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Environmental impact of mining waste disposal on a tropical lowland river system: a case study on the Ok Tedi Mine, Papua New Guinea

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Abstract The 1000 km long Ok Tedi/Fly River system receives about 66 Mt/year of mining waste from the Ok Tedi copper-gold porphyry mine. Mine input has increased the suspended sediment load of the Middle Fly River about 5–10 times over the natural background. A significant yet unknown amount of copper-rich material deposits unevenly in the extensive tropical lowland floodplain. Recent alluvial sediments of the Fly River floodplain have copper contents of 620 mg/kg ($\pm 1\sigma$: 430–900), whereas the regional background is 40 mg/kg ($\pm \sigma$: 25–60). This pattern is mirrored and enhanced by the gold dispersal pattern with a 7 ppb Au background versus a 140–275 ppb population in mine-derived material. Very high deposition rates (around 4 cm/y) of mine-derived sediment were determined in locations close to the creeks and channels which link the Fly River with the outer floodplain. A thin layer of 1–5 cm of copper-rich material (400–900 mg/kg Cu) was usually found on the bottom of drowned (tributary) valley lakes. Average dissolved copper content in waters of the inner floodplain is around 9 μg/l ($\pm 1\sigma$: 5–14) as compared to unpolluted water from the outer floodplain with < 2 μg/l Cu. The present Fly River water, about 600 km downstream of the mine site, has concentrations of 17 $\pm$ 3 μg/l dissolved Cu.

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Introduction

The Ok Tedi Mine is one of the world's premier copper-gold porphyry ore deposits, situated in arduous terrain in the highlands of western Papua New Guinea (Fig. 1). The open pit mine is state-of-the-art and has operated since 1984. The then record initial capital investment was 1400 MUS$. However, due to geotechnical problems there are no waste retention facilities, and all ore processing residues, waste rock and overburden are discharged into the headwaters of the Ok Tedi River, a mountainous tributary of the Fly River. Tailings, (most of the particles finer than 100 μm) are piped to an Ok Tedi tributary valley, and waste rock is hauled to erodible dumps adjacent to Mt. Fubilan, from where the material is washed into the upper Ok Tedi. This currently produces about 66 Mt (million tons) of mining waste per year which impact on the 1000 km long Ok Tedi/Fly River system. The whole project, with a mine life from 1984 to 2007 is scheduled to release some 1400 Mt of rock (550 Mt of mill fines, 850 Mt of overburden) into the tropical river ecosystem (Salomons and Eagle 1990).

The natural load of the Ok Tedi upstream of the mine is 0.04 Mt/year, data for Ningerum and Konkonda are 0.30 Mt/year and 6.90 Mt/year, respectively (Eagle and Higgins 1991). The massive input of mine-derived material exceeds the transport capacity of the Ok Tedi river which has led to severe aggradation and a rise of the Ok Tedi channel bed by 10 m and more in the upper reaches. The bed of the Ok Tedi at Kuambit, close to the Ok Tedi/Fly river junction 200 km downstream from the mine site, is projected to aggrade by 2.2 m during the life of the mine (Eagle and Higgins 1991). About half of the total mine input has a particle size of less than 100 μm and travels as a suspended load through the Ok Tedi into the Fly River. A large part of the suspended load is transported another 800 km by the Fly River and is mostly deposited in the Fly River delta in the Gulf of Papua (Eagle and Higgins 1991).

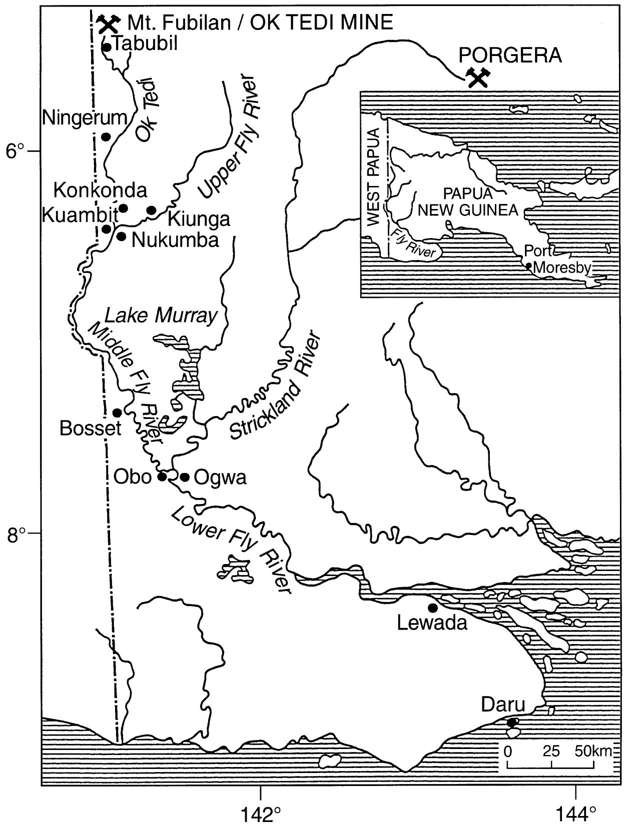

Fig. 1 The Fly River region. Sampling in the Middle Fly River floodplain concentrated on the reach between Bosset and Obo

The river section between the Ok Tedi and the Strickland River junction is termed Middle Fly River with a length of 410 river kilometres (Fig. 1). We investigated the geochemistry of modern sediments and water in the lower part of the Middle Fly River floodplain, after ten years of large-scale Ok Tedi copper-gold mining 500–600 km upstream. The floodplain is a swampy lowland extending 10–30 km away from the meandering river channel. The research project (Hettler and Lehmann 1995) was funded by the United Nations Environment Programme (UNEP) and links up with previous work supported by UNEP on potential impacts of mining on the Fly River (UNEP 1988).

Field sampling and analytical methods

Thirty-two surface sediments were sampled from the river bank of the Ok Tedi at Tabubil and 124 sediment core samples were taken along the Middle Fly River with a gravity corer during 1991–1993 (Fig. 2). The cores recovered have a diameter of 36 mm and a length of between 20 and 70 cm depending on the nature of the bottom sediment. Because of the difficult access to swampy, vegetated floodplain sites, the large majority of sediment cores and water samples were taken from channels, lakes and small water bodies which were accessible by boat or dugout canoe.

