Benthic and Pelagic Processes in the Fly River Delta and the Nearshore Gulf of Papua

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Introduction

Rivers in the tropics and subtropics contribute ~70% of the freshwater runoff and ~74% of the sediment discharge to the worlds oceans (Milliman, 1981; Meade, 1981). Little is known about how these high discharge rates and amounts of exported material influence ecological processes in adjacent nearshore habitats.

The Fly River, which lies at the northern boundary of the Torres Straits, has the potential to have a major influence on pelagic and benthic processes of the region. The Fly is approximately the tenth largest tropical river in the world, releasing ~238 km^3 of freshwater and 74 x 10^6 tonnes of suspended material annually into the Gulf of Papua (Alongi, 1990a).

Since 1984, a large gold and copper mine has been operating on the Ok Tedi, an upper tributary of the Fly, and has been depositing increasing amounts of suspended mining effluents into the Fly catchment area. Predictions for 1992 are for a 55% increase in mine-derived suspended load (see Eagle, this volume). This enormous tailings burden, plus the effluents being produced by the Porgera Joint Venture gold mine on the Strickland River, which enters the Fly approximately half way along its length, when coupled with the very high annual precipitation (up to 13 $m.y^{-1}$) in the headwaters of the catchment, suggest the potential for metal pollution and changes to the sedimentary regime of the Fly delta and the nearshore Gulf of Papua. Understandably, considerable attention has been focused on the potential impact of these mining activities on the environment, fisheries and health of the people inhabiting the Fly River and Torres Strait region (Dent, 1986; Pernetta, 1988; Georg, 1989).

During the last decade the Coastal Processes and Resources Program at the Australian Institute of Marine Science has concentrated on measuring the extent and influence of exported material from coastal habitats, mainly mangrove forests, in tropical Australia (eg. Wolanski *et al.*, 1980; Boto and Bunt, 1981; Robertson, 1986; Robertson *et al.*, 1988; Alongi, 1990 b, c; Alongi *et al.*, 1989). Recently, in order to study the influence of a major tropical river on adjacent shelf ecosystems, we mounted two, month-long expeditions to the Fly River estuary and nearshore regions (< 60 m depth) of the Gulf of Papua (July-August, 1989 and February, 1990). Sampling was performed at a number of sites in the river and the Gulf, and there were extensive examinations of mangroves on all islands within the delta (Figure 1).

The aims of these expeditions were to, (1) make first-order estimates of the net flux of carbon, nitrogen and phosphorous from the Fly River, (2) to study the influence that exported materials have on biological processes in the water column and the sediments of the Gulf of Papua and (3) to examine the vertical profiles of dissolved and particulate copper concentrations in the sediments of the region. Detailed results of this work are available in Robertson *et al.* (1990), Alongi (in press), Alongi *et al.* (in press a, b) and Robertson *et al.* (in press). Here we present a brief summary of some of the major findings of the work and suggest priority areas of future research.

Mangrove Forests: Extent and Productivity

There are 87,400 ha of mangrove forest in the Fly delta. These forests occur mainly on the delta islands (except Kiwai, which has few mangroves). Although there are at least twenty-nine mangrove plant species in the delta there are only three dominant forest types (Robertson *et al.*, in press). Forests of *Rhizophora apiculata, Bruguiera parviflora* and *B. gymnorhiza* predominate in regions where river salinity was >10 o/oo. These forests cover ~31,500 ha. Forests dominated by the mangrove palm, *Nypa fruticans*, cover 38,400 ha mainly in regions of the delta where salinity ranges from ~1 to <10 o/oo. On accreting banks of sediment throughout the delta there are extensive stands of *Avicennia marina* and/or *Sonnaratia species*. *Sonneratia lanceolata* forms large monospecific stands in regions of the delta with salinity <1 o/oo, and can be found as isolated trees up to 300 kilometres from the river mouth.

Potential net primary production (cf. Bunt *et al.*, 1979) is estimated to be 26.7, 27.1 and 19.0 for *Rhizophora-Bruguiera, Nypa* and *Avicennia-Sonneratia* forests, respectively. Total daily production by all mangroves is ~2,214 tonnes C. Using assumption about litter processing and export derived from work in tropical Australia (see Robertson *et al.*, 1990) we estimate that ~678 tonnes C. (or 31% of primary production) is exported daily from the mangrove forests to the waters of the delta.

