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Environmental Impact of Large-Scale Mining in Papua New Guinea: Mining Residue Disposal by the Ok Tedi Copper-Gold Mine

by

Jörg Hettler and Bernd Lehmann **

Summary

The Ok Tedi copper-gold mine, located in the eastern part of the central mountain range of New Guinea, discharges daily approximately 80,000 tons of ore processing residues and a similar volume of waste rock and overburden into the headwaters of the Ok Tedi River. The Mount Fubilan orebody, which is the source of heavy metal-rich sediments deposited along the Ok Tedi and on the Fly River floodplain, contains a suite of base metals, of which copper is of primary environmental concern. The Ok Tedi flows into the Fly River 200 km downstream of the discharge point, where the mining wastes carried as suspended load are diluted. In the present study, the deposition of mine-derived sediments in the lower part of the Middle Fly River floodplain, and the hydrochemistry and potential mobilization of trace metals, particularly copper, in the alluvial plain was investigated. To this end, a total of 156 sediment cores and surface sediment samples and 117 water samples from the upper Ok Tedi and the Middle and Lower Fly River floodplain were taken. The suspended matter content in Middle Fly River water today is about 5-10 times higher than the natural background of about 60 mg/l. Near-surface sediments deposited along the river channel contain up to 1100 mg/kg Cu, the mean value is 530 ($\pm\sigma$ = 240-820) mg/kg.

Of the floodplain water bodies, cut-off meanders receive the largest quantities of mine-derived sediment. Deposits of up to 70 cm in thickness of copper-rich material with 800-1000 mg/kg Cu, which have accumulated since the mine started discharging residues in 1984, were detected in oxbow lakes. Very high deposition rates (around 4 cm/year) of mine-derived sediment were determined in locations close to the creeks and channels which link the Fly River with the outer floodplain. Due to the flat terrain, turbid Fly River water intrudes regularly upstream of the floodplain tributaries (measured intrusions up to 25 km). 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. Copper in sediment deposited in the pre-mining period gave a median value of 44 ($\pm\sigma$ = 25-63) mg/kg. Riverine particulate matter also settles down on the floodplain at times of overbank flow, which leads to extensive copper contamination in low-lying swamp sites close to the river. Natural deposition rates in the floodplain were determined by C^{14} age dating to range between 0.1-1 mm/year, with the exception of oxbow lakes, where natural sedimentation is much higher. Leaching of copper from material deposited on swampy, vegetated floodplain sites was detected in sediments which were also strongly depleted in calcite and sulfide, which are the components most easily mobilized of mine-derived material. The variable water table, oxidizing environment and acidic conditions generated by decomposing vegetation, typical features of low-lying floodplain swamps, facilitate the mobilization of copper from the solid into the dissolved phase. Water taken from swampy floodplain locations showed copper values of up to 50 μg/l Cu in the filtered sample (membrane filter 0.45 μm).

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Average copper content in mixed waters of the inner floodplain is around 9 ($\pm\sigma$ = 5-14) µg/l; the Fly River water has around 17 ($\pm\sigma$ = 13-19) µg/l Cu. Copper concentrations in unpolluted floodplain waters were measured at below 2 µg/l. Nearly all dissolved copper in the Fly River system is complexed by dissolved organic carbon compounds, however, a fraction of these complexes appears to be labile and reactive. Comparison of dissolved copper levels measured during the present study in the Middle Fly River floodplain with literature data on copper toxicity and international water quality guidelines shows that chronic toxicity of the metal to the aquatic community is to be expected. Significant negative ecological effects, particularly on the local fish population, may develop with a considerable time lag, since aquatic organisms at the base of the food web are the biota most sensitive to copper.

Foreword

by Dr. David Mowbray, Professor of Environmental Science at the University of Papua New Guinea and Government Adviser to the PNG Department of Environment and Conservation

The Ok Tedi mine in PNG ranks amongst the world's largest copper mines. It is a major contributor to the PNG economy accounting for up to 45% of PNG's total annual export revenues. The PNG Government is a 30% shareholder in Ok Tedi Mining Ltd. (OTML). Mining for gold commenced in 1984, and for copper in 1986. Mining for copper is expected to continue for a further 10-15 years.

Initially it was intended that a tailings dam should be constructed to contain the mine's waste. However for economic reasons and given that the area is structurally unstable, no tailings dam was constructed, and so since 1986 from 100,000 to 150,000 tonnes of waste per day have been discharged into the Ok Tedi and Fly River system. In 1989 the PNG Government set compliance standards covering suspended particulate load, dissolved and particulate copper levels, biological parameters like fish catch, and others. It is argued by some that the environmental management of the mine is based on monitoring for compliance with standards that have been established "to facilitate the realization of OTML's mining schedule" rather than to protect the environment.

Ok Tedi Mining Ltd. has an extensive environmental monitoring programme. Assessment of compliance monitoring and interpretation are done routinely by the company (and the Government), but no detailed data are available for public scrutiny (if at all) for at least a year after data are collected. This lack of public accountability for environmental performance is unacceptable.

Inevitably the Ok Tedi mine evokes different emotions and perceptions by different groups in PNG. For example, Mr Kipling Uiari, the former Deputy General Manager of OTML and now BHP PNG General Manager, stated in 1993 at the 20th Waigani Seminar on "Environment and Development" here at the University of PNG:

> "Importantly, the mine has brought positive changes to the quality of life of neighbouring communities in the previously underdeveloped Western Province. Investment in project infrastructure has amounted to about K300m and many of the basic services now established are available to all citizens in the area. This is particularly true of the road, power, health and water systems, transport and communication facilities. These services are meeting the basic needs of local villagers by increasing life expectancy and providing access to education, employment and business opportunities.
>
> Ok Tedi Mining Ltd. has taken a number of iniatives to encourage as much participation as possible from people in the region and so ensure human development goes hand in hand with mineral development.
>
> Sustainable development also requires good environmental stewardship. During the devlopment of the Ok Tedi project there have been criticisms of its environmental impacts, many of them based on inaccurate information. Ok Tedi Mining Ltd. is a responsible resources development company which recognises that all environmental effects must be carefully considered. It is the extent of these impacts and whether they are reversible or not,

which must be considered in relation to the social and economic benefits to the communities involved and the nation as a whole."

Whereas at the same seminar Mr Alex Maun, a prominent landowner stated:

"With the mining operation our life has changed. The loss of our rainforest and degradation of the environment cannot be calculated in terms of short-term money. We are rural village subsistence farmers who depend on the environment for survival.

Before the Ok Tedi Mine operation our life was paradise, we enjoyed both the aquatic and terrestrial resources. We used the river for fishing, washing, drinking and transportation. We made gardens near the river banks which lasted 3 to 5 years.

Now we river people can no longer drink from the river nor can swim, bath or wash clothes in the river. We lack the protein in our diet that was formerly provided by the aquatic and terrestrial resources. Overflow of the Ok Tedi River has caused the wild life near the river banks and floodplains to disappear. Some game animals were drowned by sudden floods. Trees in the floodplains are dying completely forcing the wild life to migrate to other areas. Now gardens are no longer made near the river banks.

I would like to stress that Ok Tedi Mining is causing irreversible destruction along the Fly River an Ok Tedi River. Whatever it is destroying will never come back to normal, e.g. customary land, sago swamps, etc. OTML is bringing unsustainable development. We affected river people think it is nonsense talking about sustainable development when the mess done by the Ok Tedi Mining is not cleaned up."

In 1994 Ok Tedi again hit the headlines: "Ok Tedi has to build tailings dam - Zeipi", so says *Post Courier* headline on 18 March 1994. The report goes on:

"Ok Tedi Mining Ltd (OTML) will be told to build a series of dams to dispose of mine wastes or "ship out" if it refuses. Mr Zeipi has always insisted a tailings dam be built because, he says, the river dumping has damaging effects on the ecosystems."
(Mr. Zeipi is Minister for Environment and Conservation).

"K2b case looms on mine damage" again says *Post Courier* headline, this time on 4 May 1994. Then in *Post Courier* on 6 May a report states:

"The leader of a Papua New Guinean clan lodged a writ in the Melbourne Supreme Court yesterday against Australia's biggest company, BHP, seeking unspecified damages for allegedly poisoning the Ok Tedi River and destroying his people's subsistence way of life. It also alleges the PNG Goverment, a 30 percent shareholder in Ok Tedi Mining Ltd., had "failed, neglected and refused" to enforce environmental agreements and convenants."

These matters are still being dealt with in both PNG and Australian courts and have not been resolved. Furthermore present debate continues between Government ministers and leaders and Mr Zeipi on the type of compensation payments for environmental damage and whether a tailings dam should and could be built.

The Floodplains

The Ok Tedi mine adds about 58 million tonnes of sediment to the Ok Tedi River per year. It is estimated that 30% is deposited along the Ok Tedi, much of the rest reaches the Fly Delta. An unknown amount is deposited along the Fly River and in the floodplains in the middle Fly. Studies on the coastal and marine ecosystems in the Fly Delta, Papuan Gulf an Torres Straits are being done by both Ok Tedi and Australian scientists funded by Ok Tedi. Studies on the floodplains of the middle Fly are being done by Ok Tedi scientists, and are also the focus of the present UNEP study.

OTML, in its booklet "Ok Tedi, the Environment and You" states that

> "copper in the sediment in the Fly River is also being transported during floods onto the floodplain where it settles into the lakes, streams and the flooded forest. At this time there is very little scientific information to tell us what effect this copper on the floodplain might have on fish life, feed and breed in this area".

Consequently OTML has commissioned studies of the amounts in and effects of copper on the floodplain ecosystems. Unfortunately the PNG Government and independent researchers generally lack the financial and human resources to do independent monitoring and research of depth and detail. Hence most studies are done by or commissioned by OTML.

This study by Jorg Hettler and Bernd Lehmann is valuable since it is done by overseas scientists funded by UNEP through the universities of Berlin and Clausthal and the University of PNG. It is apparent from their work that copper is being deposited in the floodplain at higher than expected levels. Hopefully future independent scientists can assist in deciding if this copper contamination is likely to have biological effects, for examples if fish populations may be affected.

The present study is a valuable contribution to our present state of knowledge of the Ok Tedi/Fly River system. In fact more environmental research has been done on this tropical river system over the last 15 years than probably any other tropical river system in the world. Yet there is still much uncertainty!

Back in 1982 in his book "The Pot of Gold", Richard Jackson made a statement which (in slightly modified form) still is applicable 13 years later:

> "In our present state of knowledge of the workings of natural systems, it is only in the rarest of occasions that honest environmental experts agree as a body and confidently predict a sequence of future events and outcomes. The Ok Tedi project is not one of those occasions. Decisions have been made in the project hoping that environmental risks will be worth it, that is, hoping that in the light of the facts available the magnitude of the environmental impact will be minimal. But the facts available are, still, too few. In the Ok Tedi case, the experts, if they are honest, will be keeping their fingers crossed and environmental monitoring systems under constant scrutiny ..."

and hoping that the environmental damages remain acceptable!

Table of Contents

1. INTRODUCTION

The environmental problems of mining activities have been receiving increasing attention worldwide in the last decade. The shift in the search for raw materials outside of the classical producer countries to the world's marginal regions like tropical rainforests has led to a number of environmental and social problems. In many cases, the extraction of natural resources has been the first industrial activity being developed in peripheral regions. Requirements of infrastructure, logistics and workforce may completely change the environmental and social patterns in regions which have previously been nearly untouched by man. One of the best documented examples of such a development is the Ok Tedi gold-copper mining project in Papua New Guinea. Before the economic value of the Mount Fubilan orebody was discovered in the late 1960's, the mountain was a sacred place to the sparse population of the local Wopkaimin Papua tribe, who were inhabiting one of the world's most isolated regions. The environmental impact of the mining operation, located in a difficult physical environment, has been subject of controversy since the project's early planning stages. The fact that the Ok Tedi mine works without waste retention facilities has been in the focus of the debate in the last few years. In May 1994, local inhabitants living along the Ok Tedi River lodged a $A4,0000 million compensation claim against the mine's operator, BHP, over environmental damage caused by the discharge of tailings and waste rock into the Ok Tedi. (Mining Journal , May 6, 1994)

The mining company is engaged in an extensive environmental monitoring program and also has commissioned a number of studies on individual problems which have been executed by international research institutions and consultants. The present study, funded by the United Nations Environment Programme, is the first independent research project undertaken in the area. It investigates one of the most important environmental aspects of the mining project. Based on discussions with the Environment Department of Ok Tedi Mining Ltd., it focusses on the fate of mine-derived sediments deposited in the Fly River floodplain.

The project's coordinator was Dr. Bernd Lehmann, Professor of Applied Geology at Technische Universität Clausthal. The responsible research officer was Jörg Hettler, M. Sc. (Geology), of the Department of Environmental and Resource Geology at Freie Universität Berlin. The sedimentological part of the study was coordinated by Dr. Georg Irion, Professor at Forschungsinstitut Senckenberg, Wilhelmshaven. The University of Papua New Guinea offered comprehensive logistical support during the field and laboratory work.
A draft version of this report has been presented by the study team in a series of discussions held in September 1994 in Port Moresby and Tabubil, Papua New Guinea, with Ok Tedi Mining Limited, the Departments of Mining and Petroleum (DMP) and Environment and Conservation (DEC) of the Papua New Guinea Government, and the University of Papua New Guinea.

2. SAMPLING AND ANALYTICAL METHODOLOGY

2.1. Sampling

Sampling locations were determined with a handheld Global Positioning System (GPS) receiver and available topographic maps of scales 1:100,000 and 1:250,000. Water depth and bottom relief were measured with a portable electronic depth sounder with LCD screen.

2.1.1. Sediments

32 surface sediments from the river bank of the Ok Tedi at Tabubil and from a few locations in the Middle Fly region were sampled with a plastic spoon and collected in geochemical sampling paper bags. The large majority of sediment samples (124) taken along the Fly River was recovered with a gravity corer.
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. The

gravity corer consists of a massive aluminium tube with a backslash (floating) valve mounted on the upper end. Fins are welded to the aluminium body to stabilize the corer during its free fall through the water column. Coring tubes of transparent acrylic glass ("Plexiglas") of 1 m or 1.5 m length were fixed inside of the aluminium shaft. The corer was brought in an upright position above the water and then released for free fall. To increase penetration depth in the bottom sediment, a ring-shaped lead weight of 10 kg was fitted to the alumimium shaft. The corer is hoisted from the bottom of the sampled water body with a rope fixed to the backslash valve, which remains closed. The sediment 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. The cores, which showed no or minimal disturbance, where pushed out of the plexiglas tubes with a rubber stopper and were packed in clean polyethylene bags. On floodplain sites, the sampling tubes were driven by hand into the sediment. After closing the open end with a rubber stopper, the tube was pulled out. The sediment cores recovered were usually in the same range of lengths as the cores from water bodies.

2.1.2. Water

A total of 117 water samples in the Ok Tedi/Fly River system was taken. Water temperature, pH, conductivity and oxygen content were measured in the field using portable electronic equipment. The reduced species NH_4^+, HS^- and NO_2^- were also determined in the field using "Merck Aquaquant" reagent kits for rapid water analysis, based on a colorimetric method.
All water samples were gulp samples taken by hand 20-50 cm below the water surface, the volumes ranging between 250 and 1500 ml. The wide-mouth polyethylene bottles were soaked in dilute nitric acid for two days and washed with demineralized/distilled water before use in the field. The containers were rinsed twice with water from the sampling site before the sample was taken. Upon return to the field laboratory within a few hours after collection, alkalinity was determined by titration with 0.02 mol HCl to pH 4.5 (APHA Standard Method No. 403).
The water was filtered through 0.45 µm cellulose nitrate membrane filters (Sartorius, Germany) with a portable "ANTLIA" pressure filtration system (Schleicher & Schuell, Germany) which consists of a pneumatic pump, a 50 ml syringe cylinder and a filter holder of 50 mm diameter. Sometimes a pre-filter (Schleicher & Schuell Blue Ribbon ashless) had to be used for highly turbid water. After sufficient rinsing of the pump and filtration system, a 120 ml water sample was taken 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. The suspended matter content in some samples was measured using a 1,5 l "Imhoff" funnel-shaped sedimentation cylinder. Few water samples were split and a subsample was acidified unfiltered to determine the trace metal content associated with the particulate matter. Water samples selected for anion analysis were filtered but not acidified, DOC samples were stabilized with 2 ml/l of 50% H_2SO_4.
Great care was taken to avoid cross-contamination of collected material. All equipment was acid-washed and rinsed with distilled and deionised water between use for different samples in the field laboratory. Blanks were included and submitted to the same procedure as the samples.

2.2. Analytical Methods

2.2.1. Sediments

Sediment cores were cut in halves in the laboratory with a stainless stell knife to allow visual inspection and taking of photographs.
Sub-sections of sediment cores were wet sieved with distilled water through nylon sieves of 20, 60, 100 and 200 µm mesh size. The resulting size fractions <20 µm, 20-60 µm, 60-100 µm, 100-200 µm and >200 µm were washed from the sieves into plastic containers and dried to constant weight at 80° in a drying oven. Grain size distribution was determined after weighing.
The fraction less than 20 µm in samples selected for clay mineral analysis was submitted to gravity separation in "Atterberg" sedimentation cylinders. Of the resulting three fractions (<2 µm, 2-6.3 µm, 6.3-20 µm), the finest was used to prepare smear slides which were submitted to X-ray diffraction analysis.

NBS 2704 Buffalo River Sediment	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	P	Sc
	ppm																								
Certified	5470	20000	12000	26000	61100	41100	555	438	98.6	161	3.45		23.4	135		14	44	95	4570	300	29	414	130	998	12
Uncertainty	±140	±400	±200	±300	±1600	±1000	±19	±12	±5.0	±17	±0.22		±0.8	±5		±0.6	±3	±4	±180			±12		±28	
Analyzed (ICP-S)	6100	20100	12300	27800	61500	41000	537	397	103	129	2.4	0.6	8/20*	103	5	11	40	75	2700	102	28	467	145	990	13

EEC/BCR RM 280 Lake Sediment	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	P	Sc
	ppm																								
Certified	17600	26000	16430	16870	77500	42360	1350	291	70.5	80.2	1.6	1.1	51.0	114	1.9	20	73.6	102	4040			618		1530	12.8
Uncertainty								±4	±1.5	±2.3	±0.1		±2.4	±4			±2.6								±0.7
Analyzed (ICP-S)	15800	24800	16200	16500	77500	41400	1148	262	65	65	1.0	<.3	30	87	2	15	64	72	3100	15	30	681	203	1410	14

Table 1. Quality control with standard reference materials. Values with no uncertainty range given are noncertified. As value with * is by hydride generation/ICP-S.

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. The vigorous digestion procedure leads to potential loss of As, Sb and Cr due to volatilization during $HClO_4$ fuming. The leach, however, is partial for magnetite, chromite, barite, oxides of Al, Zr and Mn. 35 elements were determined by inductively coupled plasma spectrometry (ICP-S), of which 24 are reported in the present study. Arsenic and antimony were additionally determined by hydride generation with aqua regia digestion and ICP-S analysis. 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 Leco furnace, in which CO_2 and SO_2 gases are released during combustion and then detected. A 15 % HCl leach prior to combustion was performed to remove soluble sulfate and carbonates. This procedure ensures that only organic carbon and sulfur bound as metal sulfide is detected.

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. Results are shown in Table 1.
Radiocarbon age dating was performed on five samples of peaty sediment from drowned valley lakes at the C^{14} laboratory of Kiel University, Germany.

2.2.2. Water

Water samples were analyzed at a commercial laboratory (XRAL, Canada), at the laboratory of the Department of Environmental and Resource Geology at Freie Universitat Berlin (FUB), and at the laboratory of the Environment Department of Ok Tedi Mining Limited at Tabubil (OTML).
Commercial analysis for metals was by multi-element ICP-S, of which measurements for 13 elements are reported in this study. 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) at FUB and OTML laboratories.
Major anions (sulfate, chloride, nitrate) were analyzed by suppressed ion chromatography on non-acidified samples. Dissolved organic carbon (DOC) was determined with a "Technicon" auto analyzer.

Quality control for water analysis was more difficult as compared to sediments since no standard reference material was available. Calcium and bicarbonate values, which were determined by two different methods, gave a correlation of 99% in the data set of all measured values. Values obtained for blanks and measurements of the same sample by different methods and laboratories are given in Table 2. The analyses of blanks (demineralized/distilled laboratory water) showed no or minimal contamination, with the exception of zinc. Reported values for this metal have been corrected by subtraction of zinc content in blank samples.

Statistical analysis of sediment and water values was performed using the U.S. Environmental Protection Agency 'Geostatistical Environmental Assessment' software (GEO-EAS, USEPA 1988). Geochemical modelling and speciation determination was done with an updated version of the PHREEQE software (Plummer, Parkhurst & Thorstenson, 1980).

W1/28.10	Zn	Cu	Pb	Cd
	μg/l			
XRAL ICP-S	24	23	2	<1
FUB GFAA	25	22	3	<.1

W1/30.3.	Fe	Mn	Zn	Cu	Pb	Cd
	μg/l					
XRAL ICP-S	126	167	8	4	nd	nd
FUB GFAA	nd	nd	10	5	<1	<.1
OTML GFAA	102	76	8	5	<1	0.05

W3/1.4.	Fe	Mn	Zn	Cu	Pb	Cd
	μg/l					
XRAL ICP-S	111	21	28	<2	nd	nd
FUB GFAA	nd	nd	20	1.5	<1	<.1
OTML GFAA	87	24	19	1.3	<1	<.04

W1/7.4.	Fe	Mn	Zn	Cu	Pb	Cd
	μg/l					
XRAL ICP-S	319	13	17	53	nd	nd
FUB GFAA	nd	nd	20	50	<1	<.1
OTML GFAA	134	15	15	34	<1	0.1

W3/8.4.	Fe	Mn	Zn	Cu	Pb	Cd
	μg/l					
XRAL ICP-S	50	<5	<5	14	nd	nd
FUB GFAA	nd	nd	<5	16	<1	<.1
OTML GFAA	48	4	1.3	16	<1	0.08

Blank (DDW lab water)	Fe	Mn	Zn	Cu	Pb	Cd
	μg/l					
XRAL ICP-S	<10	<5	11	<2	nd	nd
FUB GFAA	nd	nd	20	<1	<1	<.1
OTML GFAA	27	0.5	13	0.2	<1	<.04

Table 2. Quality control for water samples. The same sample was analyzed by three different laboratories.

3. THE ENVIRONMENT OF THE OK TEDI/FLY RIVER REGION

3.1. Geology of the Mount Fubilan Ore Deposit

Trace metal contamination of the Ok Tedi/Fly River system through mine discharges is closely related to the geochemical composition of the Ok Tedi ore.

The orebody at Mount Fubilan consists largely of an intruded and altered monzonite porphyry stock of Lower Pleistocene age, which hosts a mesothermal, stockwork and disseminated copper-gold mineralization (Rush and Seegers 1990). Intense weathering at Mt. Fubilan led to the formation of a copper-depleted, but gold-enriched cap (gossan)

overlying the primary mineralization. The deposit is similar to other big copper porphyry mines in the Pacific Rim region. Pyrite and chalcopyrite are the dominant sulfide minerals in the protore below the supergene enrichment zone. Average metal concentrations in the orebody are 0.75% of copper and 0.67 grams per ton of gold (OTML 1993).
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).

Porphyry base-metal deposits of hydrothermal origin like Ok Tedi typically contain a paragenetic sequence of the metals copper, molybdenum, silver, gold, lead, zinc, iron, manganese, selenium, arsenic, cadmium, tungsten and others, which are not evenly distributed within the orebody, but are located in distinct zones around the low-grade quartz core of the intrusion. Very high values for lead (1000-3000 ppm) have been found in overburden sampled in October 1991.
The skarn mineral paragenesis, has an elevated and more variable content of trace metals as compared to the copper porphyry ore, and is more critical from an environmental point of view.
However, arsenic and mercury, which are frequently associated with gold mineralisation, show no enrichment above background levels in the Ok Tedi deposit.

Ore minerals of the oxide zone: cupriferous goethite Cu.FeOOH, cuprite Cu_2O, native Cu, malachite $Cu_2CO_3(OH)_2$, azurite $Cu_3(CO_3)_2(OH)_2$, copper carbonates

Ore minerals of the sulfide zone: chalcocite Cu_2S, digenite, covellite CuS (*supergene formations*)
chalcopyrite $CuFeS_2$, bornite Cu_5FeS_4 (very minor), pyrite/marcasite FeS_2, molybdenite MoS_2
(*protore mineralization*)

Sulfides of Se and Ag are accessory minerals in the main orebody (Fubilan Monzonite Porphyry)

Pb, Zn, Cd, As, Ag and Se minerals are found mainly in skarn ores

Table 3. Ok Tedi ore composition

3.2. Geomorphology and Vegetation

The minesite at Mount Fubilan, which had an elevation of 2094 m above mean sea level (MSL) before mining started, is located in the upper catchment of the Ok Tedi (Map 1). The site receives rainfall of 10,000 mm per annum, which is amongst the world's highest.
Dense tropical rainforest blankets the ridge and ravine topography. The area is seismically active and prone to landslides. North of the Ok Tedi catchment stretches the massive Hindenburg Range with maximum elevations of 3325 m. The range is a highly unstable, cliff-like structure build up of Tertiary Darai Limestone, which is responsible for the high natural calcium and bicarbonate content in Ok Tedi water.

The tributary streams in the area are very steep and form narrow, gorge-like valleys, with boulder-size alluvial debris. Upstream of Ningerum (60 m above MSL), the Ok Tedi is a braided river, up to 100 m wide. At Ningerum, 70 km to the south of the mine, the Ok Tedi River leaves the mountaineous region. Between Ningerum and Konkonda, the river passes through a transition phase and enters the Fly Platform, a vast alluvial plateau with very little relief and meandering streams. 130 km downstream of Ningerum, the Ok Tedi flows into the Upper Fly River at D'Albertis Junction at 20 m elevation above MSL. South of the junction, the river channel is flat and meandering, flanked by thick jungle, extensive backswamps, lakes and lagoons. The reach between D'Albertis Junction and the confluence with the Strickland River south of Obo (Everill Junction) is called Middle Fly River, with a length of 410 river kilometers. The sinuosity factor is about 2.4. The channel width varies between 200 and 300 m on average.
Downstream of Kai and Agu Rivers/Lakes, the floodplain vegetation pattern is dominated by tall, dense reed (*Phragmites, Saccharum*) and smaller grasses. Jungle is restricted to a few isolated areas of higher elevation. Trees grow only in rarely inundated areas (with the exception of Sago palms and thin-stemmed *Melaleuca*) because of their susceptibility to prolonged flooding. The fact that trees are largely missing in the lower part of the Middle Fly points to frequent natural flooding.

Lakes and shallow water bodies and channels of the floodplain often have a dense vegetation of aquatic grasses, floating *Azolla* (Equisetum), *Pistia* (Araceae), water lillies, and the submerged *Ceratophyllum*.
Below Everill Junction, the Lower Fly River is tidally influenced, reaching the delta 400 km downstream. Due to the increased flow rate and a lower gradient, the channel width and meander amplitude are greater than in the Middle Fly.
The Fly River floodplain is made up of an inner part, the channel migration zone comprising the present river channel, cut-off meanders and meander scroll complexes, and the outer part with drowned valley lakes and extensive backswamps (Fig. P1).

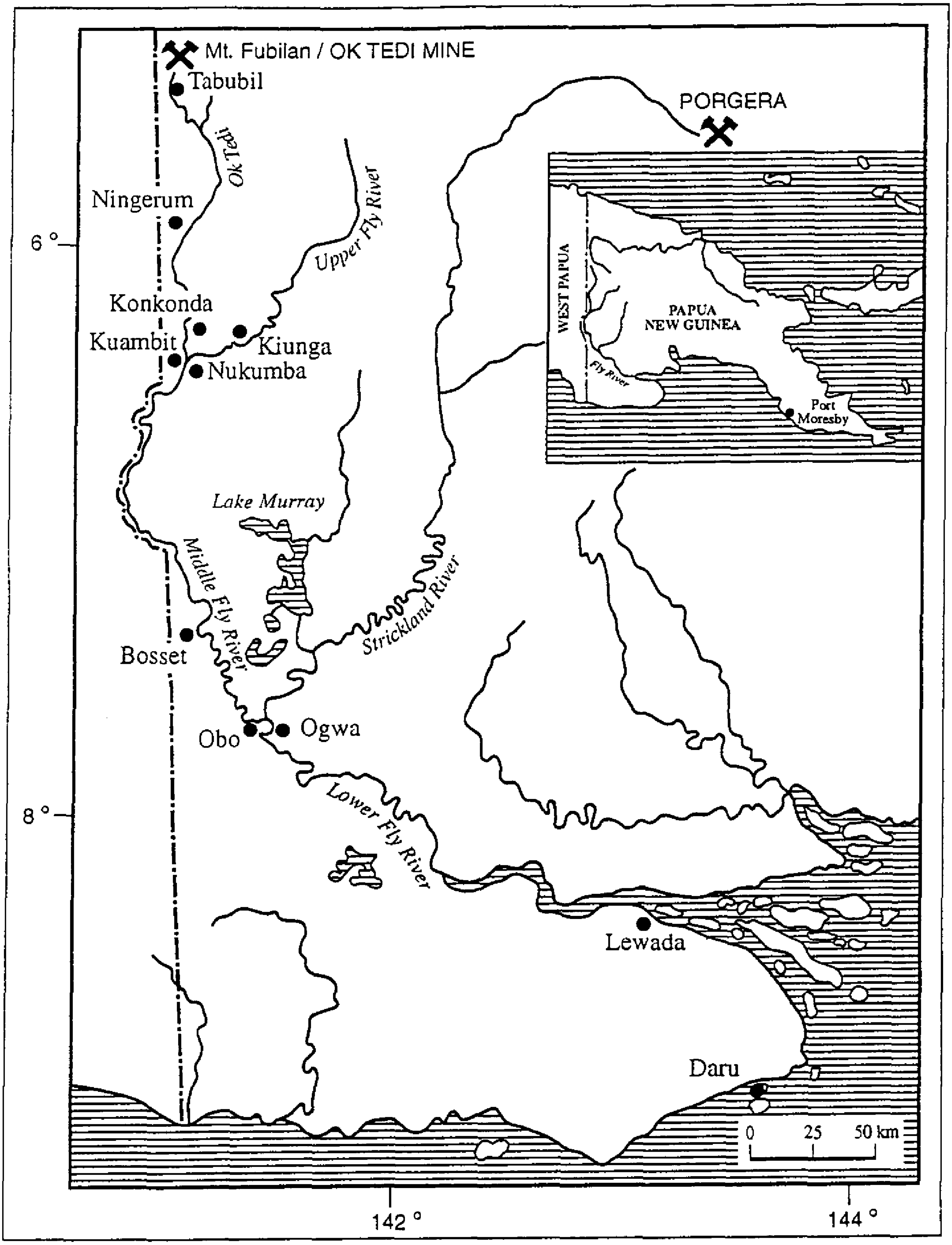
Fig. P1. Backswamp close to Obo, several hundred metres away from the Fly River. Due to difficult access, only few samples could be taken from these locations.

The floodplain widens from 4 km width near Kiunga to over 14 km close to Obo. Discontinuous low natural levees, about 1-2 m above mean river level, flank the existing river channel.
Drowned valley lakes are typically connected to the river by a narrow, sinuous channel with a length of 1-2 km, 3-10 m width and a depth of 2 to 5 m, becoming more shallow towards the lake (Fig. P2). The channel itself is being kept open by the scouring action of sediment particles in the water. The lakes have a depth of about 1.5 to 2.5 m, cut by slightly deeper channels, decreasing to less than 1 m towards the end away from the river. Their bottom relief clearly reflects their origin as tributaries to the Fly River. During the sea level rise which ended about 5,000 years ago, the river ends of the larger floodplain creeks were filled with sediment derived from the Fly River. Water can flow freely in both directions, depending on the water levels in lakes and the Fly River.

Due to the low relief, the edges of lakes or "lagoons" are not well defined and tend to merge with neighbouring grasslands at high water level (Fig. P3). Higher banks, on which the villages are usually located, are remnants of eroded plateaus of Pleistocene age. The water level in the lakes is highly variable. Following consecutive dry months, lakes may dry out completely which can result in massive fish kills.

3.3. Hydrology and Climate

The climate in the investigated area is wet tropical. The minesite receives well distributed rainfall on 325 days throughout the year. Average temperatures show a nocturnal minimum of 20°C and a mean daily maximum of 27°C.
Mean annual relative humidity is about 85% in the Fly River lowland. Temperatures are constant throughout the region with an annual mean of 29°C.
The Fly River has a total length of 1120 km. Its most important tributaries are the Ok Tedi and the Strickland River. The catchment comprises more than 76,000 km^2. The mean annual runoff per unit of catchment area is about 2500 mm, which is higher than for any other river system in the world (Maunsell and Partners 1982).



Map 1. The Fly River Region.

As the river catchment is relatively small, streamflow is characterized by short-term water level fluctuations with rapid changes between flood peaks and drought periods. Rainfall is highest in the upper Ok Tedi region, with recorded annual values up to 14,000 mm, and 7,800 mm at Tabubil, and decreases in the lowland. At Kiunga on the Upper Fly River the annual mean is 4,700 mm, at Lake Bosset in the Middle Fly area 2,670 mm, and at the coast at Daru 2,100 mm. Both rainfall and river flow show only limited seasonality. June to October usually are the dryest months in the Middle Fly region.