A total of 117 water samples (gulp samples taken by hand 20–50 cm below the water surface) in the Ok Tedi and the Middle Fly River region (Fig. 2) were taken in acid-washed polyethylene bottles. Water temperature, pH, conductivity and oxygen content were measured in the field using portable electronic equipment. Upon return to the field laboratory within a few hours of collection, alkalinity was determined by titration with 0.02 m HCl to pH 4.5 (APHA Standard Method 403, 1985). The water was filtered through 0.45 μm cellulose nitrate membrane filters (Sartorius, Germany) and was immediately acidified with 3–4 ml of concentrated nitric acid (Merck Suprapur) per litre of sample. Filters were retained for gravimetric determination of suspended solids.

Sub-sections of sediment cores at intervals of 2.5 to 5 cm were wet sieved with distilled water through nylon sieves of 20, 60, 100 and 200 μm mesh size. Samples selected for chemical analysis (grain size <20 μm was the standard fraction used) were shipped to commercial laboratories (ACME and XRAL, Canada), where the sediment was homogenized and pulverized in an agate mill. In the "total digestion" procedure, 250 mg of sample is digested with 10 ml $HClO_4$–HNO_3–HCl–HF at 200 °C to fuming and diluted to 10 ml with diluted aqua regia. Thirty-five elements were determined by inductively coupled plasma spectrometry (ICP-S), of which 24 were evaluated in the present study. Gold together with some other elements were analyzed in selected samples by neutron activation analysis (NAA) in a commercial laboratory (Bondar-Clegg, Canada). Insoluble carbon and sulfur were determined by using a "Leco" furnace.

Two reference sediment samples, NBS 2704 Buffalo River Sediment and EEC/BCR RM 280 Lake Sediment, were submitted to the commercial laboratory for quality control. The measured values were within the acceptable range of the reported values (Table 1).

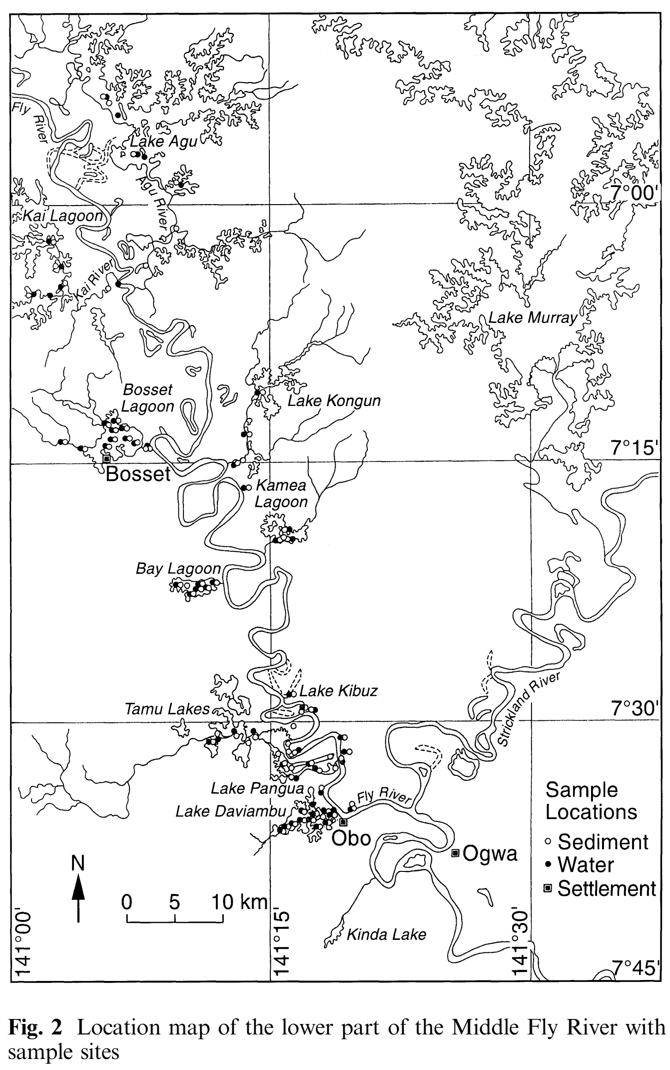

Fig. 2 Location map of the lower part of the Middle Fly River with sample sites

Table 1 Quality control of sediment analyses with standard reference materials

NBS 2704	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	As	Cr	Co	Ni	V	Ti	Ba	P
	mg/kg																		
Certified	5470	20000	12000	26000	61100	41100	555	438	98.6	161	3.45	23.4	135	14	44	95	4570	414	998
Uncertainty	±140	±400	±200	±300	±1600	±1000	±19	±12	±5.0	±17	±0.22	±0.8	±5	±0.6	±3	±4	±180	±12	±28
Measured	6100	20100	12300	27800	61500	41000	537	397	103	129	2.4	8/20[a]	103	11	40	75	2700	467	990

EEC/BCR RM 280	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	As	Cr	Mo	Co	Ni	V	Ti	Ba	P
	mg/kg																			
Certified	17600	26000	16430	16870	77500	42360	1350	291	70.5	80.2	1.6	51.0	114	1.9	20	73.6	102	4040	618	1530
Uncertainty								±4	±1.5	±2.3	±0.1	±2.4	±4			±2.6				
Measured	15800	24800	16200	16500	77500	41400	1148	262	65	65	1.0	30	87	2	15	64	72	3100	681	1410

Values with no uncertainty range given are noncertified.
[a]As value is by hydride generation/ICP-S

Radiocarbon age dating was performed on five samples of peaty sediment from drowned valley lakes at the C-14 Laboratory of Kiel University, Germany. Water samples were analyzed at a commercial laboratory (XRAL, Canada), at the laboratory of the Department of Environmental and Resource Geology at Freie Universität Berlin, and at the laboratory of the Environment Department of Ok Tedi Mining Limited at Tabubil. Commercial analysis for dissolved metals was by multi-element ICP-S. The trace metals copper, lead, zinc and cadmium, which were present in some samples in concentrations close to the detection limit of ICP-S, were additionally determined by graphite furnace atomic absorption spectrometry (GFAA). Quality control for waters was performed by splitting samples and subsequent analysis of subsamples at different laboratories, and by inclusion of blank samples (demineralized and distilled laboratory water).

