Erosion and sediment transport in Papua New Guinea. Network design and monitoring. Case study: Ok Tedi Coppermine

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ABSTRACT Erosion and sediment transport studies have largely been neglected in the past. Only studies connected to specific developments, mainly mining and hydropower, have been carried out. Some of these studies show very high intensities of erosion, indicating that certain areas of Papua New Guinea are among the most geomorphologically dynamic ares on the earth (Star Mountains with Ok Tedi Coppermine). A recent WMO/UNDP project has been addressing the lack of data, and a sediment sampling programme is at present being worked out. Lack of funds is a severe obstacle in the implementation, however.

PAPUA NEW GUINEA - PHYSICAL GEOGRAPHY

PNG (Fig.1) is a highly mountainous country, with approximately half the land area above 1000 m, and the highest point at 4500 m.a.s.l. The Central Range, which stretches from Milne Bay to the border of Irian Jaya, has only two passes lower than 1500 m. In places the mountains broaden into a series of parallel ridges with high, flat, intermontane valleys at approximately 2000 m altitude.

Geologically, PNG is located on the Circum-Pacific Earthquake zone, and numerous volcanoes exist on the northern coast and on the islands. Its geological youth is also indicated by ungraded rivers, V-shaped valleys, cliffs, and frequent landslides of large magnitude. There are extensive lowland areas to the south and north of the Central Range, where two huge rivers, respectively the Fly and the Sepik meander through broad floodplains with extensive swamplands in their middle and lower reaches. Annual rainfall in PNG varies from approximately 1000 mm to 10,000 mm. Existing rainfall statistics should not be considered as very reliable, however, as rainfall records in PNG are very short, and the raingauge network has never been properly designed. Highest rainfalls are experienced in the upper reaches of the Fly and Sepik rivers, close to the border to Irian Jaya, and in the Kikori area. Other areas of high rainfall are found in the vicinity of Lae, and along the southern coast of East New Britain. Variations in areal distribution of rainfall may be very large, while seasonal variation is generally low.

The major part of the mainland is drained by three big rivers, the Sepik (79,000 km^2), the Fly (76,000 km^2), and the Purari (30,000 km^2), while most other catchments are less

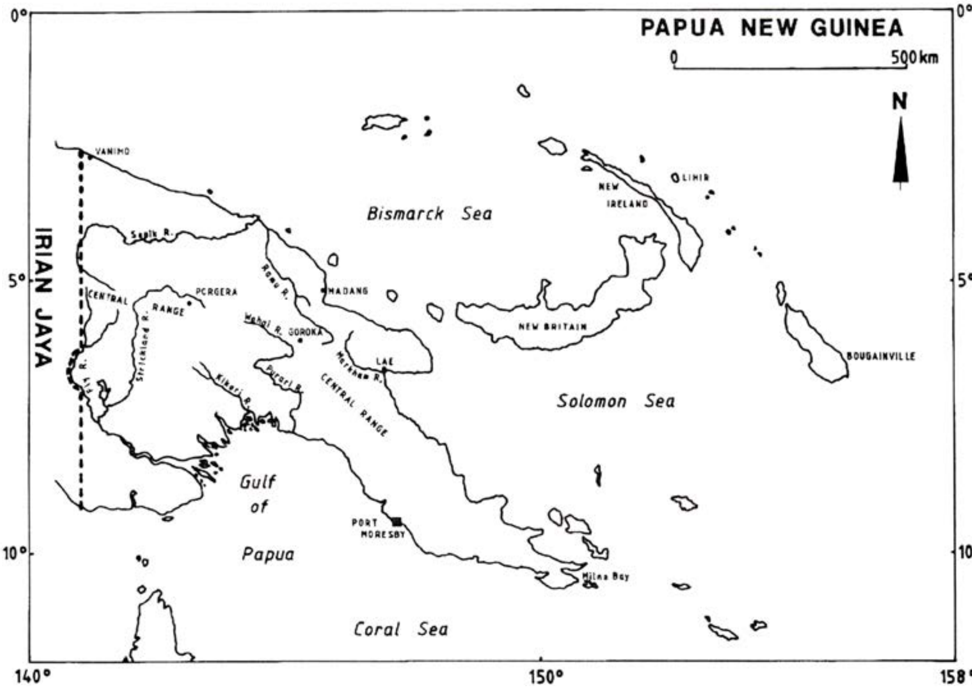

FIG. 1 Location map.

