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Sediment transport in the Fly River basin, Papua New Guinea

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Abstract Changes to the sediment budget of the tropical Ok Tedi/Fly River fluvial system have resulted from mining activity in its upper reaches. High rainfall, and seismic activity cause high rates of natural and chemical weathering, and sediment delivery. The natural sediment load of the Fly River is increased by discharges from the Ok Tedi copper mine in the headwaters of the Ok Tedi. Aggradation of the river bed is occurring in the Upper Basin while the transport of suspended sediment to the flood plain and off-river water bodies occurs further downstream in the lower-lying areas. Comprehensive studies aimed at quantifying the fate, nature and impact of the sediment load are being undertaken. These include collaborative hydrological, chemical and sedimentary studies, intensive flood plain coring and monitoring, aerial photography analysis and sediment modelling. The results are used to model the delivery, storage and transport of sediment in the fluvial system, in both the short and long-term throughout the river system, Gulf of Papua and Torres Strait. These data are used to predict the long term behaviour of the river and flood plain, and assess any effects on the ecology of the system. This paper summarizes the various studies currently underway and highlights a major project investigating the cycling of water and sediment between the main Fly River channel and off-river water bodies.

BACKGROUND

The Ok Tedi region of Papua New Guinea's Western Province is a geomorphologically dynamic area. In addition to receiving up to 10 000 mm of rain per year, the mountainous Ok Tedi area is located within the Papuan Fold Belt and affected by the active boundary between the northward-moving Australian continental plate, and the westward-moving Pacific plate. These characteristics, combined with high sediment loads result in a rapid rate of landscape evolution and fluvial response.

From its headwaters, Ok Tedi flows south through karst topography and onto the northern limit of the Fly Platform, a large alluvial plateau, at Ningerum some 70 km downstream (Fig. 1). Elevation decreases from 2000 to 60 m over this distance. From a mountain stream, the Ok Tedi becomes braided for much of its course, and then assumes a meandering planform around Konkonda where a further sharp decrease in slope occurs. The Ok Tedi joins the Fly River a further 20 km downstream from Konkonda at D'Albertis Junction. The Fly continues south and southeast across the Fly Platform and discharges into the Gulf of Papua. The Strickland River joins the Fly River at Everill Junction, 450 km downstream of D'Albertis Junction. The mean