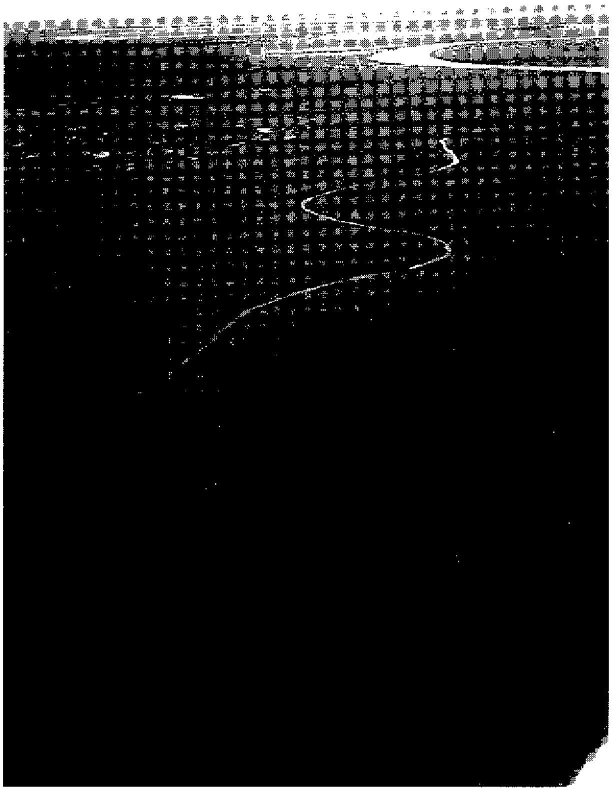


Fig. P2. The channel connecting Lake Bosset with the Fly River (right background). Deposition of riverine material is highest along the channel.

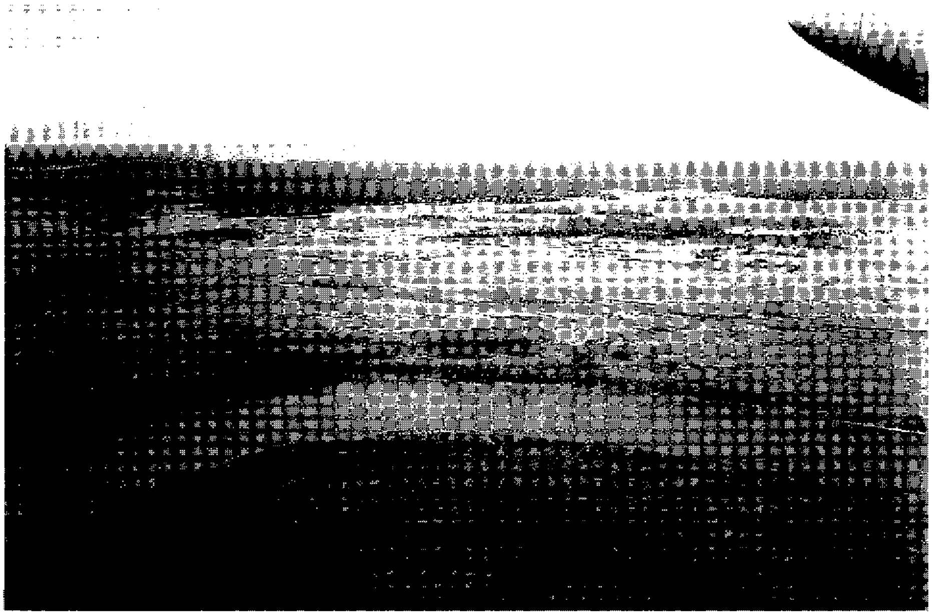


Fig. P3. The Fly River, inundated floodplain swamps and lakes, and jungle on the alluvial plateau in the background.

The long-term mean discharge rate of the Ok Tedi at the junction with the Upper Fly River (flow 1178 m^3/s at Kiunga) has been measured at 923 m^3/s. The combined flow is 2161 m^3/s in the upper Middle Fly. There exists a water exchange between the floodplain and its water bodies and the Middle Fly River. The net supply of sediment-poor, but DOC-rich floodplain water to the Middle Fly, however, appears to be small. At Obo, the long-term mean discharge is 2244 m^3/s. The Strickland River discharges 3110 m^3/s into the Fly River at Everill Junction (OTML 1994). Mean daily flow data for the last few years are summarized in Table 4.

Water level fluctuations in the Middle Fly are smaller than in the Upper Fly River, where water level changes of up to 15 m have been recorded at Kiunga. The discharge of the Fly River at its mouth of 6.000 m^3/s makes it comparable in size with the Niger and Zambesi in Africa or the Danube in Europe.

Flow rate (m^3/s)

	1988	1989	1990	1991/92	1992/93
Bukrumdaing	*	25	27	24	27
Tabubil	175	110	*	*	*
Ningerum	305	222	183	193	290
Konkonda	965	850	1122	456	805
Kiunga	1435	1197	1044	807	941
Kuambit	2400	2124	2094	1407	2061
Obo	2515	2613	2424	2057	1978
Strickland	3785	3869	3769	2870	3141
Ogwa	6300	5792	5461	*	*

* no data available

Table 4. Mean daily flow data collected by OTML for the Ok Tedi, Fly and Strickland Rivers at different locations in the catchment.

3.4. Aquatic Biology

A study conducted prior to OTML's operation (Roberts 1978) came to the conclusion that the Fly River system supports the most diverse fish fauna in the Australasian region, with at least 105 freshwater species from 33 families. The Sepik River in Northern New Guinea, the river closest to the size of the Fly on the island, has a relatively low overall fish density with a total of 57 freshwater species (Allen & Coates 1990).

The fish population in the Fly is remarkable for the large size of some species (e.g. black bass and barramundi) and the abundance of endemic species like catfish. The most targetted species by commercial fisheries is the barramundi *Lates calcarifer*, which roams the entire length of the Fly and resides in floodplain water bodies during most of its lifecycle. The barramundi migrates annually to the coastal areas for spawning (Eagle 1993).

Fish ecology is characterized by an overlap of species types resident in the two main habitats, the river channel and the floodplain with its waterbodies. Due to the high biological productivity of the Fly floodplain, the majority of the food for the Fly River fishes originates from off-river sources (Kare 1992). Overlap in diet and habitat requirements is an important mechanism for survival since prolonged periods of low water level may result in drying out of the floodplain and its shallow water bodies (Eagle 1993). Under these conditions, the fish take refuge to the stream channel and ox-bow lakes, which may represent the only standing water on the floodplain. The fish populations decline substantially, however, the recovery usually is rapid with recolonisation of the newly flooded habitat by the surviving stocks (Smith & Bakowa 1994). The most important food items for fish are aquatic and terrestrial invertebrates (freshwater prawns, mayfly larvae and other insects, worms etc.), algae, plant and organic detritus. Predatory fish like barramundi and cat-fish feed on smaller fish like *Nematalosa* herrings.

3.5. Population

In the entire Ok Tedi/Fly River drainage area lived in 1980, according to a national census, about 73,500 people. They speak 28 different languages and form five different language families: The Ok and Awin people of the Ok Tedi and Upper Fly River, the Marind of the Middle Fly and Lower Strickland (Lake Murray) region, the Suki-Gogodala people of the Lower Fly, and the Trans-Fly peoples of the southern coastal plain. The mountain people are hunter-horticulturalists living on a subsistence economy. Fish becomes a more important part of the diet for the lowland riverine people. In the Middle Fly-Lake Murray region, habitable land and ground suitable for cultivation of plant foods is scarce. The inhabitants (about 4,500 in 1980) are mainly hunter-gatherers who collect wild sago, cooking-bananas and sugar cane, and use the fish resource of barramundi, black bass and catfish (Busse 1991). The sale of crocodile skins is an important source of cash. The largest populations in the Middle Fly area are at Lake Bosset, Lake Pangua and Lake Daviambu. Small villages and homesteads are typically located along lakes and rivers. Virtually all travelling is by dugout canoe. During extremely dry periods, in which lakes may dry out completely, people abandon their villages and move to the main rivers which remain the only source of water.

The development of the Ok Tedi Mine has resulted in massive cultural and socioeconomic changes in the affected region. A former government adviser emphasized the "psychological trauma that Ok Tedi development will bring to the simple life styles of the mountain people" (Pintz 1984).

The mining company has established the "Lower Ok Tedi/Fly River Development Trust" which offers basic village infrastructure in the field of transport, health, education and business development. It supports an estimated 30,000 people in 101 villages living along the river system, who may be negatively affected by the discharge of mine residues and associated problems.

4. INPUT OF THE OK TEDI MINE INTO THE OK TEDI/FLY RIVER SYSTEM

4.1. Description of the Mining Project

Mining of the Mount Fubilan orebody as an open pit started in 1984, sixteen years after the discovery of the deposit by Kennecott exploration geologists in 1968. The particular features of the ore deposit were responsible for the development of the mine in mainly two stages: from May 1984 to late 1988, the gold-enriched cap was mined and processed. This involved the use of sodium cyanide and other process chemicals for gold extraction. Following this stage, the phase of extracting copper ore commenced. The gold is now recovered in the sulfide flotation concentrate. Mining of the Mount Fubilan deposit will continue until 2008 and involves the handling of some 1,400 million tonnes of material, comprising 550 Mt of milled ore residues and 850 Mt of overburden (Salomons & Eagle 1990).

Currently, the production is about 80,000 tons of ore and a similar volume of waste rock per day. The latter is material in which the metal content falls below the cut-off grade of 0.2% for copper or 0.8 g/t of gold.

The currently produced ore has 0.84% Cu and 0.71 ppm Au (oral comm., OTML, 1994). The sulphide flotation process has a recovery rate of 85% which leaves about 1,300 ppm Cu in the residual material. The copper content of waste rock has an average of 1,100 ppm (OTML 1994).

The ore is crushed and subsequently fed to a series of ball mills where the material is ground to fines. A copper-rich concentrate, containing all valuable metals, is recovered by means of a conventional sulfide froth-flotation process. For maximum sulfide recovery and pyrite depression, the pH of the flotation mixture is adjusted with lime to 10,5-11 and organic process chemicals are added (England et al. 1991).

The final concentrate is transported by a 160 km slurry pipeline to the river port of Kiunga on the Upper Fly River. At the Kiunga wharf, the slurry is filtered, dried and stored to await shipment by bulk carriers down the Fly River. From a storage facility in the Fly River Delta, the concentrate is sold under long-term contracts to smelters in Japan, Germany, South Korea, Finland and the Philippines.

In 1994, OTML produced 206,329 tons of copper in concentrates, containing also 15.14 tons of gold, 30.20 tons of silver, and other metals. The mine is the world's fifth biggest copper producer. Ok Tedi's mineable reserves in early 1994 were estimated at 459 Mt with 0.72% Cu and 0.70 g/t Au (DMP 1994), sufficient for another 14 years of operation.

Following a recent restructuring of ownership, the shareholders of Ok Tedi Mining Limited are as follows: 52% of shares are held by Broken Hill Proprietary, the biggest Australian mining company, which is also the project's operator; the Government of Papua New Guinea has increased its stake from 20 to 30%, and 18% of shares are now being held by Inmet of Canada (formerly Metall Mining, a German-Canadian mining company) (Mining Journal, August 18, 1995).

4.2. Discharge of Tailings and Waste Rock

The tailings from the copper extraction in the mill, approximately 98% of the original feed to the processing plant, is piped without further treatment to the Ok Mani, a tributary of the Ok Tedi (Fig. P4). Waste rock is hauled to erodible dumps adjacent to Mt. Fubilan, from where the material is washed into the headwaters of the Ok Tedi.

Fig. P4. The narrow valley of the Ok Mani, which drains the Mt. Fubilan area, has been filled up by some 20 m, as can be seen at the drowned rainforest trees.

The thickened, alkaline tailings slurry consists of approximately 55% solids of which 78% have a grain size less than 100 µm. The material has about 10-20% of its original copper content, varying amounts of trace metals including zinc, lead and cadmium which occur naturally in the porphyry ore, and small quantities of organic flotation chemicals.

Waste rock and overburden is coarser, but has a high percentage of soft material (siltstone and limestone) which breaks down easily, containing copper and significant quantities of other heavy metals. Although some of the waste rock remains temporarily in the dumps and adjacent creek valleys (depending on the rainfall activity), most of it is washed down rapidly into the Ok Tedi River.

Since the beginning of mining at Mt. Fubilan, all waste rock and overburden (with the exception of a short period during the gold stage) has been disposed off in the river system. The construction of a tailings dam was halted in early 1984 when a land slide forced the abandonment of the construction site, which was located in a geotechnically highly unstable zone.

The larger part of the mine-derived material entering the upper Ok Tedi has a particle size of less than 100 µm and can be transported as suspended load throughout the entire length of the Ok Tedi/Fly River system, given sufficiently high hydraulic transport capacity.

The massive input of mine-derived sediments into the Ok Tedi exceeds the sediment transport capacity of the river system, which has led to severe aggradation of the river and a rise of the Ok Tedi channel bed by ten meters and more in the upper reaches. Riverbank food gardens and plantations have been flooded and the natural ecology of the river and subsistence fishing has been seriously disrupted.

About 60 million tons of material are delivered to the Ok Tedi/Fly River system per year, containing approximately 69,000 tons of copper. The daily discharge rates are 160,000 tons of rock material with 190 tons of copper.

The presence of iron and base metal sulfides in the waste rock and tailings indicates the possibility of acid mine drainage (AMD) development, which arises from the oxidation of sulfide minerals and subsequent sulfuric acid production. AMD generation in the Ok Tedi waste rock dumps was considered a potentially serious problem in the Ok Tedi Environmental Study by Maunsell and Partners (1982). Low pH in waste rock drainage may result in enhanced solubility of trace metals like lead, silver, zinc, cadmium and copper (Ferguson and Erickson, 1988). However, acid formation may be buffered by alkalinity released from carbonate minerals in the mine waste, such as calcite ($CaCO_3$). Given the relatively high calcium content in the waste material, development of AMD in the waste rock dumps appears unlikely. Despite the fact that sulfide oxidation is occurring in the mine discharges, no pH values below 7 have been recorded in water of the upper Ok Tedi, neither by OTML nor in measurements during the present study.

5. SEDIMENTOLOGY OF THE FLY RIVER AND ITS FLOODPLAIN

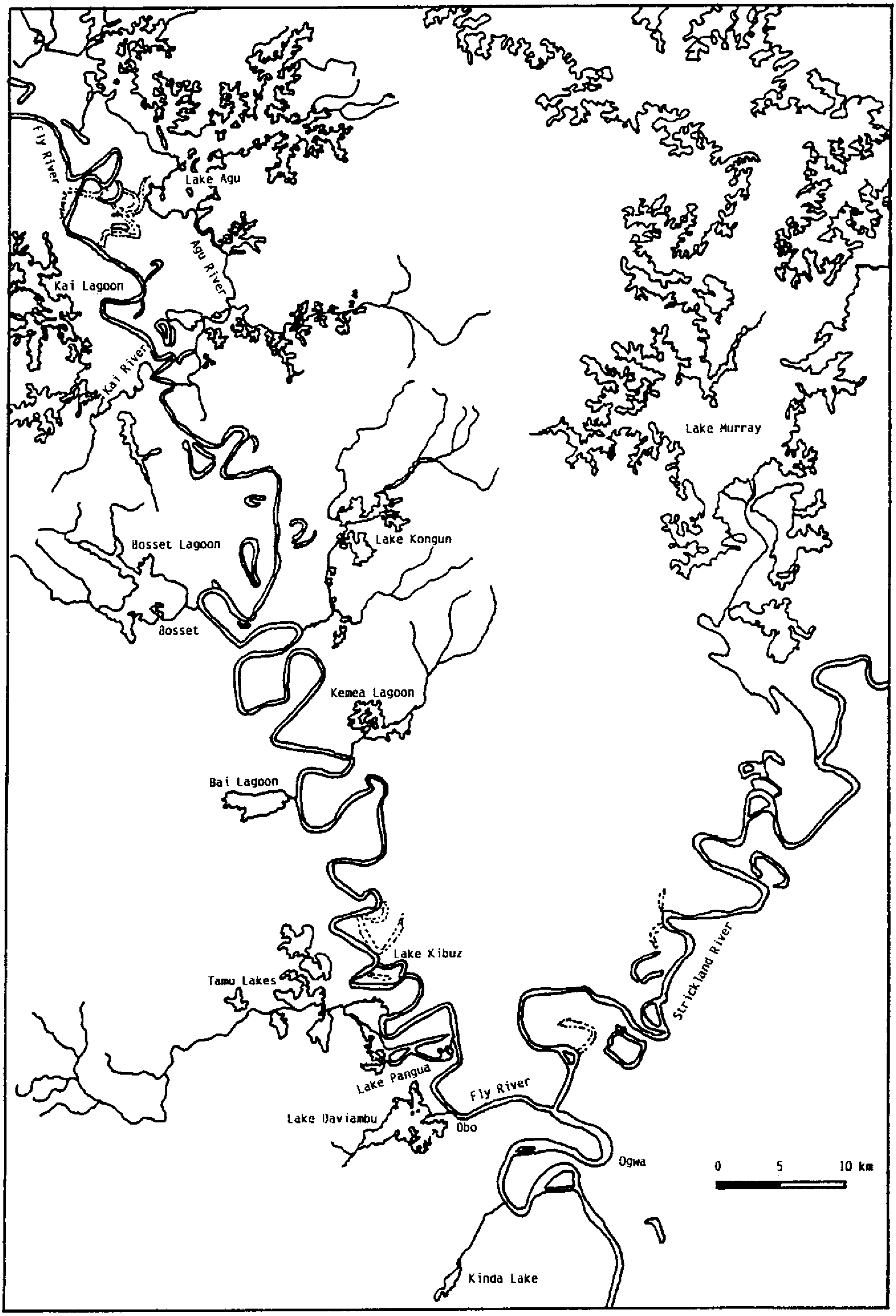
5.1. Natural Sedimentary Processes in the Floodplain

The Fly River has a highly variable flow regime where extensive flooding and overbank deposition on its wide floodplain alternates with extremely low water levels in drought periods. The sedimentary processes in the Fly River floodplain are dominated by the river itself and the suspended load it carries. Sediment delivery by floodplain creeks and channels to the system 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 the floodplain. Sedimentation is highest in oxbow lakes and tie channels, where medium to coarse silt from the river suspended load settles down, and much lower in drowned valley lakes and floodplain depressions where clay and fine silt may become deposited.
Drainage direction throughout most of the Fly River floodplain is towards the Fly, although the inner floodplain, the active meander belt, tends to be higher in elevation than the outer floodplain due to sedimentation along and in 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 higher sediment loads because of increased transport energy, river bank overflow and inundation of the alluvial plain occurs. 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 will be deposited there due to vegetative filtering in the grassland bordering the main river, and in sediment traps such as lakes.

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 kilometers across the floodplain.

The background deposition rate (i.e. before the mine started discharging material) in drowned valley lakes is very low. Analysis of the fraction less than 2 µm of sediments taken from small islands (0-1 m above mean lake level) in Lake Bosset and Bai Lagoon (Map 2) defined a mineral composition dominated by kaolinite, aluminium chlorite, quartz and gibbsite. All four minerals are typical of highly weathered tropical sediments. The fact that sediment of probable Pleistocene age was found on the surface of these shallow islands indicates that no Fly River material has been deposited there in the last 120,000 years, when the sea level began to drop and Pleistocene sedimentation in the alluvial plain ended.



Map 2. The lower part of the Middle Fly River (study area).

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
C14 age (years before present)	5265 ±215	2950 ±70	4030 ±110	4380 ±125
Sedimentation rate mm/1000 years	24	95	67	64
Water depth at site (mean water level)	1.10	2.40	1.70	2.60
Distance from Fly (air km)	6	5	3	9

Table 5. Results of radiocarbon age dating of sediment cores from drowned valley lakes.

Table 5 shows the results of C14 age dating which was performed to determine sedimentation rates in drowned valley lakes. 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. Core 3/30.3. was taken from the distal end of Lake Daviambu. The upper 13 cm consist entirely of peat-like organic debris. Accumulation of this material, derived from the catchment of the lake itself, is much slower than at those sites which receive suspended sediment from the Fly River. In the case of the other three cores, the sediment layer above the peat was made up of Fly River material, as determined from its characteristic clay mineral assemblage with dominantly (low charged) smectite. A thin layer of copper-rich material on the top of the cores was observed.

Due to the lack of dateable organic matter in sediment cores from tie channels and their banks, where sedimentation certainly was much higher, no data are available to establish deposition rates at these sites. The simple fact that the shallow lakes still exist after about 5,000 years of possible sedimentation from the Fly River points to very low deposition rates. Assuming that the maximum channel depth of 5.4 meters, measured in Lake Bosset channel close to the Fly River, reflects the original channel depth of the drowned tributary, then the deposition rate was about 1 mm/year in the last 5,000 years at sites close to the Fly.

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. 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 million tons and bed load at 1-2 million tons per year.

5.2. Deposition of Mine-Derived Material

The suspended sediment concentrations in the Middle Fly River today are 5 - 10 times above the natural load of about 60 mg/l. Significant quantitities of mine-derived sediments are deposited and trapped in creeks, lakes and swamps adjacent to the Fly River. Such off-river sites play an important role in the food web and in the reproduction cycle of aquatic organisms like invertebrates and fish.
Flow inversion in channels linking the floodplain with the Fly River is an important process because it is responsible for suspended sediment transport to off-river sites during mean flow conditions (Fig. P5-6). Reverse flow upstream the tributary channels was frequently observed during the three field trips undertaken. On April 8, 1993 slightly turbid water (sample W1/8.4.) with elevated calcium, copper (9 µg/l) and cadmium (0.12 µg/l) levels was encountered in the

Agu River/Lake system about 25 km upstream of the junction with the Fly River, which had about mean flow. The Agu River/Lake in this reach runs roughly parallel to the Fly. As a result of a recent Fly River intrusion upstream the Agu River, turbid water was visible in the densely vegetated parts of Agu Lake, whereas in the Agu main channel, Fly water was slowly pushed out in southerly direction (downstream) due to heavy rainfall in the days before the site was visited. A similar observation was made in the Kai River/Lake system which was sampled on April 9, 1993, although in this case Fly River water was still flowing upstream. The upstream current observed close to the Kai River mouth was remarkably strong and made the use of the outboard motor necessary for passage.

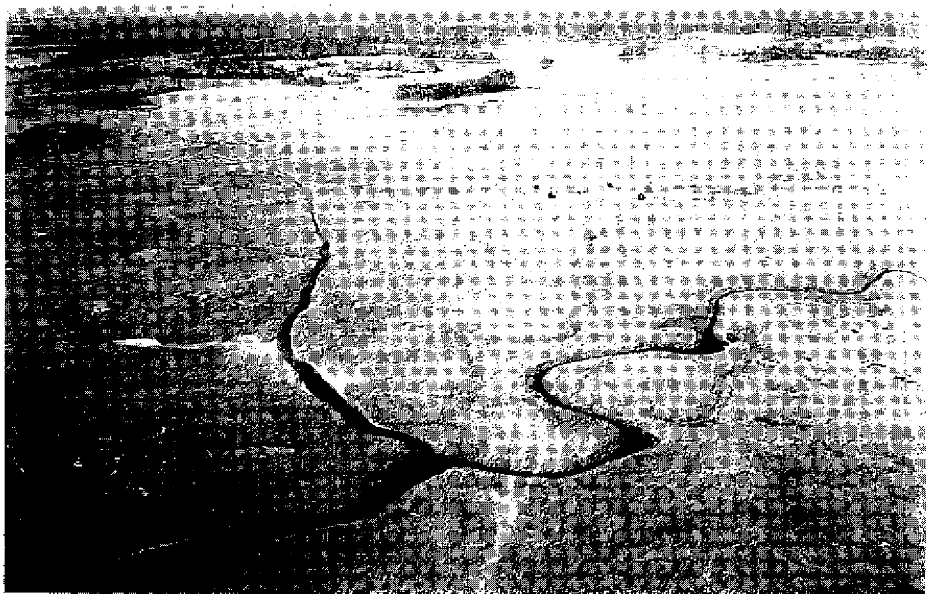


Fig. P5. The channel linking Lake Daviambu (background) with the Fly River. Lake water of light orange-brown colour, rich in humic substances, drains into the Fly. The vegetated areas in the foreground are swamp.

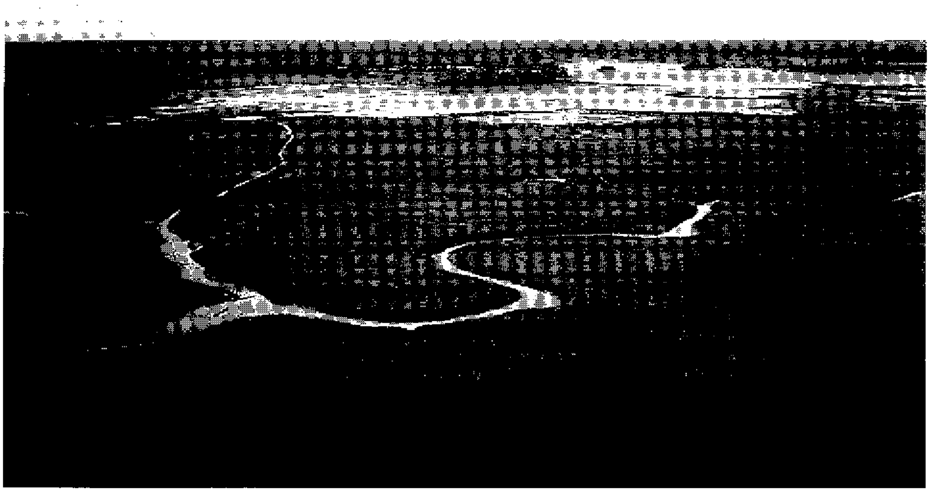
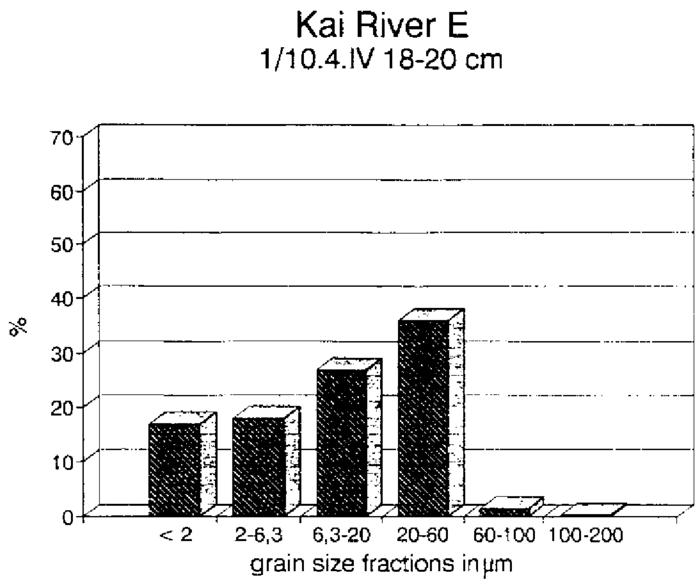
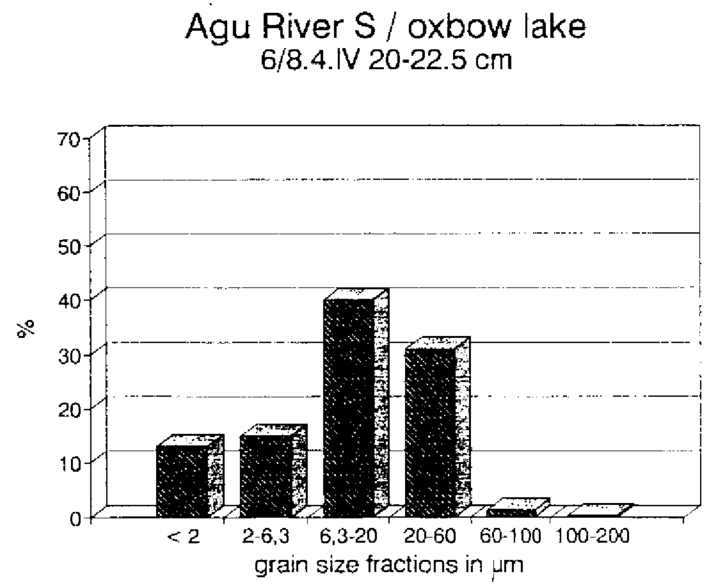


Fig. P6. The same location, but at a higher water level in the Fly River. Turbid, white river water flows into the lake.

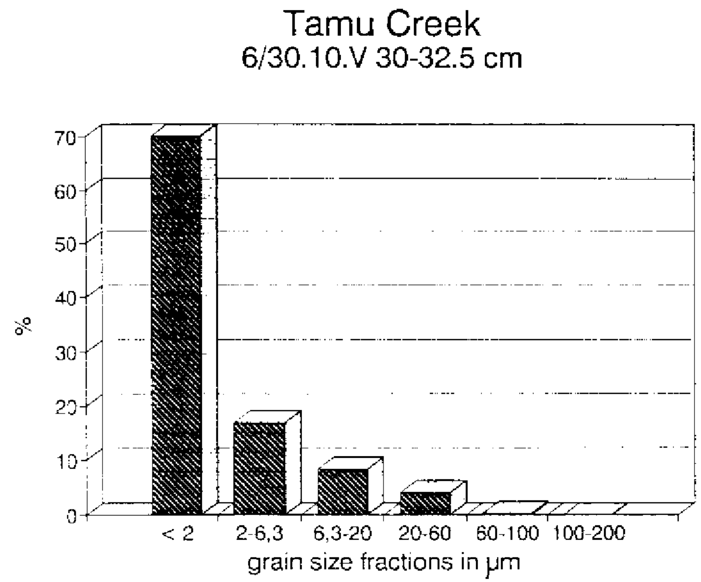
Water with high conductivity, neutral pH and elevated copper values (39 µg/l in unfiltered sample W4/9.4.) was encountered 19 channel km upstream of the Kai River confluence with the Fly River. Water movement at the sampling location was in northerly direction (upstream). One could expect that there exists a flow-through mechanism in which Fly River water enters the Kai River/Lake system (which is about parallel to the Fly) through an upstream connection.



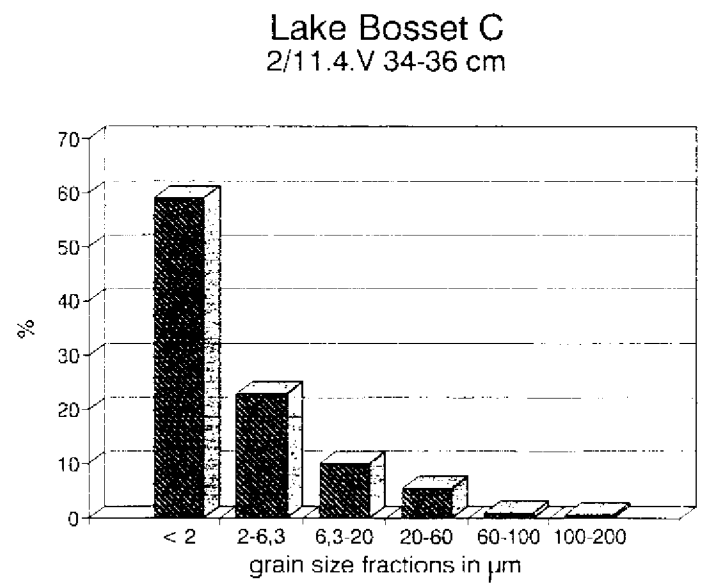
S1. Relatively coarse mine sediment deposited on a channel bank 3 km from the Fly.



S2. Coarse mine-derived material becomes deposited in cut-off meanders close to the Fly.



S3. Very fine sediment is carried into floodplain lakes far from the Fly channel (7 km).



S4. Fine material deposited in the middle part of Lake Bosset.

However, satellite images and aerial photographs show no such connecting channel and give no indication of flow across the floodplain, away from the river. The same observation was made for the Agu River system, although maps show a northerly channel connection of the Agu with the Fly River. According to local villagers, this flow-through mechanism is only active at very high water level in the Fly.

The frequent intrusions of highly turbid Fly River water should result in widespread sedimentation of mine-derived material in the Kai and Agu Lakes. Sediment sample analysis revealed moderate copper pollution. Only the uppermost 3-5 cm of sediment cores showed strongly elevated trace metal contents with Cu around 300-600 ppm. In the Kai River samples, the contaminated sections consisted of deposited riverine suspended matter. In the Agu River system, 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.
Deposition of mine-derived sediments generally is highest at locations close to the channels which connect 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 (Fig. S1-S4). Trace metals are generally enriched in the finest particle fractions.

In a sediment core from the Kai River channel bank (1/10.4.), taken approximately 3 km upstream of the Fly River confluence, the upper 38 cm showed strongly elevated copper values (400-700 ppm). This material must have been deposited within the last ten years, since the Ok Tedi mine is operating. The sedimentation rate is about 4 cm/year.
Similar observations were made at the other drowned valley lakes investigated (Bosset, Kongun, Kemea, Bai, Daviambu). Where the well defined channels extend into the lake, substantial deposition of 20-40 cm of copper-contaminated sediment was detected several kilometers away from the Fly River, whereas in the proper lake copper-rich sedimentation did not exceed 5 cm. Sediment core 4/11.4., which showed elevated trace metal levels in the upper 23 cm with about 200 ppm copper at the bottom and 800 ppm at the top section, was taken in Lake Bosset at the location where channel and lake water merge, about 2 km inside the lake (as depicted in topographic maps). Sedimentation of mine-derived material was highest in oxbow lakes with up to 70 cm measured at sites close to the river end of Lake Pangua and Lake Kibuz (Fig. P7). 29 oxbow lakes at different infilling stages exist along the Middle Fly River.