Water Column Processes

In the delta, suspended sediment concentrations varied over an order of magnitude, depending on river flow conditions. Mean concentrations over all sites, depths and times of tide in the delta were 451 mg.l^{-1} and 100 mg.l^{-1} in July/August and February, respectively. Suspended loads at nearshore Gulf of Papua stations in February (a period of record low river flow) were similar to those in the delta. The suspended

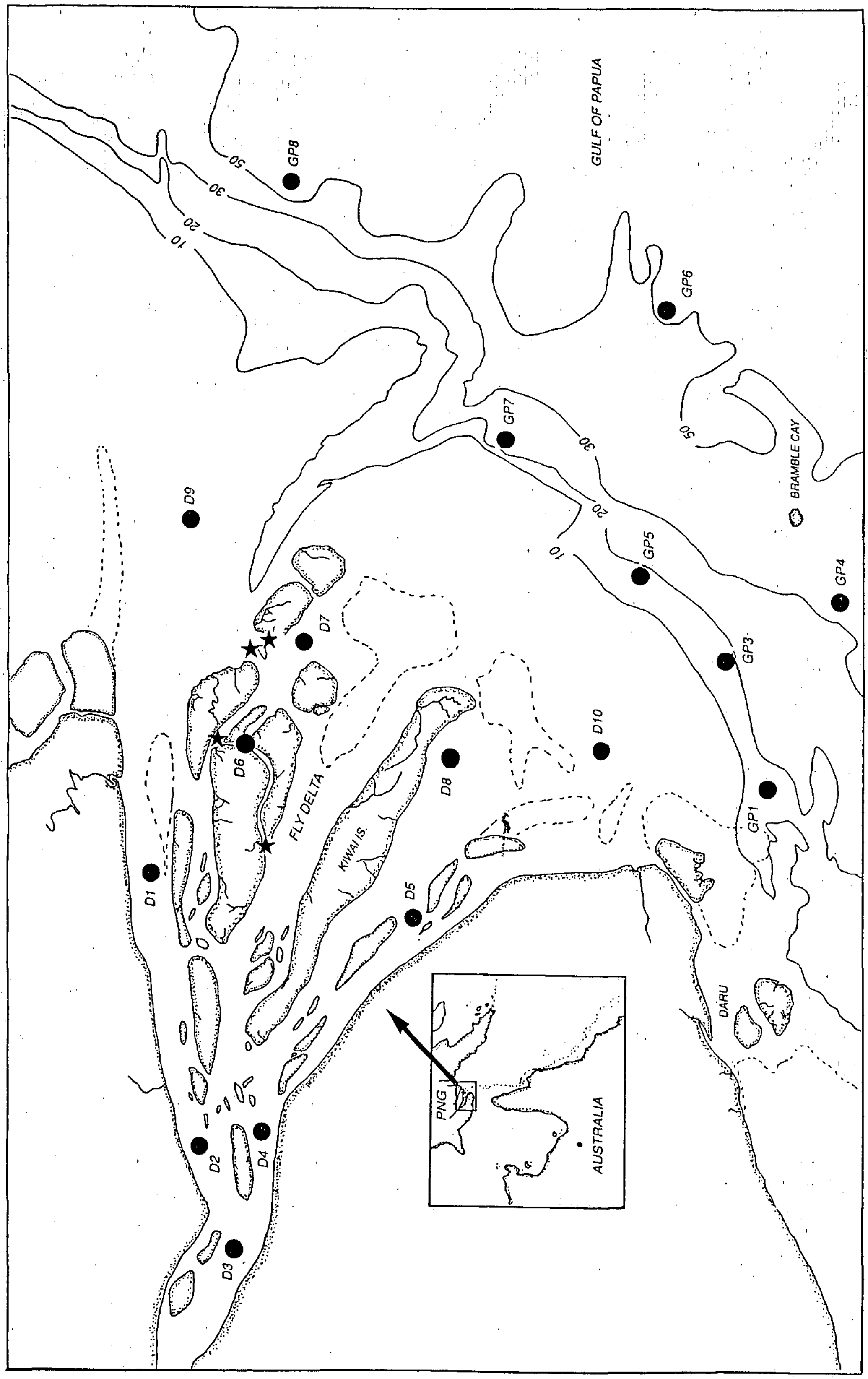

Figure 1. Location of sampling stations in the Fly Delta (D) and Gulf of Papua (GP) where water-column and subtidal sediment processes were measured. Stars mark the sites where intertidal sediment processes were measured. Contours are water depths in meters.

loads measured in the delta in the July/August period are similar to those in other large tropical rivers such as the Amazon, Niger and Mekong (Milliman, 1981; Meade, 1981).

