferred to the estuary. Once in the estuary, only small amounts of phosphorus and nitrogen are retained with most of the phosphorus being transferred to the ocean and it is suggested that most of the nitrogen may be used biologically. The fact that the Moresby Estuary is not a strong sink for nutrients (*i.e.*, it is not becoming eutrophic with time) suggests that current levels of agricultural activity in the catchment can be maintained without adverse effects on ecological components of the estuary and catchment.

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