Geology and mining of the Mount Fubilan ore deposit

The orebody at Mount Fubilan consists largely of an altered monzonite porphyry stock of Plio-Pleistocene age, which hosts a mesothermal stockwork and disseminated copper-gold mineralization (Rush and Seegers 1990). Despite the young age of the intrusion/hydrothermal mineralization and rapid uplift and erosion, the Mount Fubilan stock has deep secondary enrichment. A copper-depleted, but gold-enriched cap (gossan) overlies the copper enrichment blanket and protore mineralization. This limonitic material of 50 Mt with 2.4 g/t Au was mined during the first years of mine life. Current production is from the secondary enrichment zone. Secondary enrichment occurs mainly as chalcocite with minor covellite. Marcasite is locally the predominant iron sulfide. Pyrite and chalcopyrite are the dominant sulfide minerals in the protore below the supergene enrichment zone. The overall volume ratio of chalcopyrite to pyrite/marcasite is about three (Arnold and Griffin 1978). At the contact between the intrusive and adjacent sediments, calc-silicate, sulfide and magnetite skarns have formed, which make up approximately 10% by volume of the orebody (Jones and Maconochie 1990). Average metal concentrations in the orebody are 0.72 wt.% Cu and 0.70 g/t Au with a reserve tonnage of 460 Mt (DMP 1994).

Porphyry base-metal deposits typically contain a concentrically zoned hydrothermal metal suite of copper, molybdenum, silver, gold, lead, zinc, selenium, cadmium, and others. Arsenic and mercury, which are frequently associated with gold mineralization, show no enrichment above background levels in the Ok Tedi deposit. The skarn mineral paragenesis has an elevated and more variable content of trace metals as compared to the copper porphyry ore, and may be more critical from an environmental point of view. However, this material is not a major mining target at present.

The currently produced ore has 0.84% Cu and 0.71 g/t Au (oral communication, OTML 1994). The sulphide flotation process has a recovery rate of 85% which leaves about 1300 mg/kg Cu in the residual material. The copper content of waste rock has an average of 1100 mg/kg (OTML 1994).

Natural sedimentary processes in the Fly River floodplain

The Fly River is a strongly meandering tropical lowland river with a highly variable flow regime. Extensive flooding and overbank deposition on its several kilometre-wide floodplain alternates with extremely low water levels in drought periods. The sedimentary processes in the Fly River floodplain are dominated by the suspended river load. Sediment delivery by floodplain creeks and channels is negligable. The catchment in the outer floodplain and the adjacent piedmont plain comprises forested areas with some swamp savannah. The content of particulate matter in floodplain creek waters generally is very low (below 15 mg/l), consisting of organic material, mainly plant debris and strongly weathered soil material. At mean flow in the Fly River and low water table in the floodplain, intrusion of riverine suspended sediment occurs along pre-existing channels linking the river with drowned valley lakes in the floodplain. Highest sedimentation rates were detected in oxbow lakes and tie channels, where medium to coarse silt from the river suspended load settles. Much lower rates occur in drowned valley lakes and floodplain depressions where clay and fine silt are deposited.

Drainage direction throughout most of the Fly River floodplain is towards the Fly River, although the inner floodplain, i.e. the active meander belt, tends to be higher in elevation than the outer floodplain due to sedimentation in and along the main river channel. No broad continuous levee is developed along the river and where there is a dam, it is cut by small drainage channels. During periods of high water level in the Fly River, which are associated with high sediment loads because of increased transport energy, river bank overflow and inundation of the alluvial plain occur.

Maunsell and Partners (1982) recorded a period of very high flow in the Fly River in July 1981, which was the highest since 1977. The water level was about 1 m above the natural levees. According to their observation, grassland and forests adjacent to the river channel in the reach between Lake Bosset and Obo were flooded to a width of about 16 km on either side of the channel. Although this situation is highly anomalous, it is evident from aerial photographs that at high water level in the Fly River, turbid flood water may flow several kilometres across the floodplain.

Overbank flooding during moderate floods is localized close to the Fly River channel in flanking swamps. The water returns to the river when the flood recedes, although most of the suspended load carried into the floodplain is deposited due to vegetative filtering in the grassland bordering the main river, and in sediment traps such as lakes.

The background deposition rate (i.e. before mine-derived material was deposited) in drowned valley lakes is very low. The shallow lakes, originating from drowned tributary valleys, are the most important bodies of stagnant water in the alluvial plain. C^{14} age dating was performed to determine sedimentation rates in these lakes (Table 2). The overall deposition rate seems to be well below 1 mm/year, and may be as low as 0.1 mm/year. The sediment deposition at a particular site within a lake is very much dependent on bottom relief and shape of the lake. The simple fact that the shallow lakes still exist after about 5000 years of possible sedimentation from the Fly River also points to very low deposition rates. Natural deposition rates in cutoff meanders are much higher.

At times when discharge from the Strickland River is greater than the flow of the Fly, a backwater effect develops, which results in decreasing river velocity in the Middle Fly and subsequent settling of suspended material on the river bed (Pickup et al. 1979). The same occurs during low-flow periods. The deposited material may be resuspended at high flows. Pickup et al. (1979) estimated the natural suspended load of the Middle Fly at 7–10 Mt and bed load at 1–2 Mt per year. In the same study, the authors report mean suspended matter concentrations in the range of 60–80 mg/l for the Middle Fly River and note that "the Fly and the lower Ok Tedi are very clean rivers by Papua New Guinea standards".

Sedimentation of mine-derived material

The suspended matter content in present-day water of the Middle Fly River is between 330–600 mg/l, i.e. about

Table 2 Results of radio carbon age dating of sediment cores from drowned valley lakes

Core	3/30.3.	3/11.4.	1/5.4.	1/9.4.
Locality	L. Daviambu W	L. Bosset NW	Bai L. C	Kai L. SW
Depth of peaty layer below sediment surface	13 cm	28 cm	27 cm	28 cm
C^{14} age (years before present)	5265 ±215	2950 ±70	4030 ±110	4380 ±125
Sedimentation rate mm/1000 y	24	95	67	64
Water depth at site (mean water level)	1.10 m	2.40 m	1.70 m	2.60 m
Distance from Fly (air km)	6	5	3	9

5–10 times higher than the estimated natural background of about 60 mg/l (the measured long-term median value for the unaffected Upper Fly is 45 mg/l (OTML 1993, 1994). Significant quantitities of mine-derived sediments are deposited and trapped in creeks, lakes and swamps adjacent to the Fly River. Such off-river sites are likely to play an important role in the food web and in the reproduction cycle of aquatic organisms like invertebrates and fish.