The carbon to nitrogen ratios of suspended material showed a wide range of values (1-80), but mean values were low. In July/August 1989 mean C:N ratios in the delta were all <7, while in February, most delta station averaged ≤8. The worldwide C:N ratio for riverborne particulates is 8.8 (Maybeck, 1982).

As in all large rivers, there is a large quantity of floating plant tissue in and near the Fly. Except for the more freshwater stations we sampled, most of this material in the delta and coastal regions is of mangrove origin. The overall mean mass of macro-particulate detritus in the surface waters of the delta was ~200 $mg.m^{-3}$ (or ~80 mg C and 2.2 mg N per m^3).

Zooplankton species richness (total number of taxa at each station) ranged from 11 in the freshwater regions of the delta to 57 at 50 metres depth in the Gulf of Papua. Lowest densities (range 153-4155 $individ.m^{-3}$) and biomasses (<1-14 $mg.m^{-3}$) of zooplankton were recorded in the freshwater regions of the delta, but there was no clear relationship between salinity and densities or biomasses. Grand mean densities and biomasses of zooplankton in the delta and Gulf of Papua were 4798 $individ.m^{-2}$ and 157 $mg.m^{-3}$ and 8892 $individ.m^{-2}$ and 54 $mg.m^{-3}$, respectively.

Water column primary productivities from 0.4-28.0 $mgC.m^{-3}.h^{-1}$ were recorded in the delta and nearshore Gulf of Papua in February 1990. Daily production (integrated over depth) was lowest at the low salinity delta stations (22.1-94.5 $mgC.m^{-2}.d^{-1}$) and highest at stations at or beyond the highly stratified salinity zone near the river mouth (134.0-693.2 $mgC.m^{-2}.d^{-1}$). Production rates at most Gulf of Papua stations were similar to those from inshore samples near other large river plumes (see also Furnas, this volume).

The Fly delta and inshore Gulf of Papua waters are highly heterotrophic as evidenced by the very high community metabolism rates (0.8-36.0 $gC.m^{-2}.d^{-1}$), which are 1-2 orders of magnitude higher than *in situ* production (see above). Oxygen consumption rates in the study area (0.6-3.2 $g0_2.m^{-3}.d^{-1}$) are amongst the highest recorded for estuarine and coastal systems (Hopkinson, 1985).

Water column bacterial production ranged from 20-43 $mgC.m^{-2}.d^{-1}$ in the low salinity regions of the delta and from 143-2089 $mgC.,^{-2}.d^{-1}$ at the front of the delta and in the Gulf of Papua. We estimate that bacterial respiration accounts for ~9-49% of total community metabolism, implying the presence of a very active protozoan community in the water column.

Benthic Processes

Intertidal Mudbanks

Intertidal mudbanks are a prominent feature of the Fly delta region and appear to be a major site for the deposition of sediment and associated organic matter. A summary of data for intertidal mudbanks is given in Table 1.

Table 1. Summary of sedimentary, inorganic nutrient and biological characteristics for intertidal mudbanks in the Fly Delta. Source Alongi (in press).

A. Sedimentary characteristics

Vary from sites with rapid sediment deposition and erosion to more biologically controlled sites.

B. Particulate nutrients (C, N, P)

1. Range of values; carbon 0.7-1.9% DW, nitrogen 0.11-0.26% DW, phosphorous 5.8-7.3% DW.
2. C:N ratios, 3.9-8.5.
3. No depth profiles.

C. Dissolved nutrients (porewaters).

1. Range of values; DOC 2.9-29.5 $mgC.l^{-1}$, DON 7.9-79 µM, DOP 0.01-8.0 µM, NH_4 3-461 µM, NO_2 + NO3 0.8-3.8 µM, PO_4^{3-} 0.3-6 µM, $Si(OH)_4$ 41-99 µM.
2. Nutrient flux rates mostly undetectable.

D. Infauna

1. Meiofauna density 29-340 individ.10 cm^{-2} (other tropical sites, range 3-5380, mode ~800).
2. Macrofauna
   (a) density 174-6185 $individ.m^{-2}$
   (b) biomass 0.17-1.38 $gDW.m^{-2}$
   (other tropical sites; density 200-6000 $individ.m^{-2}$, biomass 1-40 $gDW.m^{-2}$).