than 5,000 km^2 in area. The upper reaches of most of the catchments are very steep with rapid runoff. These characteristics, together with soft and easily erodible rocks, probably result in very high rates of sediment delivery to the rivers. Longterm quantitative measurements of the sediment budget for PNG have not been undertaken, however. Generally the runoff is high, with an estimated average for the mainland of 2,100 mm/year.

THE DATA NEED

With a total area of 461,500 km^2 and a population of 3.6 million, there are large areas of sparsely populated land with high potential for development of natural resources as well as expansion of agriculture. Two huge coppermines, Ok Tedi and Panguna, ranking among the biggest in the world, have been developed during the last twenty years. A large goldmine, Porgera, started production the last year, while Lihir, potentially one of the biggest in the world, may be opened in the next couple of years. Besides these more recent developments, mineral exploration was the driving force behind much of the opening-up of the country early this century, and extensive gold-panning is still carried out in a number of rivers in PNG. Mining is, today, the major contributor to the national economy, besides agriculture and forestry.

The main agricultural area is the Highlands, where more than one third of the population in PNG lives widely scattered. Subsistence farming and coffee growing dominate, while palm oil and rubber are significant in lower areas and on the islands.

The most pronounced change to the environment in PNG has probably been caused by the forestry industry. Undisturbed native forest was some years ago estimated to cover nearly 70% of the land area, but this value has been continuously diminished by extensive logging, especially along the northern coast and on the islands. Many of the Highland valleys, and lowland areas in the Sepik, Strickland, Markham and Upper Ramu and Upper Wahgi valleys are largely treeless and dominated by grasslands.

The effect on erosion from the agriculture and forestry has largely been neglected. One of the reasons might be that at the same time as the large scale logging operations started, investigations for the coppermines on Bougainville and at Ok Tedi started, as well as the planning of the huge hydropower scheme on the Purari River (7,000 MW). Not surprisingly, PNG's environmental resources were mainly directed at these projects. Several large-scale forestry projects developing at the same time, combined with lack of expertise and low priority, probably explain the noticeable lack of information on soil erosion related to the operations, which often occurred in very steep terrain. In late 1974 a set of standards were developed, however, to minimize the risk of erosion. Since only sparse baseline data were available, these standards were based on investigations from other parts of the world (Lamb,1990). Obviously there is a need for baseline data as well as data from areas affected by logging operations. The need for erosion and sediment transport data related to mining activities will be clearly exemplified in the case study from Ok Tedi, and will not be elaborated upon here.

Limited suspended sediment sampling has been carried out in connection with hydropower planning and development. 591 samples were collected in the Upper Ramu River during 1972-74 and 1980-84, with suspended sediment concentrations varying from 1 to 3,744 ppm, with discharges varying from 5.2 to 403 m^3s^{-1} (ELCOM,1985). The Upper Ramu valley is rather densely populated, dominated by subsistence farming, and the results are hardly applicable to the major part of PNG. Baseline data are also available for the Fly River catchment. The upper catchment is located in a tectonically very unstable area, however, with a very rugged topography, and receives an annual rainfall of 10,000 mm. The representativeness of the data are therefore highly questionable, and the data can probably not be transposed to any other parts of PNG.

PRESENT AND FUTURE MONITORING

Currently, no regular sediment sampling is being carried out in any rivers by the government. Sediment transport in the Fly and Ok Tedi rivers has been closely monitored for a number of years by Ok Tedi Mining, however, and recently Placer Porgera started monitoring in the upper reaches of the Strickland River. Similarly, sediment sampling were carried out in connection with the Panguna coppermine at Bougainville, before the mine was closed down in 1989.