Due to the flat terrain, turbid Fly River water intrudes regularly upstream of the floodplain tributaries (measured intrusions at a distance of 25 km). Flow inversion in channels linking the floodplain with the Fly River is an important process, responsible for suspended sediment transport to off-river sites during mean flow conditions. Deposition of mine-derived sediments generally is highest at locations close to the channels linking floodplain water bodies with the Fly River. Comparatively coarse material (medium to coarse silt) is deposited there, whereas the remaining fractions of clay and fine silt of the riverine suspended load is carried into the floodplain water courses. Trace metals are generally enriched in the finest particle fractions. Where the channels extend into the floodplain lakes, deposition of 20–40 cm thick copper contaminated sediment was detected several kilometres away from the Fly River. The heavy metal-rich material has been accumulating since the mine started operations in 1984 with a resulting sedimentation rate of up to 4 cm/year. A thin layer of 1–5 cm of copper-rich material (400–900 mg/kg Cu) was usually found on the bottom of drowned (tributary) valley lakes. Deposits of up to 70 cm in thickness of copper-rich material with 800–1000 mg/kg Cu were detected at sites close to the river end of oxbow lakes like Lake Pangua and Lake Kibuz (Fig. 2). Twenty-nine oxbow lakes at different infilling stages exist along the Middle Fly River. Riverine particulate matter also settles sporadically on the floodplain at times of overbank flow, which leads to extensive copper contamination in low-lying swamp sites close to the river.

Two sediment cores were taken from the Fly River channel bed (Figs. 3, 4), one at Lake Pangua (water depth 10.5 m) and the other downstream of Obo (depth 14.5 m), both in the deepest part of the channel cross section. The entire bed core from the Lake Pangua site (56 cm) consisted of fine grained sediment with 55–75% finer than 20 μm (clay, fine and medium silt fraction), and displayed a constantly high copper content of about 850 mg/kg. The upper 38 cm of the core taken close to Obo were very similar in composition, however the bottom section (41–43 cm) showed much coarser material with 75% fine sand (63–200 μm). The copper content dropped to 48 mg/kg in this section. From both cores, it is evident that suspended load has settled on the channel floor. Only the section with mainly fine sand, from the sample taken downstream of Obo, shows the typical grain size of bed load. It is known from earlier sedimentological studies (Pickup et al. 1979) that fine material does temporarily deposit on the river bed upstream of the Strickland River junction. Due to the cohesive forces among fine grained particles, high current speeds are necessary to erode these deposits. The resuspension of mine-derived clay- and silt-size material from the channel floor today may be limited because much more sediment settles down, and will be flushed downstream at high flows only at hydraulically preferred sites like meander bends and immediately upstream of the Strickland junction.

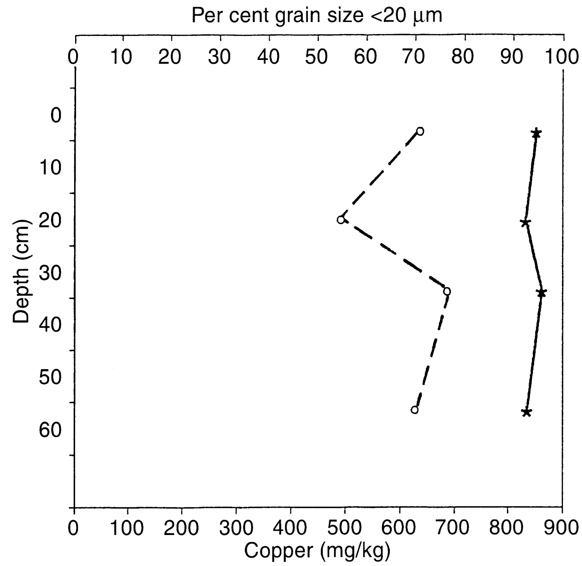

Fig. 3 Percentage of fine-grained sediment less than 20 μm (o) and copper concentration (*) in a core taken from the Fly River bed at Lake Panguna. Copper-rich clay and silt dominate over the entire core length of 56 cm

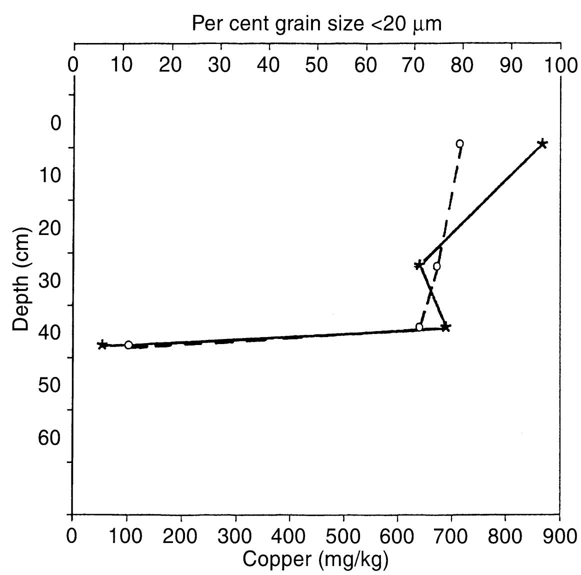

Fig. 4 Percentage of fine-grained sediment less than 20 μm (o) and copper concentration (*) in a core taken from the Fly River at Obo coarse bed sediment with background copper levels encountered at 41 cm core depth

In this connection, it is interesting to note that two islands within the Fly River channel, one immediately downstream of Lake Bosset and the other at the junction of Tamu Creek, have been observed during the field trips undertaken. Sediment samples taken showed relatively coarse, copper-rich material. No such islands are visible in aerial photographs from the 1960s and 1970s. The formation of islands in the river channel suggests insufficient transport capacity of the Fly River to carry all mine-imposed waste material. OTML (1993) reports an increase in bed level at Kuambit, immediately downstream of the Ok Tedi/Fly River confluence, of more than 1 m above the 1984 pre-mine baseline. River bed sedimentation is also dependent on flow velocity, which at Obo is significantly lower than at Kuambit/Nukumba. A detailed comparison of flow data gathered in February and April of 1992 by OTML gave a mean value of 1.12 m/s for Kuambit and 0.66 m/s flow velocity at Obo.

Two effects probably are responsible for the strongly increased deposition rates compared to earlier sedimentation. Firstly, the increase in (mine-derived) suspended sediment load of the Fly River, which today also contains more coarse material (silt) than the natural particulate load. Secondly, the reduction in channel capacity due to bed aggradation leads to an increase in overbank flow frequency. In the lower part of the Middle Fly, close to the Strickland River junction, aggradation of the main river channel is higher due to the backwater effect from the Strickland.

Metals in floodplain deposits

Copper

The chemical composition of the Mount Fubilan porphyry orebody is reflected in the chemical signature of the mine-derived sediments deposited along the Ok Tedi and on the Fly River floodplain (Tables 3 and 4). The characteristic suite of porphyry trace metals such as Cu, Au, Ag, Mo, (Pb), (Zn), (As) is strongly enriched over average crustal composition.