E. Biological Processes

1. Bacterial production 187-413 $mgC.m^{-2}.d^{-1}$ (other tropical sites, 100-651 $mgC.m^{-2}.d^{-1}$).
2. Community respiration 145-206 $mgC.m^{-2}.d^{-1}$ (other tropical sites, 47-1200 $mgC.m^{-2}.d^{-1}$).

Our studies reveal that the intertidal mudbanks in the Fly delta possess a combination of characteristics rarely, if ever, observed in temperate intertidal muds, including; (1) a general lack of vertical profile in dissolved and particulate nutrients and in bacterial numbers and activity; (2) high bacterial growth rates; (3) lack of detectable nutrient fluxes; (4) low faunal biomasses; and (5) low net primary production.

The lack of solid-phase and porewater nutrient profiles in sediments are usually attributed to low sediment accumulation rates or to low reactivity of deposited organic matter. In most temperate muds, recycling of labile organic matter attenuates rapidly with sediment depth, leaving only the refractory matter to be deposited,

and observed as an increase in organic content with depth. In the Fly mudbanks, it appears that the high rates of bacterial productivity throughout the sediment led to the observed pattern of vertical distribution and exchange of particulate and dissolved nutrients. It is likely that organic detritus is rapidly deposited onto the mudbanks and is very rapidly remineralised by bacteria. Rapid rates of decomposition over the depth profile may be maintained by remixing due to physical processes and/or bioturbation. Both high temperatures and low grazer (meiofauna) populations lead to high bacterial production rates.

It thus appears that the highly active bacterial communities in intertidal mudbanks sequester, mineralise and recycle most of the labile organic detritus. These mudbanks therefore function as net sinks for organic matter, rather than as net exporters of nutrients to the pelagic portion of the system.

Subtidal Sediments

In the delta there are two main types of subtidal sediment (Table 2). In exposed regions, there are compacted, very fine sands with high iron (up to 9.8% DW) and low water content. On the leeward side of delta islands there are highly laminated muds and muddy sands without any biogenic structures. There are three major categories of sediments in the nearshore Gulf of Papua. Close to the delta there are muds and muddy sands with high sedimentation rates, obvious layering and some biogenic structures. Towards Bramble Cay there are mixed terriginous-carbonate sediments with lower sedimentation rates and some biogenic structures. In deeper waters to the north-east of the delta there are fluid muds which are well bioturbated.

There are noticeable differences in the stocks of fauna and the rates of biological processes between subtidal sediments in the delta and the nearshore Gulf of Papua. For instance, meiofaunal and macrofaunal densities are generally greater in the Gulf than the delta, as is bacterial production and community respiration (Table 2). In addition, there is little or no net flux of nutrients between the sediment and water in the delta, but significant fluxes in the Gulf of Papua. It appears that most organic material is remineralised at sites with the muddiest sediments in the delta and at the deeper (>50 m) sites in the Gulf, where lower water motion and lower sedimentation rates have allowed a stable seabed and benthic community to develop.

Faunal densities in the Gulf are low compared to most other shelf regions, but equivalent to faunal abundances near the Amazon (Alongi, 1990a). Low densities in the delta are probably due to the compacted, eroded nature of the main channels and low organic resources.

There are no clear increases or decreases in the concentrations of particulate carbon, nitrogen or phosphorous with depth in subtidal sediments. This is identical to the situation for sediments in the central Great Barrier Reef region, but in contrast to the benthic chemistry off the Amazon and Changjang Rivers, where sharp vertical profiles have been measured for most elements. X-radiographs indicate that the lack of profiles in the Fly is due to vertical mixing either from physical disturbance, bioturbation or both.

Table 2. Summary of sedimentary inorganic nutrient and biological characteristics for subtidal sediments in the Fly delta and nearshore Gulf of Papua. Source Robertson *et al.*, (1990).

A. Sedimentary characteristics

1. Exposed regions of the delta – compacted, very fine sands with high iron and low water content.
2. Leeward side of delta islands – highly laminated muds and muddy sand with no biogenic structures.
3. Nearshore Gulf of Papua – (a) mud-muddy sands, with high sedimentation rates, layering and biogenic structures; (b) mixed terriginous – carbonate sediments with low sedimentation rates and some biogenic structure; (c) fluid muds, well bioturbated and low sedimentation rates.