Financial constraints are the main reasons why the government has not been able to pay much attention to sediment transport. A project funded jointly by the New Zealand government and the United Nations Development Programme, with WMO as the executing agency, has recently undertaken a comprehensive study of the hydrometric network in PNG. The study also includes recommendations for sediment sampling sites, as well as water quality (Repp,1991). With limited funds available and low priority given to water resources at present, this programme can hardly be implemented in the near future. It has therefore been decided to embark on a very modified programme. A few sites have been selected for weekly sampling around the capital, Port Moresby, and

Goroka in the Highlands, where the Bureau of Water Resources has got a regional office. These stations are all accessible by car, while the major part of the hydrometric stations can only be reached by helicopter. The low priority given to hydrological investigations in PNG at present, combined with the high operational costs caused by excessive use of helicopters, makes a further extension of the sedimentological investigations impossible. Besides those, sampling will be carried out in rivers with high priority, where discharge measurements are being carried out once a year. Ideally, most of the rivers should be gauged every year, due to their unstable control. Because of the reasons mentioned above, however, the number unfortunately has to be reduced, and priority given to the rivers with the most unreliable rating curves. Sediment sampling will be conducted during a two weeks period while a team is based at the site, and the number of samples will depend on water level variations during the period. In this way 30 - 40 rivers may be visited each year. The programme will, hopefully, provide some useful baseline information for assessing acceptable levels of sediment transport during future mining and forestry operations, as well as estimates of reservoir sedimentation in future hydropower development. Considering the very short observation period, however, it is extremely important to try to assess any exterior influence on the results, like landslides, which occur frequently throughout the whole PNG, and which might bias the results totally (see case study later). All sampling will be carried out with the hand-held US DH-48 sampler, and the winch operated US D-49 sampler. Most of the filtering of samples will be carried out in the field, using Millipore equipment, while a limited number of the samples will be brought back to the laboratory for filtering. Occasionally bedload samples will be collected at one or two sites close to Port Moresby. The frequency of sampling will depend on waterlevel variations.

Even if not mentioned above, it should also be remembered that one major aim of the monitoring programme is the training aspect, training on sampling techniques as well as laboratory analyses.

A research project has also been proposed in connection with the National Forest Action Plan, which aims to compare the runoff conditions, erosion, sediment transport, and water quality in an untouched catchment, with a catchment where different types of logging are being carried out. This project has not yet been approved, however. Besides the above mentioned programme plans, limited investigations might be carried out in connection with specific projects.

CASE STUDY: THE IMPACT OF OK TEDI SEDIMENT ON THE OK TEDI-FLY FLUVIAL SYSTEM

Background

The Ok Tedi region of Papua New Guinea's Western Province is one of the more geomorphologically dynamic areas on Earth. 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. The geology of the area is characterized by Quaternary limestones, siltstones and mudstones. The Ok Tedi area is flanked to the north-west by the rugged Victor Emmanuel fold belt. These characteristics, combined with sediment loading from the Ok Tedi mine result in a rapid rate of landscape evolution and fluvial response. Aggradation, degradation and channel morphology change daily in the upper catchment. The system provides a unique opportunity to study a dynamic fluvial system.

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. Ningerum is also the location of a sharp break in longitudinal slope (Fig. 2). Elevation decreases from 600-60 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 is located. Konkonda also marks the transition from gravel to sand bed material. The Ok Tedi joins the Fly River some 200 km downstream at D'Albertis Junction. The Fly continues south and south-east 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 annual freshwater discharge to the Gulf is estimated at 6000 m^3s^{-1}. The three rivers have high natural sediment loads (Table 1). The steep terrain and high rainfall in the upper Ok Tedi catchment cause frequent slope failures and high rates of sediment delivery to the rivers. Recent mapping revealed evidence that a failure containing 7 km^3 of material occurred some 8000 years B.P. A return period for the failure was calculated tentatively to be around 10,000 years. By comparison, the failure of the northern face of Mt St Helens in 1980 had a volume of 2.5 km^2. A failure containing 7×10^6 m^3 of material occurred in the Ok Tedi catchment in 1989. A failure of that magnitude may, on average, be expected to occur every 30 years (Blong, 1991).