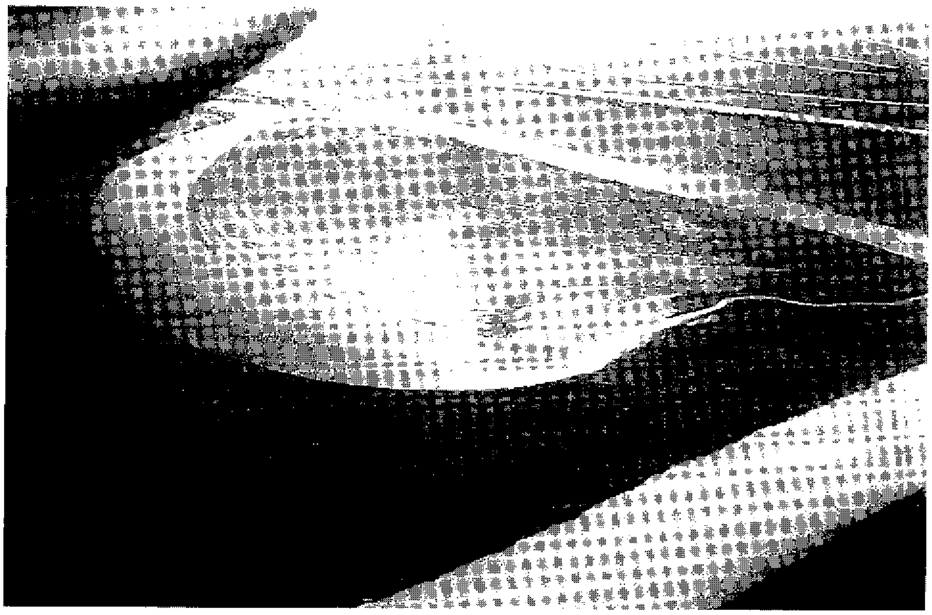
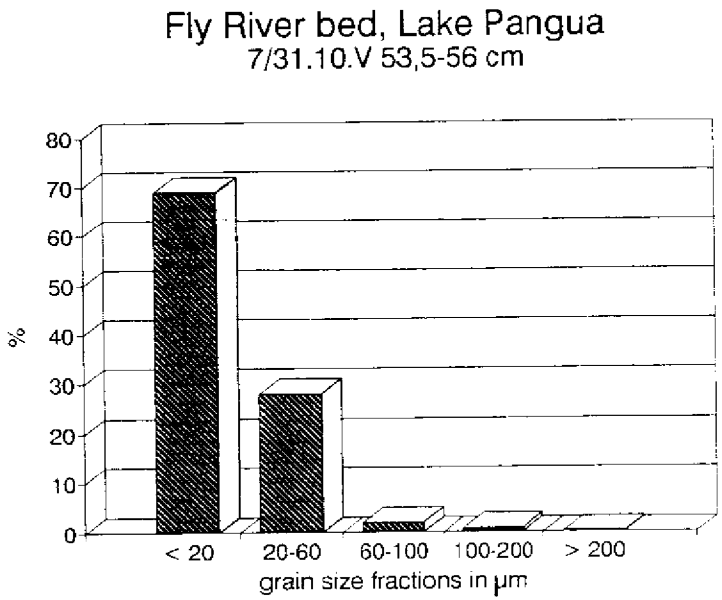
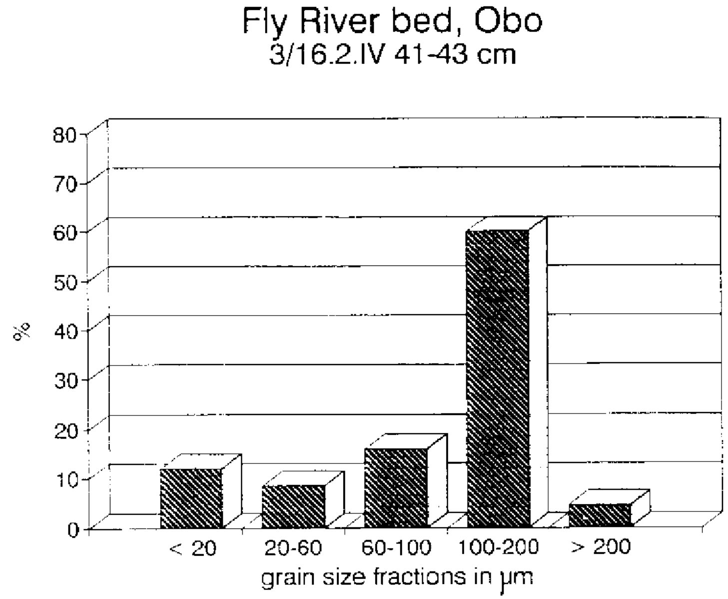


Fig. P7. Inflow of Fly River water, rich in mine-derived suspended matter, into the Pangua oxbow lake. Deposition of copper-rich material is highest at the river end of the lake.

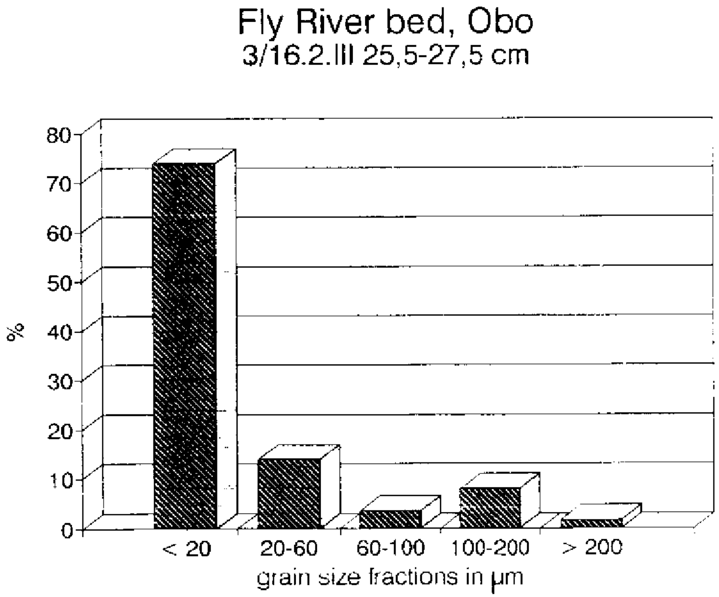
Two sediment cores were taken from the Fly River channel bed (Fig. S5-S7), one at Lake Pangua (water depth 10.5 m) and the other downstream of Obo (depth 14.5 m), both in the deepest part in the channel cross section. The entire bed core from the Lake Pangua site (56 cm) consisted of fine grained sediment with 55-75% finer than 20 µm (clay, fine and medium silt fraction), and displayed a constantly high copper content of about 850 ppm.



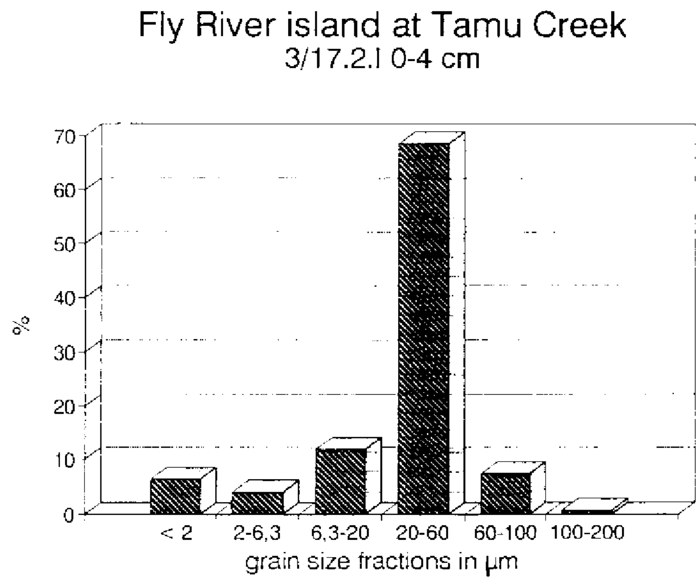
S5. Copper-rich clay and silt deposited on the Fly River bed at Lake Pangua.



S7. Coarse bed sediment with background copper values from a deeper section.



S6. Mine-derived fine material in a core from the Fly River bed at Obo.



S8. Copper-rich coarse silt is deposited on a newly formed island in the Fly channel.

The upper 30-35 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 ppm in this section. From both cores, it is evident that suspended load has settled down 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 Everill 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.

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 (Fig. S8). No such islands are visible in aerial photographs from the 1960's and 1970's. The formation of islands in the river channel also indicates 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 one meter above the 1984 pre-mine baseline.

Two effects probably are responsible for the strongly increased deposition rates as compared to earlier sedimentation: Firstly, because of the increase in the (mine-derived) suspended sediment load of the Fly River, which today also contains more silt than the natural particulate load. Secondly, as a result of the reduction in channel capacity due to bed aggradation, overbank flow frequency increases. 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.
Sedimentation studies which were undertaken before the Ok Tedi mine was developed (Pickup et al. 1979) assumed that frequent landslides, particularly in the upper Ok Tedi catchment, have lead to a high natural suspended sediment load in the Fly River. Had this been the case, this should have resulted in much higher natural deposition rates in the Middle Fly floodplain. The comparison of sedimentation rates before and after the mining at Mt. Fubilan started, points to the fact that the background suspended sediment concentration in the Fly River was very low, probably in the range of 40-60 mg/l.

	ss/gulp (mg/l)			**ss/DI (mg/l)**	
	1988	**9/88-8/90**	**10/91-9/92**	**1990/91**	**1991/92**
Bukrumdaing	*	151(3)	44(5)	57	64
Tabubil	4709	7825(25)	6696(12)	8095	10626
Ningerum	1802	524(124)	3477(12)	5846	5882
Konkonda	698	1420(24)	949(12)	2072	2744
Kiunga	*	60(24)	26(12)	186	149
Kuambit	305	520(24)	316(12)	625	573
Bosset	*	171(23)	118(12)	*	*
Obo	65	92(25)	103(12)	649	450
Strickland	*	414(24)	239(12)	690	509
Ogwa	326	283(23)	*	677	323

* no data available

Table 6. Average data on suspended sediment concentrations in gulp (surface) and depth-integrated (DI) samples. Medians shown and number of measurements in brackets. Data from OTML (1988-92).

Attempts were made to establish a suspended sediment balance using data collected by OTML. A proper balance would show sediment losses (or gains) in the system. A brief examination of data in Table 6 shows that there is a large scatter in the measured concentrations over several sampling periods. Of main interest to the present study is the deposition of suspended riverine material in the Middle Fly region. The measured suspended matter content in gulp samples of near-surface water in the Fly River reach between Kuambit and Obo shows a strong decrease in all sampling periods. This effect can not be seen clearly in the depth-integrated measurements in which the suspended matter content is determined in vertical sections through the water column.

Typically, the suspended sediment concentration of near-surface river water (gulp samples) is 70-90% of the depth-integrated suspended matter content (Higgins 1990). No such relationship can be established in the data of Table 6. Differences between suspended sediment content determined by gulp and depth-integrated sampling were up to 90% in measurements from the same site and date (data in OTML 1993). It is difficult to explain this discrepancy, which is particularly evident at Obo. There obviously exists a pronounced stratification within the flowing water body, with particulate-rich water travelling close to the bottom. Due to the shift of the main current in river bends, which leads to a more turbulent (spiral) flow, the bottom strata with a higher suspended solids content rise to the surface. This effect was observed in the depth-integrated measurements at Obo where suspended sediment concentrations are usually highest close to the outer bend.
The stratification in suspended sediment concentration within the water body points to the settling down of suspended load on the channel floor. River bed sedimentation is largely 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.

Ok Tedi Mining Ltd. has tried to establish an annual suspended sediment mass balance based on its regular measurements taken in the Ok Tedi and the Fly River (Table 7). The calculations illustrate the complexicity of the system and the difficulties in predicting sediment transport in the two rivers. The measured load values (calculated from a small number of measurements) in the 1991/92 data indicate a loss of sediment from Ningerum to Obo (46 to 35 Mt/a), whilst the model predicts a steady increase in the same reach (43 to 55 Mt/a). In the data set for the following year, the discrepancy between observed and predicted load is minor. Given the fact that sediment input by the Ok Tedi mine into the system is fairly constant over the years, the massive adjustment of the predictive model between the two years (at Obo 38 instead of 55 Mt/a) is hard to understand. The flow weighted load data for 1992/93 suggest heavy erosion of material in the Middle Fly between Kuambit and Obo (increase of suspended load by 4 Mt/a), which is hard to explain, too. This may be attributed to the limited number of data collected (9 depth-integrated samples).

Station	Flow Weighted Load (Mt/a)	Flow Weighted Conc. (mg/l)	Predicted Load (Mt/a)	Predicted Conc. (mg/l)
Ningerum	46	5750	43	5991
Konkonda	40	2001	43	1862
Kuambit	37	646	44	724
Obo	35*	450*	55	687
Strickland R.	84*	900*	85	-
Ogwa	119*	323*	140*	807

Station	Flow Weighted Load (Mt/a)	Predicted Load (Mt/a)
Ningerum	40	-
Konkonda	31	35
Nukumba/ Kuambit	34	38
Obo	38	38

* insufficient records; estimates based on available data

Table 7. Suspended sediment mass balances for 1991/92 (above) and 1992/93 (below) calculated by OTML (1993, 1994).

6. POTENTIAL MOBILIZATION OF HEAVY METALS AND HYDROCHEMISTRY

6.1. Heavy Metals in Sediments of the Ok Tedi/Fly River System

Analytical results for sediments from the Fly River floodplain are shown in Tables 8 and 10 (A1 and A3 in annex) and from the upper Ok Tedi in Table 9 (A2 in annex). The samples from the Fly River section are grouped into two populations, i.e. sediments which were deposited before the Ok Tedi mine started discharging residues into the Ok Tedi/Fly River system (Table 8), and sediments controlled by mine-derived material (Table 10). This classification is easily practicable due to the distinct geochemcial signature in the mine-derived material, which shows for some elements a significant enrichment above the natural background. The frequency distribution plotted in log probability graphs for copper in 385 sediment samples is shown in Fig. D1 and for gold (27 samples) in Fig. D2. The distributions are roughly bimodal. The subpopulations have approximately lognormal distribution.

Parameter	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	44	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 %	6.7	9.4	2.6	1.3	6.0
S mg/kg	1447	1445	800	300	2525

Table 8. Mean, standard deviation, median values and 25% - 75% confidence intervals for 27 elements in Middle Fly River background sediment samples (n = 128).

Gold gives the highest enrichment factor of 53, followed by molybdenum (factor 23), copper (factor 12), lead (factor 4.4), calcium (factor 4.1), silver (factor 3.5), sulfur (factor 2.6) and strontium (factor 2.5). Zinc shows an enrichment factor of 1.6. The elements Al>V>Co>Cr>Sc>Ni>Ti>Zr (in decreasing order) are present in mine-derived material in lower concentrations than in background sediments. It is evident that the elements associated with the copper-gold ore from Mount Fubilan are also found in the lowland depositional sites. Those metals which are typically enriched in soils during tropical weathering are found in higher concentrations in unpolluted lowland sediments as in material from the mine, deposited in the floodplain. The comparison of mine-derived sediments from the Fly River floodplain (Table 10) with material from the upper Ok Tedi, which consists nearly exclusively of tailings and waste rock (Table 9), gives the following results: Calcium is found in upper Ok Tedi material 4 times and sulfur 3.8 times higher as compared to lowland mine-controlled sediments.

Parameter	**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 %	1.8	0.5	1.9	1.3	2.1
S mg/kg	15211	20643	7900	4425	10625

Table 9. 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).

Factors for other important elements which are found in the Mount Fubilan orebody are: copper (2.2), silver and cadmium (both 2), zinc and strontium (1.8), gold (1.7), arsenic and molybdenum (1.6) and lead (1.5). The elements K>Ba>Mg>La>V>Ti>Ni>Sc>Zr (in decreasing order) are present in tailings and waste rock in lower concentrations than in mine-derived sediments of the Middle Fly region.

Evaluation of relationships between elements in the data obtained for the upper Ok Tedi sediments give the result that sulfur versus Fe, Mn, Zn, Cu, Pb, Cd, Ag and Mo is strongly positively correlated (r = 0.80-0.99, significance level $p < 0.05$). This can be explained by the fact that most metals are dicharged in sulfidic form into the Ok Tedi River. In the Fly River floodplain sediments, the positive relationship between trace metals and sulfur is much weaker (in the range of r = 0.31-0.71 for the metals mentioned above) with the exception of iron, which shows no correlation with sulfur in lowland mine sediments.

Parameter	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	0139	23842	24800	8200	50350
Al mg/kg	0994	14915	81100	72325	91025
Fe mg/kg	0004	11012	39500	32200	46850
Mn mg/kg	528	254	510	310	710
Zn mg/kg	211	68	204	163	245
Cu mg/kg	530	289	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 %	1.6	1.5	0.9	0.6	2.0
S mg/kg	2464	2160	2100	675	3425

Table 10. 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).

In sediments from the upper Ok Tedi, the metals Fe, Mn, Zn, Cu, Pb, Cd, Ag and Mo are all highly intercorrelated (r = 0.65-0.95). As in the case of sulfur, the positive relationship is lost or becomes weaker in the Fly River floodplain data for the same metals. It is interesting to note that gold shows no relationship with any of the trace metals mentioned above in the upper Ok Tedi sediments. In the mine-affected lowland sediments exists a positive correlation with lead (r = 0.68) and molybdenum (r = 0.66).

There are mainly two processes operating in the river system which are responsible for the differences in the element concentrations in upper Ok Tedi and lowland sediments: Sediment admixture/erosion and mobilization of metals from the solid phase. The Ok Tedi River on its 200 km long way to the Fly River junction receives water and suspended sediments from several tributaries. Further dilution with uncontaminated riverine particulate matter occurs at the Ok Tedi/Upper Fly River confluence. Due to the fact that unpolluted tributaries have a much lower suspended load than the Ok Tedi, dilution effects, however, are small. Lateral erosion in the highly sinuous channel of the Middle Fly appears to be a more important process. Admixture of weathered floodplain sediment in the river course is responsible for increasing concentrations of elements like zirconium, scandium, titanium and chromium (which are highly persistent in chemical weathering) in the mine-derived sediments deposited downstream in the Middle Fly floodplain.

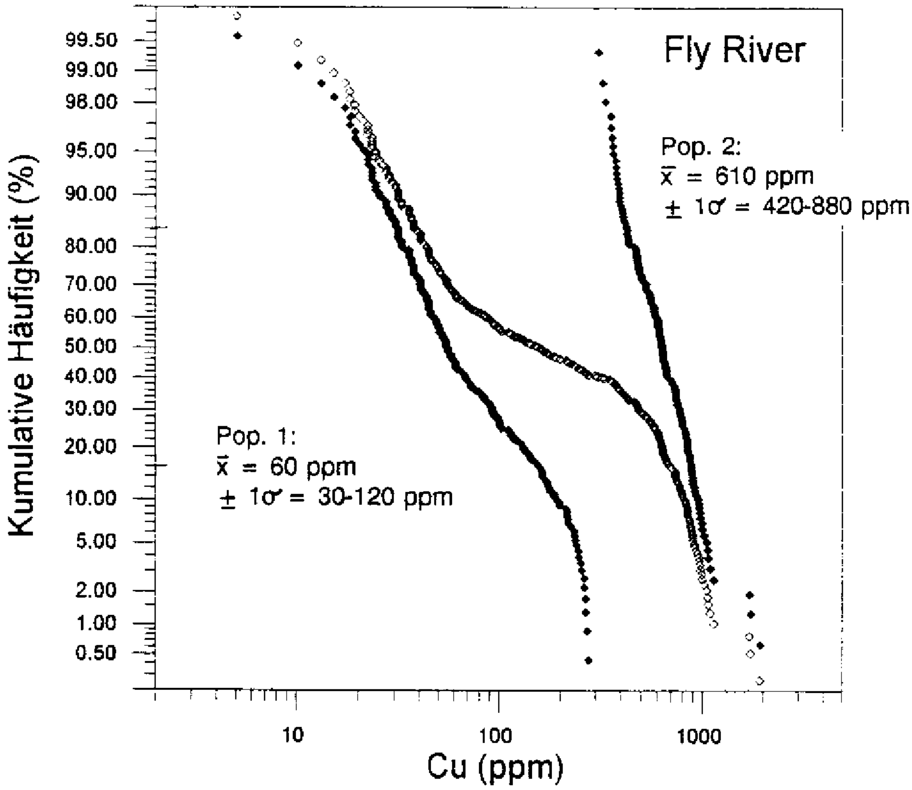


Fig. D1. Copper distribution in alluvial sediments of the Middle Fly River floodplain. The probability graph of the composite population of 385 data points (open squares) separates into two approximately lognormal subpopulations (closed squares) with a natural background population of about 50 ppm Cu, and a second population of mine-derived material at 610 ppm (geometric means).

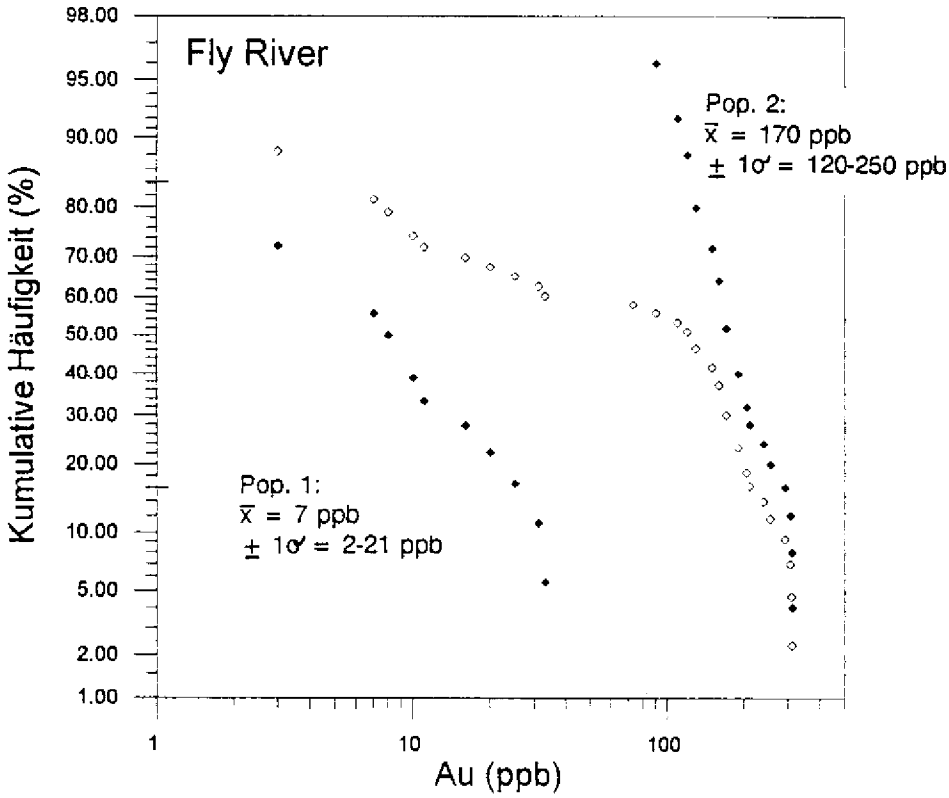


Fig. D2. Gold distribution in alluvial sediments of the Middle Fly River floodplain. The probability graph of the composite population of 27 data (open squares) separates into two approximately lognormal subpopulations (closed squares) with a natural background population of about 7 ppb Au, and a second population of mine-derived material at 170 ppb.

A sediment particle which is discharged into the upper Ok Tedi travels about 7 days until it reaches Everill Junction 610 km downstream of the discharge point. During this time, mineral dissolution occurs. It is evident that particulate, mine-derived calcite is being dissolved in Ok Tedi and Fly River water. Particulate sulfide minerals, mainly pyrite and chalcopyrite, are also unstable in the oxygenated river waters and are oxidized to sulfates. The trace metals associated to these minerals either go in solution or become adsorbed to particulate matter, mainly to unsoluble iron oxyhydrates or organic matter. They are partitioned between the solid and dissolved phase according to their geochemical mobility in the aquatic environment of the Ok Tedi/Fly River system.

Sediment core 1/10.4.	**Ca**	**Cu**	**Pb**	**S**
section	ppm	ppm	ppm	ppm
0-2 cm	35400	663	51	2300
2-4 cm	44300	668	54	1700
18-20 cm	50000	664	98	nd
28-30 cm	56800	618	78	2700
30-32.4 cm	50200	574	94	nd
32.4-34.5 cm	35200	483	83	<100

Sediment core 5/27.3.	**Ca**	**Cu**	**Pb**	**Au**	**S**
section	ppm	ppm	ppm	ppb	ppm
19.5-22 cm	48700	977	76	205	5300
30-32 cm	56000	929	79	nd	3000
46-48 cm	47800	891	71	nd	4600

Table 11. Typical vertical profiles of mine-controlled sediments (fraction <20 μm) in the Middle Fly River floodplain dTeposited at sites close to the river at high deposition rates.

Sediment core 4/7.4.	**Ca**	**Cu**	**Pb**	**Au**	**S**
section	ppm	ppm	ppm	ppb	ppm
0-2.5 cm	7800	583	92	130	600
2.5-5 cm	6600	576	122	160	300
7-9 cm	4200	557	140	nd	nd
19-21.5 cm	6400	37	16	<2	<100

Sediment core 1/7.4.	**Ca**	**Cu**	**Pb**	**Au**	**S**
section	ppm	ppm	ppm	ppb	ppm
7.5-10 cm	8700	401	102	310	200
27-29 cm	14000	356	79	291	500
33-35 cm	7500	69	29	nd	200

Sediment core 2/27.3.	**Ca**	**Cu**	**Pb**	**Au**	**S**
section	ppm	ppm	ppm	ppb	ppm
3.5-5.5 cm	6100	430	110	240	<100
5.5-8 cm	6900	320	81	nd	100
30-32.5 cm	5900	40	19	nd	100

Sediment core 1/30.3.	**Ca**	**Cu**	**Pb**	**S**
section	ppm	ppm	ppm	ppm
2-4 cm	7300	409	81	100
26-28 cm	5800	35	14	400

Table 12. Vertical profiles of mine-controlled sediments (fraction <20 μm) deposited at swampy sites on the Middle Fly River floodplain.

Table 11 shows analytical data for two sediment cores sampled from locations close to the Fly River channel (Kai River channel, 1/10.4., and Fly River bank at Obo, 5/27.3.), whereas Table 12 shows data from swampy sites (locations in Table A3).

Calcium and sulfur values are much higher than in the cores shown in Table 12. Very little calcite dissolution and sulfide oxidation has taken place in the material from the river channel. The declining copper values towards the base of the sediment core 1/10.4. reflect the development stages of the mine. In the early mining phase of gold extraction only, tailings and waste rock consisted mainly of oxidized gossan material with a relatively low copper content and almost no sulfide minerals, which can also be seen in the base section of core 1/10.4. It was frequently observed that copper values increased in steps from the base to the top of a sediment core whereas gold showed the opposite behaviour (Table A3 in annex).

Sediments of Table 12 display very low calcium and sulfur values, although high lead and gold contents indicate that it is largely mine-derived material. Gold is a very resistant element in tropical weathering, and lead also shows very little mobility in the Ok Tedi/Fly River environment (see following section). Copper, together with calcium and sulfur, is clearly depleted in the sediments in Table 12.

Ca and S remain in the sediment body when the deposition rate is high and each layer of riverine suspended matter is rapidly covered by fresh sediment. Sulfide minerals are stable under conditions of oxygen deficiency, which are generated by the decay of riverine organic matter. The pore water in the fine-grained sediment will soon be saturated with calcium which prevents further calcite dissolution. Mobilization of trace metals will be minimal under these conditions.

To the contrary, mine-derived material deposited sporadically on swampy floodplain sites is subject to intense leaching. The undulating water table permits penetration of atmospheric oxygen into the sediment body, which is facilitated by the roots of floodplain vegetation. Both factors result in sulfide oxidation. Rainwater leaches calcite from the deposited material, and the rotting of swamp vegetation generates acidic pore waters which may bring trace metals in solution.

6.2. Hydrochemistry of the Ok Tedi/Fly River System

6.2.1. General

Earth alkaline and alkaline metals. These elements have a high solubility of their salts in common, which is independent of redox changes and partly independent of pH (Na, K). Because of the reaction:

$CaCO_3 + H_2CO_3 \rightleftharpoons Ca^{2+} + 2\ HCO_3^-$

calcite dissolution requires the presence of carbon dioxide, which forms the carbonic acid consumed in the reaction. The carbon dioxide partial pressure in water decreases with increasing temperatures. Dissolved Ca, Mg and Sr compounds are stable in water in the presence of carbon dioxide. Calcite is abundant in the mine waste discharged into the Ok Tedi/Fly River. Its dissolution exerts a buffering effect on pH which will remain in the range of about 6.4 to 8.0, in spite of concomitant dissolution of sulfides from mine discharge. Calcium forms complexes with humic acids. Mg compounds are, in general, more soluble than their Ca counterparts. Na is the most mobile metal in the aquatic environment. K is usually present in lower concentrations than Na. The natural leaching of K from minerals does not result in significantly increased solubilization because K is usually readily incorporated into new mineral structures like clays.

Iron and manganese. Both metals show a similar hydrochemical behaviour. Manganese tends to be more mobile as compared to iron.

Compounds of ferric iron (Fe^{3+}) and Mn^{4+}, which are the stable oxidation states in aerobic waters, are nearly insoluble. In reducing waters, the divalent reduced forms (ferrous/manganous) can persist in the absence of sulfide and carbonate anions. Iron and manganese may also occur in both oxidation states in inorganic or organic complexes. In oxygenated, alkaline waters both metals are present as colloidal suspensions of ferric resp. manganic hydroxide particles which pass through a 0.45 µm membrane filter. For this reason, the "dissolved" concentrations reported for iron and manganese in neutral or alkaline waters in most cases do not correspond to electrolyte solutions.

Trace metals. Copper, zinc, molybdenum, cadmium and lead were analysed in waters.

Between pH 6.5 and 8.5, **lead** speciation in the aquatic environment is dominated by carbonates and hydroxides (Hem and Durum, 1973), which are almost insoluble. Pb may be complexed with organic ligands, yielding soluble, colloidal and particulate compounds. It can easily be adsorbed to particulate organic and inorganic matter, which is the dominant mechanism controlling the distribution of lead in the aquatic environment above pH 6 (Farrah and Pickering 1977).

Copper generally shows a higher geochemical mobility than lead. The distribution of copper species in the aquatic environment depends on pH and on the presence of inorganic and organic ligands. Carbonates and hydroxy-anions are the favoured inorganic complexing ligands in oxidized freshwaters with pH above 7. In the presence of soluble organic matter, sorption of copper to particulates may be relatively ineffective because complexation with humic acids is the dominant process (Jackson and Skippen 1978).

Cadmium and **zinc** are characterized by a lower affinity to carbonate and hydroxy anions at near neutral pH values. The influence of pH and alkalinity on the solubility of Cd^{2+} and Zn^{2+} is much lower as compared to lead and copper. Zinc also forms complexes with humic substances, a process which is favoured by increasing pH.
Molybdenum occurs in oxidized waters as molybdate (MoO_4^{2-}) and bimolybdate ($HMoO_4^-$) anions. The anions are readily adsorbed by iron and aluminium oxyhydroxides at pH values below 5. Above this value, molybdenum in natural waters is essentially dissolved.
Aluminium in the aquatic environment is mainly present in the form of dissolved and colloidal aluminium hydroxide, $Al(OH)_3$. Its minimum solubility is at pH 5.5-6. Above pH 6.5, soluble aluminium exists primarily as $Al(OH)_4^-$. It is capable of forming complex ions with inorganic and organic substances.

pH. The pH value in the Ok Tedi/Fly River system is not only controlled by the dissolved carbon dioxide concentration in waters and calcite dissolution, but also by the biochemical processes of photosynthesis and respiration. Photosynthesis of subaquatic plants is accompanied by the assimilation of ions such as NO_3^-, NH_4^+ and HPO_4^{2-}. Charge balance is maintained by the uptake or release of H^+ or OH^-, which lead to alkalinity changes.
Alkalinity increases in oxygenated waters as a result of photosynthetic nitrate assimilation according to the bulk reaction (Stumm and Morgan 1981):
$106\ CO_2 + 16\ NO_3^- + HPO_4^{2-} + 122\ H_2O + 18H^+ \rightleftharpoons C_{106}H_{263}O_{110}N_{16}P_1$ (mean algae composition) $+ 138\ O_2$
NH_4^+ is the dominant nitrogen species in reducing waters. NH_4^+ assimilation during photosynthesis causes a decrease in pH:
$106\ CO_2 + 16\ NH_4^+ + HPO_4^{2-} + 108\ H_2O \rightleftharpoons C_{106}H_{263}O_{110}N_{16}P_1 + 107\ O_2 + 14\ H^+$
Respiration of plant material leads to reactions in opposite direction. When photosynthesis and respiration are in overall equilibrium, no change in pH will be observed, although there exists a pH variability over the day/night cycle. When the rate of production of organic matter (assimilation of NH_4^+) is larger than the rate of decomposition, alkalinity will decrease. Peat formation, which was frequently observed in the Fly River floodplain, leads to low pH values in the overlying water.

Reduced species. NH_4^+, HS^- and NO_2^- were determined in waters as indicators of reducing conditions. All three compounds are unstable in oxygenated water. Nitrite is metastable in both reducing (conversion to N_2 and N_2O) and oxidizing waters (nitrate formation). The stability of NH_4^+ and HS^- is pH-dependent. HS^- is converted to volatile H_2S at pH values below 7. To the contrary, NH_4^+ forms volatile NH_3 at pH above 9 (at 30°C). Within the pH range observed in the investigated waters with oxygen deficiency, only NH_4^+ was a reliable indicator of reducing conditions. Many redox reactions are slow and depend on biological mediation, hence the concentrations of species encountered in natural waters may be far from those predicted thermodynamically (Stumm and Morgan 1981).

Only the elements C, N, O, S, Fe and Mn are important participants in redox processes in the aquatic environment. However, since the mobility of trace metals is influenced by the adsorption to Fe and Mn oxides and fixation in reduced species (e.g. formation of metal sulfides), redox conditions are of importance to predict trace metal behaviour.

Dissolved organic carbon (DOC). The term DOC is a sum parameter for a number of polymeric organic substances which contain a sufficient number of hydrophile functional groups (-COO, $-NH_2$, R_2NH, -RS-, ROH, RO-) to remain in solution despite their molecular size. Polypeptides, amino acids, certain lipids, polysaccharides, humic and fulvic acids and Gelbstoffe belong to this group. Humic substances in general are a result of the transformation of biogenic material. DOC levels in interstitial waters of deposited organic debris may be much higher than in the overlying water.