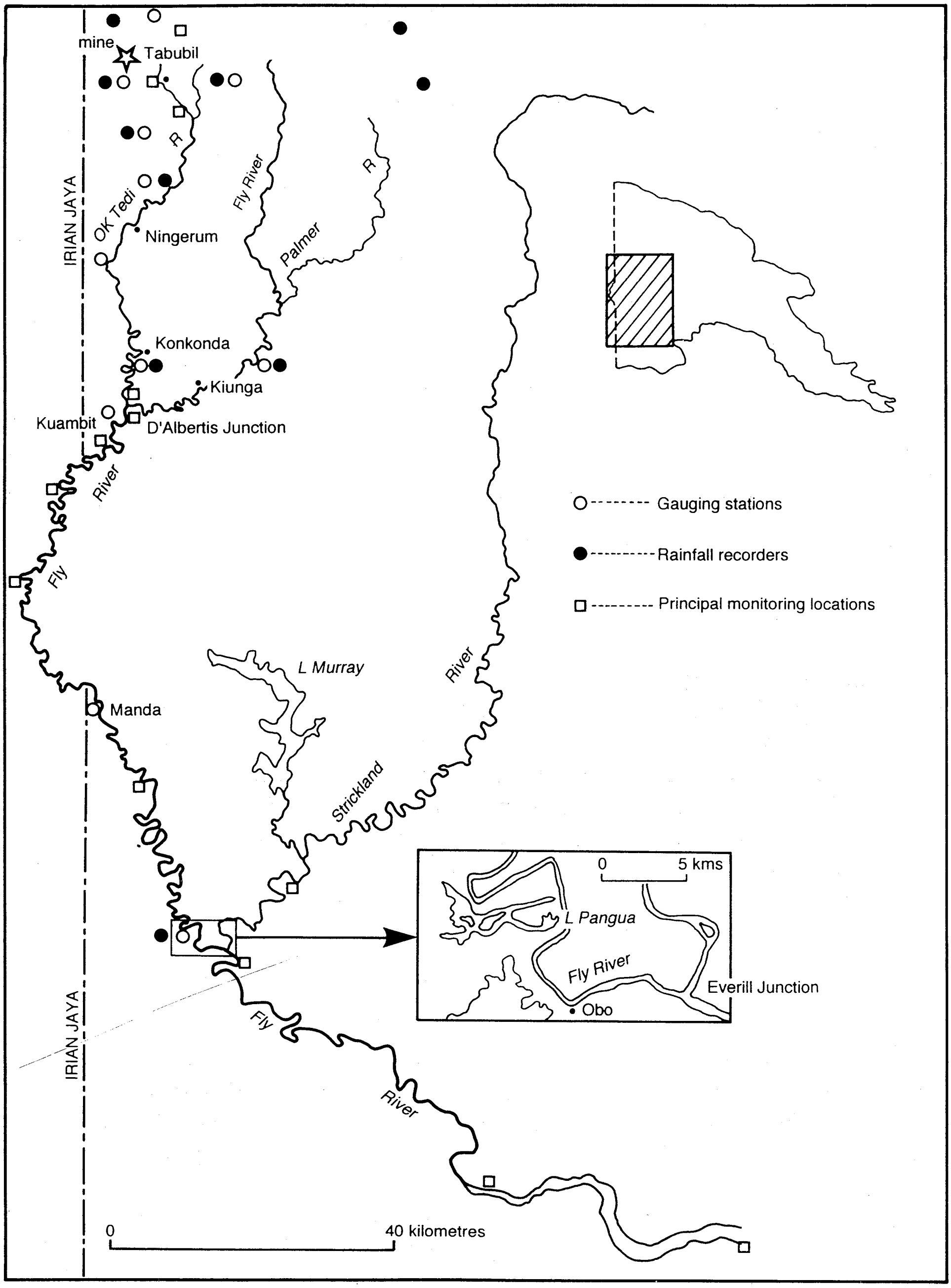

Fig. 1 Location map of Fly River basin.

annual freshwater discharge to the Gulf is estimated at 6000 m^3 s^{-1} from a basin of 76 000 km^2.

The three rivers have high natural sediment loads (Table 1). The steep terrain and high rainfall in the upper Ok Tedi basin cause frequent slope failures and high rates of sediment delivery.

Table 1 Flows and sediment loads for selected nodes in the Fly basin.

Station	Median daily flow (m^3 s^{-1})	Suspended sediment load (Mt $year^{-1}$):	
		Pre-mine	1992 measured
Bukrumdaing	23	0.04	
Ningerum	240	1.20	46.00
Konkonda	670	2.90	40.00
Kiunga	1110	2.60	2.70
Kuambit	1820	6.30	37.00
Obo	2800	9.10	35.00
Strickland	3500	76.10	84.00
Ogwa	6000	81.30	119.0

The Ok Tedi mine

The Ok Tedi mine is located in the headwaters of the Ok Tedi system (Fig. 1). Open cut techniques are used to extract copper ore which is processed using conventional flotation technology to produce a gold-enriched copper concentrate. Due to the seismic characteristics and the high rainfall of the area, stable overburden and tailings retention facilities are not considered feasible. Both overburden and tailings are thus discharged to the Ok Tedi via a tributary network. Current mean rates of discharge are 78 000 t day^{-1} for tailings and 80 000 t day^{-1} of overburden.

Fate of mine-derived sediment

Tailings are discharged as a slurry. It is assumed that material finer than 0.1 mm diameter moves through the entire river system in suspension which constitutes 78% of the tailings discharge. Approximately 23% of the overburden is fine enough to be thus transported as it is dumped. However, it abrades quickly so that approximately 55% ends up in suspension.

Gravel and coarse sand is stored in the channel, resulting in stream bed aggradation. Finer material is routed downstream. Approximately 3% is thought to be deposited overbank in the Middle Fly River.

It has always been acknowledged that mining operations would increase the sediment load of the Ok Tedi and a number of studies addressing the fate of mined sediment and its consequences have been undertaken throughout the history of the project (Higgins *et al.*, 1987). Predictions of transport rates and deposition have been made using various sediment routing procedures. A sediment routing model was developed at St Anthony Falls Hydraulics Laboratory to estimate sediment transport and aggradation in the Ok Tedi and Fly Rivers (Parker, 1990).