Comparison with the abundance of metals in tailings and waste material from other copper porphyry mines (Table 5) illustrates that the Mount Fubilan orebody is a rather "clean" deposit where mainly copper is of environmental concern. Natural background concentrations given below are "average shale" values cited from Turekian and Wedepohl (1961). These values are very similar to the background levels determined for unpolluted sediments from the Ok Tedi and Fly River floodplains (Table 6).

There is very little dilution of the mining waste by natural sediment load from tributaries in the Ok Tedi-Fly River system upstream of the Strickland River junction (610 km below the mine site). The nature of the alluvial sediments in the Fly River floodplain, i.e. natural versus mine-derived material, can easily be distinguished by their different copper contents. The copper frequency distribution of 385 sediment samples is shown in Fig. 5. The distribution is roughly bimodal and can be

Table 3 Mean, standard deviation, median values and 25%–75% confidence intervals for 27 elements in sediments from the upper Ok Tedi, mainly tailings and waste rock ($n = 24$)

Element	Unit	Mean	SD	Median	Percentiles	
					25	75
Na	mg/kg	11921	4159	10950	8100	15000
K	mg/kg	30350	7395	27950	24400	37200
Mg	mg/kg	6733	1463	6350	5700	7700
Ca	mg/kg	86117	33796	98450	54800	115900
Al	mg/kg	61462	11766	62750	54800	65800
Fe	mg/kg	47512	29854	40900	29300	54200
Mn	mg/kg	700	323	775	436	965
Zn	mg/kg	541	450	378	182	779
Cu	mg/kg	1523	976	1158	805	1791
Pb	mg/kg	463	744	123	63	488
Cd	mg/kg	1.6	1.3	1.0	0.6	2.2
Au	µg/kg	426	381	266	107	609
Ag	mg/kg	2.4	2.5	1.4	0.8	3.3
As	mg/kg	14.9	11.5	11	5	19
Cr	mg/kg	30	12	26	21	33
Mo	mg/kg	38	14	36	27	45
Co	mg/kg	13	10	11	5	16
Ni	mg/kg	17	9	14	10	23
V	mg/kg	111	21	105	99	120
Ti	mg/kg	1788	305	1750	1500	1900
Zr	mg/kg	22	11	19	13	29
La	mg/kg	23	6	22	19	26
Ba	mg/kg	410	202	368	275	599
Sr	mg/kg	576	86	548	510	620
Sc	mg/kg	7.3	2.4	7	5	9
C	wt.%	1.8	0.5	1.9	1.3	2.1
S	mg/kg	15211	20643	7900	4425	10625

Table 4 Mean, standard deviation, median values and 25%–75% confidence intervals for 27 elements in mine-controlled sediments from the Middle Fly River floodplain ($n = 197$)

Element	Unit	Mean	SD	Median	Percentiles	
					25	75
Na	mg/kg	8010	3218	8200	6025	9800
K	mg/kg	28807	11610	30300	18850	36950
Mg	mg/kg	7242	1831	7400	6200	8575
Ca	mg/kg	30139	23842	24800	8200	50350
Al	mg/kg	80994	14915	81100	72325	91025
Fe	mg/kg	40004	11012	39 00	32200	46850
Mn	mg/kg	528	254	510	310	710
Zn	mg/kg	211	68	204	163	245
Cu	mg/kg	530	249	529	278	732
Pb	mg/kg	79	36	80	48	104
Cd	mg/kg	0.5	0.3	0.5	0.2	0.7
Au	µg/kg	166	81	160	120	205
Ag	mg/kg	0.7	0.5	0.7	0.3	1.0
As	mg/kg	8.3	5.8	7.0	4.0	12
Cr	mg/kg	48	14	46	39	56
Mo	mg/kg	24	13	23	13	32
Co	mg/kg	10	5	10	7	12
Ni	mg/kg	21	9	19	15	24
V	mg/kg	145	35	139	123	163
Ti	mg/kg	2753	801	2600	2200	3200
Zr	mg/kg	44	16	41	32	52
La	mg/kg	26	7	27	22	30
Ba	mg/kg	415	100	420	363	466
Sr	mg/kg	330	139	313	226	438
Sc	mg/kg	13	4	12	10	15
C	wt.%	1.6	1.5	0.9	0.6	2.0
S	mg/kg	2464	2160	2100	675	3425

further refined into one background and two anomalous subpopulations.

The populations have approximately lognormal distribution and are plotted in log probability graphs. The background population of 40 mg/kg Cu ($\pm 1\sigma$: 25–60) characterizes natural sediment in the lowermost sections of sediment cores and surface samples from the outermost parts of the floodplain. Near-surface sediments along the river channel contain up to 1100 mg/kg Cu with a mean of 620 mg/kg Cu ($\pm 1\sigma$: 430–900). This result is corroborated by the much larger data base from the monitoring programme of the Ok Tedi Mine which has defined a bulk arithmetic mean of 453 ± 332 ($\pm 1\sigma$) for more than 5000 samples from the floodplain (oral communication Environment Department of OTML 1994). Note that this value is the arithmetic mean of all samples, both natural and contaminated material.

The early development stage of the Ok Tedi mine is probably reflected in the intermediate copper subpopulation with a mean of 140 mg/kg Cu ($\pm 1\sigma$: 100–230). During the construction period which commenced in 1982, and during the early gold mining stage starting in 1984, the leached cap of the orebody was stripped with very low copper values (< 0.05 wt.% Cu). The copper-rich sediments in the Middle Fly region usually consist of deposited riverine suspended matter. In some tributary valley lakes, however, the uppermost, copper-rich sediments were mainly made up of humic material in which the high copper content may be secondary, due to adsorption on flocs of organic matter.