Humic acid is extracted from humic matter in alkaline solution. Fulvic acid is the humic fraction that remains in acidified solution and is soluble over the entire pH range. Humin is the fraction which cannot be extracted by either acids or bases. Structurally, the three groups are similar; differences are in molecular weight and functional group content. The analytical determination of soluble chelates in natural waters is very difficult, particularly with the minute quantities of metal ions that are usually present.
Humic substances have a strong tendency to become adsorbed on inorganic surfaces like hydrous oxides and clays through a mechanism involving ligand exchange of humic anionic groups with H_2O and OH^- of mineral surfaces (Tipping 1981). These negatively charged coatings may themselves become active absorbers of trace metals. Colloidal iron and aluminium oxides are stabilized by humates. In highly dispersed form, these colloids pass through an 0.45 µm membrane filter.
The most important feature of humic and fulvic acids is there tendency to form complexes with metal ions. As polycarboxylic acids, humates precipitate in the presence of dissolved Ca and Mg due to coagulation. Humic substances display colloid-chemical behaviour.

In the present study, three types of water were distinguished for their different chemistry and main constituents: Fly River water, unpolluted floodplain waters, and mixed waters.

6.2.2. Fly River Water

Water from the Middle Fly River (Table 13 and Table A4 in annex) 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 which is carried in suspension from the Mount Fubilan minesite 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 mol 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 (low number of samples, not reported in Tables). 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. Reduced species (NH_4^+, HS^-, NO_2^-) were present at or below detection limit which indicates oxygenated conditions.

Within the temperature range observed in Fly River water, p_{CO2} does not change to an extent which would markedly affect calcite dissolution. The plot of pH versus calcium (Fig. 1) shows a significantly negative correlation ($p < 0.05$). The plot of suspended solids versus calcium (Fig. 2) displays a significantly positive relationship. It can be concluded that at low pH, more calcite from the suspended particulate fraction is dissolved, which means that the dissolved calcium concentration is controlled by pH (assuming constant atmospheric p_{CO2}).
The fact that the highest suspended solid concentrations are associated with the lowest pH values may indicate that high flows in the Fly River are associated with low pH. Since high flows are a result of heavy rainfall, and because rainwater is saturated with atmospheric CO_2, the increased input of carbonic acid may explain near neutral pH values in the river water at high flows.
There exists a positive relationship between conductivity and suspended solids ($p < 0.05$, Fig. 3). A high concentration of suspended matter is associated with high values for earth alkaline and alkaline metals (Ca, Mg, Sr, Na and K).
No correlation was found for suspended solids versus Fe, Mn and Mo. A negative correlation between suspended matter and dissolved copper and zinc was observed, however statistically not significant. Na, Ca, Mg and Sr are highly intercorrelated.
Sample W1/21.2., which has the highest Fe value of 339 µg/l, also gave the highest values for dissolved Zn and Cu. In the acidified water sample, the colloidal iron oxide particles are dissolved and adsorbed trace metals are released. This explains the high Zn and Cu values associated with iron. This correlation was not observed in other samples. Dissolved trace metal levels, with the exception of copper (median value: 17 µg/l) 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.

Fig. 1

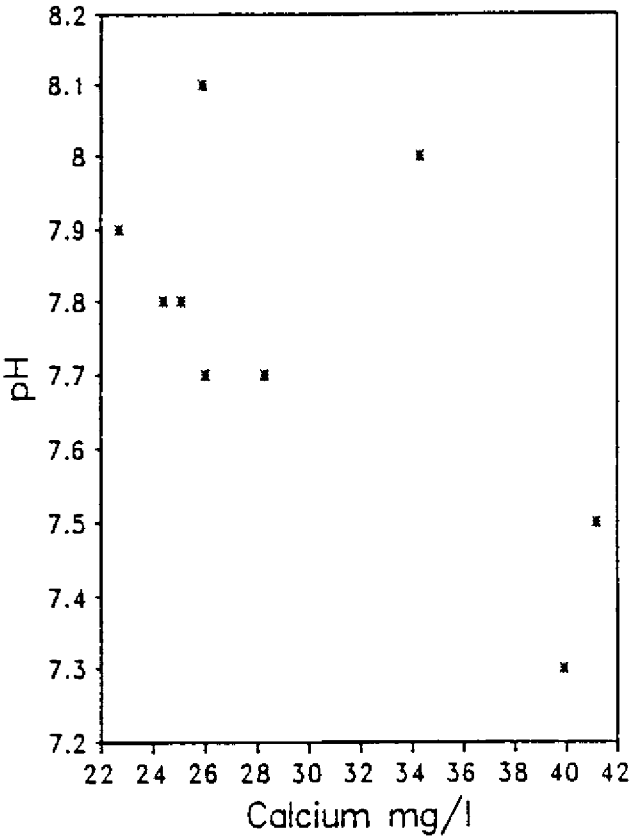


Fig. 2

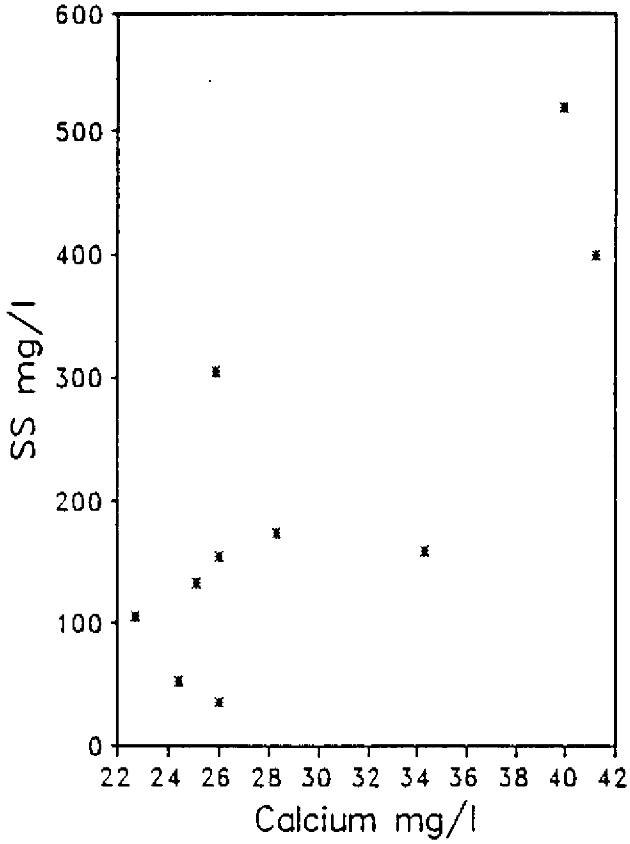


Fig. 3

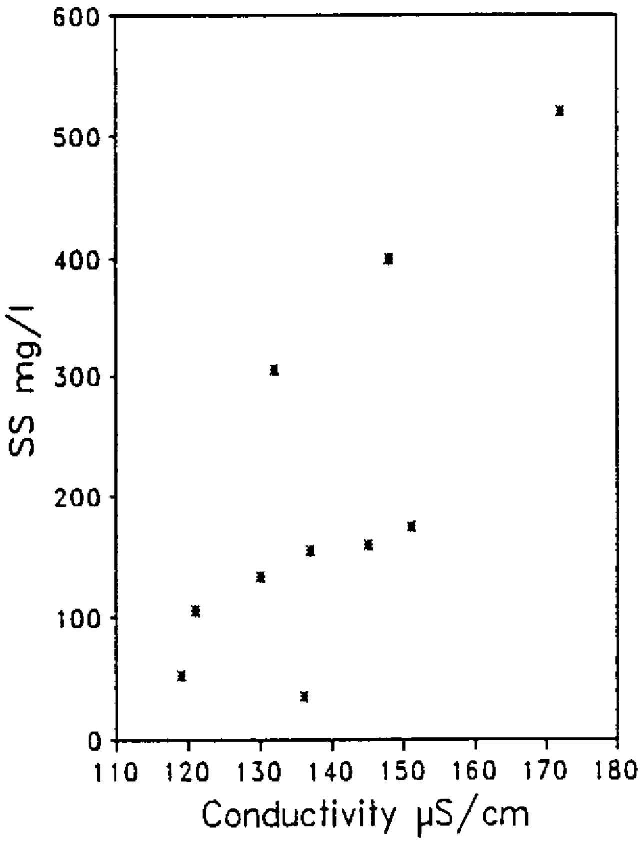
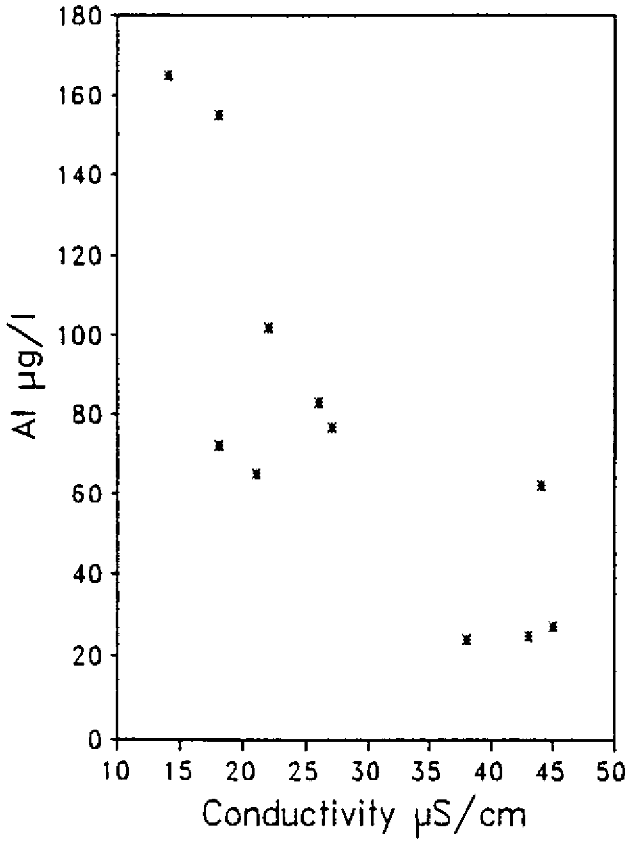


Fig. 4



Scatter plots for selected parameters in Fly River water (Fig. 1-3) and floodplain waters (Fig. 4).

Analytical data from the pre-mining period (Maunsell 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. Fly River water chemistry probably was not much different from present day conditions, although Maunsell (1982) and Kyle (1988) report slightly acidic pH values in the range of 5.5 to 6.7 which appear erroneous. Trace metal levels measured by Maunsell (1982) were at or below the detection limit of 1 µg/l with the exception of Fe, Mn and Zn. Pickup et al. (1979) report mean suspended solid concentrations in the range of 60 to 80 mg/l for the Middle Fly and note that "the Fly and the lower Ok Tedi are very clean rivers by Papua New Guinea standards".

Parameter	**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

Table 13. Mean, standard deviation, median values and 25% - 75% confidence intervals for Fly River water samples (n = 11).

6.2.3. Floodplain Waters

The term floodplain waters is used for courses of water which drain the outer Fly River floodplain. Their catchment comprises forested areas and low-lying swamps of high biological productivity with dense subaquatic and swamp vegetation. The main features of floodplain waters are low pH and conductivity (Table 14 and Table A5 in annex) and their yellow-brown colour ("blackwater").

The content of suspended solids is very low as compared to the Fly River. The material retained on the membrane filter is orange brown, consisting of iron oxides (about 10-15% Fe) and particulate organic matter. The high content of iron, most probably in the form of oxyhydrate colloids, is particularly evident in the non-filtered water samples, but also in the filtered water in which the iron values are much higher than in the Fly River water. Sodium, an ubiquitous element, is present in floodplain waters in a similar concentration range as in the Fly River. Aluminium values were highest at low pH and conductivity (Fig. 4). The overall Al content was higher than in the Fly River, where the metal was below the detection limit (50 µg/l) in the four samples measured.

An influence from the mine discharges was detectable in some water samples (slightly elevated trace metal, calcium and sulfate levels). However, since the main features of floodplain drainage such as low pH and conductivity and high DOC levels were observed in these samples, they were included in this category. Metal levels for Cu, Pb, Cd and Mo in floodplain waters unaffected by mining are at or below detection limit (e.g. <2 µg/l for Cu, Table 14). Zinc is the only heavy metal present in measurable concentrations. Since floodplain waters drain lowland areas of intensely weathered Pleistocene sediments, extremely low trace metal are to be expected.

Low alkalinity is a result of active accumulation of organic material. Peaty sediments were repeatedly encountered during lake bottom coring. Oxygen deficiency in stagnant or slowly moving, warm waters does not allow complete respiration (oxidation) of organic matter. There is a positive correlation between temperature and oxygen saturation (Fig. 5), which is contradictory at first sight. However, the oxygen measured was a result of photosynthetic activity, which is highest at intense sunshine, which in turn is responsible for high water temperatures. It is obvious that the waters are not in redox equilibrium. The photosynthetic oxygen production masks the overall oxygen deficiency of the system, which is evident from the relatively high concentrations of reduced species like NH_4^+ and HS^-. Of both compounds, NH_4^+ is the better indicator of reducing conditions because hydrogen sulfide is volatile at the low pH and high water temperatures measured. NH_4^+ shows a significantly positive correlation with dissolved organic carbon (DOC)(Fig. 6), which is also positively linked with water temperature. NH_4^+ and DOC are both a result of decomposition of organic matter. The DOC produced in off-river sites is the main source of organic ligands which are responsible for trace metal complexation in polluted waters.

Parameter	**Mean**	**SD**	**Median**	**Percentiles**	
				25	**75**
Temperature °C	30.6	2.2	30.0	29.2	31.4
pH	6.0	0.5	6.0	5.7	6.4
Conductivity µS/cm	28.5	10	27	20	34
Suspended Solids mg/l	21	11	19	11	24
Na µg/l	1233	409	1140	1020	1280
K µg/l	188	107	193	89	244
Ca µg/l	4295	1992	4110	3060	5890
Mg µg/l	477	141	480	372	499
Sr µg/l	27	10	24	21	34
Al µg/l	67	48	64	25	80
Fe µg/l	values highly variable				
Mn µg/l	15.4	15.1	7.5	2.5	27
Zn µg/l	close to detection limit of 5 µg/l				
Cd µg/l	below detection limit of 0.1 µg/l				
Cu µg/l	close to detection limit of 2 µg/l				
Pb µg/l	below detection limit of 1 µg/l				
Mo µg/l	below detection limit of 5 µg/l				
HCO_3 mg/l	13	6.5	13	9	17
NH_4 mg/l	0.3	0.2	0.20	0.14	0.38
SO_4 mg/l	0.37	0.26	0.27	0.18	0.45
DOC mg/l	9.4	3.0	8.0	7.0	11.0

Table 14. Mean, standard deviation, mean values and 25% - 75% confidence intervals for outer floodplain water samples (n = 15).

6.2.4. Mixed Waters

Mixed waters are generally intermediate in composition between Fly River and floodplain waters, although the influence of the Fly River is clearly dominant (Table 15 and Table A6 in annex).

Due to the generally flat terrain, the location of the mixing zone of floodplain drainage and Fly River water depends mainly on rainfall in the upper catchment of the Fly River/Ok Tedi and in the Fly River lowland. When there is high rainfall in both catchment areas, the mixing front between Fly water rich in suspended solids and blackwater from the floodplain will be located close to the mouths of creeks and tie channels.

Fig. 5

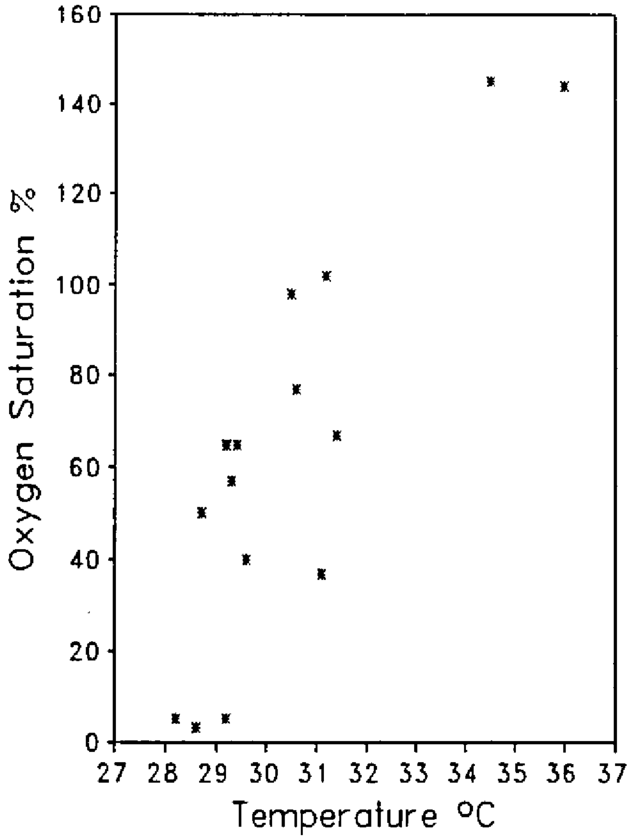


Fig. 6

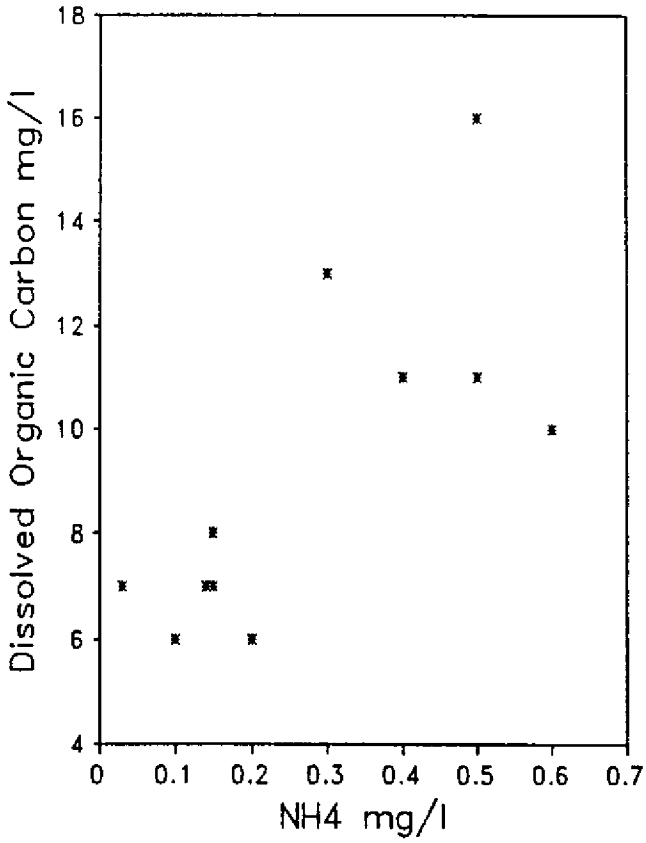


Fig. 7

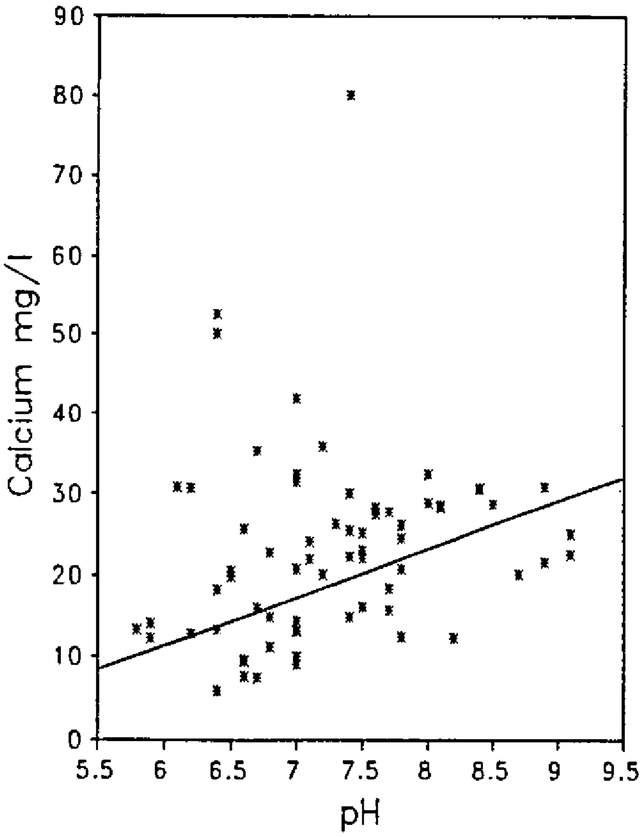
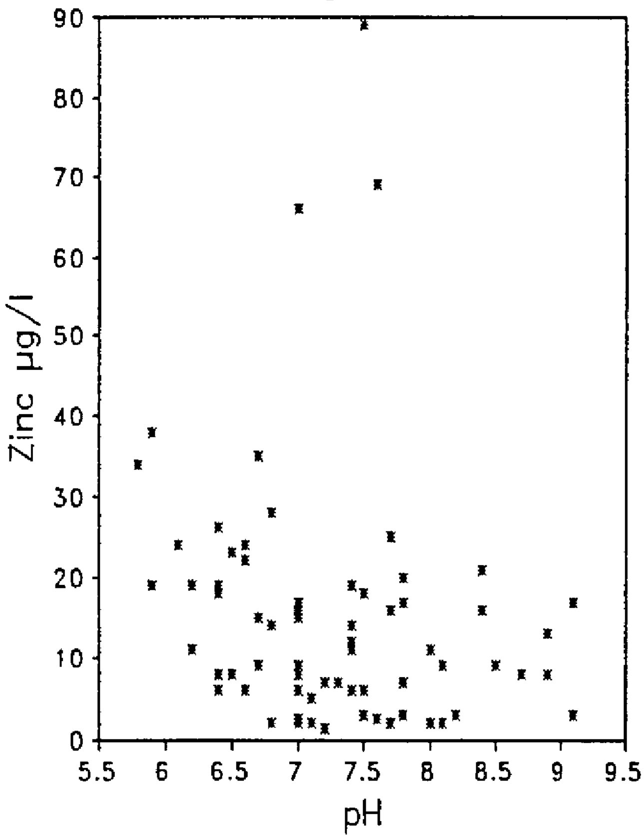


Fig. 8



Scatter plots for selected parameters in floodplain waters (Fig. 5-6) and mixed waters (Fig. 7-8).

At high flow conditions in the Fly River and previously little rainfall in the lowland, river water intrudes several kilometers upstream of the channels and lakes which drain into the main river under reverse conditions. The intrusion of Fly River water is associated with transport of mainly mine-derived suspended matter, which is deposited in the waters of the inner floodplain. 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.

Because of the different composition of Fly River waters and those draining the outer floodplain, the physical and chemical interactions occuring are of environmental interest (Fig. P8). Particular attention has to be paid to the behaviour of trace metals, of which copper is the most relevant.

Parameter	**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 1 µg/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

Table 15. Mean, standard deviation, median values and 25% - 75% confidence intervals for mixed water samples (n = 65).

As mentioned above, the pH of floodplain waters is much lower than in the Fly River. Decreasing alkalinity may lead to increased heavy metal mobility due to desorption from particulate matter and formation of free dissolved metal species.

The plot of pH versus Ca shows a weakly positive correlation (Fig. 7). Mg, Sr, Na, K and HCO_3^- give similar plots. Calcite in particulate form carried into the floodplain waters is rapidly dissolved and exerts a buffering effect on the local waters. Opposite to the main trend in the pH/Ca plot, there are samples showing a high calcium content at comparatively low pH. These data are from small ponds on the swampy floodplain and slightly acidic floodplain seepage, i.e. extremely iron-rich water trickling from exposed channel or river banks into the river during low flow conditions.

No clear influence of pH on dissolved iron and manganese concentrations was observed, although the highest Fe values tend to be associated with low pH.

None of the trace metals showed a significant correlation with pH. The plots of pH versus zinc (Fig. 8) and cadmium display a slightly negative trend. No correlation between pH and Cu (Fig. 9) and pH and Mo was detected. DOC and pH are weakly negatively correlated (Fig. 10) which is due to the acidic nature of humic and fulvic substances. In the absence of calcium bicarbonate buffering, the organic acids control water pH.

Fig. 9

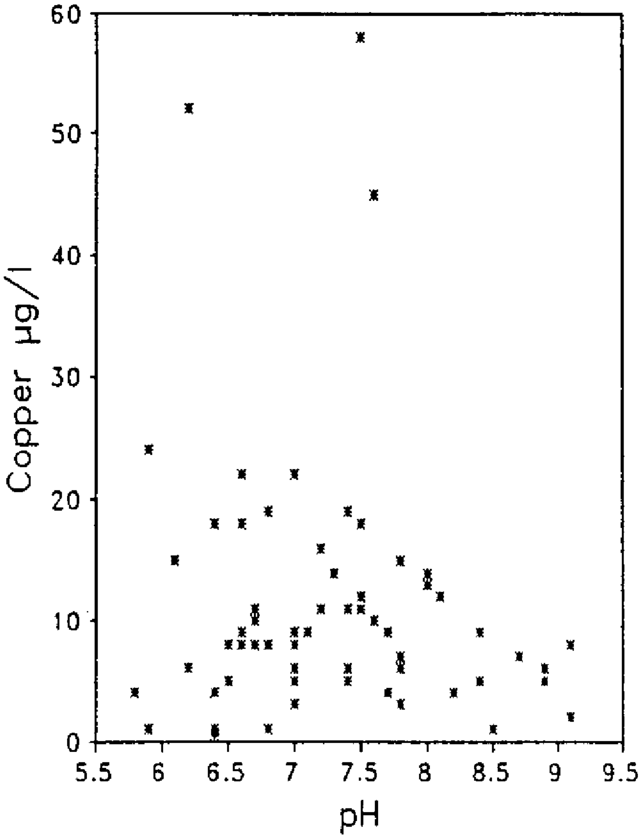


Fig. 10

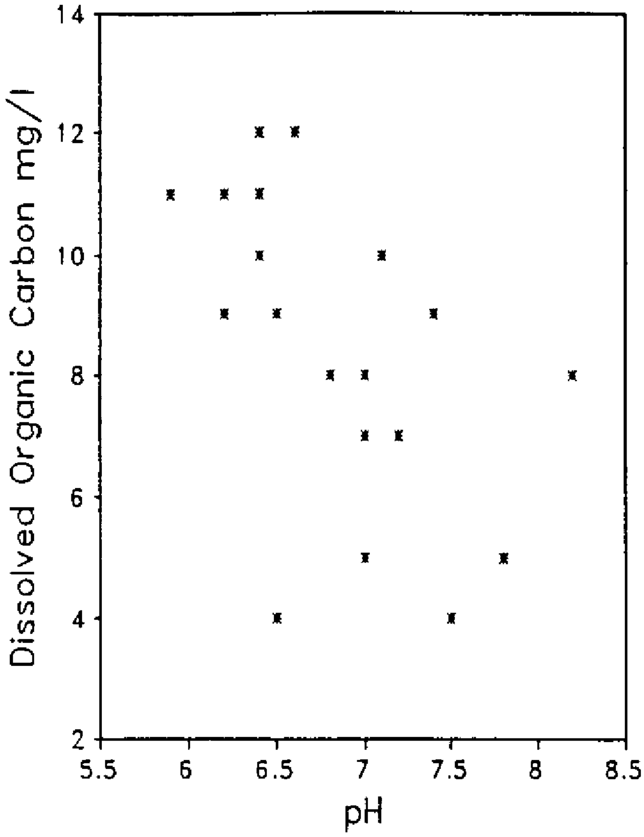


Fig. 11

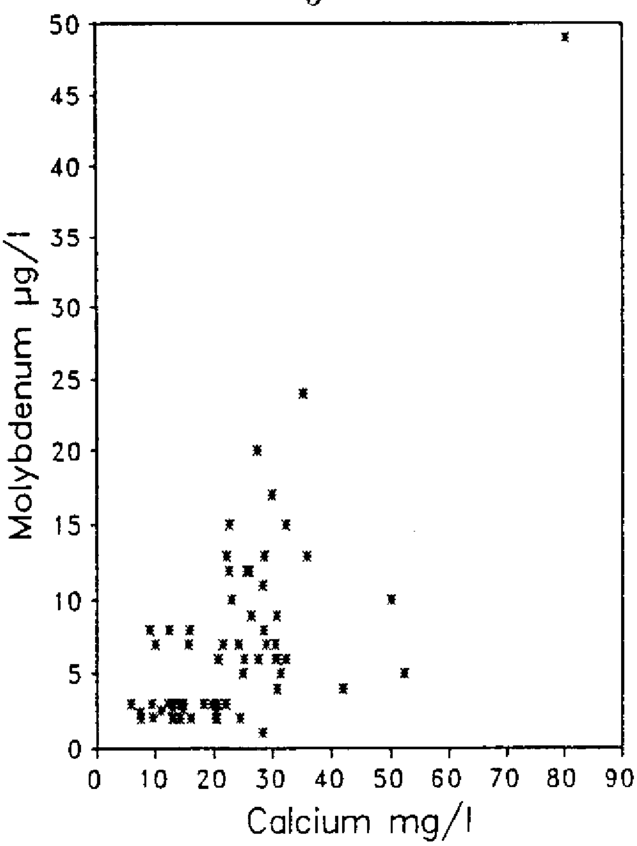
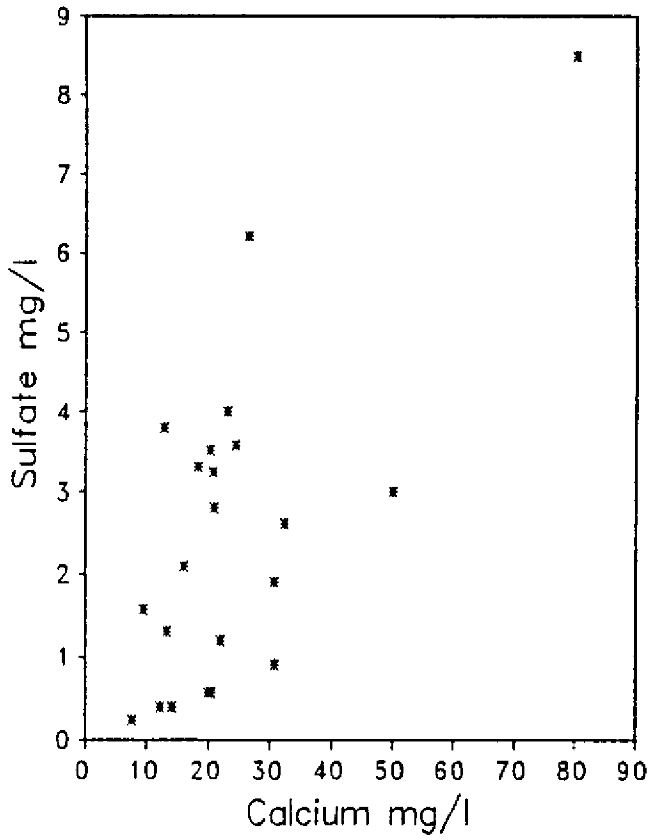


Fig. 12



Scatter plots for selected parameters in mixed waters (Fig. 9-12).

Reducing conditions, indicated by an elevated NH_4^+ content, also seem to have little influence on dissolved trace metal concentrations. Only zinc gave a moderately positive correlation with NH_4^+.
Ca shows a weakly positive correlation with Mo (Fig. 11). A positive relationship of the alkaline and earth alkaline metals with sulfate (calcium versus sulfate, Fig. 12) was observed. Elevated concentrations of Ca, Mg, Na, K, and Sr are clear indicators of the influence of mine discharges. High sulfate levels are a product of active dissolution of mine-derived sulfide minerals. Although the metals iron, zinc, copper and molybdenum are discharged into the river system primarily in the form of sulfides and undergo oxidation to sulfates, no positive correlation between sulfate and any of the metals was observed. Iron and zinc even displayed a weakly negative relationship with sulfate. This illustrates the complexity of solution chemistry in the investigated waters, and the fact that aqueous metal transport is not controlled by sulfate complexation. There was also no significant correlation of dissolved organic carbon (DOC) and trace metals found. Only the plot of zinc versus DOC shows a weakly positive correlation.

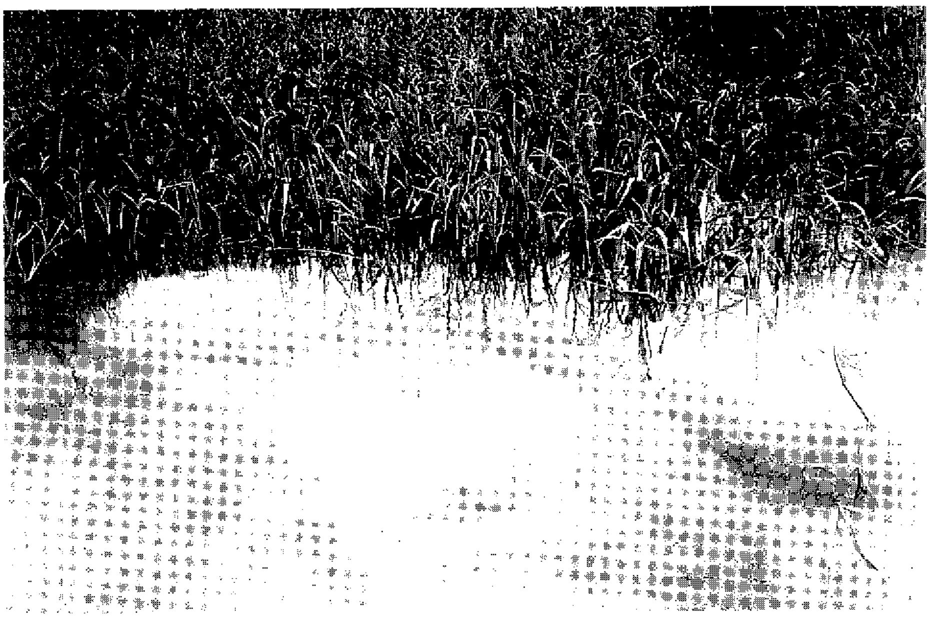
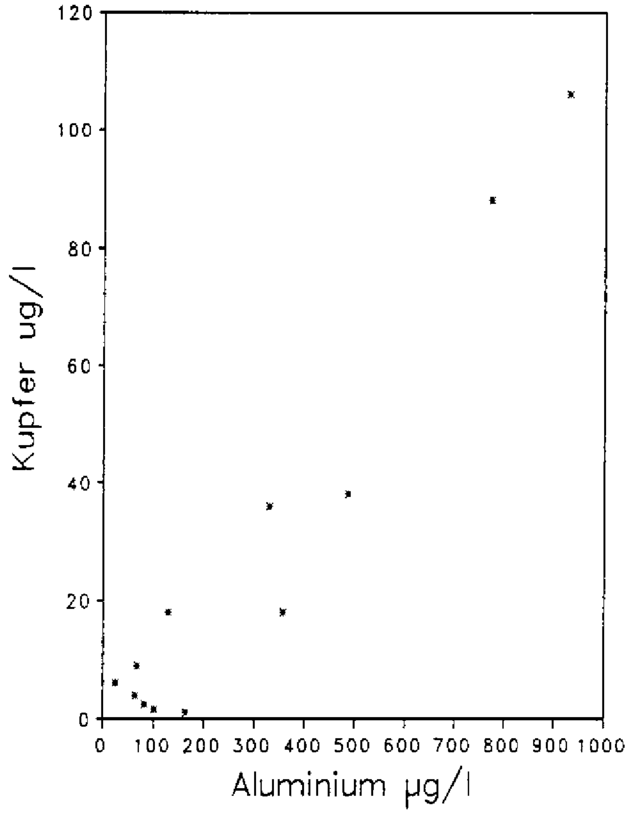


Fig. P8. Mixing of acidic, humic-rich floodplain drainage (blackwater, DOC 12 mg/l, 18 µg/l Cu) and sediment-laden white water of the Fly River (DOC 5 mg/l, 9 µg/l Cu) in the Lake Bosset channel.