TABLE 1 Flows and Sediment Loads for Selected Nodes in the Fly Catchment.

Station	50th Percentile Flow (m^3s^{-1})	SEDIMENT LOADS (mt/a) pre-mine	1990
Bukramdaing	23	0.04	0.04
Ningerum	240	1.20	32.00
Konkonda	670	2.90	61.90
Kiunga	1110	2.60	2.70
Kuambit	1820	6.30	53.80
Obo	2800	9.10	46.80
Strickland	3500	76.10	70.10
Ogwa	6000	81.30	117.00

The Ok Tedi mine

The Ok Tedi mine, operational since 1984, is located in the headwaters of the Ok Tedi system (Fig. 2). Open cast techniques are used to extract copper ore which is sold as a silver and gold-enriched concentrate. Waste rock overburden is disposed of via two dumps. The ore is milled and separated using conventional flotation methods. The ore residue is discharged as waste into Ok Mani. Due to the seismic characteristics and the high rainfall of the area, residue retention facilities are not considered feasible. Both rock waste and ore residue are thus supplied to Ok Tedi as sediment load via a tributary network. Current mean rates of discharge are 80,000 tonnes per day (tpd) for ore residue and 100,000 tpd of rock waste. The Ok Mani is a conduit for a proportion of the rock

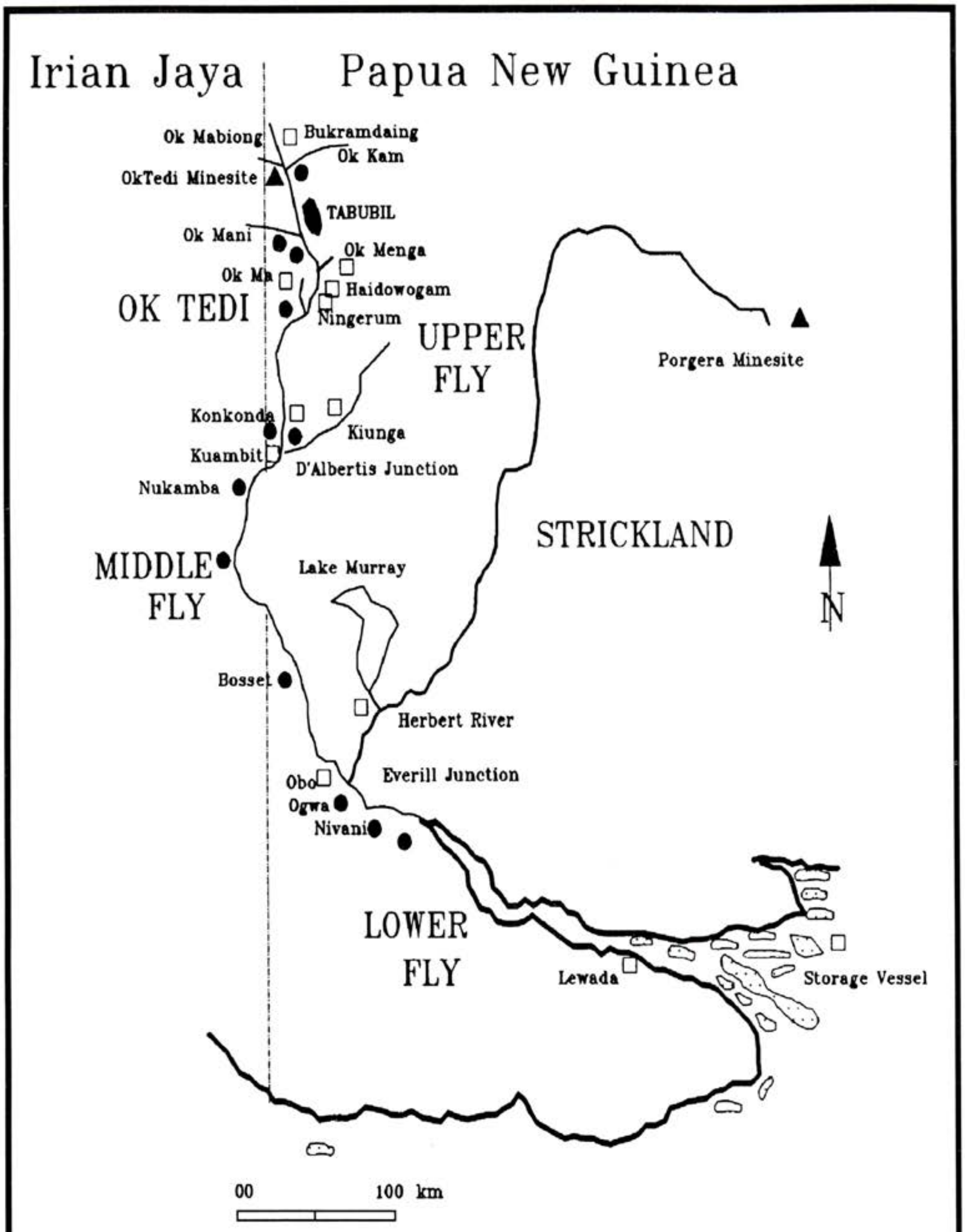

FIG. 2 Location of principal stations.

waste (approximately 40,000 tpd) and all the ore residue. Dumping to this tributary via Harvey Creek commenced only in late 1990. Harvey Creek flows into the Ok Mani and, at their confluence, a large alluvial fan has developed, estimated to contain around 2.5×10^6 m^3 of waste material. Incision in upper Harvey Creek has varied between 5 and 20m in response to dumping (Humphries, 1991). Material from the Northern Dump is transported along Ok Gilor, Ok Mabiong and finally Ok Tedi. In August 1989, a major rock avalanche occurred in the valley of Ok Gilor estimated at some 166×10^6 t. Effects of the failure were noted throughout the fluvial system in terms of higher concentrations of suspended sediment and in the rise and fall of mean bed elevations (Fig. 3).