FIELD INVESTIGATIONS AND MONITORING PROGRAMMES

The focus for current monitoring programmes and investigations is the suspended sediment criterion, established by the Government of Papua New Guinea (Eagle & Higgins, 1990), with which Ok Tedi Mining Ltd (OTML) is obliged to comply. In addition, dissolved and particulate copper levels and rates of bed aggradation are among a number of other environmental parameters which are monitored by OTML and reported to the Government of Papua New Guinea. A key area for investigation is the potential effect of mine-derived sediments on the biota of the off-river water bodies of the Fly River. There are 29 water bodies between the Ok Tedi/Fly and Strickland/Fly confluences, comprising oxbow lakes and blocked-valley lakes. These areas are important habitats for fish and provide the basis for subsistence fishing activity along the Middle Fly. A number of monitoring programmes are underway aimed at determining the effects of the sediment in the water bodies.

CSIRO/OTML collaborative work

There is now substantial evidence showing that total metal concentrations in sediments correlate poorly with metal bioavailability and toxicity. Metal concentrations in porewaters are a much better indicator. Sediment/water "peepers" have been developed by CSIRO. The peepers have been deployed in selected lakes and flood plain locations to ascertain the copper concentrations in pore waters. This information will be used in association with analysis of copper in the sediments to determine the extent of metal mobilization.

Gravity coring in the middle Fly flood plain

Annual coring of over 200 locations in the Middle Fly flood plain has been undertaken since 1990. During 1992, over 600 locations were cored to reduce at-site variability. The results show that an increasing number of locations are showing elevated copper concentrations as the sediment is transported further onto the flood plain. Increased particulate copper levels are associated particularly with off-river water bodies connected to the main river channel via tie channels. This is because the tie channels themselves provide an efficient mechanism for the exchange of water and sediment.

Frequency and magnitude of filling and draining events

Quantities of water and suspended sediment cycle between the main river channel and the river flood plain. Because much of the lower middle Fly River flood plain is only marginally above sea level, a large proportion of the grassed flood plain remains submerged for extended periods. Such fluctuations occur over a timescale of months in response to seasonality and other climatic phenomena. A second, and more efficient, mechanism for the transfer of water and sediment is via tie channels connecting off-river oxbow lakes and blocked-valley lakes.

Flows in the tie channels can vary tremendously from less than 10 to approximately 50 $m^3\ s^{-1}$, depending on conditions. Peak inflows occur during quickly-rising river stage.

Conversely, when the river is falling, lake outflows are at a maximum. However, a third equilibrium state exists when river and lake heights are almost equal and steady, resulting in negligible flow either way.

The dynamics of filling and draining also vary with distance downstream. Farther upstream in the non-tidal zone, where river levels can fluctuate on a daily basis, periods of "slack" water are relatively less frequent (Fig. 2). Draining and filling phases in this upstream zone are more clearly defined events. Further downstream, river fluctuations and, therefore filling and draining phases are more gradual and prolonged. However, the diurnal tide causes shorter-term events.

Investigations to determine the frequency, magnitude and implications of water and sediment cycling through off-river water bodies commenced during 1992. Lake Pangua is the deepest of the middle Fly lakes, with depths of up to 30 m. The lake has two distinct parts. That nearest the river is an oxbow lake, which merges with a blocked-valley lake further from the river. The lake is tidally-affected, and located immediately upstream of the confluence between the Fly and Strickland Rivers. It is, therefore, affected also by backwater.

The instrument station deployed consisted of a "General Oceanics" winged current meter measuring current velocity, direction, temperature and conductivity. Unfortunately the sensor measuring static head of water was not supplied to order and did not function over the range of depths encountered (this problem has now been rectified). Moored to the instrument gantry was a "Branckner" optical backscatter (OBS) unit measuring turbidity. Both instruments were moored in the tie channel of lake Pangua between 1 August 1992 and 10 October 1992. The GO meter ran out of memory around the 30 September 1992 although the turbidity meter continued to log until it was retrieved. Water level was also logged at Obo station, a gauging station nearby on the main river channel.

The three-month survey revealed that inflows were dominated by mainstream stage and the tidal cycle. The period was characterized by an initially falling Fly River stage, followed by a sharp increase in river level and a subsequent drop. The river level varied