Intercorrelations between elements in mixed waters are very high in the group Ca, Mg, Sr, Na, K and HCO_3^-, with the exception of Na versus K. Zn and Cd display a positive correlation, too. A significantly positive correlation was found for Al and Cu in unfiltered water samples (Fig. 13). Aluminium hydroxide may complex or adsorb dissolved copper. Al/Zn displayed a similar correlation. Fe versus Cu in unfiltered water shows no clear trend. Fe is weakly positively correlated with DOC and Mn.
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.
Dissolved trace metal levels in mixed 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, 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.
Both factors interact in a complicated manner which cannot be predicted from thermodynamic equilibrium calculations.

Despite the fact that **lead** in mine wastes is clearly enriched above background values, the dissolved metal contents were in the great majority of samples below detection limit (< 1 µg/l). Elevated concentrations were found only in unfiltered samples and in a few samples which also showed a high content of presumably colloidal iron and manganese, which offer adsorption sites for lead.

Speciation modelling of inorganic lead with PHREEQE suggests that at near neutral pH values and oxic conditions in waters, more than 70% of soluble lead exists in the form of the $PbCO_3^0$ complex which easily precipitates out. Between 0-30% of lead may be present in the free ionic form Pb^{2+} under the environmental conditions in the floodplain.



Scatter plot for Al versus Cu in mixed waters (Fig. 13).

Cadmium and zinc are among the geochemically most mobile elements. Their mobility is less pH dependent as compared to lead. Cd was found in concentrations above detection limit (> 0.1 µg/l) only in waters with a pH below 7. Because of the low Cd values in mining residues, the metal is not considered as being of environmental concern. The same holds true for zinc, which showed a similar concentration range in all waters investigated.

Molybdenum, because of its anionic form in water, showed a different behaviour than the other trace metals. Highest concentrations were usually found in alkaline waters, or linked with high calcium values. Mo as well as Zn is considered an essential element to biota. The concentrations observed are much below the toxic threshold.

Copper is an essential element to plants and animals, too.

Because of its environmental importance, the fate of copper in the investigated waters will be discussed in some detail in the following chapter.

6.2.5. The Behaviour of Copper

The statistical data analysis showed that copper concentrations in water do not appear to be significantly controlled by inorganic factors.

Alkalinity and pH, adsorption to oxide surfaces (with the exception of aluminium) and reducing conditions (e.g. formation of soluble copper amine complexes) do not seem to have a significant effect on dissolved copper levels. The abundance of organic complexing agents in the investigated Middle Fly floodplain waters may be responsible for the observed behaviour of dissolved copper. No correlation was observed between DOC and copper levels in the floodplain waters. It is evident that dissolved organic ligands, even at comparatively low concentrations in waters of the Fly River system, are always present in excess of trace metals which may become complexed (although some complexing capacity may be occupied by major cations like Ca and Mg). In the Lower Fly River, downstream of the Strickland junction, measured dissolved copper values are still moderately high at 6 µg/l (Table A6, annex) despite the massive

admixture of uncontaminated suspended matter from the Strickland River. It appears that the lowering of dissolved copper levels in the Lower Fly is mainly due to dilution effects and that adsorption to riverine particulate matter is of secondary importance.
Davis and Leckie (1978) tested the influence of dissolved organic substances on copper adsorption. Certain organic ligands which form coatings on suspended mineral particles enhance the extent of trace metal adsorption, while others show opposite behaviour. Some organic acids inhibit copper adsorption by forming soluble, stable complexes which keep the metal in solution. When the complexing capacity of dissolved organic carbon substances is larger than the rate of adsorption to inorganic surfaces, copper will remain in solution.

Sholkovitz and Copland (1981) also investigated the solubility and adsorption properties of a number of trace metals in the presence of humic acids. Contrary to similar studies which were performed with synthetic laboratory waters, Sholkovitz and Copland used natural water from a small stream in Scotland which drains peaty soils. The properties of this water (DOC 7 mg/l, pH 6.5, low conductivity) are similar to those of the Fly River floodplain. The authors detected a coagulating effect on humic acids and trace metals, particularly iron and copper, upon adding of only 0.5 mmol/l of Ca, which is equivalent to 20 mg/l Ca. The mean Ca concentration in mixed waters of the Fly River inner floodplain is about 25 mg/l. Coagulation of humic substances with adsorbed trace metals may be an important process when calcium-rich Fly River water mixes with floodplain blackwaters. This is consistent with the detection of elevated copper levels on the top of black, peat-like sediments sampled from lake bottoms far from direct Fly River influence. The experiments carried out by Sholkovitz and Copland (1981) also gave the result that there was no precipitation of trace metals and humic acids when pH (starting point pH 6.5) was changed in the range of 9.5 to 3, below which humic acids, Fe, Mn, Cu, Ni and Cd began to precipitate. This behaviour is contrary to that predicted by inorganic solubility considerations. Complexation of the trace metals by dissolved organic matter is the most reasonable explanation. Organic copper complexes are known to be particularly stable because of their favourable electron configuration (Stumm and Morgan 1981).

Fe and Mn in floodplain waters, despite their chemical similarity, showed no significant correlation in any data set. Of the elements investigated by Sholkovitz and Copland (1981), Fe>Cu>Ni>Cd (in decreasing order) showed the strongest affinity for the dissolved humic substances, Mn and Co the least. The differing tendency of Fe and Mn to form complexes with dissolved organic carbon may explain the missing correlation in data from the Middle Fly River region.
In a copper adsorption experiment (spiking to yield 20 µg/l Cu) with natural waters containing different concentrations of suspended solids and dissolved organic carbon, Sholkovitz and Copland (1981) obtained results which suggest that solubilization of Cu by dissolved organic ligands, forming ultrafine colloids (< 0.01 µm), is a more important process than the adsorption onto riverine particulate matter. Even in water containing 100 mg/l mostly inorganic suspended matter and 3 mg/l DOC, most of the copper was kept in solution as the pH increased from 4 to 9.

CSIRO of Australia (1989) performed mixing experiments commissioned by Ok Tedi Mining Ltd. with water from the Fly River and a floodplain tributary. Mine derived sediment with high copper values was added to different admixtures. Total dissolved copper concentrations increased with sediment admixture, the pH remained fairly constant. Dissolved copper species in the resulting solutions were analyzed by Anodic Stripping Voltametry (ASV). The method is used to determine labile trace metal species supposed to be present in the ionic, most bioavailable form. Interestingly, between 30-50% of dissolved copper in the final test solutions was measured as labile or "ionic" copper. Assuming that the copper was present as dissolved organic species, the results point to great reactivity of humic copper complexes in the Fly River system. This is consistent with more recent laboratory work undertaken by CSIRO on behalf of OTML (OTML 1994). Electrochemical measurements of bioavailable copper in the Ok Tedi/Fly River system gave the result that the fraction of potentially bioavailable copper is up to 50% of the total dissolved copper concentration.

In the presumably unpolluted waters of the outer floodplain (it is difficult to establish the maximum intrusion range of Fly River water) copper was at or below the detection limit of 2 µg/l. In the Fly River, copper values were about tenfold above this "background", which may actually be much lower than 2 µg/l, i.e. 0.2 µg/l.
Mixing of both waters should result in dilution. This is the case in most mixed water samples, however in some waters copper concentrations were much higher. Sample W1/7.4., which had a dissolved copper concentration of 52 µg/l in the filtered and 106 µg/l in the unfiltered sample, was taken from a depression in flat swampy terrain about 150 m behind the low dam paralleling the Fly River channel.

Table 2. Particulate and dissolved copper and fish catch for Kuambit/Nukumba, Obo and Ogwa.

YEAR	KUAMBIT/NUKUMBA			OBO			OGWA		
	pCu	dCu	fish catch	pCu	dCu	fish catch	pCu	dCu	fish catch
	ug/g	ug/l	kg	ug/g	ug/l	kg	ug/g	ug/l	kg
1990	1236	11	15	1202	17	35	524	3	95
1991	905	6	28	879	9	66	401	2	118
1992	715	3	38	693	5	94	321	11	35
1993	875	4	29	850	6	70	388	1	120
1994	581	3	49	564	4	119	270	1	147
1995	581	3	49	564	4	119	270	1	147
1996 to 2008	562	3	49	544	4	119	253	1	147

Source: pCu -Supplementary Investigations, Vol. II, Appendix B.
dCu -Supplementary Investigations, Vol. I, Figure 3.
Fish Catch -Supplementary Investigations, Vol. III, Appendix H, Figures 10a, 11a, & 12a and Table 4A.

Table 18 Dissolved Copper Predictions (µg/L) Provided to the State in June 1992.

Year	Nukumba	Obo	Ogwa
1991	11 (10.5)	15 (14.2)	6 (5.4)
1992	13 (13.1)	17 (15.0)	6 (6.6)
1993	14	17	7
1994	11	15	6
1995	11	15	6
1996	12	18	7
Error Estimate	+- 78%	+- 80%	+- 85%

( ) annual (calendar year) means of observed data

Table 5.8 Revised Predictions for dCu in the Fly River and Mean Data for 1993

Year	Nukumba	Obo	Ogwa
1993	16 {4 - 28}(13.8)	17 {3 - 31} (17.6)	6.3 {1 - 12} (7.4)
1994	18 {4 - 32}	18 {4 - 32}	7.5 {1 - 14}
1995	14 {3 - 25}	14 {3 - 25}	6.7 {1 - 12}
1996	14 {3 - 25}	14 {3 - 25}	6.6 {1 --12}
1997	13 {3 - 25}	13 {3 - 25}	6.1 {1 - 11}
1998	14 {3 - 25}	14 {3 - 25}	6.6 {1 - 12}

{ } Upper and lower error estimates
() Annual (calendar year) means of observed data

Table 16. Predictions made by OTML in 1989 for key environmental parameters in the Fly River system, and revised predictions for dissolved copper in 1992 and 1993 (OTML 1990, 1993, 1994).

Water sampled from small pools and shallow water courses in the periodically flooded grassland sites usually gave high copper values. The water samples taken generally had low pH and/or alkalinity. It appears that active leaching of copper from deposited mine-derived material is responsible for the high dissolved values observed. In the floodplain swamps, redox conditions change easily depending on the undulating water table which may result in trace metal mobilization. Because of the dense vegetation and the low rate of water exchange, soluble organic chelates are abundant and may facilitate copper mobilization. The buffering effect of calcium disappears as the easily soluble element is leached from the sediments. Because of the favourable conditions for trace metal leaching, even a thin layer of deposited mine-derived material will be an important source of copper. Due to difficult access, only a few samples from the swamp sites were taken (water was sampled within a maximum distance of one kilometer from the main river channel). It seems that the copper levels in floodplain waters investigated in the present study are biased towards low values (in samples from large lakes and tie channels) and are not representative for the entire floodplain.

Where floodplain swamp waters with leached copper drain into lakes and the main river, they will increase copper concentrations. This may explain why OTML (1991, 1993, 1994) reports higher dissolved copper levels at Obo as compared to the upstream site at Nukumba, below the Ok Tedi/Upper Fly River confluence.
A different type of water in which high trace metal concentrations could be expected are the samples called "floodplain seepage". These moderately acidic waters percolate through the floodplain sediments and drain spring-like into the channels and rivers. The waters are highly reducing and have a very high Fe^{2+} and Mn^{2+} content which is immediately oxidized to orange coloured gels and flocs upon exposure to atmospheric oxygen. Although the floodplain seepage samples showed high Cd and Pb levels, this was not the case for copper, which probably remains in sulfidic binding in the sediment body.

Table 16 shows predictions based on computer modelling by OTML (1990) of various environmental parameters in the Fly River system in response to the impact of mine discharges. These additional environmental monitoring conditions were established to ensure that *the Acceptable Particluate Level of 940 mg/l at Nukumba does not result in actual environmental damage to the Fly River System beyond the level actually specified in the predictions* (OTML 1990).

The predictions resulting from the Supplementary Environmental Investigations (undertaken in 1986-89 by OTML) have been established for testing whether or not the State's conditions for environmental management of the Fly River System and off-shore are met. Due to a number of reasons, there has been a non-compliance with monitoring conditions beginning in 1990. Particularly the dissolved copper levels were much higher than expected. Measured values at the APL sites Kuambit/Nukumba, Obo and Ogwa have been in a steady increase between 1990 and 1993 (OTML 1994) contrary to the trend predicted by the models. Revised prediction values for the key environmental parameters were developed by OTML in July 1992 and again in December 1993.

7. DISCUSSION OF BIOLOGICAL IMPACTS

The discharge of ore processing residues and mining wastes has significantly changed the aquatic environment of the Ok Tedi/Fly River system. From the discussion in previous sections it can be concluded that there are three factors of particular environmental concern: the increase in particulate copper, in dissolved copper, and in suspended solids concentrations. The negative impact of each effect on the fluvial system is spatially different.

The massive increase in the suspended load of the Ok Tedi is mainly responsible for the decline in aquatic life upstream of the confluence with the Fly River, where fish populations and species diversity have been dramatically reduced (Smith 1991). The persistently high concentration of suspended sediments in the water interferes with gill respiration of fish and aquatic organisms, modifies the movement and migration of fish and prevents successful development of eggs and larvae. Heavy metals in particulate and dissolved form, and toxic process chemicals like xanthates probably play a minor role in the adverse impact on the aquatic life of the Ok Tedi River.
In the Fly River itself, a combined detrimental effect of suspended sediment, particulate and dissolved copper on the aquatic ecology is to be expected. Monitoring undertaken by OTML (Smith 1991, OTML 1993, 1994) shows that fish populations in the Middle Fly River at Kuambit, immediately downstream of D'Albertis Junction, are continuously

declining, in the range of 30-50% (M. Eagle, pers. comm.). Statistical analyses gave the result that particulate copper (pCu) was the best negative correlate of fish catches, but dissolved copper and suspended solids also have a negative effect. OTML (1994) speculates that the relationship between pCu and fish catch may either be attributed to an avoidance of pCu by fish or by a correlation of pCu with a toxic fraction of dissolved copper.

Both total fish catches and the diversity of the aquatic fauna are affected. No clear negative impact of mine discharges on the abundance of fish in the Middle Fly River downstream of D'Albertis Junction can be established from the data collected so far because of their high variability. Fish biomass monitoring in the last three years has been strongly influenced by low river levels concentrating fish into the river channel as the floodplain dried, hence leading to high catches at the river sites. Clearly, the exact determination of fish populations (including migratory species) in a dynamic fluvial ecosystem is a difficult undertaking since fish catches are influenced by a number of factors which cannot be attributed to the mine waste, like periods of droughts and commercial and subsistence fishing pressure. In addition, OTML (1994) admits that its database on fish biomass is limited with respect to baseline data and comes to the conclusion that "changes between before and after mine start-up conditions cannot be quantified for any site (in the Fly River system)".

Considering the homogeneity of the Middle Fly River system and the fact that the key water parameters influenced by the mine's operation (dissolved and particulate copper and suspended solids) show little changes in the Middle Fly River reach between Kuambit/Nukumba and Obo, negative effects on the fish populations in the lower part of the Middle Fly region are to be expected.
OTML (1993) report elevated copper levels in body tissue of the catfish *Arius berneyi* caught in Lake Pangua, a deep oxbow lake. *Arius* is a bottom feeding omnivore. Aquatic invertebrates form the most important part of its diet, but detritus/mud is also an important food item (Kare 1992). It is not clear whether the copper detected in the fish was taken up via the bottom dwelling invertebrates, or directly from the copper-rich sediment, the metal being released in the intestinal tract of the catfish. In both cases, it is evident that copper in particulate form on the lake bottom is bioavailable.

In the off-river floodplain sites of the Middle Fly region, elevated concentrations of dissolved copper may negatively affect aquatic life. The floodplain plays an important role in primary productivity to support fish stocks in the river system, and for the recruitment of fish. OTML (1991) states that the floodplain supports a greater stock of fish than do oxbow and drowned valley lakes. The Fly River channel is to a large extent a fish migration route and a refuge during dry periods. Subsistence and commercial fisheries target mainly the off-river water bodies because of their high productivity. Although the vegetated floodplain sites may not be inundated over the whole year, fish invade rapidly into the alluvial plain at higher water levels because of the abundance of food sources.

Animals at lower trophic levels, such as aquatic invertebrates, and juvenile stages of fish are known to have a high sensitivity to dissolved copper. According to Moore and Ramamoorthy (1984), sensitivity to copper is inversely related to the age or size of an animal. A decrease in the abundance of macroinvertebrates, which are at the base of the food web, may lead to a decrease in the overall fish population. Copper is a strong toxicant to aquatic organisms but does not biomagnify in the food chain. End consumers like carnivorous fish show a much lower copper body burden than benthic invertebrates like burrowing mayfly larvae which feed directly from the contaminated substrate (Karbe 1988).
The average copper concentration in mixed waters of the inner floodplain is around 10 μg/l; the Fly River water has about 17 μg/l of copper. These are concentrations which may be harmful to biota. The applicable United States Environmental Protection Agency (USEPA) "Water Quality Criteria for the Protection of Aquatic Organisms and Uses" (1986) recommends a maximum value of 6.5 μg/l (hardness 50 mg/l as $CaCO_3$, unfiltered water) for the "chronic" 4-day average concentration, and 9.2 μg/l for the "acute" 1-hour average concentration. The Canadian Water Quality Guidelines (1987) are even more stringent (Table 17).

Dissolved copper levels detected in mixed floodplain waters of the present study are in the concentration range which is reported in the literature to be harmful to sensitive freshwater aquatic organisms. Clements et al. (1989) found a significant decrease in total aquatic insect abundance after 4 days of exposure to 6 μg/l of copper in an outdoor experimental stream. The most sensitive species, a chironomid larva (midges, Diptera), was eliminated at 13 μg/l copper after 10 days. Moore and Winner (1989) also found out that benthic chironomid and mayfly larvae show a high sensitivity to dissolved copper.

Table 3-1. Summary – Guidelines for Freshwater Aquatic Life

Parameter	Guideline	Comments
Inorganic parameters		
Aluminum[1]	0.005 $mg\cdot L^{-1}$	pH<6.5; $[Ca^{2+}]$<4.0 $mg\cdot L^{-1}$; DOC<2.0 $mg\cdot L^{-1}$
	0.1 $mg\cdot L^{-1}$	pH≥6.5; $[Ca^{2+}]$≥4.0 $mg\cdot L^{-1}$; DOC≥2.0 $mg\cdot L^{-1}$
Antimony	ID[2]	
Arsenic	0.05 $mg\cdot L^{-1}$	
Beryllium	ID	
Cadmium	0.2 $\mu g\cdot L^{-1}$	Hardness 0-60 $mg\cdot L^{-1}$ ($CaCO_3$)
	0.8 $\mu g\cdot L^{-1}$	Hardness 60-120 $mg\cdot L^{-1}$ ($CaCO_3$)
	1.3 $\mu g\cdot L^{-1}$	Hardness 120-180 $mg\cdot L^{-1}$ ($CaCO_3$)
	1.8 $\mu g\cdot L^{-1}$	Hardness >180 $mg\cdot L^{-1}$ ($CaCO_3$)
Chlorine (total residual chlorine)	2.0 $\mu g\cdot L^{-1}$	Measured by amperometric or equivalent method
Chromium	0.02 $mg\cdot L^{-1}$	To protect fish
	2.0 $\mu g\cdot L^{-1}$	To protect aquatic life, including zooplankton and phytoplankton
Copper	2 $\mu g\cdot L^{-1}$	Hardness 0-60 $mg\cdot L^{-1}$ ($CaCO_3$)
	2 $\mu g\cdot L^{-1}$	Hardness 60-120 $mg\cdot L^{-1}$ ($CaCO_3$)
	3 $\mu g\cdot L^{-1}$	Hardness 120-180 $mg\cdot L^{-1}$ ($CaCO_3$)
	4 $\mu g\cdot L^{-1}$	Hardness >180 $mg\cdot L^{-1}$ ($CaCO_3$)
Cyanide	5.0 $\mu g\cdot L^{-1}$	Free cyanide as CN
Dissolved oxygen	6.0 $mg\cdot L^{-1}$	Warm-water biota – early life stages
	5.0 $mg\cdot L^{-1}$	– other life stages
	9.5 $mg\cdot L^{-1}$	Cold-water biota – early life stages
	6.5 $mg\cdot L^{-1}$	– other life stages
Iron	0.3 $mg\cdot L^{-1}$	
Lead	1 $\mu g\cdot L^{-1}$	Hardness 0-60 $mg\cdot L^{-1}$ ($CaCO_3$)
	2 $\mu g\cdot L^{-1}$	Hardness 60-120 $mg\cdot L^{-1}$ ($CaCO_3$)
	4 $\mu g\cdot L^{-1}$	Hardness 120-180 $mg\cdot L^{-1}$ ($CaCO_3$)
	7 $\mu g\cdot L^{-1}$	Hardness >180 $mg\cdot L^{-1}$ ($CaCO_3$)
Mercury	0.1 $\mu g\cdot L^{-1}$	
Nickel	25 $\mu g\cdot L^{-1}$	Hardness 0-60 $mg\cdot L^{-1}$ ($CaCO_3$)
	65 $\mu g\cdot L^{-1}$	Hardness 60-120 $mg\cdot L^{-1}$ ($CaCO_3$)
	110 $\mu g\cdot L^{-1}$	Hardness 120-180 $mg\cdot L^{-1}$ ($CaCO_3$)
	150 $\mu g\cdot L^{-1}$	Hardness >180 $mg\cdot L^{-1}$ ($CaCO_3$)
Nitrogen		
Ammonia (total)	2.2 $mg\cdot L^{-1}$	pH 6.5; temperature 10°C (see Table 3-12)
	1.37 $mg\cdot L^{-1}$	pH 8.0; temperature 10°C
Nitrite	0.06 $mg\cdot L^{-1}$	
Nitrate		Concentrations that stimulate prolific weed growth should be avoided
Nitrosamines	ID	
pH	6.5-9.0	
Selenium	1 $\mu g\cdot L^{-1}$	
Silver	0.1 $\mu g\cdot L^{-1}$	
Thallium	ID	
Zinc[3]	0.03 $mg\cdot L^{-1}$	
Physical parameters		
Temperature		Thermal additions should not alter thermal stratification or turnover dates, exceed maximum weekly average temperatures, and exceed maximum short-term temperatures (see Section 3.2.3.1.1)
Total suspended solids	increase of 10.0 $mg\cdot L^{-1}$	Background suspended solids ≤100.0 $mg\cdot L^{-1}$
	increase of 10% above background	Background suspended solids >100.0 $mg\cdot L^{-1}$

[1] Concentrations of heavy metals reported as total metal in an unfiltered sample.
[2] ID = insufficient data to recommend a guideline.
[3] Tentative guideline.

Table 17. Canadian Guidelines for the protection of freshwater aquatic life (CCREM 1987).

Burrowing mayfly larvae of the genus *Plethogenesia* (together with *Macrobrachium* freshwater prawns) were the dominant constituents of the macroinvertebrate fauna in terms of biomass in the Fly River (OTML 1987). Both are important food items for the local fishes. Toxicity of particulate copper in mine wastes on mayflys has been proven by bioassays undertaken by OTML in 1988 (OTML 1989).

Williams et al. (1991) report a 50% mortality after three days of exposure of the extremely sensitive tropical freshwater shrimp *Caridina sp.* to 4 µg/l copper. Most studies on copper toxicity consider the free ionic species as the most bioavailable form, and copper complexed with naturally derived dissolved organic carbon (DOC) as much less toxic or even non-toxic (e.g. Flemming and Trevors 1989; Meador, 1991). Recent scientific work (Winner and Owen, 1991), however, has provided further evidence that dissolved organic carbon also may enhance copper toxicity. The authors used the alga *Chlamydomonas reinhardtii* to test the bioavailability and toxcity of organically complexed copper in water from a freshwater pond.

Toxic effects of dissolved copper on alga deflagellation and population growth were observed at values above 12.2 µg/l in natural waters with DOC concentrations varying from 5 to 14 mg/l.
They found a positive correlation between DOC and copper on alga toxicity and concluded that labile organic copper complexes may be responsible for this effect, demonstrating that a simple relationship between DOC concentration and copper toxicity cannot be established. OTML (1994) has commissioned toxicity tests with the freshwater green alga *Chlorella protothecoides*. No reduction in algal growth rate occurred at dissolved copper concentrations of 12 µg/l, which was the highest concentration used in the tests. Since copper values measured both during the present study and by OTML in waters of the Fly River and its floodplain were much higher than 12 µg/l, it appears justified to repeat the tests with copper concentrations of up to 50 µg/l in order to obtain more information on the species' sensitivity.

8. CONCLUSIONS

The following conclusions can be drawn from the informations gathered in the present study:

1. Of the trace metals contained in the Ok Tedi mine waste, copper is of main environmental concern because of its strong enrichment above background (about twentyfold) and its relatively high geochemical mobility.

2. The discharge of mining residues into the Ok Tedi/Fly River system leads to a substantial deposition of copper-rich material in the Middle Fly River floodplain, although most of the mining wastes carried as suspended load finally reach the delta. Areas of standing water and vegetated parts of the floodplain play an important role in the recruitment of fish and primary productivity. Hence, this part of the fluvial ecosystem is particularly sensitive to mine-induced changes in the local environment.

3. 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 sediments, which is responsible for reducing conditions, only copper in the uppermost layer (few centimeters) of bottom sediments may become dissolved. When copper-rich sediment is permanently covered by water, mobilization and bioavailability of the metal, except to bottom-dwelling invertebrates, is low. However, when mine-derived sediments settle on extensive areas of the vegetated floodplain, the conditions are quite different. Chemical and biological factors facilitate the mobilization of copper. Even a thin layer of copper-rich material may have a negative ecological impact.

4. The way in which copper affects the aquatic community is not clear. Dissolved organic carbon substances, which are present in high concentrations in the Fly River system, complex the metal and keep it in solution. Little is known about the bioavailablity and toxicity of these organic copper species. Recent research has shown that these compounds may exert toxic effects comparable to the free ionic copper species.

The most sensitive biota to dissolved Cu are juvenile stages of fish and aquatic invertebrates which form the base of the trophic web. Populations of larger fish species will only show a response after their reproduction cycle has been completed. Measurable negative effects may develop with a considerable time lag.

5. The copper pollution in the Fly River floodplain is of persistent nature. Even after the cease of deposition of copper-rich suspended load, the environmentally detrimental effects will continue to exist. There is no mechanism to "detoxify" the alluvial plain. Erosion processes will only 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. The mine-derived material deposited in oxbow and drowned valley lakes, and in the floodplain swamps, will remain and may be covered by less contaminated sediments carried by the Fly River in the post-mining period. However, when sedimentation rates in the floodplain return to pre-mining values, it may take centuries until copper-rich sediment deposits are sealed by an unpolluted sediment cover.

6. The possibilities to mitigate the detrimental effects of the Ok Tedi mine wastes on the Ok Tedi/Fly River system are limited when the construction of tailings and waste retention facilities is deemed uneconomical by the mining company. In order to reduce the amount of metal discharged into the environment, the recovery of copper in the mill, currently at around 85%, could be increased. This may be possible through installation of additional flotation cells, re-flotation of tailings, increase of the residence time of ore in the cells, improved control of grain size in the flotation process, sulfidization of non-sulfide ores, and other optimisation strategies. Thus, a recovery of 90% may be achievable. The cut-off grade for waste rock could be lowered which would also result in less copper reaching the fluvial environment. Measures of this kind are most probably not viable from an economic point of view; however, as an environmental protective action, they should be investigated thouroughly by the mining company.

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ANNEX

Tables A1 to A6

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
1/15.2.I Kinda channel 0-3.5 cm	8800	18600	8200	6000	86800	48700	401	113	35	18	0.2	nd	0.2	10	77	1	19	50	199	4300	49	25	397	149	19	nd	nd
20-60 µm	11600	14300	7300	7200	74100	38100	432	101	37	4	0.2	nd	0.2	4	60	1	16	41	139	3400	43	22	1115	178	14	1.2	600
60-100 µm	11100	12900	8200	11200	70100	39800	465	99	43	4	0.2	nd	0.2	4	60	1	16	48	127	2900	34	20	375	203	13	nd	nd
3/15.2.IV Lower Fly isl. 26-31 cm	9300	15900	8800	27000	80100	55300	984	163	90	26	0.2	nd	0.4	19	68	3	33	70	186	3700	39	16	474	281	16	nd	nd
20-60 µm	12000	13900	8200	28900	71800	46000	563	97	72	6	0.2	nd	0.2	9	60	4	16	46	151	3600	44	25	356	285	13	nd	nd
60-100 µm	10400	10900	8800	28500	66600	62000	731	123	60	6	0.2	nd	0.2	8	69	1	22	52	212	4400	37	20	358	259	13	nd	nd
> 200 µm	9600	9000	13300	16900	66000	55400	804	93	28	4	0.2	nd	0.3	7	99	1	31	99	133	3200	47	20	385	235	15	nd	nd
4/15.2.III Lower Fly bank 27-31cm	9300	17800	8700	31900	82300	53200	754	115	77	22	0.2	nd	0.2	13	73	1	22	54	182	4100	45	18	404	257	16	nd	nd
20-60 µm	11900	13100	8000	24400	71000	40300	501	90	30	11	0.2	nd	0.2	4	56	1	15	41	127	3100	29	17	307	226	13	nd	nd
60-100 µm	11700	14700	9300	25300	75500	43200	511	97	24	17	0.3	nd	0.2	6	59	2	17	55	127	2900	27	17	348	257	14	1.1	900
1/16.2.I Strickland 0-2.5 cm	8900	15300	8600	21900	76700	51100	824	123	40	14	0.2	nd	0.3	8	77	1	22	58	183	4300	59	22	398	209	17	1.8	3900
20-60 µm	11400	13300	7700	21500	69700	37900	563	97	28	6	0.2	10+	0.3	8+	58	1	16	46	133	3300	40	21	761	217	13	nd	nd
60-100 µm	10600	14100	8300	22200	71700	39600	585	100	24	5	0.2	nd	0.2	5	59	1	17	52	128	2800	34	19	426	240	14	nd	nd
1/16.2.II 2.5-5 cm	9100	15800	8500	19900	74700	51200	818	119	42	20	0.2	20+	0.2	16+	76	1	22	62	190	4100	49	18	361	195	15	nd	nd
1/16.2.III 30-33 cm	9000	17400	7300	24800	77900	49100	777	118	40	13	0.2	nd	0.3	13	70	1	21	52	181	4200	61	24	380	209	16	nd	nd
SS1/16.2. susp. solids Strickland	9800	20100	8900	30200	94600	45400	640	127	38	39	0.2	nd	0.2	4	80	1	21	55	207	4100	39	25	399	255	20	nd	nd
2/16.2.I Strickl/Fly junct. 0-5cm	8800	16100	8100	34900	72200	51000	833	165	55	22	0.2	nd	1.0	13	74	1	29	64	194	4100	54	19	383	237	14	nd	nd
2/16.2.V 34.5-39.5 cm	8900	16700	8000	32000	75500	51300	765	143	40	16	0.2	nd	0.2	16	74	1	31	66	196	4200	54	15	423	240	14	nd	nd
20-60 µm	10900	14300	8000	29100	71200	47700	594	102	23	4	0.2	nd	0.8	12	70	1	18	49	170	4200	66	32	338	242	15	nd	nd
60-100 µm	10300	11400	9300	31600	63800	52900	667	106	22	14	0.2	nd	0.2	4	69	1	19	55	179	4000	33	21	276	236	14	nd	nd
100-200 µm	10600	10800	10900	35100	63400	48800	660	95	23	10	0.2	nd	0.9	9	84	2	23	76	137	3300	42	23	307	250	14	1.1	500
> 200 µm	15500	9700	10900	19700	62800	54500	697	95	27	18	0.2	nd	18.2	9	88	2	29	106	109	2700	126	24	382	223	14	nd	nd
3/16.2.IV Fly R.bed/Obo 41-43 cm	7100	13200	8000	13300	92900	68200	715	173	48	16	0.2	nd	0.2	9	64	1	25	34	219	4800	110	31	390	240	19	nd	nd
20-60 µm	9600	10600	7300	12200	72400	64400	698	121	31	4	0.2	nd	0.2	4	53	1	22	24	229	5800	155	43	554	254	15	nd	nd
60-100 µm	10600	10300	7400	11600	64900	52400	592	98	19	4	0.2	nd	0.2	4	38	1	19	22	188	4800	66	31	334	241	13	nd	nd
100-200 µm	11200	9400	6500	12100	59500	41200	446	65	25	7	0.2	<2+	2.7	3+	47	1	16	43	89	2400	74	19	373	253	10	nd	nd