Heavy mineral concentrates from modern Middle Fly River sediments have a sulfide population which is very similar to the mineral association in the orebody as well as in tailing material a few kilometres downstream from the mine site. The sulfide grains from a sampling locality at Lake Agu are in the 0.01–0.2 mm size range (average around 0.05 mm) and consist of little corroded pyrite, marcasite, chalcopyrite, chalcocite and covellite (Fig. 6). Pyrite has the typical pyrrhotite and chalcopyrite inclusions of the porphyry system. Chalcopyrite occurs mostly as relic cores within chalcocite. Covellite locally forms rims on covellite/chalcopyrite aggregates and on fractures. The same replacement fabrics with chalcopyrite → chalcocite → covellite at slightly larger grain sizes (average around 0.1 mm) occur also within the orebody and at a sampling site 3 km downstream from the open

Table 5 Average trace metal values for mine-derived sediments from the Ok Tedi (PNG) and Clark Fork River (Montana, USA) (data from Andrews 1987)

Location	Cu	Pb	Zn	Cd	As	Mn
	mg/kg					
Upper Ok Tedi R	1158	123	378	1.0	11	775
Upper Clark Fork R	2490	179	1770	9.7	199	8500
Global background	45	20	95	0.3	13	850

Table 6 Mean, standard deviation, median values and 25%–75% confidence intervals for 27 elements in Middle Fly River background sediment samples ($n = 128$)

Element	Unit	Mean	SD	Median	Percentiles	
					25	75
Na	mg/kg	4365	3146	3700	2000	5400
K	mg/kg	10829	4448	12050	7200	14100
Mg	mg/kg	5335	2320	5900	3400	7200
Ca	mg/kg	8787	7493	6100	4875	8025
Al	mg/kg	85538	25348	91100	71700	102400
Fe	mg/kg	37302	15185	33700	7200	46300
Mn	mg/kg	289	225	197	136	334
Zn	mg/kg	142	54	130	115	164
Cu	mg/kg	45	19	40	32	54
Pb	mg/kg	18	9	18	11	23
Cd	mg/kg	0.26	0.13	0.2	0.2	0.2
Au	μg/kg	6.7	6.5	3.0	1.0	8.5
Ag	mg/kg	0.24	0.26	0.2	0.1	0.3
As	mg/kg	4.6	3.6	4.0	2.0	5.0
Cr	mg/kg	61	16	61	55	70
Mo	mg/kg	1.7	1.4	1.0	1.0	2.0
Co	mg/kg	13	6	12	9	16
Ni	mg/kg	33	13	29	24	41
V	mg/kg	165	49	171	143	196
Ti	mg/kg	3765	1269	4100	3100	4400
Zr	mg/kg	67	25	67	49	83
La	mg/kg	24	7	25	20	28
Ba	mg/kg	309	119	309	255	361
Sr	mg/kg	137	57	127	101	162
Sc	mg/kg	17	5	18	14	20
C	wt.%	6.7	9.4	2.6	1.3	6.0
S	mg/kg	1447	1445	800	300	2525

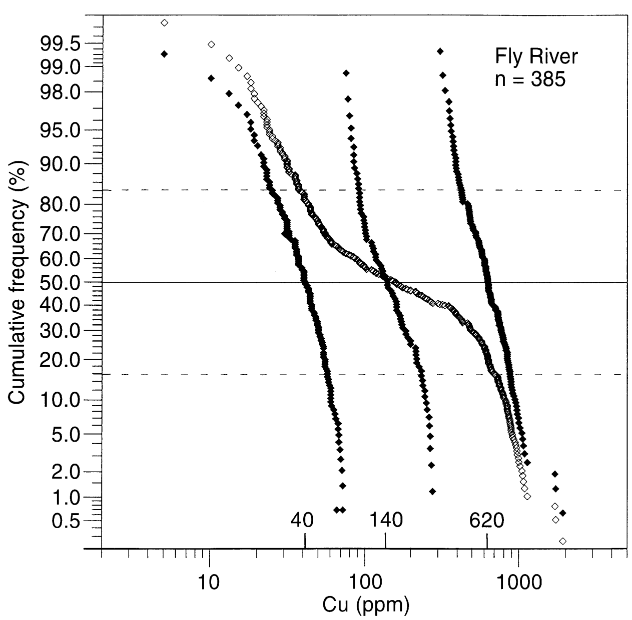

Fig. 5 Lognormal probability plot of the copper distribution in alluvial sediments in the Middle Fly River floodplain. The probability graph of the composite population of 385 data points (*open squares*) separates into three approximately lognormal subpopulations (*solid squares*). Median copper values for the subpopulations are shown above the x-axis

pit. This situation suggests that the mineralogical expression of the copper anomaly in the Middle Fly River sediments directly mirrors the conditions in the orebody, i.e. in situ-weathering at Mt Fubilan, and is little modified by hundreds of kilometres of fluvial sediment transport and the depositional time interval of several years.

The copper content in sediments from the Clark Fork River in Montana (USA) which drains the historically active Butte-Anaconda copper mining district where about 500 Mt of material were handled over 100 years of mining, displays values comparable to the Ok Tedi in the upper catchment, but drops to background values 400 km downstream of the mine sites (Andrews 1987). In the Belle Fourche River, South Dakota, the discharge of about 100 Mt of finely milled mine tailings from the Homestake gold mine in a 100 y period has lead to extensive floodplain deposition of metal-contaminated sediment. The mine wastes are visually distinguishable from pre-mining alluvium up to 160 km downstream of the mine and range as far as 200 m away from the present channel location (Marron 1987).

In the combined Ok Tedi/Fly River system with a total length of over 1000 km, copper sediment values decrease to background levels only in the vast estuary zone where the Fly River sediment load (ca. 100 Mt/year) mixes with a large volume of fluidized mud of an estimated order of up to 10×10^6 Mt (Eagle and Higgins 1991). Baker and Harris (1991) analyzed a large number of surficial grab samples and sediment cores from the Fly River delta and concluded that no increase in trace metal levels due to mining activities had occurred in the Fly Delta between 1986–1990. Baker and Harris (1991) observed two geochemically distinct regions: the Fly Delta where metal levels are comparatively high (mean

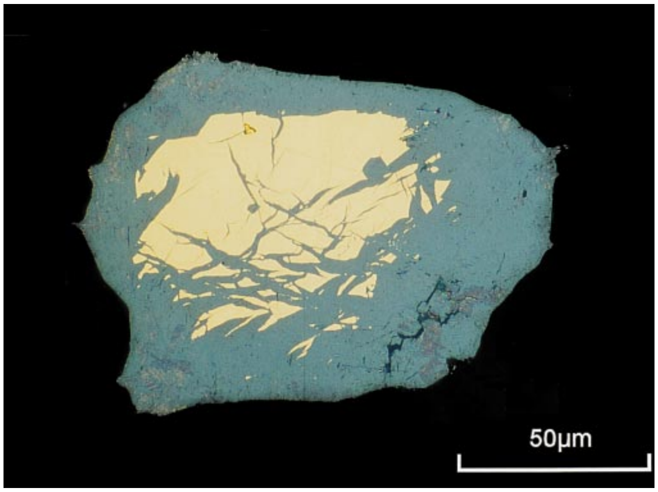

Fig. 6 Copper sulfide particle in sediment sample 6/8.4 (0–4 cm depth; 554 ppm Cu in < 20 μm fraction) from Lake Agu, 500 km below the mine site: intergrowth of chalcocite and covellite (outer part of grain) replacing chalcopyrite (core zone). Polished section, plane-polarized light, oil immersion