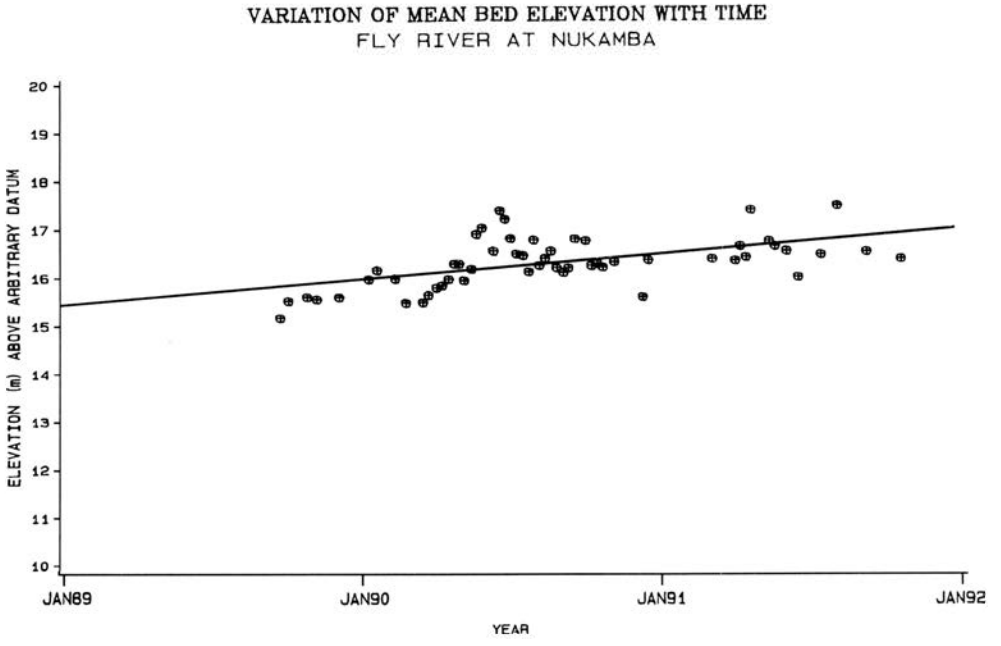

FIG. 3 Variation of bed elevation at Nukamba.

A sediment delivery schedule for the slide was developed to estimate total suspended solids (TSS) concentrations downstream. At the time of writing the delivery from the failure is estimated to be 10 mt per year. The November 1992 prediction is 1mt per year. This schedule assumes that approximately 40% of the failure material is unavailable for delivery. This material is stored behind a ridge in the valley of the Ok Gilor. The expected failure of that ridge and the subsequent release of the remaining sediment will be accompanied by a revised delivery schedule.

Approximately 22% of rock waste and 78% of ore residue is transported in suspension through the fluvial system. Suspended material is found to have a diameter of less than 100 microns. Additional material becomes available for suspension as coarser material is broken down by collisions with other coarse particles during transport. The coarser bedload is transported more slowly along the river. Much is stored in the channel itself, leading to measurable aggradation as far downstream as the Middle Fly. Of an estimated discharge to the estuary of 100 mt per year of suspended material, approximately 40% is mine-derived. A small proportion is deposited on the river floodplain and in off river water bodies.

Modelling of sediment transport

Because of the terrain, high rainfall and geology of the area, 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 were made using various sediment routing procedures. Currently the OKMODEL suite of sediment routing models is used to predict flow and sediment transport characteristics using hydrologic, topographic and sedimentological information as inputs (Parker, 1990). Flow depth, area and hydraulic radius are computed from a resistance relation and known cross-sectional geometry at different sections. Submodels for the gravel and sand-bed reaches of the Ok Tedi and Fly rivers were developed, and resistance relations suitable for each scenario employed. For a given flow and bed topography, sediment transport is computed for each grain size range at each section.

Suspended sediment is modelled using simpler, mass-balance calculations. The equations incorporate a term for the quantity of material abraded to washload size in the river system. This abrasion volume is computed from the gravel submodel of OKMODEL.

Field investigations and monitoring programmes

Currently, comprehensive hydrological, chemical and biological investigations are being undertaken by OTML and have been running since 1981. A number of organisations world-wide are involved in a multidisciplinary study aimed towards a better understanding of the response of the physical system to mining operations. The focus for current investigations is the environmental criteria, established by the Government of Papua New Guinea in collaboration with OTML (Eagle & Higgins, 1990), with which OTML is obliged to comply. Sediment concentrations and rates of aggradation are among a number of environmental parameters for which OTML is tested by the Government of Papua New Guinea. Currently an acceptable particulate limit (APL) of 940mg/l must not be exceeded at Nukamba after allowing for sediment inputs from sources other than the mining operation. Compliance is tested by reference to the upper 95% confidence limit of the mean suspended sediment concentration determined over a moving period of 30 consecutive weeks. Furthermore, the rate of bed aggradation at Kuambit should not exceed predictions over the life of the mine.

Sediment dynamics are monitored throughout the Ok Tedi/Fly system. In addition to weekly APL sampling at Nukamba and quarterly aggradation measurements at Kuambit, weekly samples are collected at selected tributaries of the system, namely Ok Mani, Ok Kam, Ok Menga and Bukramdaing. Ok Kam and Ok Menga rise from the Hindenberg wall, an almost vertical limestone cliff reaching a height of 1000 m, forming part of the Victor Emmanuel range. Failures are common at the base of the wall, and sediment may be routed along the Ok Menga or the Ok Kam to the Ok Tedi. The size of the delivery will determine its impact upon the mine, but any material deemed to be derived from sources other than the mine may be subtracted from the APL of 940 mg/l. At Ningerum, total suspended solids (TSS) concentrations are sampled on a 6-hourly basis (Fig. 4) and non-routine sampling is undertaken at additional nodes throughout the network.