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
1/27.3.V Fly bank Xs. 8-10 cm	4200	12200	6700	7700	102400	32300	136	129	51	22	0.7	16+	<.3	4+	62	5	11	26	156	4500	83	28	346	147	21	nd	nd
1/27.3.III Fly bank Xs. 27-29 cm	5600	14600	6700	4900	100000	41900	164	129	32	16	<.4	nd	0.3	<4	56	<2	11	25	147	4200	80	27	409	141	19	0.83	<100
2/27.3.V Fly bank Xs. 30-32.5 cm	5300	13000	6700	5900	94400	67300	289	147	40	19	<.4	nd	<.3	4	54	<2	17	27	157	4100	86	28	390	148	20	1.31	100
4/16.2.II L.Dav chan./Fly 3-5 cm	5300	13300	6900	6200	83600	53300	461	113	39	14	0.6	nd	<.3	5*	57	<2	15	26	148	4300	79	26	340	154	19	1.6	600
4/16.2.IV 18-20.5 cm	5000	12800	7200	6800	92000	64400	760	124	32	21	<.4	nd	0.4	6*	58	<2	14	24	150	4400	82	27	364	153	20	nd	nd
4/1.11.III L. Dav.chan. 20.5-22cm	2500	11800	4900	5300	106200	30600	185	145	36	14	0.2	nd	0.5	9	87	1	13	32	208	4700	80	32	335	127	20	nd	nd
1/30.3.III L. Dav. chan. 26-28 cm	4100	12900	6200	5800	95700	28300	122	116	35	14	0.6	nd	<.3	<4	64	<2	7	26	155	4400	82	25	321	133	20	1.29	400
1/19.2.II L.Daviambu E 2.5-5 cm	2900	11600	4000	5200	90300	28800	221	92	37	11	0.3	nd	0.2	4	66	3	10	27	208	4200	90	28	271	109	18	4.8	600
1/19.2.III 5-7.5 cm	2300	8900	3500	5200	87500	34900	250	69	36	9	0.2	3+	0.2	3+	60	1	11	31	188	3700	82	28	262	104	18	nd	nd
1/1.11.I L.Daviambu N 0-2.5cm	1200	3600	2300	5700	59600	23900	197	281	27	11	0.2	nd	0.1	2	61	3	17	38	130	2300	42	15	261	87	12	nd	nd
2/1.11.II L.Daviambu N 2.5-5cm	1200	5100	2400	4500	71100	18200	121	139	35	10	0.2	nd	0.2	4	54	1	12	33	166	2600	51	20	199	71	14	nd	nd
2/1.11.III 14-16.5 cm	100	100	500	nd	6500	38600	442	132	22	22	0.2	nd	0.1	7	20	2	16	20	38	300	7	5	114	123	3	nd	nd
5/30.3.I L. Daviambu N 0-3 cm	2500	8800	4200	8000	73600	37800	270	183	55	18	<.4	nd	0.5	5	44	3	15	24	130	2500	52	18	263	102	15	nd	nd
> 200 µm	900	3400	1900	6000	41100	21100	157	193	35	12	<.4	nd	0.4	4*	30	<2	19	21	79	1200	30	12	116	59	9	nd	nd
5/30.3.III L. Dav. N 19.5-22 cm total																										49.6	3000
2/1.4.I L. Daviambu N 0-2.5 cm	1200	3500	2100	8200	40100	25600	276	220	71	19	<.4	nd	0.8	10*	27	3	16	18	70	1200	28	11	167	74	8	nd	nd
2/1.4.II L. Daviambu N 2.5-5 cm	2100	7400	2400	6600	49200	23400	288	226	74	21	<.4	nd	<.3	5	28	2	15	18	85	1400	30	11	198	94	9	nd	nd
7/24.10.III L.Dav. S 27.5-30 cm	4300	12200	5500	3700	90400	31500	201	98	41	35	0.4	<2+	0.4	2+	75	2	11	37	174	5600	101	28	302	111	18	nd	nd
3a/30.3.I L. Daviambu W 0-2 cm. t	1100	2300	1200	3500	31500	10100	86	77	21	5	<.4	nd	0.4	<4	22	<2	4	16	50	1000	22	13	122	48	8	14.5	2600
3a/30.3.IV L. Daviambu W 22-24 cm	5100	10600	6200	5100	90900	58900	1110	115	18	15	<.4	nd	0.5	6	63	<2	10	21	134	4500	76	24	328	118	19	nd	nd

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
3b/30.3.I L. Daviambu W 0-3 cm. t	1300	2700	1400	5500	30900	14600	92	104	23	9	<.4	nd	<.3	<4	23	2	6	17	43	1000	23	11	139	59	7	16.7	3000
3b/30.3.III L. Dav. W 22-24 cm t.	700	1700	1100	7700	19400	16900	217	29	13	<4	<.4	nd	<.3	<4	18	<2	7	13	43	600	16	9	163	85	6	37.8	4200
3b/30.3.V L. Daviambu W 39-41 cm	5500	13000	6700	4600	84500	34800	284	142	29	13	0.4	nd	<.3	4	61	<2	12	24	143	4700	81	24	321	126	18	2.1	700
4/30.3.IV L. Dav. W 31-33 cm. t	750	1600	1000	6700	21700	18500	173	45	15	5	<.4	nd	<.3	<4	17	<2	6	12	33	650	15	7	104	59	5	40.1	3000
3a/1.4.I L. Daviambu C 0-2 cm	2400	8200	3200	6200	80400	32400	247	187	54	18	<.4	nd	<.3	<4	47	3	13	29	109	2500	44	18	304	98	13	nd	nd
3a/1.4.IV L. Daviambu C 18-20 cm	6000	14000	5700	4100	88600	30000	161	115	19	16	<.4	nd	<.3	<4	53	<2	6	19	127	4100	80	23	315	107	16	nd	nd
3b/1.4.I L. Daviambu C 0-2 cm. t.	1600	5700	2400	5500	70800	20900	196	148	31	13	<.4	nd	<.3	<4	47	<2	11	27	100	2300	46	17	255	78	14	9.13	1800
2/28.10.VI Fly R. bank 51-54 cm	5600	15100	7700	6600	102500	47000	285	143	58	11	0.2	8+	0.1	4+	81	1	11	44	209	7100	122	38	360	173	22	nd	nd
20-60 µm	9200	12200	5800	8100	63300	41600	285	103	68	30	0.3	nd	0.1	2	59	2	8	14	131	5100	94	27	388	217	12	nd	nd
60-100 µm	9600	11200	6000	8800	54600	35800	301	97	54	30	0.2	nd	0.1	2	49	1	8	27	112	4700	71	23	390	226	11	nd	nd
100-200 µm	9200	13900	5300	11700	52900	30200	320	95	89	29	0.7	nd	0.1	5	39	4	8	29	97	3400	56	22	453	263	10	nd	nd
2/31.10.IV L. Pangua N 7.5-10 cm	1300	5200	2200	4000	66500	21100	192	136	50	18	0.5	nd	0.9	6	51	2	18	35	187	2700	50	26	179	72	14	nd	nd
2/31.10.V 16.5-18.5 cm	3700	13000	6500	4000	64700	31500	193	101	39	14	0.3	3+	0.1	2+	80	1	9	18	197	6900	112	26	289	101	13	nd	nd
3/31.10.II L. Pangua W 2.5-4.5 cm	5100	18300	6800	5500	85300	32900	184	116	30	25	0.9	nd	1.9	7	82	2	9	25	198	6500	108	31	372	151	17	nd	nd
3/31.10.III 16.5-17.5 cm	4800	15800	7400	5200	89100	33800	222	117	31	2	0.4	nd	0.1	2	82	1	8	35	196	6600	111	31	344	148	17	nd	nd
4/31.10.II L. Pangua C 14.5-16.5cm	4300	16100	7100	5400	109900	60400	324	118	57	15	0.2	nd	0.2	4	68	1	16	35	224	4200	89	22	325	162	23	3.0	5200
4/31.10.III 28.5-30.5 cm	4200	14100	6400	4300	88500	61100	334	135	59	31	0.2	nd	0.6	2	80	5	21	35	221	5400	112	31	315	131	18	nd	nd
5/31.10. L. Pangua SE 10-12.5 cm	3300	12400	6400	6400	93900	64200	272	118	41	18	<.4	nd	<.3	5*	60	3	15	27	174	3900	75	26	295	125	19	nd	nd
5/31.10. 16-18 cm	3500	12900	6600	5900	96900	64400	352	117	40	13	0.4	nd	<.3	4*	63	<2	18	27	176	4100	77	26	309	129	20	nd	nd
5/31.10. 23-25 cm	3400	13300	6900	5900	100600	67800	320	120	45	12	0.4	nd	<.3	5*	66	2	18	28	195	4200	79	28	302	129	21	2.6	700
5/31.10.III 28.5-30.5 cm	3800	17400	7700	5000	112400	67600	312	121	43	12	0.2	nd	0.3	14	72	1	22	37	245	4200	83	22	293	153	23	3.15	4500
5/31.10.V 42.5-44.5 cm	3500	14400	7100	5200	94300	70300	355	148	67	45	0.3	nd	0.1	2	85	4	22	41	243	5800	107	31	310	137	19	nd	nd
1/4.4.IV L. Pangua NE 23-28 cm	3700	10500	5500	7700	89600	42500	220	198	58	23	<.4	nd	0.3	5	52	<2	22	27	146	3400	77	25	311	132	18	7.84	3200
1/4.4.VI L. Pangua NE 33-38 cm	5400	13300	6900	8300	95000	48800	723	122	40	19	<.4	nd	0.4	<4	53	<2	17	25	139	4100	84	27	375	160	19	2.55	1700

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
2/4.4.V L. Pangua NW 32-34 cm	3900	15100	6900	6300	94500	33500	203	129	36	14	<.4	nd	<.3	2*	56	<2	9	20	135	4300	82	23	314	108	19	2.21	200
8/28.10.I Swiss Lake 0-2.5 cm	4500	12500	7300	6500	89500	32600	154	148	60	21	0.2	nd	0.1	2	84	2	8	33	201	5200	80	20	379	165	15	nd	nd
8/28.10.II 2.5-5 cm	5200	12400	7300	6700	108900	31600	149	133	31	7	0.7	3+	0.1	1+	89	1	9	23	188	5600	89	26	417	185	12	nd	nd
10/28.10.II Swiss Lake 16-18.5 cm	5400	14300	6900	9500	94100	41100	215	117	60	18	0.4	nd	<.3	<4	59	3	10	23	153	4500	80	27	350	170	20	nd	nd
3/19.2.II Tamu Cr./Fly jct.3-5 cm	5400	13500	7100	7700	92600	46300	247	116	45	16	<.4	nd	<.3	<4	60	<2	15	26	152	4600	82	27	351	166	20	nd	nd
3/19.2.III 13-15 cm	5400	13100	7200	8700	93300	47900	408	110	37	14	0.4	nd	<.3	<4	58	<2	13	24	150	4600	85	27	357	171	20	nd	nd
8/30.10.I Tamu Cr.0-2.5cm < 200µm	500	1800	1200	16500	27700	15500	355	70	48	9	<.4	nd	<.3	<4	27	3	5	17	85	1000	22	12	100	114	9	24.7	3300
8/30.10 II 2.5-5 cm < 200 µm	300	900	900	16800	20900	14400	260	44	31	7	<.4	nd	<.3	<4	25	2	5	16	78	700	17	11	88	112	8	29.4	3200
5/30.10.I Lake Tamu II 0-4 cm	2200	9100	3400	6800	79700	42100	398	194	157	46	0.5	nd	0.8	2	77	5	21	44	154	4600	72	28	253	118	16	nd	nd
100-200 µm	2600	7100	2400	6800	50700	34500	618	146	266	42	0.2	nd	1.8	12	61	4	19	38	101	3300	56	24	208	104	12	nd	nd
3/30.10.I Lake Tamu I 0-3 cm	1300	4400	2000	3500	52100	20100	151	176	49	7	0.5	nd	0.1	6	72	1	15	52	175	4400	58	25	185	57	12	nd	nd
6/28.10.II floodpl./Kibuz 12-14cm	5400	15000	7200	7800	96600	54800	712	117	60	21	<.4	nd	<.3	<4	60	2	15	27	151	4400	79	27	380	174	20	1.1	1000
1/20.2.I Bai Lagoon NW 0-2.5 cm	1400	4600	2500	8000	41600	17300	146	114	84	23	0.2	nd	0.2	4	22	5	7	16	93	1300	23	16	142	120	9	13.5	2900
3/20.2.II Bai Lagoon SW 1-5.5 cm	1100	2900	1600	9200	46200	17100	140	99	56	9	0.2	nd	0.2	4	29	3	5	16	80	1600	31	14	148	108	9	nd	nd
1/5.4.V Bai Lag. C 23.5-27 cm	1100	6000	2900	10900	61300	25700	181	85	26	10	0.5	nd	<.3	<4	45	<2	5	20	108	2400	49	19	181	110	13	25.4	2800
4/20.2.II Bai Lagoon C 3-5 cm	2100	8400	4600	7300	91300	28400	224	170	54	18	0.2	nd	0.2	7	49	2	14	32	169	3000	52	23	261	139	16	nd	nd
4/20.2.III 5-7 cm	700	3900	1900	12600	47500	28500	243	61	30	7	0.2	nd	0.2	4	32	1	7	20	105	1700	39	20	185	148	10	nd	nd
4/20.2.IV 11-14 cm	1800	9100	4400	6300	100600	25300	195	126	28	15	0.2	nd	0.2	4	59	1	10	29	171	3600	73	28	280	134	19	nd	nd
4/20.2 V 14-16 cm	1300	6600	2900	12800	51000	31300	307	191	47	11	0.2	nd	0.6	4	37	2	7	21	136	2000	46	23	188	154	12	nd	nd

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
2/5.4.I Bai Lag. E 0-2 cm	3800	15000	6200	6900	95500	37500	212	159	75	28	<.4	nd	<.3	13	54	4	10	25	148	3300	65	23	327	132	18	nd	nd
2/5.4.II Bai Lag. E 2-4 cm	3100	13400	6900	6900	108200	33300	176	154	32	27	<.4	nd	0.3	<4	65	2	11	27	161	4300	80	26	317	131	21	nd	nd
2/5.4.III Bai Lag. E 23-25 cm	2700	13000	5200	7100	111900	23300	124	192	25	18	<.4	nd	<.3	0.4*	64	<2	6	25	148	4100	85	21	349	122	20	4.82	300
5/20.2. Bai Lag. chan. 43-45.5 cm	4900	14100	7000	12300	95200	41700	257	124	43	11	0.4	nd	0.3	<4	57	11	12	24	150	4300	75	25	359	178	19	2.6	800
6/20.2.II Kemea Lagoon C 2-4 cm	2600	11300	4400	7100	92300	34500	243	144	63	17	0.2	nd	0.2	4	52	4	17	25	165	3100	54	25	254	142	16	nd	nd
3/5.4.X Kemea channel 36-41 cm t.																										42.7	2200
4/5.4.V Kemea Lag. W 14.5-17 cm	1200	8200	4000	3700	116500	41500	193	128	40	23	<.4	nd	0.3	<4	55	<2	12	24	175	4800	85	45	291	78	22	0.79	<100
5/5.4.IV Kemea L. E 17.5-21 cm t.																										34.8	4600
1/7.4.V Fly R. bank 33-35 cm	7000	18500	7400	7500	102100	35700	212	122	69	29	<.4	nd	<.3	5	58	3	9	24	151	4100	78	26	415	174	19	1.06	200
1/7.4.V < 2 µm	8300	16700	8200	9100	116300	39400	218	134	54	38	<.4	nd	<.3	<4	74	<2	9	37	171	4500	90	27	365	152	26	nd	nd
2/7.4.III L. Kongun N 8.5-11 cm	4000	15300	6600	5700	111200	33300	163	188	54	29	<.4	nd	<.3	<4	66	<2	10	30	177	3900	77	27	442	128	21	nd	nd
3/7.4.V Kongun Cr. M 30-32 cm	4800	14300	7300	6500	110400	38200	182	130	44	24	0.5	nd	<.3	<4	66	2	11	27	168	4800	90	28	370	155	23	nd	nd
4/7.4.III Kongun Cr. S 19-21.5 cm	4800	14500	6600	6400	103200	33900	155	112	37	16	<.4	<2+	<.3	2	58	<2	8	23	143	4200	83	24	369	142	21	0.83	<100
1/23.2.I L. Boss.SW creek 0-2.5cm	1900	5200	1800	2400	95200	21200	97	133	44	8	0.2	nd	0.2	4	80	1	9	46	239	4000	58	18	215	74	16	nd	nd
2/23.2.I L. Boss. SW creek 0-7 cm	2200	6700	2000	3700	94000	27200	128	167	50	21	0.2	nd	1.4	4	82	2	12	46	207	4500	59	23	221	82	16	nd	nd
4/23.2. L. Bosset island	1600	6100	1900	1500	107200	21400	46	62	20	21	0.2	nd	0.2	4	120	1	12	41	294	6800	102	24	215	80	16	nd	nd
20-60 µm	200	500	200	400	7000	2100	22	8	5	4	0.2	nd	0.2	4	28	1	1	2	26	2400	53	6	40	15	3	nd	nd
60-100 µm	200	800	200	400	9000	2900	17	14	5	4	0.2	nd	0.2	4	34	1	1	3	39	1000	16	4	32	12	6	nd	nd
5/23.2.III L. Bosset SW 5-7.5 cm	2200	10300	4200	4400	114800	27600	147	181	47	14	0.2	nd	0.2	5	73	1	14	43	242	3600	59	35	249	116	22	nd	nd
5/23.2.IV 7.5-10 cm	2600	11000	5000	5600	130500	29300	176	180	53	22	0.2	nd	0.2	6	75	1	16	48	274	4000	67	29	294	137	25	nd	nd

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
1/24.2.II L. Bosset NW 5-7.5 cm	1700	6000	2200	3500	103700	28600	92	156	67	32	0.5	nd	0.2	4	69	5	14	39	255	3200	47	25	191	87	16	nd	nd
1/24.2.III 7.5-10 cm	1700	4700	2800	4600	102000	27000	131	224	55	21	0.8	nd	<.3	<4	61	3	12	36	195	3300	52	24	225	85	19	4.7	1000
3/11.4.II L. Bosset NW 2-4 cm	2000	7100	3400	4700	92600	31700	140	216	60	25	<.4	nd	<.3	11	57	3	12	33	165	2600	48	18	244	85	16	nd	nd
3/11.4.III L. Bosset NW 4-6 cm	1700	5700	2600	3900	85600	25100	116	255	53	23	<.4	nd	<.3	<4	59	2	10	60	168	2800	48	18	256	75	17	nd	nd
3/11.4.X L. Bosset NW 6-8 cm	3900	7200	3900	4000	109900	27600	93	227	44	23	<.4	nd	<.3	4	58	<2	11	35	176	3200	58	25	291	82	19	nd	nd
3/11.4.V L. Bosset NW 18-20 cm	2300	7300	2800	2700	61000	20100	101	254	51	32	0.4	<2+	0.7	4+	66	<2	10	39	198	3400	67	13	247	59	12	nd	nd
3/11.4.XI L. Bosset NW 30-42 cm																										41.5	2400
2/24.2.II L.Bosset N 2.5-5 cm	1200	3000	2000	4500	66100	18600	111	159	45	11	0.4	nd	<.3	<4	42	<2	9	32	134	2300	40	20	174	70	15	6.1	1300
3/24.2.III L. Bosset N 9-11 cm	2000	6900	4000	4800	92000	36500	161	269	70	17	0.2	nd	0.2	6	65	3	27	42	245	3200	58	26	264	110	18	nd	nd
3/24.2. 10.5-12.5 cm	1500	5900	3500	4800	82700	27100	131	173	44	10	0.4	nd	0.3	4	50	<2	14	29	171	2800	52	21	240	85	18	5.4	1200
3/24.2.IV 24.5-26.5 cm	1500	6100	3200	5300	85900	25000	150	156	32	13	0.2	nd	0.2	4	55	1	14	35	221	2900	59	30	251	101	17	10.3	2300
4/24.2.IV L. Bosset C 13-16 cm	2100	10000	4600	4800	96400	30000	156	167	52	18	0.2	nd	0.2	4	62	1	15	36	227	3100	61	31	257	119	20	nd	nd
2/11.4.I L. Bosset C 0-4.5 cm	2600	10500	4700	4600	97900	32200	146	154	68	26	<.4	nd	<.3	2.4*	59	4	10	27	178	3100	65	24	285	103	20	5.76	800
2/11.4.I < 2 µm	2100	9800	4700	5500	103800	32600	169	168	64	36	<.4	nd	0.3	11	65	5	10	28	172	3300	60	20	268	102	19	nd	nd
2/11.4.II L. Bosset C 4.5-6.5 cm	2200	8800	4400	5300	92800	25900	124	185	66	23	<.4	nd	<.3	<4	56	<2	10	31	181	2900	59	21	290	94	19	nd	nd
2/11.4.V L. Bosset C 34-36 cm	2100	10900	4400	4400	108400	23600	105	144	31	22	<.4	nd	<.3	0.8*	62	<2	7	27	151	3800	78	24	313	97	22	3.61	400
4/11.4.IV L. Boss.E 23-25 cm <2µm	3900	12900	6700	8000	113100	73800	163	124	48	21	<.4	nd	0.3	<4	71	2	10	27	201	4100	88	27	322	117	25	nd	nd
1/25.2.VI Boss.chan/Fly 28-30 cm	1300	5700	2300	3500	83500	15900	91	128	44	15	0.2	nd	0.3	4	60	1	10	54	183	3100	61	40	275	78	19	nd	nd
1/9.4.III Kai Lag. SW 15.5-18 cm	1700	8100	3800	3900	102000	22600	94	344	52	28	<.4	nd	0.8	1*	73	<2	8	35	214	3200	64	26	263	82	22	nd	nd
1/9.4.V Kai Lagoon SW 33-35.5 cm	2100	7200	3300	4300	80500	32600	120	381	44	24	<.4	nd	<.3	7	58	<2	25	44	174	2600	59	23	225	79	17	nd	nd
2/9.4.IV Kai River S 18-20.5 cm	4300	14700	6200	6100	110200	30200	109	123	44	19	<.4	8+	<.3	2+	62	<2	7	25	165	4200	89	28	387	138	23	1.44	300

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
3/9.4.II Kai Lagoon N 5-7 cm	3300	13300	6000	5800	112800	35900	134	142	49	28	<.4	nd	<.3	<4	71	<2	8	26	204	4500	87	29	305	119	24	nd	nd
3/9.4.III Kai Lagoon N 15-17 cm	2700	13300	5000	4900	110700	33600	124	125	37	20	<.4	nd	0.3	<4	67	<2	7	22	197	4000	89	29	306	109	22	1.44	100
3/9.4.III < 2 µm	2300	14800	6000	5600	125300	39300	131	142	37	24	<.4	nd	<.3	<4	75	<2	8	27	234	4300	92	29	308	113	26	nd	nd
1/8.4.III Agu L. bank N 7.5-10 cm	4100	12200	5400	5000	112400	33400	176	246	50	27	<.4	nd	<.3	<4	64	<2	10	32	159	4300	83	28	330	121	21	nd	nd
2/8.4.III Agu Lake N 5-7.5 cm	4800	10000	5100	7200	122100	30200	128	190	45	28	0.5	nd	<.3	<4	68	<2	9	34	181	4500	88	30	295	116	23	nd	nd
2/8.4.IV Agu Lake N 7.5-10 cm	3600	11000	4900	5900	105300	31600	158	164	98	26	<.4	nd	<.3	<4	63	2	10	32	160	4000	76	28	299	115	20	nd	nd
2/8.4.IV < 2 µm	3400	9800	5400	5800	135400	31000	102	181	46	27	<.4	nd	<.3	<4	75	<2	10	41	194	4700	89	24	268	105	26	nd	nd
4/8.4.II Agu Lake E 5.5-8 cm	3800	13000	6000	5100	115700	26900	127	164	57	26	<.4	nd	<.3	<4	64	2	8	33	173	4200	80	29	412	125	21	2.22	100
4/8.4.III Agu Lake E 15-16.5 cm	4400	14000	6500	6900	117600	33900	125	146	49	24	<.4	nd	<.3	<4	65	<2	9	29	176	4300	85	30	389	148	22	nd	nd
5/8.4.IV Agu River S 22.5-25 cm	4300	11900	5300	6000	109300	64000	149	148	50	22	<.4	nd	0.3	13	64	2	8	27	168	4400	82	26	325	123	23	nd	nd
5/8.4.IV < 2 µm	2100	11000	5600	5900	126000	83000	79	140	42	22	<.4	nd	<.3	8	77	<2	8	32	196	4400	87	26	280	107	26	nd	nd
Mean	4365	10829	5335	8787	85538	37302	289	142	45	18	0.26	6.7	0.24	4.6	61	1.7	13	33	165	3765	67	24	309	137	17	6.7	1447
SD	3146	4448	2320	7493	25348	15185	225	54	19	9	0.13	6.5	0.26	3.6	16	1.4	6	13	49	1269	25	7	119	57	5	9.4	1445
Median	3700	12050	5900	6100	91100	33700	197	130	44	18	0.20	3.0	0.20	4.0	61	1.0	12	29	171	4100	67	25	309	127	18	2.6	800

+ INAA analysis
* hydride ICP analysis

Table A 1. Analytical results for sediments from floodplain sites in the Middle and Lower Fly River region where no deposition of mine-derived material was detected, and of sediments deposited in the pre-mining period. Sediments with no grain size given are <20 µm. Statistics have been calculated for the fractions <100 µm only. Total or t. means analysis of the complete, unsieved sediment core section.

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
OTML copper flotation concentrate	600	2900	2800	600	5500	181200	132	1098	33%	88	21.5	nd	25.1	73*	9	'2317'	137	32	41	300	4	10	39	23	<1	0.04	309000
19/18.10. Ok Tedi, Tedawoim br.	8100	28800	8800	104500	73900	59400	1048	780	3181	987	2.4	nd	3.2	4	51	50	29	37	157	2600	44	27	369	538	12	nd	nd
20-60 µm	8600	25800	5800	103200	48700	93200	1087	1530	3041	2900	4.2	nd	7.8	5	30	69	33	31	123	1800	37	26	60	480	5	2.1	68200
> 200 µm	11100	23900	4500	106300	56800	49700	857	334	556	79	0.6	nd	0.5	5	28	21	14	19	82	1500	23	18	120	623	6	1.9	20100
6/18.10. Ok Tedi bank, Tabubil br	6200	22400	9100	115900	59300	54700	1160	657	3170	800	1.6	nd	4.4	10	42	45	18	28	127	2100	39	28	273	715	9	nd	nd
20-60 µm	6800	19800	5700	102600	36200	119600	1131	1394	3204	2514	4.6	nd	10.4	38	27	62	27	38	102	1700	40	32	41	579	4	nd	nd
60-100 µm	7000	17600	4700	96800	35600	132500	1165	1619	3569	647	4.8	nd	3.9	37	24	50	35	30	100	1500	19	24	40	555	4	nd	nd
100-200 µm	9900	21500	4600	96500	47700	80600	1101	875	1568	138	2.3	190+	1.8	63+	25	41	21	23	86	1400	18	24	69	650	4	1.4	38700
> 200 µm	12100	22600	5400	79600	59100	41000	862	191	376	36	0.2	nd	1.2	6	36	23	11	30	77	1500	26	17	495	683	6	nd	nd
7/18.10. dto.	7800	27100	7800	127600	59200	42000	924	511	1183	374	0.7	nd	1.3	4	38	45	12	17	120	1900	26	24	318	672	8	nd	nd
20-60 µm	10200	27400	6400	131300	54800	54200	965	779	1496	488	2.2	190+	1.4	40+	26	47	15	17	101	1700	25	19	305	655	5	nd	nd
100-150 µm	12500	22700	5000	91400	57100	23700	709	429	661	61	1.1	53+	0.3	14+	18	37	5	3	73	1000	14	14	387	688	5	1.9	6000
150-200 µm	12900	24700	4900	80300	59100	41100	868	322	657	82	0.8	nd	1.1	4	32	31	10	23	80	1400	21	16	459	673	5	nd	nd
9/18.10. dto.	7400	24400	7800	124100	61300	46900	918	593	1443	389	2.1	nd	1.9	13	40	39	16	23	124	1900	33	22	281	618	9	nd	nd
20-60 µm	8600	22700	5900	127600	48800	64100	968	954	1791	630	2.5	nd	2.1	6	25	40	17	20	97	1700	27	21	241	613	5	nd	nd
60-100 µm	10500	23300	4800	118500	50500	49700	853	811	1380	217	2.7	nd	1.2	11	21	35	14	13	85	1400	15	20	294	617	4	nd	nd
100-200 µm	12900	25400	4300	103400	56200	36300	757	446	699	70	1.5	81+	1.4	27+	25	27	9	20	77	1200	17	19	420	647	4	1.7	11900
> 200 µm	15500	32000	4700	114600	65700	24000	695	155	408	60	0.6	nd	0.2	4	24	24	5	13	80	1300	17	17	627	801	5	nd	nd
3/14.4. dto.	11400	38000	7000	67800	64200	32300	518	215	908	91	0.9	343+	0.7	23+	29	36	5	12	105	2000	18	28	561	517	9	2.17	8000
20-60 µm	14900	38200	6600	54500	64700	29300	452	256	805	63	1.1	120+	0.4	19+	22	32	5	10	97	1800	13	19	606	521	7	1.50	7900
60-100 µm	16200	34600	5700	41800	62700	18200	338	163	542	25	0.6	94+	<.3	12+	18	25	3	7	81	1300	9	13	558	510	6	1.15	3200
100-200 µm	18100	38400	5500	35900	67700	14400	298	78	469	21	0.6	77+	<.3	9+	18	20	3	6	80	1200	8	11	619	521	6	0.94	1300

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
4/14.4. dto.	12000	37200	7700	74600	65800	29700	470	182	895	84	1.0	874+	0.9	18+	33	30	5	14	112	1900	17	24	516	540	9	2.44	7100
20-60 µm	15000	36800	6600	54800	62800	34500	436	266	943	91	0.7	935+	1.3	27+	21	35	5	10	103	1700	13	17	652	507	7	1.57	11500
60-100 µm	15900	34000	5900	47000	61300	51700	483	357	1268	71	1.0	nd	3.4	28*	21	36	9	12	107	1700	13	21	599	515	6	1.19	21900
100-200 µm	16300	34700	5400	41300	62400	43400	420	247	1112	36	0.9	140+	0.6	33+	19	31	8	9	96	1500	11	17	625	525	6	1.03	19400
1/14.4. SS Ok Tedi, Tabubil br.	15600	43600	7700	57900	72300	21500	324	124	889	48	0.6	nd	0.4	7*	30	27	4	10	119	1700	12	28	573	513	9	1.86	4300
20-60 µm	19000	39900	6100	36600	72500	20100	236	140	633	44	0.6	nd	0.7	9*	19	21	4	8	99	1500	8	15	641	463	7	nd	nd
60-100 µm	19400	38100	4900	31300	70500	21100	225	176	659	37	0.6	nd	0.7	11*	17	18	4	8	85	1400	8	15	637	459	6	nd	nd
2/14.4. SS Ok Tedi, Tab.br. <2 µm	10300	27900	10400	84700	87500	32100	520	223	2144	124	0.9	nd	1.4	16	62	62	6	23	167	2000	23	40	617	619	13	nd	nd
20-60 µm	19100	41100	6300	36800	74600	18700	230	138	622	43	0.7	nd	0.8	8*	19	20	4	8	99	1400	9	15	652	484	7	nd	nd
SS3/29.2. susp.sol. Ok Tedi/Menga	9600	25400	8400	119700	64500	31800	812	221	728	119	0.4	nd	3.9	4	47	27	10	17	141	2300	30	26	275	745	10	2.1	4800
20-60 µm	13000	28000	6300	107100	63100	39800	772	398	917	206	0.7	nd	1.5	4	30	31	12	12	111	2100	29	21	360	702	8	nd	nd
60-100 µm	13500	26300	5200	100100	60300	43200	777	497	1132	122	0.6	nd	0.8	4	24	32	12	11	104	1800	18	20	367	689	6	nd	nd
100-200 µm	16400	32400	5100	105300	68500	46300	888	244	661	63	0.2	nd	0.2	4	39	27	9	24	99	1800	25	23	538	790	6	nd	nd
Mean	11921	30350	6733	86117	61462	47512	700	541	1523	463	1.6	426	2.4	14.9	30	38	13	17	111	1788	22	23	410	576	7.3	1.8	15211
SD	4159	7395	1463	33796	11766	29854	323	450	976	744	1.3	381	2.5	11.5	12	14	10	9	21	305	11	6	202	86	2.4	0.5	20643
Median	10950	27950	6350	98450	62750	40900	775	378	1158	123	0.95	268	1.4	11.0	26	36	11	14	105	1750	19	22	368	548	7.0	1.9	7900

+ INAA analysis
* hydride ICP analysis

Table A 2. Analytical results for river bank sediments and suspended solids from the upper Ok Tedi. Sediments with no grain size given are <20 µm. Statistics have been calculated for the fraction <100 µm only.