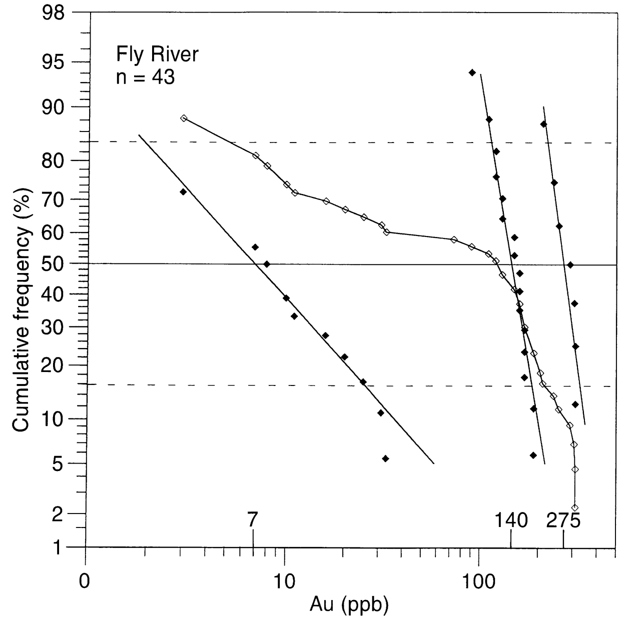

Fig. 7 Lognormal probability plot for gold concentrations in the Middle Fly River floodplain. The composite population of 43 data points (*open squares*) separates into three approximately lognormal subpopulations (*solid squares*). Median gold values for the subpopulations are shown above the x-axis

values of Cu = 28, Pb = 13 and Zn = 91 mg/kg) and the adjacent shelf environment with much lower trace metal levels (mean values of Cu = 8.2, Pb = 2.8 and Zn = 23 mg/kg). Alongi et al. (1991) also detected no change of copper levels with depth in 14 box core samples from the delta region. Similar to the observations by Baker and Harris (1991), Alongi et al. (1991) found slightly elevated sediment copper values (71 mg/kg in top 2 cm) in the southern channel of the estuary which may represent the first evidence of tailings input from the mine, the authors concluded. According to a recent OTML report (OTML 1994), copper concentrations in the benthic sediments of the Fly River delta remain at background levels.

Gold

Gold is of no environmental concern but shows an interesting secondary dispersion pattern in the Fly River sediments. The Ok Tedi mine operated during the first four years of production a closed-system cyanide leach plant without copper recovery, designed for the leached cap with supergene enriched gold of the porphyry system. After this initial period the sulfide flotation plant took over which has a gold recovery of only about 70%. This leaves the tailings material with about 200 μg/kg Au. The unprocessed overburden can have even higher Au values.

The probability plot of Fig. 7 defines three gold subpopulations. The background population has a mean around 7 μg/kg Au, whereas the two other subpopulations are highly anomalous with means of 140 and 275 μg/kg Au, respectively. We interpret the first population as a signature of the early mining stage when gold recovery was optimized, whereas the higher gold population is a signature of the current sulfide flotation process which has an optimal copper recovery at a heavy gold loss. Both high-gold populations are clear signals of the Ok Tedi mining activity, and gold is an even better tracer for discrimination of mine-derived material than copper. It is interesting to note that the Fly River at a distance of several hundred kilometres below the mine site deposits sediments with gold contents close to the cut-off grade of some heap-leach precious metal mines, such as Round Mountain, Nevada (cut-off: 180 μg/kg Au in dedicated pads; oral communication RMGC 1993).

Trace metals in waters

Water from the Middle Fly River (Table 7) is characterized by a moderately high content of earth alkaline and alkaline metals which is due to the active mineral dissolution of freshly eroded rock material carried in suspension from the Mount Fubilan mine site and the Ok Tedi catchment. The major anion is bicarbonate, followed by the minor anions sulfate, chloride and nitrate. The dominating dissolved electrolytes are calcium and bicarbonate, which account for approximately 90% of conductivity (calculated from mole equivalents), and which also control the moderately alkaline pH of 7.7. The content of dissolved organic carbon (DOC) is fairly high at about 6 mg/l (small number of samples, not reported in Table 7). Oxygen saturation measurements of Fly River water gave a mean value of only 66% which is obviously influenced by the oxygen-consuming decay of dissolved and particulate riverine organic matter. Re-

Table 7 Mean, standard deviation, median values and 25%–75% confidence intervals for Fly River water samples ($n = 11$)

Parameter	Unit	Mean	SD	Median	Percentiles	
					25	75
Temperature	°C	28.2	1.6	28.9	26.4	29.4
pH		7.7	0.2	7.7	7.7	7.8
Conductivity	μS/cm	138	15	136	128	146
Oxygen saturation	%	66	0.2	64	60	68
Suspended solids	mg/l	199	149	155	92	207
Na	μg/l	1564	299	1425	1350	1660
K	μg/l	622	87	615	536	667
Ca	μg/l	29380	6654	26000	24750	31300
Mg	μg/l	1237	170	1190	1075	1345
Sr	μg/l	172	36	158	144	181
Al	μg/l	below detection limit of 50 μg/l				
Fe	μg/l	72	102	30	8	75
Mn	μg/l	18.4	13.2	12.5	8.5	25
Zn	μg/l	9.2	6.2	8.0	4.0	10.5
Cd	μg/l	below detection limit of 0.1 μg/l				
Cu	μg/l	19.6	11.8	17.0	13.0	19.3
Pb	μg/l	below detection limit of 1 μg/l				
Mo	μg/l	7.9	5.0	7.0	3.0	12.0
HCO_3	mg/l	77	4.0	76	73	78
SO_4	mg/l	5.0	2.5	3.5	0.0	6.0

duced species (NH_4^+, HS^-, NO_2^- were present at or below detection limit which indicates oxygenated conditions. Dissolved trace metal levels, with the exception of copper (median value: 17 μg/l Cu), are generally low due to alkaline pH and high bicarbonate content. Solubility of inorganic copper species in the pH range measured in the river water is very low. The fact that, in spite of the high concentration of suspended matter (which offers adsorption sites), dissolved copper values are relatively high, points to the presence of soluble organic copper complexes which probably dominate the dissolved copper geochemistry. In a recent field and laboratory study on copper speciation in the Fly River by Apte et al. (1995) the authors conclude that the majority of dissolved copper is present in the form of organic complexes and that complexation capacity is in excess of dissolved copper concentration.