Regular profiling ensures that up-to-date rates of bed aggradation are available

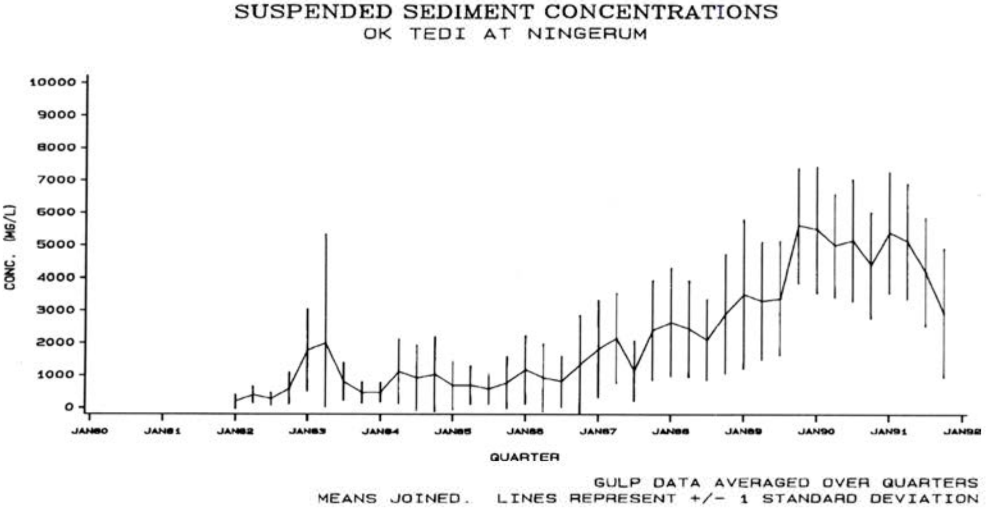

FIG. 4 Suspended sediment concentrations at Ningerum.

(Table 2). The deposition of mine-derived sediments outside of the main-stream flow is currently monitored by the periodic sampling of 200 locations in the Middle Fly Floodplain. It is estimated that around 2% of average annual mainstream flow enters the floodplain in this region (Higgins, 1991).

TABLE 2 Aggradation Rates at Selected Nodes

Node	Aggradation rate (m $year^{-1}$)	Significant at 95%
Tabubil	0.60	Y
Ningerum	0.05	Y
Nukamba	0.59	Y

Aggradation in the Ok Tedi is predicted to be as much as 30 m adjacent to Tabubil although much less is being observed. In the Upper-Middle Fly, the total aggradation is expected to be 2-4 m which, to date, is consistent with observations. The particular problems resulting from aggradation include increased incidence of overbank flow and the backing-up of tributaries at higher flows. Aggradation in the Middle Fly around D'Albertis Junction causes minor navigation difficulties for the barges carrying the copper concentrate to an offshore terminal.

Of the material that is transported into the estuary, data suggest that most is transported no further and, rather, is deposited and becomes part of a large fluidized mud layer existing in the estuary (Eagle & Higgins, 1990). Given that preliminary estimates indicate that the volume of material may be as great as $1x10^{10}$ mt substantial dilution of copper-enriched sediments is expected. To date, there is no detectable enrichment above background copper levels.

Ok Tedi provides a unique opportunity to study the response of all aspects of the fluvial system to sediment loading. A small number only have been touched upon in this paper. At the end of the life of the mine in 2008, waste discharges will cease and the recovery of the fluvial system in terms of channel geomorphology is expected to be substantially complete within 20 years.

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