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
1/3.4.II Lower Fly bank 11-13.5cm	9000	22800	9300	35200	87200	49200	734	152	239	40	<.4	nd	0.8	16*	58	9	14	37	140	3600	44	22	458	274	17	nd	nd
2/15.2.I Lower Fly bank 0-3 cm	8200	17100	6400	32200	68200	46100	956	161	185	26	0.2	nd	0.8	12	66	6	20	52	171	3600	47	21	330	246	15	nd	nd
20-60 µm	11900	15000	7600	26900	64600	36900	608	108	79	5	0.2	nd	0.2	4	55	2	15	42	133	3300	37	22	324	240	13	nd	nd
60-100 µm	10900	13500	7900	24800	65200	37600	527	111	65	23	0.2	nd	0.6	6	56	2	16	51	125	2800	31	19	333	242	12	nd	nd
2/15.2.III 17-19 cm	7900	17900	8500	39100	78700	51000	1039	163	225	44	0.2	nd	0.2	10	70	8	22	57	181	4000	61	28	359	298	18	nd	nd
SS3/15.2. susp. solids Lower Fly	9300	26700	9900	27800	110100	49700	777	152	140	54	0.2	nd	0.4	16	82	3	22	55	223	4400	60	35	446	294	24	nd	nd
4/15.2.I Lower Fly bank 0-3 cm	7600	19900	9500	50900	82000	54000	1029	170	389	64	0.9	nd	0.9	12	69	19	21	54	180	3600	51	28	363	370	17	nd	nd
20-60 µm	11100	14700	8100	30600	72200	40200	757	119	151	10	0.4	nd	0.2	4	54	5	16	39	131	3100	38	19	333	288	13	nd	nd
60-100 µm	10500	12800	8500	25100	72800	42200	630	102	99	13	0.2	nd	0.2	4	57	5	17	47	131	2900	31	16	325	256	13	nd	nd
100-200 µm	9500	11200	9000	25700	69700	60100	1039	113	198	26	0.2	nd	0.5	6	86	12	23	89	118	2800	52	20	352	274	14	nd	nd
3/16.2.I Fly R. bed/Obo 0-4.5 cm	10000	34400	8600	51600	82800	42300	803	237	887	93	0.5	150+	1.0	20+	52	41	14	22	179	2600	37	34	423	464	12	nd	nd
3/16.2.III 25.5-27.5 cm	7300	31700	9700	61000	68200	38500	802	270	626	117	0.9	nd	1.0	15*	41	28	6	15	114	2000	30	21	388	447	10	0.6	3500
1/27.3.II Fly bank Xs. 4-6 cm	8300	43700	6100	6100	94700	21700	122	164	360	99	<.4	160+	<.3	6+	38	8	6	17	143	2200	37	23	531	278	11	nd	nd
2/27.3.II Fly bank Xs. 3.5-5.5 cm	9800	52700	8000	6100	94200	23400	143	175	430	110	0.4	240+	0.7	4+	40	13	4	15	126	2100	31	26	603	296	11	1.07	<100
2/27.3.III Fly bank Xs. 5.5-8 cm	8200	35800	6200	6900	93800	35000	136	108	320	81	0.5	nd	0.7	5	43	19	5	15	139	3000	46	25	463	264	13	0.93	100
3/27.3.I Fly bank Xs. 0-2.5 cm	7500	31700	7900	23400	77500	45000	648	243	424	85	0.9	nd	0.8	7	46	27	10	17	142	2800	42	26	403	297	13	1.43	1000
4/27.3.II Fly bank Xs. 19-21.5 cm	5800	23600	6800	8000	70800	49500	502	224	330	82	<.4	nd	0.6	10	60	22	13	20	168	3900	71	17	354	190	12	nd	nd
20-60 µm	10200	25000	5400	8500	58700	35300	357	106	190	41	<.4	nd	0.5	6	60	14	8	19	123	3000	55	16	531	246	8	nd	nd
60-100 µm	10200	18700	4800	8200	58500	29300	289	93	133	42	<.4	nd	<.3	<4	45	9	7	8	90	2400	36	14	399	259	8	nd	nd
100-200 µm	8900	12800	5200	10100	54900	35500	418	112	198	41	0.4	nd	<.3	<4	36	5	10	14	82	2400	51	11	436	264	9	nd	nd
4/27.3.III Fly bank Xs. 22-24 cm	6400	24900	7300	11200	95600	52100	510	205	263	65	<.4	nd	0.4	8	50	21	12	25	160	3500	66	27	439	216	18	nd	nd

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
5/27.3.III Fly bank Xs. 20-22 cm	8400	31100	8600	48700	80900	45900	682	238	977	76	0.5	205+	0.9	21+	43	30	10	19	130	2900	45	30	425	365	15	0.83	5300
20-60 µm	13900	40300	6500	38000	73100	24400	426	172	471	38	<.4	nd	0.4	9*	20	20	6	11	86	1600	23	13	529	411	9	0.52	3000
5/27.3.V Fly bank Xs. 30-32 cm	9600	35200	9000	56000	83300	42100	609	225	929	79	0.5	nd	0.7	8	42	30	9	17	134	2600	38	29	441	411	14	nd	nd
5/27.3.VI Fly bank Xs. 46-48 cm	9100	36100	8700	47800	81100	41000	615	213	891	71	<.4	nd	0.7	16*	42	31	9	16	126	2600	36	28	450	377	14	0.66	4600
5/27.3.VI < 2 µm	4000	20100	10600	38500	101000	57900	790	336	1710	142	1.2	nd	1.6	29	71	45	11	23	171	3300	47	35	416	320	19	nd	nd
1/29.10. Obo floodplain 0-1 cm	1700	7600	2400	2900	33300	78800	73	98	424	66	0.2	33+	0.1	14+	80	14	3	27	137	5600	68	18	159	61	6	nd	nd
20-60 µm	19500	4000	1600	17400	28100	51700	77	78	266	47	0.7	nd	0.1	5	50	6	1	10	69	3200	69	13	117	68	6	nd	nd
60-100 µm	8400	6300	2400	9600	43200	9500	323	123	524	99	0.2	nd	0.1	13	62	16	3	23	104	3800	61	23	188	84	9	nd	nd
4/16.2.I L.Dav. chan./Fly 0-2 cm	9600	31000	7300	25300	83400	44100	742	144	383	35	0.3	nd	0.2	4	49	16	15	18	171	3200	57	29	415	335	14	1.5	2200
20-60 µm	12000	27800	6100	25400	73300	30600	520	130	252	26	0.5	nd	0.2	4	31	11	13	15	115	2400	42	19	487	387	10	nd	nd
1/19.2.I L.Daviambu Ost 0-2.5cm	4600	17300	4700	9100	87700	31000	433	127	161	24	0.3	25+	1.2	15+	63	6	12	27	198	3600	71	34	327	156	18	4.2	700
20-60 µm	6800	12600	2700	7800	47800	16500	431	99	160	20	0.2	nd	0.2	4	31	5	7	15	90	1900	41	25	256	149	10	nd	nd
1/30.3.II L. Dav. chan. 2-4 cm	8300	37600	8700	7300	92200	26500	165	178	409	81	0.5	nd	0.9	<4	46	15	5	15	129	2500	34	28	506	300	12	1.27	100
2/30.3.I L. Daviambu chan. 0-2 cm	10000	37100	7700	39500	76000	34100	462	203	679	61	0.9	nd	1.1	<4	42	21	7	15	133	2500	29	28	440	383	12	0.70	2500
4/30.3.I L. Daviambu W 0-5 cm	2700	9200	3300	9200	61600	37000	276	206	123	30	<.4	nd	0.4	5	38	7	15	25	96	1900	42	18	235	115	12	nd	nd
4/1.4.II L. Daviambu E 6-8 cm	9800	36500	7200	37800	80400	37600	526	211	748	70	0.5	nd	0.6	<4	37	24	8	16	118	2500	35	27	455	344	12	nd	nd
4/1.4.III L. Daviambu E 12-14 cm	8600	30300	8300	52900	78900	42500	690	227	842	81	0.7	nd	0.9	12	44	29	10	19	121	2800	41	27	430	398	13	0.66	5100
20-60 µm	13400	37200	7100	41000	75900	25900	565	223	522	34	0.6	nd	0.5	<4	25	18	7	12	93	1800	25	15	530	423	9	nd	nd
4/1.4.V L. Daviambu E 20-22 cm	7700	32100	7900	48200	70400	35300	533	228	575	80	0.8	nd	0.5	<4	42	23	9	16	125	2100	29	24	394	384	11	1.94	3000
4/1.11.I L.Daviambu/channel 0-6cm	8300	35300	10300	13100	95100	41000	389	257	612	102	1.5	170+	0.1	11+	75	27	11	24	199	3200	41	36	534	362	13	nd	nd
2/26.10.III Fly bank 15-19 cm	7000	28900	7300	6200	71500	37800	212	177	237	67	0.8	nd	0.1	2	66	9	8	15	189	5100	75	30	423	226	12	nd	nd

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
1/28.10.I Fly bank 4-7 cm	6900	26800	9400	67400	74800	51000	778	353	747	98	1.2	nd	1.1	18*	47	34	11	19	133	2800	41	29	404	440	13	0.7	6500
1/28.10.II 10.5-12.5 cm	8400	39700	8400	46500	77300	32100	460	224	500	82	0.7	nd	1.0	<4	37	26	5	13	108	2000	27	25	466	407	9	nd	nd
1/28.10.III 19-21 cm	7100	32400	10200	74400	72800	37600	673	295	573	121	0.8	nd	0.9	<4	42	26	6	15	108	2000	30	23	400	494	9	nd	nd
1/28.10.IV 36-38 cm	7000	29500	8100	19400	87600	56300	1027	267	778	101	0.9	nd	1.0	13*	46	38	11	18	151	3200	51	30	461	295	14	0.8	1700
2/28.10.II Fly bank 13.5-17.5 cm	6900	27600	9600	68900	69800	54400	887	389	866	106	1.3	211+	0.1	23+	58	38	11	11	167	3800	53	50	356	458	12	nd	nd
2/28.10.III 23-25 cm	6000	23200	8900	62800	72700	49800	824	373	739	103	1.0	nd	1.0	18*	46	31	10	19	131	2900	44	26	369	409	13	0.8	4400
2/28.10.IV 32-34 cm	6200	23800	9000	65400	73500	46900	793	325	736	103	1.0	nd	1.0	14	47	32	10	18	130	2800	42	27	363	422	13	nd	nd
2/28.10.V 40-42 cm	6700	30300	7000	22500	87700	43400	629	167	394	98	0.5	nd	0.6	10*	44	28	8	18	157	3100	48	25	429	300	14	0.9	1600
2/19.2.I L.Pangua SW 0-2.5 cm	4300	17700	6100	7600	90400	45200	480	182	246	64	0.3	nd	1.0	10	65	16	18	31	221	3500	68	35	318	186	17	nd	nd
1/31.10.I L.Pangua Isl. 0-2.5 cm	4300	18700	7300	6100	89100	29500	165	170	622	124	0.5	nd	0.9	<4	52	20	6	18	146	2500	41	31	382	225	15	5.6	1300
2/31.10.I L.Pangua N 0-5.5cm	2800	12600	4100	8700	50000	45200	328	189	353	66	0.4	nd	0.5	15	55	12	16	22	143	2700	42	25	253	145	10	nd	nd
2/31.10.III 5.5-7.5cm	1400	5700	2200	5600	54800	21800	252	87	113	28	0.2	nd	0.6	7	32	9	15	25	134	1600	34	21	152	91	11	nd	nd
1/4.4.I L. Pangua NE 0-2 cm	4100	14500	6600	7500	96200	54300	265	183	218	48	<.4	nd	0.7	11*	53	7	13	27	160	3200	68	28	343	155	17	5.23	400
1/4.4.II L. Pangua NE 2-4 cm	8600	17200	6400	10600	90800	70400	483	186	485	78	0.5	nd	<.3	7	55	12	13	34	151	2800	65	28	375	182	15	4.29	700
20-60 µm	8000	10100	4700	10600	74800	53100	510	200	501	76	0.7	nd	<.3	4	45	6	19	24	124	2400	62	24	309	149	14	nd	nd
1/4.4.III L. Pangua NE 7-9 cm	4900	13600	5900	8700	89200	89400	584	163	234	47	<.4	nd	<.3	<4	56	7	19	47	156	2900	67	26	313	144	16	nd	nd
2/4.4.I L. Pangua NW 0-2 cm	4900	19300	6300	6600	91700	42600	250	222	351	62	<.4	90+	1.0	7+	51	8	10	21	143	2800	52	26	365	172	15	nd	nd
2/4.4.II L. Pangua NW 2-4 cm	4100	14700	5900	6800	90600	34900	231	157	113	35	<.4	31+	<.3	5+	51	3	10	23	137	2900	60	23	321	142	16	nd	nd
3/31.10.I L. Pangua W 0-2.5 cm	4700	17100	6300	6400	76900	40300	295	153	142	41	0.2	nd	0.5	2	73	5	10	28	191	5700	93	28	344	155	15	nd	nd
4/31.10.I L.Pangua Mitte 0-5 cm	6100	27300	9300	12900	92400	63900	622	254	751	132	0.6	nd	0.3	19	80	27	12	17	219	4800	78	42	440	275	17	nd	nd
20-60 µm	7300	12500	5200	10100	61900	51300	1196	158	550	62	0.4	nd	0.1	10	60	7	20	25	141	4300	91	26	360	204	12	nd	nd
4/31.10. 5-7 cm	5500	24300	8400	8900	96400	51900	387	228	656	119	0.8	nd	0.9	11*	59	32	8	22	170	3000	50	34	461	274	16	nd	nd
4/31.10. 7-9 cm	4800	20400	7400	8200	94400	54600	337	162	371	80	0.5	nd	0.3	8*	59	23	10	22	168	3300	59	30	420	227	17	nd	nd

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
5/31.10.I L.Pangua SE 0-2.5 cm	6900	33900	9000	14700	92100	53100	456	245	842	131	0.2	nd	0.4	2	69	32	10	33	202	3600	55	37	464	330	14	nd	nd
5/31.10. 5-7 cm	3700	15900	6500	6800	95400	63100	308	141	153	46	0.5	nd	0.3	6*	60	12	13	23	181	3600	67	28	328	168	18	nd	nd
6/31.10.I L.Pangua/channel 0-3 cm	7900	32400	9200	61600	73900	45000	830	321	863	117	0.9	nd	1.3	4	59	37	12	19	161	3600	53	41	378	461	13	nd	nd
20-60 µm	12900	40200	7300	45400	67600	29200	674	240	599	79	0.8	nd	2.1	2	37	26	9	20	126	2800	34	21	521	454	9	nd	nd
6/31.10.V 45-50 cm	8100	36800	10000	78800	79800	42700	867	285	946	139	0.9	nd	1.5	6	53	56	9	16	157	3200	49	41	423	623	12	nd	nd
20-60 µm	12600	42300	8000	50400	69500	27300	596	246	638	64	0.7	nd	1.2	2	41	25	7	17	127	2500	34	22	498	495	9	nd	nd
7/31.10.I Fly River bed 0-3 cm	8800	32500	9400	63400	81800	46100	870	356	861	105	1.0	nd	0.1	2	60	39	12	19	164	2900	41	32	436	518	12	nd	nd
20-60 µm	12000	29700	6900	49300	69800	34800	750	303	551	57	0.8	nd	0.1	2	40	25	7	7	120	2500	42	18	456	482	9	nd	nd
7/31.10.II 17.5-20 cm	6200	23500	9500	74300	66900	49900	915	420	840	116	1.5	nd	1.1	22*	48	39	11	19	139	2900	41	30	352	466	13	0.7	5100
7/31.10.III 32-34.5 cm	7700	27400	9800	78100	81100	50200	1091	335	881	131	0.7	nd	0.1	7	62	55	7	18	154	3300	53	31	426	638	12	nd	nd
7/31.10.V 53.5-56 cm	8200	31500	9500	93100	77500	45300	1018	306	845	129	1.0	nd	0.6	5	55	50	7	15	145	2500	44	30	426	713	10	nd	nd
20-60 µm	13400	37000	7700	59200	74500	30800	667	300	508	63	0.8	nd	0.1	2	36	29	5	10	122	2300	27	17	513	574	8	nd	nd
7/28.10.I Komovai shortcut 7-9 cm	8700	41900	7400	55500	75900	29500	521	186	564	78	0.8	nd	0.9	<4	32	36	4	11	100	1700	25	23	457	453	8	0.3	2100
20-60 µm	10600	30200	6200	51500	63700	27200	518	258	475	46	0.7	nd	0.7	<4	25	24	6	11	88	1800	24	15	408	424	8	nd	nd
7/28.10.II 16.5-19 cm	5900	24900	6400	8100	91700	48700	500	132	170	43	<.4	nd	0.3	11*	49	19	11	20	141	3500	58	14	415	220	16	0.9	700
20-60 µm	9400	21700	5400	8000	68800	36800	435	98	110	16	0.4	nd	0.7	7*	33	8	9	15	109	3100	49	25	414	258	11	nd	nd
7/28.10.III 19-24.5 cm	5900	22700	6800	9900	93800	52800	492	141	138	36	0.5	nd	0.3	12*	51	14	12	22	146	3900	69	20	493	225	17	nd	nd
10/28.10.I Swiss Lake 11-13 cm	6700	27900	9300	90000	70200	36400	613	243	705	99	0.8	nd	1.0	<4	41	40	6	17	114	2200	34	28	374	557	10	nd	nd
3/19.2.I Tamu creek/Fly jct.0-3cm	7900	18400	8100	13400	93200	47200	423	139	161	24	0.4	nd	0.7	12	66	7	19	36	204	4700	91	30	386	244	18	1.9	1300
3/17.2.I Tamu island/Fly	6400	21100	6900	42100	65200	45000	762	314	730	93	0.6	nd	1.3	15	41	37	12	21	140	2400	37	30	308	363	10	2.5	9500
20-60 µm	13100	32900	6200	55600	69900	30000	620	199	484	38	0.5	nd	0.4	4	23	32	8	10	110	1800	22	21	420	524	7	1.7	2900
60-100 µm	16200	34700	6400	30900	80500	24600	670	213	473	55	0.5	nd	0.2	9	22	25	10	17	119	1600	25	15	666	559	8	nd	nd
5/26.10.I Tamu Creek bank 8-10 cm	8300	39700	8700	58700	74900	32100	497	226	582	86	0.8	nd	0.9	10*	35	35	5	12	108	1800	26	24	432	453	9	0.3	1300
5/26.10.II 14-16 cm	7400	34000	9100	35000	83300	46700	733	279	794	105	0.8	nd	1.1	<4	45	36	8	16	139	2600	38	27	433	354	12	nd	nd
20-60 µm	11200	35800	5800	18700	70800	27000	486	128	483	40	0.4	nd	0.8	<4	22	19	6	9	103	1800	22	14	474	338	7	nd	nd
5/26.10.III 20-22 cm	9200	45900	6900	19800	89900	38100	417	188	914	104	0.8	nd	1.2	<4	35	41	6	14	136	2200	29	30	515	354	10	nd	nd

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
6/26.10.I Tamu creek 0-3 cm	9900	52700	8100	12700	80100	47000	690	210	999	111	0.2	306	1.5	14	52	42	9	14	180	3600	50	42	509	330	11	nd	nd
20-60 µm	12200	41400	6100	12800	60000	28200	638	191	538	65	0.5	nd	0.1	2	35	20	10	20	127	2400	37	19	497	322	7	nd	nd
6/26.10. 12-13.5 cm	8000	40500	6600	26100	86400	38300	448	165	875	95	0.5	nd	1.2	8*	34	36	7	13	134	2200	34	28	467	343	11	0.4	2400
6/26.10. 24-26 cm	9100	48400	5800	8400	89700	36100	388	170	803	94	0.5	nd	1.3	<4	33	40	6	11	123	1900	25	24	527	309	9	nd	nd
7/30.10.I Lake Tamu III 0-5 cm	1200	3600	2300	9500	43300	25700	814	185	100	39	0.2	nd	0.1	2	45	6	11	26	112	1600	31	14	195	108	10	nd	nd
20-60 µm	2800	7300	2700	18500	47800	26800	900	130	217	42	0.2	nd	0.1	2	46	11	7	12	102	1700	33	16	245	184	11	nd	nd
5/30.10.I Lake Tamu II 0-4 cm	2200	9100	3400	6800	79700	42100	398	194	157	46	0.5	nd	0.8	2	77	5	21	44	154	4600	72	28	253	118	16	nd	nd
100-200 µm	2600	7100	2400	6800	50700	34500	618	146	266	42	0.2	nd	1.8	12	61	4	19	38	101	3300	56	24	208	104	12	nd	nd
4/26.10.I Lake Kibuz 0-6 cm	9500	41700	8500	49500	67200	36700	679	241	653	95	0.7	nd	0.8	8	49	30	8	18	146	3400	41	42	415	427	10	nd	nd
20-60 µm	12500	40000	6200	40100	60200	26000	460	177	389	49	0.8	nd	2.5	9	32	20	6	4	110	2700	30	23	451	406	8	nd	nd
4/26.10.V 45-50.5 cm	9100	46400	9500	61600	74800	32600	756	246	635	129	0.9	nd	0.9	5	44	30	5	21	126	2300	28	22	433	513	8	nd	nd
6/28.10.I floodpl./Kibuz 7-9.5 cm	8600	41900	8700	8600	95800	30600	217	200	601	129	0.7	nd	0.8	<4	47	22	5	14	141	2300	32	29	536	332	11	0.6	400
4/28.10.I Fly bank 0-3.5 cm	5700	22100	7600	6600	92700	57400	582	158	173	43	0.2	nd	0.1	2	69	13	15	22	187	5100	83	29	367	204	18	nd	nd
20-60 µm	9900	20100	5500	8100	56100	38900	437	109	92	33	0.4	nd	0.1	5	45	7	12	14	123	4400	83	27	427	261	10	nd	nd
60-100 µm	11200	14800	6000	12300	46500	35600	430	89	81	28	0.2	nd	0.1	5	39	3	12	14	101	3000	46	19	437	300	9	nd	nd
100-200 µm	9800	12600	4300	10600	48000	27800	317	88	102	53	0.2	nd	0.1	2	30	7	10	12	66	2400	48	17	534	331	7	nd	nd
4/28.10.II 3.5-7 cm	5300	18500	6800	6700	89800	51300	471	133	118	29	<.4	nd	0.3	<4	54	9	12	22	147	3900	70	27	363	183	18	1.6	400
4/19.2.I Oriv bed N'L.Kibuz 0-3cm	8800	36500	8800	53600	78300	45200	990	294	895	126	1.1	190+	1.1	18+	45	41	12	21	157	2400	39	32	396	477	11	nd	nd
20-60 µm	12100	37300	6300	46500	66300	24900	585	247	470	34	0.5	nd	0.5	4	24	24	8	11	111	1600	21	17	425	466	7	1.8	3300
4/19.2.II 3-6 cm	8900	42200	9000	61700	79200	40300	911	279	823	136	1.2	nd	1.7	22	46	49	12	23	151	2100	34	33	414	517	11	nd	nd
4/19.2.IV 22-24 cm	9100	44600	8400	19400	86900	51000	916	237	1092	129	0.8	nd	1.9	15	45	52	13	20	181	2700	39	30	447	356	11	nd	nd
4/19.2. 26-28 cm	8800	42600	6800	12500	88900	44500	604	199	958	97	0.7	nd	1.1	12*	37	44	8	14	142	2500	34	27	506	308	11	0.6	2900
20-60 µm	11900	40500	6100	14700	79400	26900	517	149	631	34	0.5	nd	0.6	<4	23	20	7	10	111	1800	24	13	538	350	8	nd	nd
4/19.2. 33-35 cm	6800	29600	9100	11300	90400	54200	855	243	497	113	0.5	nd	1.2	<4	49	45	10	18	162	3300	50	28	433	270	15	0.9	2900
4/19.2. 38-40 cm	6400	26800	7600	10900	92500	57500	846	201	432	94	0.6	nd	0.6	15*	50	34	12	20	164	3500	58	29	494	260	16	nd	nd
20-60 µm	9300	25500	6100	10100	70900	38500	748	135	233	26	0.6	nd	0.3	<4	32	13	10	14	130	3200	47	19	429	276	10	nd	nd
4/19.2.V 43-45 cm	8800	45300	7200	8200	97800	45000	530	155	419	105	0.7	nd	0.5	10	51	38	13	26	211	3100	49	32	481	326	14	nd	nd
4/20.2.I Bai Lagoon Mitte 0-3 cm	3500	16000	6300	7400	86400	40700	297	273	390	82	0.2	nd	0.2	4	53	18	14	25	175	2500	44	29	296	207	14	nd	nd

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
1/5.4.I Bai Lagoon M 0-2 cm	7100	22800	7200	8400	89000	48900	314	205	612	96	0.4	nd	0.3	5	53	14	10	22	144	2400	50	29	415	207	14	nd	nd
5/20.2.I Bai Lagoon chan. 0-5 cm	9100	39400	8400	30100	91100	39500	651	228	733	110	0.6	nd	0.5	9	45	32	11	18	163	2300	33	36	409	418	12	nd	nd
5/20.2.IV 22-25 cm	8700	34400	7800	39700	82500	45900	806	271	788	113	0.4	nd	0.9	12	41	34	12	18	161	2300	36	37	348	468	12	nd	nd
20-60 µm	12400	27500	6200	54600	68100	28300	560	269	463	52	0.8	nd	0.7	11	23	28	8	11	107	1800	21	19	404	543	7	1.8	4800
60-100 µm	13200	31100	7300	36400	83000	29000	514	215	376	49	0.6	nd	0.2	6	22	22	10	13	128	1900	30	18	542	561	10	nd	nd
5/20.2. 32-34 cm	7000	29800	8700	69600	74000	40400	621	226	794	96	0.7	nd	0.9	<4	43	53	7	16	126	2400	35	31	385	481	12	nd	nd
5/50.2. 41-43 cm	7800	34000	9400	73000	74400	34200	634	238	708	87	0.8	nd	1.2	12*	39	42	6	14	116	2000	29	26	420	522	9	0.5	3100
3/5.4.IV Kemea channel 18-20 cm	9600	52300	7400	41300	79400	25700	404	165	524	72	<.4	nd	1.3	<4	28	33	5	10	96	1500	26	22	526	401	8	0.51	1900
3/5.4.V Kemea channel 25-27 cm	6500	31600	8000	15400	93400	29000	257	167	432	108	0.7	nd	0.7	<4	49	22	7	16	137	2500	39	28	465	301	13	nd	nd
4/5.4.I Kemea Lagoon W 0-3.5 cm	7500	33800	7200	9100	88900	37600	297	189	475	77	<.4	nd	1.0	6*	44	16	10	18	137	2400	43	26	458	236	13	3.72	700
4/5.4.II Kemea Lag. W 3.5-7.5 cm	7700	38300	5700	9600	65900	33500	325	152	378	91	<.4	255+	0.5	10+	45	27	8	15	163	2800	44	16	420	224	9	1.44	700
4/5.4.III Kemea Lag. W 7.5-11 cm	3600	14600	5100	7300	89800	40500	240	212	111	28	<.4	nd	<.3	<4	46	10	15	25	124	2800	57	22	393	140	16	6.81	400
5/5.4.I Kemea Lagoon E 0-2 cm	2700	12100	5400	4900	82200	37300	171	231	255	59	<.4	nd	0.7	5*	47	10	14	26	135	2200	45	24	322	137	14	nd	nd
6/20.2.I Kemea Lagoon C 0-2cm	6000	26200	6600	8200	116100	39600	291	197	214	61	0.2	nd	0.5	8	64	8	21	30	204	3500	65	32	374	226	21	nd	nd
7/20.2.I Kemea Lagoon/chan. 0-4cm	6800	24600	8900	67100	76700	51000	1129	376	993	155	0.9	nd	1.5	16	48	46	17	22	163	2700	46	37	324	540	13	nd	nd
20-60 µm	11500	31900	7200	51400	73200	32700	764	384	657	72	1.1	nd	1.1	4	28	32	11	15	125	2000	28	20	403	531	9	2.1	5300
60-100 µm	12300	29600	8500	31100	92400	34500	878	289	651	92	0.6	nd	0.7	14	29	24	13	18	146	2100	37	18	557	550	12	nd	nd
7/20.2.III 25-27 cm	7600	31400	8400	43500	89400	47200	859	264	964	146	0.8	nd	1.6	11	47	55	14	22	169	2800	48	40	382	490	14	2.5	7900
7/20.2.IV 27-29 cm	7800	32500	8100	56300	83800	47900	929	279	1050	141	0.9	nd	1.4	9	45	68	12	20	160	2600	43	40	375	549	12	nd	nd
7/20.2.V 41.5-43.5 cm	8100	30000	8700	76400	77200	39400	940	266	892	130	0.7	nd	1.2	4	39	61	9	17	148	2100	34	34	381	691	10	nd	nd
7/20.2.VI 46-48 cm	6300	26300	9900	97900	71200	43500	757	292	827	106	0.8	nd	1.2	6	45	50	7	18	122	2500	38	31	374	597	11	nd	nd
8/20.2.I Kemea chan. bank 0-2.5cm	9300	33900	8500	80100	84000	40600	958	365	840	177	nd	0.8	1.4	6	47	39	15	20	172	2700	41	32	391	574	13	2.8	7300
20-60 µm	12200	33800	7200	52500	78700	26200	866	287	637	90	1.2	nd	0.4	4	29	26	11	13	127	1700	27	17	446	499	10	2.1	3000
8/20.2.II 2.5-5 cm	9800	39700	8200	67800	87000	38800	751	283	771	150	0.5	nd	0.8	4	46	35	12	19	167	2600	35	33	416	552	12	nd	nd
8/20.2.III 5-7.5 cm	8400	34000	7600	67200	83600	38400	686	233	876	129	0.7	nd	0.9	4	45	46	11	21	159	2300	39	34	388	531	12	nd	nd
8/20.2.IV 7.5-10 cm	9000	38300	7600	63900	85400	32600	625	222	751	126	0.9	nd	1.1	4	40	50	9	17	151	2000	34	30	419	538	10	nd	nd

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
1/7.4.II Fly River bank 7.5-10 cm	7300	33900	6900	8700	92400	52800	650	261	401	102	0.4	310+	0.8	22+	43	32	10	20	147	3100	56	26	486	242	15	1.18	200
20-60 µm	11000	33500	5400	8600	72900	33400	350	123	246	42	<.4	73+	0.4	8+	27	12	6	14	111	2100	36	16	483	275	9	nd	nd
1/7.4.IV Fly R. bank 27-29 cm	10300	54100	5700	14000	87800	30900	402	134	356	79	<.4	291+	0.4	9+	32	21	6	17	126	2100	33	19	528	313	9	0.64	500
2/7.4.I Lake Kongun N 0-2.5 cm	9900	44100	9100	18700	92400	37800	398	222	612	93	0.4	nd	0.9	6	47	18	8	16	134	2300	37	27	532	312	13	0.41	200
2/7.4.I < 2 µm	8800	21100	10500	31500	98700	59700	440	336	1062	160	0.7	nd	1.6	28	69	26	10	25	163	2900	45	33	421	280	17	nd	nd
2/7.4.II L. Kongun N 2.5-5 cm	8300	38900	8900	36900	81400	35100	399	172	611	88	0.6	130+	0.8	10+	47	25	7	15	137	2280	28	28	470	397	12	0.62	900
3/7.4.I Kongun Creek M 0-2.5 cm	11100	45000	8200	31500	85600	32600	415	164	727	58	<.4	120+	0.4	12+	39	22	6	14	122	2300	28	25	511	350	13	0.53	1700
3/7.4.III Kongun Cr. M 19.5-22 cm	8500	41300	9000	73700	77500	31600	536	198	735	93	0.5	nd	0.9	<4	36	42	6	16	105	1800	31	26	473	513	9	0.38	3000
3/7.4.III < 2 µm	2300	15100	8700	29100	110000	42900	280	174	374	70	<.4	nd	0.6	10	69	28	8	24	165	3900	73	25	335	231	22	nd	nd
4/7.4.I Kongun Creek S 0-2.5 cm	10700	46200	8600	7800	91200	32700	257	239	583	92	0.4	130+	1.0	9+	43	15	6	17	126	2400	31	31	547	281	12	0.93	600
4/7.4.II Kongun Cr. S 2.5-5 cm	8900	42800	10000	6600	87900	31300	177	202	576	122	0.7	160+	0.6	7	52	21	5	15	145	2300	29	29	517	325	12	0.79	300
4/7.4.X Kongun Cr. S 7-9 cm	9500	48200	6900	4200	63700	21800	143	204	557	140	0.6	nd	0.3	<4	45	13	5	19	131	2200	32	14	463	261	6	nd	nd
> 200 µm	2900	13100	2800	6600	29500	11700	208	127	1926	145	1.1	nd	1.7	<4	30	7	7	15	61	900	17	15	183	123	6	nd	nd
5/7.4.III Kongun Cr./Fly 20-23 cm	8700	33800	8000	45000	78100	49700	751	340	628	93	0.6	nd	1.0	14	40	33	11	21	121	2500	45	27	436	358	12	nd	nd
5/7.4.IV Kongun Cr./Fly 23-26 cm	8300	32000	9300	68300	76900	46100	686	335	825	113	0.6	311+	1.2	26+	40	34	11	19	126	2400	40	26	437	454	12	0.70	5900
5/7.4.VI Kongun Cr./Fly 38-40 cm	8100	36000	9300	64900	76300	35500	588	258	639	107	0.9	nd	1.0	13*	43	33	7	16	120	2200	29	29	418	459	11	nd	nd
1/24.2.I L. Bosset NW 0-5 cm	2000	6800	2700	5600	83400	41500	171	240	185	43	0.2	nd	0.7	4	63	14	14	33	214	2800	52	20	196	102	13	nd	nd
3/11.4.I L. Bosset NW 0-2 cm	2200	8600	3600	5500	91700	42500	193	211	131	40	<.4	nd	0.6	5	56	8	15	28	164	2600	53	23	267	106	16	nd	nd
2/24.2.I L. Bosset N 0-2.5cm	2800	10800	4100	3900	83900	38200	136	162	306	77	0.2	nd	0.6	12	65	22	13	31	225	2900	52	27	234	134	14	nd	nd
3/24.2.I L. Bosset N 0-6.5cm	3700	16200	5500	4600	94100	55100	233	200	406	86	0.2	nd	0.2	13	70	27	22	34	256	3000	51	25	308	189	15	6.9	4300
20-60 µm	1500	5300	2700	3800	69900	45500	280	152	547	66	0.6	nd	0.2	12	52	15	28	32	172	2000	45	27	175	99	15	nd	nd
3/24.2.II 6.5-8.5 cm	2800	11300	4500	4400	92100	41500	171	195	148	44	0.2	nd	0.2	13	66	16	27	37	253	3200	55	23	280	140	16	nd	nd
5/23.2.I L. Bosset SW 0-4 cm	2600	12000	4300	8600	110700	35300	182	176	166	40	0.2	nd	0.2	4	76	8	15	41	243	3500	50	33	267	161	19	nd	nd

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
4/24.2.I L. Bosset C 0-8 cm	5800	28700	7800	6200	103800	51200	334	224	628	125	0.2	nd	0.2	14	65	29	12	27	237	3000	47	39	387	267	17	4.3	3600
20-60 µm	2400	10800	3800	5200	72800	46100	644	209	1138	140	0.5	nd	0.2	9	55	19	21	28	178	2200	44	33	231	148	16	nd	nd
4/24.2.II 8-10.5 cm	5800	30100	8400	7200	111100	45900	262	202	602	123	0.4	nd	0.4	14	70	26	11	28	237	2900	43	27	403	288	17	nd	nd
4/24.2.III 10.5-13 cm	5000	23900	7400	7000	105500	42400	249	206	415	88	0.2	nd	0.2	4	66	19	13	27	230	3100	50	28	893	236	18	nd	nd
4/11.4.I L.Bosset E 0-2.5 cm <2µm	5200	21800	9800	33000	103900	54000	610	277	1730	141	0.5	nd	1.0	13	66	45	10	25	182	3000	59	37	430	306	20	nd	nd
4/11.4.II L. Bosset E 2.5-5 cm	11000	42900	8100	27500	87000	35000	414	178	698	70	<.4	120+	0.5	14+	41	19	7	15	122	2500	32	28	523	343	14	0.60	2100
4/11.4.III L. Bosset E 5-7.5 cm	10100	36100	8700	50900	84500	41300	551	218	786	78	<.4	nd	0.7	7	44	30	9	17	131	2600	36	27	464	413	14	0.53	3400
4/11.4.III L.Boss. E 5-7.5 cm<2µm	2500	14900	6800	14200	115900	49900	240	156	215	65	0.5	nd	<.3	7	72	16	9	26	184	4200	86	26	349	161	24	nd	nd
4/11.4.XI L. Bosset E 15-17.5 cm	7300	32200	6500	21900	85800	31800	288	162	388	80	0.6	170+	1.2	11+	44	22	8	18	132	2800	41	26	429	297	13	nd	nd
4/11.4.X L.Bosset E 20-23 cm <2µm	2400	15000	7400	14100	118700	51500	221	169	215	52	<.4	nd	<.3	7	75	15	10	29	208	4300	88	29	354	159	25	nd	nd
1/25.2.I L. Boss. chan./Fly 0-5cm	10000	35400	7600	54200	74400	35100	717	220	974	85	0.3	nd	0.8	4	45	46	11	19	175	2500	40	37	385	443	12	2.1	4900
2/25.2.I L. Boss.chan.bank 0-4 cm	9600	32500	7500	60100	74600	42500	906	313	733	118	0.9	nd	2.0	21	43	45	13	22	155	2600	51	40	385	471	12	2.3	5700
20-60 µm	13800	37200	6000	53800	64700	26000	741	210	529	52	0.6	nd	1.0	9	25	32	10	17	117	1700	23	21	439	494	7	nd	nd
60-100 µm	15300	32100	7000	35500	71500	23300	1128	240	663	67	0.8	nd	0.5	4	24	30	11	16	131	1600	28	18	573	526	9	nd	nd
1/10.4.I Kai River E 0-2 cm	10000	36000	7500	35400	75600	33800	473	164	663	51	0.6	nd	0.8	11*	40	23	7	15	128	2500	31	25	428	363	12	0.54	2300
1/10.4.II Kai River E 2-4 cm	11100	43800	7600	44300	80400	31300	412	154	668	54	<.4	nd	0.8	10*	33	23	6	14	112	2200	27	25	485	393	11	0.43	1700
1/10.4.IV Kai River E 18-20 cm	6700	25000	8900	50000	81200	47000	587	347	664	98	0.5	nd	1.5	15*	44	24	11	20	132	2700	48	26	402	355	13	nd	nd
1/10.4.V Kai River E 28-30 cm	7800	35000	7900	56800	69000	31700	463	207	618	78	0.9	nd	0.5	11*	39	31	6	14	111	2100	27	25	402	432	10	0.52	2700
1/10.4.VI Kai River E 30-32.4 cm	12000	38800	8000	50200	64200	26400	393	189	574	94	0.7	nd	0.9	5	41	30	6	16	101	1800	29	20	474	344	8	nd	nd
1/10.4.VII Kai River E 32.4-34.5	17500	50900	7500	35200	64900	19100	244	166	463	83	0.8	110+	0.7	8+	38	18	4	9	96	1500	25	16	420	306	6	0.49	<100
2/9.4.I Kai River S 0-2 cm	9400	40200	8300	27300	88500	35500	342	221	619	90	<.4	150+	0.6	13+	44	20	8	17	133	2400	35	27	510	335	14	0.96	1400
20-60 µm	9000	40200	8100	53500	77700	32500	451	213	626	87	0.4	nd	0.7	6	35	25	6	13	108	2000	29	23	459	412	10	nd	nd
2/9.4.II Kai River S 2-4 cm	13700	40900	6900	40700	74700	23000	362	170	427	48	0.5	160+	0.5	15+	23	15	6	12	88	1500	24	13	536	414	8	nd	nd
3/9.4.I Kai Lagoon N 0-3 cm	7500	35800	8300	5800	95500	39100	224	235	601	116	<.4	nd	0.8	5*	51	16	9	21	162	2600	41	30	501	257	13	1.97	500
3/9.4.I < 2 µm	4400	21400	9700	6700	107400	54800	325	324	813	163	0.7	nd	0.7	12	75	22	12	32	189	3200	49	33	451	228	18	nd	nd

(cont.)