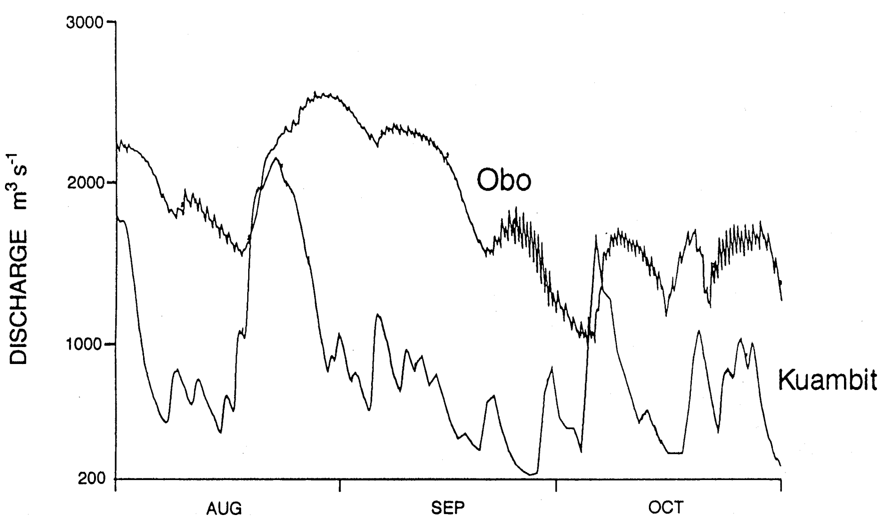

Fig. 2 Hydrographs showing river level at Kuambit (upstream) and Obo (downstream).

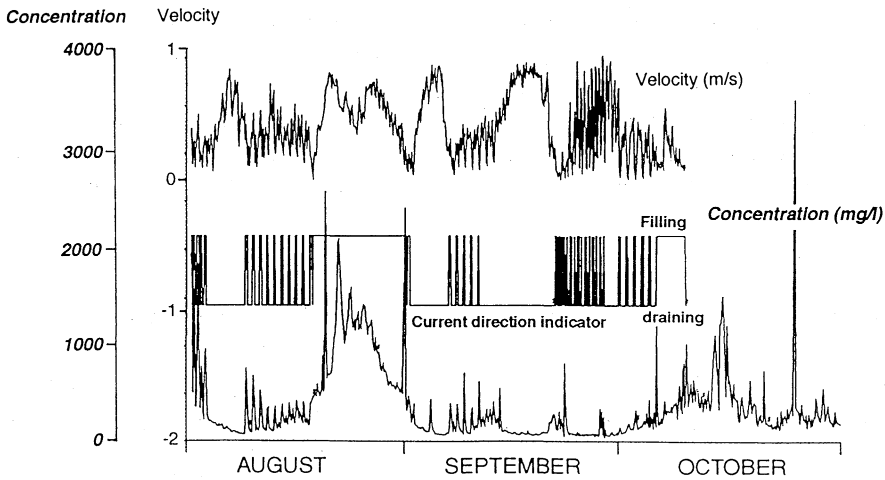

Fig. 3 Graph showing velocity, current direction and turbidity (expressed as concentration) for initial instrument station deployment, Lake Pangua, 1992.

over approximately 2 m. A regular daily cycle of filling and draining was attributed to tidal influence, while longer phases of filling and draining depended upon river stage.

During the period of increasing river height, a net inflow was observed (Fig 3). However on lower and falling stages, the data show periods of alternating current direction. This pattern occurs when the lake and river heights are almost in equilibrium and more than 40 reversals were recorded on 22 September 1992. Such rapid reversals may be due to a wave oscillation between the end of the lake and the river channel, forced by changes in the river level (Peter Ridd, personal communication). However, the rapid reversals would have little effect on the annual sediment budget.

Data showed that turbidity was considerably higher during inflow than outflow as sediment settled out in the lake (Table 2). The coarser fraction of the washload is expected to have been deposited at the lake end of the tie channel forming a submerged "reverse" delta, a natural process which has been observed in upstream lakes.

Table 2 Filling and draining characteristics, Lake Pangua.

	Temperature (°C)	Conductivity (μS cm^{-1})	Velocity (m s^{-1})	Turbidity (mg l^{-1})	Flow hours
In	26.6	173.9	0.40	648	592
Out	28.0	175.3	0.48	153	1035

FUTURE WORK

The instrument station is currently deployed for the third time in Lake Pangua so that longer-timescale events may be recorded and understood. Subsequent deployments will be made in the upstream reaches to determine any differences in the frequency and magnitude of cycling. A control deployment will also be made in the Strickland River or upper Fly River, outside the influence of the mining operation. Ultimately, enough data will be retrieved to allow sediment and water budgets to be constructed for key locations and, thereafter, applied as appropriate to all lake and tie-channel systems in the middle Fly. These data will be combined with results from the other studies described to develop a clear understanding of the physical and biological processes occurring in the fluvial system.

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