Analytical data of trace metals in waters of the Middle Fly region from the pre-mining period (Maunsell and Partners 1982; Kyle 1988) are of poor quality and make comparison with present data difficult. Dissolved calcium concentrations are reported to have been in the range of 13 to 16 mg/l, which corresponds to about half of the present values. Fly River water has a high natural content of earth alkaline and alkaline metals because of the limestone formations mainly in the Ok Tedi catchment. The natural Fly River water chemistry probably was not much different from present-day conditions, although Maunsell and Partners (1982) and Kyle (1988) report acidic pH values in the range of 5.5 to 6.7 which appear erroneous. Trace metal levels measured by Maunsell and Partners (1982) were at or below the detection limit of 1 μg/l with the exception of Fe, Mn and Zn.

The heavy metal concentrations in waters of the Fly River inner floodplain, the zone of mixed water, are of particular interest because of the prominent role which off-river waters play in the ecology and biological productivity of the entire river system. Copper concentrations in unpolluted floodplain waters of low pH and conductivity ("blackwaters") were measured at below 2 μg/l; average copper content in mixed waters of the inner floodplain is around 9 μg/l ($\pm 1\sigma$: 5–14, n = 69) (Table 8). The intrusion of Fly River water into the floodplain watercourses and lakes is associated with the transport of mainly mine-derived suspended matter, which is deposited there. Hence, it is not possible to distinguish between dissolved metals in mixed waters which are directly derived from an intrusion of Fly River water and those that may be mobilized secondarily from the sediments already deposited. Dissolved organic carbon and pH are weakly negatively correlated which is due to the acidic nature of humic and fulvic substances. Calcite in particulate form carried into unpolluted floodplain waters, which show a mean pH of 6.0, is rapidly dissolved and exerts a buffering effect. In the absence of calcium bicarbonate buffering, the organic acids control water pH. A positive relationship of the alkaline and earth alkaline metals with sulfate was observed. Elevated concentrations of Ca, Mg, Na, K, and Sr are clear indicators of the influence of mine discharges.

Dissolved trace metal levels in mixed (floodplain/Fly River) waters are controlled by a number of abiotic and biotic factors. The most important inorganic factor is the moderately high bicarbonate content of Fly River water and the high earth alkaline metal concentrations, dominated by calcium in dissolved and particulate form,

Table 8 Mean, standard deviation, median values and 25%–75% confidence intervals for mixed water samples ($n = 65$)

Parameter	Unit	Mean	SD	Median	Percentiles	
					25	75
Temperature	°C	30.2	2.0	30.1	28.9	31.7
pH		7.3	0.8	7.1	6.6	7.7
Conductivity	µS/cm	130	90	119	80	151
Oxygen saturation	%	77	42	77	41	107
Suspended solids	mg/l	36	72	15	7	28
Na	µg/l	1587	541	1480	1185	1755
K	µg/l	539	657	385	272	603
Ca	µg/l	21390	8372	21900	13425	28050
Mg	µg/l	1226	725	1140	881	1345
Sr	µg/l	150	111	138	82	176
Al	µg/l	102	139	25	25	101
Fe	µg/l	357	590	145	32	457
Mn	µg/l	82	308	2.5	2.5	24.5
Zn	µg/l	15.4	15.5	12	6	19
Cd	µg/l	close to detection limit of 0.1 µg/l				
Cu	µg/l	11.8	11.3	9	5	14
Pb	µg/l	close to detection limit of 1µ g/l				
Mo	µg/l	7.8	9.9	5.0	2.5	9.0
HCO_3	mg/l	53	28	47	39	62
NH_4	mg/l	0.21	0.16	0.15	0.10	0.25
SO_4	mg/l	2.5	2.0	2.1	0.7	3.4
DOC	mg/l	9.0	2.5	9.0	7.3	11.0

which are responsible for the neutral to alkaline pH values in mixed waters. The most prominent biotic factor are the dissolved organic carbon substances which play a very important role as complexing agents.

Water taken from swampy floodplain locations close to the Fly showed copper values of up to 50 µg/l Cu in the filtered sample (membrane filter 0.45 µm). The water table in the floodplain may be located anywhere within the upper part of the stratigraphic profile depending on the river stage, resulting in changing redox conditions in the sediment body. Acidic conditions and humic substances generated by decomposing vegetation, typical features of low-lying floodplain swamps, facilitate the mobilization of copper from the solid into the dissolved phase.

Conclusions

Besides the physical impact of suspended sediment load, the chemical impact of the Ok Tedi Mine waste is mainly by copper because of its strong enrichment above background (about 15 times) and its relatively high general geochemical mobility. There is substantial deposition of copper-rich material in the Middle Fly River floodplain, although most of the mining waste finally reaches the delta. Areas of standing water and vegetated parts of the floodplain play an important role in the recruitment of fish and primary productivity, and this part of the fluvial ecosystem has locally very high dissolved Cu values.

The pollution by copper-rich material is not only a problem of quantity, but also of spatial distribution and the potential mobilization of the trace metal. Deposition of mine-derived sediments in the Fly River floodplain is highest in oxbow lakes. Because of the naturally high organic carbon content in lake sediments, which is responsible for reducing conditions, copper is probably largely immobile and has little bioavailability. However, when mine-derived sediments settle on extensive areas of the vegetated floodplain under a variable redox regime, even a thin layer of copper-rich material may have a negative ecological impact.

The copper pollution in the Fly River floodplain is of persistent nature. Erosion processes in the post-mining period will remove deposits in the main river channel and on the banks immediately adjacent to it, and, to a minor degree, along the channels connecting drowned valley lakes with the main river. However, the mine-derived material deposited in oxbow and drowned valley lakes, and in the floodplain swamps, will remain and will be covered by natural sediments only very slowly, given the very low background sedimentation rates in the floodplain.

The practical balance between economic benefit and environmental damage is a matter of widespread current debate. The island of New Guinea hosts a number of modern large-scale mines which, in spite of otherwise very advanced technology, operate without mining waste retention facilities. An even more dramatic example, 400 km to the west of Ok Tedi, is the 3000 MUS$ Grasberg project in Irian Jaya where the tailings-laden Ajkwa River is causing severe aggradation and flooding of an extensive area of vegetated lowland (Mining Journal, April 26, 1996). The use of rivers for tailings disposal may clearly create problems for local communities which live along (and from) the river system.

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