Sediment Sample	Na	K	Mg	Ca	Al	Fe	Mn	Zn	Cu	Pb	Cd	Au	Ag	As	Cr	Mo	Co	Ni	V	Ti	Zr	La	Ba	Sr	Sc	C	S
	ppm											(ppb)														%	ppm
4/9.4.I Kai Lagoon M 0-2.5 cm	7500	35100	6900	5800	93700	44400	219	169	478	86	<.4	170+	0.4	12+	47	20	7	18	142	2600	44	26	468	229	15	2.22	800
4/9.4.II Kai Lagoon M 2.5-5 cm	6600	29100	6300	6200	92600	40500	192	152	272	73	<.4	190+	0.9	9+	49	24	8	20	160	3100	48	26	843	223	14	1.96	100
2/8.4.I Agu Lake N 0-2 cm	3500	13000	5300	5800	95200	28200	140	241	297	57	<.4	nd	0.7	4	51	11	8	24	144	2900	59	28	318	146	17	nd	nd
> 200 µm	2400	7700	3400	4900	58700	26100	206	138	276	40	<.4	nd	<.3	5	39	5	8	22	93	1800	39	18	206	88	12	nd	nd
2/8.4.II Agu Lake N 2-5 cm	3900	11600	5200	5600	107800	48800	258	152	131	38	<.4	nd	<.3	<4	63	6	11	37	160	3900	76	29	322	127	19	nd	nd
4/8.4.I Agu Lake E 0-2.5 cm	7900	36000	7300	4500	99700	28200	144	176	404	84	0.4	nd	0.6	4*	49	12	7	20	153	2600	39	28	474	237	13	1.94	200
4/8.4.I < 2 µm	4200	18700	8000	5500	115600	39900	217	249	601	115	0.5	nd	0.6	16	70	17	9	29	179	3500	53	33	384	201	19	nd	nd
5/8.4.II Agu River S 4.5-7 cm	4900	15400	5900	12400	108100	35600	249	185	140	31	<.4	nd	<.3	6	61	9	9	29	157	4200	78	27	361	164	21	nd	nd
6/8.4.IV Agu R. S. oxbow 20-23cm	11200	51400	7600	58000	81900	35900	553	202	554	72	<.4	nd	1.1	7	31	34	6	15	105	1700	45	24	530	473	9	nd	nd
20-60 µm	14300	46700	6000	53400	70300	21600	363	124	362	37	<.4	nd	0.4	<4	15	20	3	7	78	1300	18	13	538	471	6	nd	nd
Mean	8010	28807	7242	30139	80994	40004	528	211	530	79	0.52	166	0.69	8.3	48	24	10.3	21	145	2753	44	26	415	330	12.6	1.6	2464
SD	3218	11610	1831	23842	14915	11012	254	68	289	36	0.30	81	0.45	5.8	14	13	4.5	9	35	801	16	7	100	139	3.7	1.5	2160
Median	8200	30300	7400	24800	81100	39500	510	204	529	80	0.50	160	0.70	7.0	46	23	10.0	19	139	2600	41	27	420	313	12.0	0.9	2100

\+ INAA analysis
* hydride ICP analysis

Table A 3. Analytical results for floodplain sites in the Middle and Lower Fly River region where deposition of mine-derived material occurs. Sediments with no grain size given are <20 µm. Statistics have been calculated for the fractions <100 µm only.

sample	temp.	pH	cond.	oxy.	ss	Na	K	Ca	Mg	Sr	Fe	Mn	Zn	Cd	Cu	Pb	Mo	HCO_3	SO_4
	C°		µS/cm	%	mg/l	µg/l												mg/l	
W1/22.10. Fly R,/Obo	26.2	7.5	148	65	400	1570	nd	41200	1450	231	130	42	11	<.1	18	<.5	<10	nd	nd
W11/22.10. Fly R./Obo	26.1	8.0	145	64	159	2270	nd	34300	1520	243	<10	8	7	0.1	14	<.5	15	nd	nd
W1/24.10. Fly R./Obo	26.4	7.7	137	60	155	1420	nd	26000	1190	161	17	9	13	<.1	10	nd	13	nd	nd
W2/28.10. Fly R./Kibuz	27.3	7.3	172	66	520	1750	nd	39900	1400	200	<10	14	<5	<.1	10	nd	14	nd	8.1
W2/16.2. Fly R./Obo	29.3	7.9	121	73	105	1380	nd	22700	1070	146	25	11	9	<.1	20	<.5	<5	72	3.5
W1/21.2. Fly R./Kemea L.	28.9	7.8	119	85	52	1320	nd	24400	1140	154	339	20	24	0.1	53	<.5	<5	nd	6.0
W2/27.3. Fly R./Obo	29.6	7.8	130	64	133	1300	667	25100	1040	136	65	11	<5	<.1	24	<.5	<5	76	2.5
W5/1.4. Fly R./Obo	30.0	7.7	136	54	35	1430	536	26000	1080	141	34	30	7	0.06	17	<.5	<5	78	nd
W4/3.4. Fly R./Obo	30.2	7.7	151	63	174	1780	563	28300	1290	161	85	36	10	<.1	19	<.5	11	84	nd
W11/10.4. Fly R./Kai L.	26.7	8.1	132	72	305	1420	722	25900	1190	152	11	<5	5	<.1	15	<.5	9	76	nd
Fly R./Obo 28.3.	29.2	7.7	132	60	150	nd	nd	nd	nd	nd	nd	nd	nd	<.1	16	<.5	nd	nd	nd
Mean	**28.2**	**7.7**	138	66	199	1564	622	29380	1237	172	72	18	9	<.1	20	<.5	8	77	5.0
SD	1.6	0.2	15	8	149	299	87	6654	170	36	102	13	6		12		5	4	2.5
Median	**28.9**	**7.7**	136	64	155	1425	615	26000	1190	158	30	13	8		17		7	76	3.5

sample	temp.	pH	cond.	oxy.	ss	Na	K	Ca	Mg	Sr	Fe	Mn	Zn	Cd	Cu	Pb	Mo	HCO_3	SO_4
	C°		µS/cm	%	mg/l	µg/l												mg/l	
W2/18.10. Ok Tedi, Tedawoim Bridge	18.8	8.1	150	102	2079	2020	nd	30700	1710	233	63	40	<5	0.5	11	2	<10	nd	nd
W1/18.10. Ok Tedi, Tabubil Bridge	21.4	7.8	245	96	3537	2700	nd	47200	2160	338	80	45	<5	<.1	13	<1	<10	nd	nd
W1/14.4. Ok Tedi,	nd	7.6	300	94	5889	4430	1790	55700	2550	388	46	80	7	<.1	32	<1	17	158	16.0
W2/14.4. Tabubil bridge	nd	8.3	242	97	4513	4370	1780	44700	2430	337	63	27	<5	<.1	21	<1	17	124	16.6
W3/29.2. Ok Tedi/Ok Menga	nd	7.9	204	nd	10610	3660	nd	35500	2140	316	10	33	<5	<.1	6	<1	26	120	9.4
W1/29.2. Ok Menga	nd	7.9	186	nd	146	1080	nd	38400	2330	418	96	11	19	<.1	<2	<1	<5	nd	1.5
W2/29.2. creek/Ok Menga	nd	7.7	197	nd	2	2720	nd	37100	1210	146	54	17	8	<.1	<2	nd	<5	nd	1.6

Table A4. Analyses of Fly River and Ok Tedi waters. Medians, means and standard deviation only given where appropriate.

sample	temp.	pH	cond.	oxy.	ss	Na	K	Ca	Mg	Sr	Al	Fe	Mn	Zn	Cd	Cu	Pb	Mo	HCO_3	NH_4	NO_2	HS	SO_4	DOC
	C°		µS/cm	%	mg/l	µg/l													mg/l					
W2/30.3. Lake Daviambu Creek	36.0	4.8	18	144	11	1890	96	1360	410	11	155	356	49	17	<.1	<2	<1	<5	2	0.50	0.016	<.005	0.03	16
W3/30.3. Lake Daviambu W	34.5	5.7	43	145	nd	1960	<20	6420	549	32	<50	89	<5	<5	<.1	<2	<1	<5	20	0.30	<.002	nd	0.19	13
W2/4.4. Tamu Creek mouth/Fly	29.2	6.0	45	5	nd	1560	146	7190	672	42	<50	182	26	19	0.04	5	<1	<5	21	0.40	0.004	0.01	0.92	11
W1/5.4. Bai Lagoon C	29.4	6.2	27	65	13	1020	186	5890	371	34	77	272	<5	13	<.1	6	<1	<5	16	0.60	0.025	0.005	0.3	10
W3/5.4. Kemea Lagoon W	29.6	5.6	18	40	30	1220	82	2010	496	18	72	195	31	15	0.04	6	<1	<5	6	0.30	0.012	0.015	0.15	13
W4/5.4. Kemea Lagoon E	30.6	5.4	14	77	NF	1020	62	1080	418	13	165	1940	32	<5	<.1	<2	<1	<5	3	0.50	0.003	nd	0.23	11
W2/7.4. Lake Kongun N	31.2	6.4	22	102	NF	741	131	3350	349	21	102	2000	27	<5	<.1	<2	<1	<5	12	0.10	nd	nd	nd	6
W3/7.4. Lake Kongun S	28.6	5.8	26	3	NF	693	199	3960	376	24	83	2100	31	<5	0.2	3	<1	<5	13	0.15	0.010	nd	nd	7
W4/7.4. Lake Kongun	28.2	5.8	28	5	nd	715	206	4240	372	24	<50	72	<5	7	<.1	4	<1	<5	14	0.15	0.003	0.02	0.38	8
W2/8.4. Agu Lake	31.4	6.5	44	67	nd	1150	392	7870	499	47	62	137	<5	<5	<.04	4	<1	<5	24	0.14	nd	nd	nd	7
W1/9.4. Kai Lagoon SW	29.2	6.4	30	65	10	1130	254	4380	476	24	<50	241	<5	<5	<.1	2	<1	<5	16	0.02	nd	nd	0.58	7
W11/9.4. dto.					NF	1120	282	4350	486	23	<50	1210	8	5	<.1	6	<1	<5						8
W1/11.4. Lake Bosset SW	29.3	6.0	21	57	NF	1170	337	3380	484	23	65	2270	11	<5	<.1	4	<1	<5	13	0.15	0.012	0.015	0.4	8
W3/11.4. Lake Bosset NW	28.7	6.4	38	50	19	1120	234	6200	521	36	<50	124	<5	<5	<.1	4	<1	<5	21	0.20	0.025	0.015	0.67	6
W2/20.2. Bai Lagoon W	30.5	6.5	21	98	39	1280	nd	3060	284	23	nd	585	7	<5	<.1	3	<1	<5	10	nd	nd	nd	0.2	nd
W1/23.2. L. Bosset Creek	31.1	5.9	32	37	22	1940	nd	3980	875	36	nd	1440	<5	10	<.1	3	<1	<5	11	nd	nd	nd	nd	nd
Mean	30.6	6.0	28.5		20	1230	188	4295	477	27	67		15.4		<.1		<1	<5	13	0.27			0.37	9.4
SD	2.2	0.5	10.0		11	409	107	1990	141	10	48		15.1						6	0.18			0.26	3.0
Median	30.0	6.0	27.0		19	1140	193	4110	480	24	64		7.5						13	0.20			0.27	8.0

Table A5. Analyses of Fly River floodplain waters. Medians, means and standard deviation only given where appropriate. NF means unfiltered water sample.

sample	temp.	pH	cond.	oxy.	ss	Na	K	Ca	Mg	Sr	Al	Fe	Mn	Zn	Cd	Cu	Pb	Mo	HCO_3	NH_4	NO_2	HS	SO_4	DOC
	°C		µS/cm	%	mg/l	µg/l													mg/l					
W2/15.2. Kinda Ch. flow -> river	28.7	6.8	46	47	11	1340	nd	7520	486	47	nd	302	23	34	<.1	8	<1	<5	20	nd	nd	nd	0.8	nd
W2/3.4. Jasetei Creek	29.7	6.4	95	14	nd	1840	144	17300	1130	100	<50	335	38	15	<.1	2	<1	<5	52	0.5	0.015	0.005	1.8	9
W3/15.2. Lower Fly/Ogwa	28.2	7.8	151	75	558	2280	nd	26400	2210	200	nd	44	<5	<5	<.1	6	<1	6	nd	nd	nd	nd	nd	nd
W1/15.2. Lower Fly/Ogwa	28.6	7.6	153	74	214	2320	nd	26700	2120	198	nd	37	8	<5	<.1	7	<1	<5	nd	nd	nd	nd	nd	nd
W3/3.4. Lower Fly/Ogwa	29.9	7.7	153	65	nd	2350	405	27600	2120	175	<50	20	11	<5	<.1	5	<1	<5	83	<.05	nd	nd	7.3	7
W1/3.4. Strickland River	29.2	7.7	162	74	184	3360	426	27400	2920	187	119	43	<5	14	<.1	<2	<1	<5	83	nd	nd	nd	9.9	6
W1/16.2. Strickland River	27.5	7.6	156	77	1164	2840	nd	26200	2670	213	nd	242	8	9	<.1	2	<1	<5	84	nd	nd	nd	8.8	nd
W1/27.3. floodplain pond Obo	32.8	6.5	106	39	12	1460	845	19800	987	113	<50	387	26	23	<.1	8	<1	<5	63	0.3	0.005	0.01	0.57	9
W2/28.3. floodplain seepage/Obo	28.0	6.4	280	29	46	2480	811	50000	2840	277	<50	3845	971	18	0.08	<2	<1	10	162	0.6	0.008	0.02	3.0	11
W1/26.10. floodplain seepage/Obo	29.0	6.6	661	29	nd	2440	nd	135700	5360	826	nd	<10	2290	21	0.3	14	<1	65	nd	nd	nd	nd	nd	nd
W2/26.10. floodplain seepage/N'Obo	nd	6.4	264	41	nd	1430	nd	52300	1960	297	nd	316	675	19	0.2	<1	<1	<10	nd	nd	nd	nd	nd	nd
W2/1.4. floodplain seepage/N'Obo	27.8	6.2	166	11	nd	1590	371	30600	1870	168	<50	810	249	19	nd	6	nd	9	91	0.25	0.003	0.15	1.9	11
W1/28.10. pond/Fly N'Obo flow ->Fly	28.8	6.6	132	38	18	1490	nd	25600	1180	153	nd	145	5	24	<.1	22	2	12	nd	nd	nd	nd	nd	nd
W1/29.10. pond/ floodplain Obo	nd	5.8	67	42	nd	1720	nd	13200	341	82	nd	48	49	34	<.1	4	<1	<5	nd	nd	nd	nd	nd	nd
W2/29.10. floodplain drain Obo	nd	7.0	158	nd	nd	1950	nd	31400	920	191	nd	<10	<5	<5	<.1	3	<1	<10	nd	nd	nd	nd	nd	nd
W1/30.10. floodplain seepage N'Obo	nd	6.1	151	43	nd	1610	nd	30700	1760	209	nd	600	247	24	0.3	15	2	<10	nd	nd	nd	nd	0.9	nd
W1/30.3. Lake Daviambu channel	28.9	6.5	106	2	58	1350	350	20500	1040	113	<50	114	122	8	0.05	5	<1	<5	65	0.15	0.015	0.02	0.57	5
W1/1.4. Lake Daviambu channel	28.6	6.4	95	4	nd	1340	289	18200	950	95	144	497	38	26	<.1	4	<1	<5	55	0.15	0.010	0.02	nd	10
W2/22.10. L. Daviambu channel	26.2	7.6	150	63	445	1520	nd	28200	1320	176	nd	15	10	<5	<.1	10	<1	11	nd	nd	nd	nd	nd	nd
W2/24.10. L. Dav. channel	26.5	7.8	137	69	212	1390	nd	26000	1210	162	nd	<10	<5	7	<.1	3	<1	12	nd	nd	nd	nd	nd	nd
W1/19.2. Lake Daviambu NE	29.4	7.3	140	70	55	1640	nd	26300	1260	171	nd	42	<5	7	<.1	14	nd	9	nd	nd	nd	nd	6.2	nd
W4/30.3. Lake Daviambu NE	32.2	6.8	81	95	nd	1420	234	14800	885	83	<50	195	28	<5	<.1	<2	<1	<5	47	0.15	0.005	nd	nd	nd

(cont.)

sample	temp.	pH	cond.	oxy.	ss	Na	K	Ca	Mg	Sr	Al	Fe	Mn	Zn	Cd	Cu	Pb	Mo	HCO_3	NH_4	NO_2	HS	SO_4	DOC
	°C		µS/cm	%	mg/l	µg/l													mg/l					
W3/1.4. Lake Daviambu NE	30.0	5.9	80	17	nd	1330	241	14100	838	79	<50	111	23	19	<.04	<2	<1	<5	46	0.4	0.012	0.01	0.4	11
W4/22.10. L. Daviambu E	nd	8.0	nd	86	114	1740	nd	32300	1390	197	nd	<10	<5	11	<.1	14	<1	15	nd	nd	nd	nd	nd	nd
W5/22.10. L. Daviambu C	29.0	8.9	155	144	2	1910	nd	30700	1380	189	nd	<10	<5	13	<.1	5	<1	<10	nd	nd	nd	nd	nd	nd
W5/30.3. Lake Daviambu C	nd	7.4	78	77	nd	1300	<20	14800	823	74	<50	141	<5	19	<.1	5	<1	<5	45	0.15	0.000	0.01	nd	9
W4/1.4. Lake Daviambu SE	32.1	8.2	71	140	nd	1340	124	12200	633	57	<50	11	<5	<5	<.1	4	<1	<5	38	0.15	0.002	0.01	nd	8
W3/24.10. L. Daviambu SE	30.1	8.4	153	127	39	1450	nd	30400	1250	183	nd	<10	<5	16	<.1	9	nd	<10	nd	nd	nd	nd	nd	nd
W4/24.10. L. Daviambu SE	32.8	7.4	170	115	5	2700	nd	29900	1580	200	nd	185	<5	14	<.1	5	nd	17	nd	nd	nd	nd	nd	nd
W5/24.10. L Dav. island SE	31.7	7.0	167	53	10	3750	nd	32300	1790	217	nd	27	<5	8	0.1	5	<1	<10	nd	nd	nd	nd	2.6	nd
W6/24.10. L. Daviambu S	29.7	8.5	151	106	1	2400	nd	28600	1360	186	nd	62	<5	9	<.1	<2	<1	13	nd	nd	nd	nd	nd	nd
W7/22.10. L. Daviambu S	31.2	9.1	132	132	1	3420	nd	22500	1290	147	nd	97	<5	17	<.1	8	nd	12	nd	nd	nd	nd	nd	nd
W6/22.10. L. Daviambu W	29.5	8.4	159	100	8	1880	nd	30500	1390	193	nd	<10	<5	21	<.1	5	<1	<10	nd	nd	nd	nd	nd	nd
W9/22.10. L. Daviambu W	30.2	9.1	135	172	2	1620	nd	24900	1360	170	nd	24	<5	<5	<.1	2	<1	<10	nd	nd	nd	nd	nd	nd
W4/26.10. floodplain pond/ Lake Pangua, flow -> Fly	nd	8.1	142	116	22	1440	nd	28200	1240	171	nd	31	<5	9	<.1	12	<1	<5	nd	nd	nd	nd	nd	nd
W5/28.10. floodplain pond/ Lake Pangua	31.8	7.1	158	113	19	1500	nd	24200	1140	148	nd	58	<5	<5	<.1	9	<1	<10	nd	nd	nd	nd	nd	nd
W4/28.10. Komovai shortcut/ L. Pangua, flow -> Fly	nd	7.4	423	107	25	2390	nd	80200	3940	530	nd	21	282	12	<.1	19	1	49	nd	nd	nd	nd	8.5	nd
W1/31.10. pond, L. Pangua channel	34.1	7.0	209	70	16	1660	nd	41900	1690	247	nd	83	180	17	<.1	9	<1	<10	nd	nd	nd	nd	nd	nd
W4/31.10. Lake Pangua/channel flow -> Fly	29.5	8.0	147	102	13	1730	nd	28800	1330	174	nd	26	<5	<5	<.1	13	<1	7	nd	nd	nd	nd	nd	nd
W1/4.4. Lake Pangua NE	32.5	7.0	80	105	nd	1840	412	14300	984	82	91	647	<5	16	<.1	6	<1	<5	nd	0.25	nd	nd	nd	nd
W2/19.2. Lake Pangua NE	30.0	7.7	152	83	24	1960	nd	27600	1410	179	nd	88	25	16	<.1	9	<1	6	nd	nd	nd	nd	nd	nd
W2/31.10. L. Pangua NW	32.2	8.9	117	170	9	2110	nd	21500	1180	128	nd	114	<5	8	<.1	6	<1	7	nd	nd	nd	nd	nd	nd
W3/31.10. Lake Pangua SE	30.4	8.1	149	108	6	1800	nd	28400	1370	176	nd	23	8	<5	<.1	12	<1	<10	nd	nd	nd	nd	nd	nd
W2/30.10. Lake Tamu III	33.5	8.7	115	174	2	2210	nd	20200	1140	128	nd	282	<5	8	<.1	7	1	<5	nd	nd	nd	nd	nd	nd
W3/30.10. Lake Tamu I	31.7	7.8	111	108	6	2020	nd	20800	1240	134	nd	80	<5	20	<.1	6	<1	<10	nd	nd	nd	nd	2.8	nd
W4/30.10. Tamu Creek, E' L. Tamu I	31.0	7.5	127	107	5	1600	nd	25100	1260	152	nd	18	<5	6	<.1	11	<1	6	nd	nd	nd	nd	nd	nd
W5/30.10. channel E' L. Tamu III	34.2	7.4	117	103	7	2170	nd	22200	1200	133	nd	478	30	6	<.1	6	<1	13	nd	nd	nd	nd	nd	nd

(cont.)

sample	temp.	pH	cond.	oxy.	ss	Na	K	Ca	Mg	Sr	Al	Fe	Mn	Zn	Cd	Cu	Pb	Mo	HCO_3	NH_4	NO_2	HS	SO_4	DOC
	°C		µS/cm	%	mg/l	µg/l													mg/l					
W3/26.10. pond/Lake Kibuz	nd	7.2	170	nd	13	1560	nd	35900	1380	209	nd	15	<5	7	<.1	11	<1	13	nd	nd	nd	nd	nd	nd
W3/28.10. floodplain pond S' L. Kibuz	30.7	6.7	170	60	20	1580	nd	35200	1350	198	nd	170	<5	9	<.1	11	<1	24	nd	nd	nd	nd	nd	nd
W3/19.2. old river bed, flow -> river	30.3	7.6	148	73	27	1480	nd	27300	1260	167	nd	1110	33	69	<.1	45	2	20	nd	nd	nd	nd	nd	nd
W3/20.2. Bai Lagoon C	30.1	7.0	43	96	41	1180	nd	9090	511	59	nd	1090	14	66	<.1	22	nd	8	nd	nd	nd	nd	nd	nd
W4/20.2. Bai Lagoon/channel flow river -> lake	28.8	7.5	111	71	69	1200	nd	22000	1080	140	nd	593	17	89	nd	58	3	<5	nd	nd	nd	nd	nd	nd
W2/5.4. Bai Lagoon C	29.3	6.4	29	63	NF	1030	124	5790	423	34	358	1630	44	8	<.04	18	1	<5	17	0.55	0.004	nd	nd	12
W5/20.2. Kemea Lagoon C	29.1	6.7	90	32	13	1000	nd	15900	845	97	nd	177	11	35	<.1	10	<1	8	54	nd	nd	nd	2.1	nd
W6/20.2. Kemea Lagoon/channel	28.3	6.8	123	14	22	1120	nd	22700	1050	140	nd	156	6	28	<.1	19	<1	15	nd	nd	nd	nd	nd	nd
W4/11.4. Lake Bosset/channel	28.7	7.0	114	29	nd	1120	618	20700	995	118	<50	45	<5	9	0.06	9	<1	<5	62	0.10	0.040	0.01	3.2	5
W5/11.4. Lake Bosset/channel	31.8	6.6	42	110	12	744	295	7650	518	46	<50	166	<5	6	0.06	18	<1	<5	24	0.25	0.003	0.005	0.24	12
W1/25.2. Bosset channel, flow -> river	30.2	7.4	135	77	29	1440	nd	25500	1210	156	nd	110	<5	11	<.1	11	<1	12	nd	nd	nd	nd	nd	nd
W2/25.2. Bosset channel, floodplain runoff	25.8	5.9	71	3	6	1160	nd	12200	715	80	nd	2040	71	38	nd	24	2	<5	37	nd	nd	nd	0.4	nd
W2/23.3. Lake Bosset SW/village	31.3	7.8	62	109	14	1500	nd	12400	885	85	nd	325	<5	17	<.1	7	nd	8	nd	nd	nd	nd	nd	nd
W1/24.2. Lake Bosset NW	31.1	6.7	44	98	6	960	nd	7390	608	55	nd	1160	<5	15	<.1	8	<1	<5	nd	nd	nd	nd	nd	nd
W2/24.2. Lake Bosset N	33.0	6.6	47	98	10	1390	nd	9590	1210	66	nd	798	<5	22	<.1	8	<1	<5	nd	nd	nd	nd	nd	nd
W3/24.2. Lake Bosset N	31.5	7.0	57	99	16	1020	nd	10000	710	71	nd	975	<5	15	<.1	8	<1	7	nd	nd	nd	nd	nd	nd
W2/11.4. Lake Bosset C	29.0	6.8	62	41	nd	1100	385	11100	733	62	<50	491	<5	14	<.1	8	<1	<5	35	0.12	0.016	0.01	nd	8
W4/24.2. Lake Bosset C	31.6	7.7	109	107	14	1420	nd	18300	1040	119	nd	71	<5	<5	<.1	4	<1	<5	50	nd	nd	nd	3.3	nd
W3/25.2. L. Bosset E	nd	7.5	119	nd	22	1760	nd	23000	1180	146	nd	227	10	18	<.1	12	<1	10	nd	nd	nd	nd	4.0	nd
W4/25.2. L. Bosset E	nd	7.7	nd	nd	34	1540	nd	15700	1000	106	nd	231	<5	25	<.1	9	<1	7	nd	nd	nd	nd	nd	nd

(cont.)

sample	temp.	pH	cond.	oxy.	ss	Na	K	Ca	Mg	Sr	Al	Fe	Mn	Zn	Cd	Cu	Pb	Mo	HCO_3	NH_4	NO_2	HS	SO_4	DOC
	°C		µS/cm	%	mg/l	µg/l													mg/l					
W1/7.4. floodplain pool/Fly near L.Kongun	27.2	6.2	81	14	nd	1000	3390	12800	892	75	363	319	13	11	0.1	52	<1	<5	41	0.35	0.020	0.025	nd	9
W10/7.4. dto.					NF	944	3440	12800	877	75	930	2800	125	15	0.1	106	3	<5					3.8	9
W1/8.4. Agu Lake N	29.4	6.6	54	63	nd	1090	282	9450	593	58	<50	156	8	6	0.12	9	<1	<5	29	0.15	0.007	0.005	1.6	12
W3/8.4. Agu Lake/Mipan	32.2	7.2	111	86	nd	1270	667	20200	953	119	<50	49	4	1.3	0.08	16	<1	<5	62	0.10	0.014	0.01	3.5	7
W4/8.4. Agu Lake S	30.6	7.0	74	75	NF	1140	447	13200	760	80	330	817	27	6	<.1	36	2	<5	40	nd	nd	nd	1.3	5
W5/8.4. Agu Lake E	32.0	7.5	90	92	NF	1330	474	16100	840	96	131	393	<5	<5	<.1	18	<1	<5	49	0.05	nd	nd	nd	4
W2/9.4. Kai Lagoon S	28.6	6.4	75	33	nd	1120	433	13200	880	77	<50	238	<5	6	<.04	4	<1	<5	41	0.03	0.004	nd	nd	nd
W3/9.4. Kai Lagoon S	26.4	7.8	125	58	92	1010	598	24400	1050	138	<50	33	<5	<5	<.04	15	<1	<5	73	nd	nd	nd	3.6	4
W30/9.4. dto.					NF	1020	715	24600	1180	140	772	1140	31	7	<.1	88	6	<5					nd	5
W4/9.4. Kai Lagoon N	28.0	7.1	120	26	NF	1170	660	21900	1080	124	486	936	16	5	0.06	39	1.3	<5	66	0.03	0.016	0.01	1.2	10
W5/9.4. Kai Lagoon N	29.8	7.0	72	68	NF	967	344	13000	720	73	68	484	8	<5	<.1	9	<1	<5	40	0.05	0.015	0.01	nd	8
Mean	30.2	7.3	130	77	36	1587	540	21390	1225	150	102	357	82	15		12		8	53	0.21	0.01	0.02	2.5	9.3
SD	2.0	0.8	89	42	72	541	657	8372	725	111	139	590	308	15		11		10	28	0.16	0.01	0.03	2.0	2.4
Median	30.1	7.1	119	77	15	1480	385	21900	1140	138	25	145	3	12		9		5	47	0.15	0.01	0.01	2.1	9.0

Table A6. Analytical results for mixed waters. Medians, means and standard deviation calculated only for filtered waters of the Middle Fly region.

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