B. Particulate nutrients (C, N, P)

1. Range of values; carbon 0.14-1.39% DW, nitrogen 0.05-0.24% DW, phosphorous 0.062-0.113% DW.
2. Nutrient concentrations greater in muds than sands.
3. No clear vertical profiles in C, N or P, indicating strong vertical mixing from physical disturbance, bioturbation or both.

C. Dissolved nutrients (porewaters)

1. Range of values; NH_4 <1->500 µM – increasing with depth; NO_2 +NO_3 <1-44 µM – no depth profile, PO_4 <1-6.9 µM – no depth profile, $Si(OH)_4$ 22.5-180 µM - no depth profile.
2. Fluxes; (a) delta – with the exception of silicate, no flux or net uptake by sediments, (b) Gulf of Papua – net flux to water for all nutrients, (c) dissolved organic carbon – net uptake by sediments, particularly in the delta.

D. Infauna

1. Meiofauna; (a) delta 5-107 individ.10cm^2, (b) Gulf of Papua 81-750 individ.10cm^2.
2. Macrofauna; (a) delta 86-811 individ.m^{-2}, (b) Gulf of Papua 726-5555 individ.m^{-2}.

E. Biological Processes

1. Bacterial production 325-2108 mgC.m^{-2}.d^{-1}.
2. Community respiration; (a) delta mean 102 mgC.m^{-2}.d^{-1}, (b) Gulf of Papua mean 406 mgC.m^{-2}.d^{-1}.

Copper Concentrations

Particulate copper concentrations and dissolved copper in porewaters were measured at 2 cm intervals in 20 cm sediment cores at all subtidal stations (Figure 1). Trends in particulate copper levels with sediment depth were not consistent among stations. For most stations there was no change with depth. Two stations in the southern channel of the delta had the highest mean concentrations of copper (means of top 2 cm, 71 and 48 $mg.g^{-1}$ DW), but other delta stations did not contain significantly higher levels of copper than stations in the Gulf of Papua (Table 3).

Table 3. Concentrations of copper in the surface (2 cm) sediment of the Fly delta and nearshore Gulf of Papua in July/August 1989 and February 1990. Also shown are ranges of values for other tropical coastal areas.

Site		Particulate copper ranges (ppm)
Fly River region	(a) delta	8-71 (mean 30)
	(b) nearshore Gulf	7-24 (mean 17)
Upper Gulf of Thailand*		0.5-20
Malay Peninsular coast*		10-38
Coastal Java Sea*		9-58

* Source Everaats (1989)

Dissolved copper concentrations in the porewaters and in the bottom waters near sediments were consistently less than or at the detection limits for our techniques (0.01 $mg.ml^{-1}$; Alongi *et al.*, in press a). Fluxes of dissolved copper across the sediment-water interface were detected only at two of the stations in the delta and were low and in different directions (uptake and efflux of 6 $mg.m^{-2}.d^{-1}$), indicating that diagnesis of deposited copper was minor.

Average total copper concentrations cited as baseline levels for coastal habitats are often not necessarily comparable, as these levels are based on samples taken mainly from temperate areas. Comparisons with copper levels in other tropical sediments is more appropriate (Table 3) and indicate that particulate copper levels in the region of the Fly delta for July/August 1989 and February 1990 were not abnormally high.

Copper concentrations need to be determined from sediments of other Papuan rivers, where no mining exists, in order to develop appropriate baseline levels. It is likely that metal concentrations will eventually increase in the Fly River region as mining operations are expected to reach peak production by the mid-1990s. The slightly greater concentrations of particulate copper in actively accreting sediments of the southern channel in the Fly delta (see Wolanski, this volume) may represent the first evidence of tailings input from the mine.

Conclusions

Given the increase in the activities of mining and petroleum industries in the Gulf of Papua region during the last 2-3 years there has arisen a legitimate concern for the environment of the Gulf of Papua and the Torres Strait region, including the northern parts of the Great Barrier Reef.

From a biologist's point of view, a key problem in trying to assess the possible impacts of developments in the region is the lack of any background information on biological processes within the water column and benthos of most of the Gulf of Papua. Of particular concern is our ignorance of the way in which materials exported from rivers in the Gulf are processed through food chains supporting the important demersal fisheries in the northern Torres Strait and the northern Gulf of Papua. We suggest that in addition to the proposed baseline study of heavy metal concentrations in the Torres Strait, support be given for more process-oriented research in the region.

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