UNEP

REGIONAL SEAS

# J.C. Pernetta:

# Potential impacts of mining on the Fly River

UNEP Regional Seas Reports and Studies No. 99
SPREP Topic Review No. 33

Prepared in co-operation with

SPC SPEC ESCAP

UNEP 1988

# PREFACE

Sixteen years ago the United Nations Conference on the Human Environment (Stockholm 5-16 June 1972) adopted the Action Plan for the Human Environment, including the General principles for Assessment and Control of Marine Pollution. In the light of the results of the Stockholm Conference, the United Nations General Assembly decided to establish the United Nations Environment Programme (UNEP) to "serve as a focal point for environmental action and co-ordination within the United Nations system" (General Assembly resolution 2997 (XXVII) of 15 December 1972). The organizations of the United Nations system were invited "to adopt the measures that may be required to undertake concerted and co-ordinated programmes with regard to international environmental problems", and the "intergovernmental and non-governmental organizations that have an interest in the field of the environment" were also invited "to lend their full support and collaboration to the United Nations with a view to achieving the largest possible degree of co-operation and co-ordination". Subsequently, the Governing Council of UNEP chose "oceans" as one of the priority areas in which it would focus efforts to fulfill its catalytic and co-ordinating role.

The Regional Seas Programme was initiated by UNEP in 1974. Since then the Governing Coucil of UNEP has repeatedly endorsed a regional approach to the control of marine pollution and the management of marine and coastal resources and has requested the development of regional action plans.

The Regional Seas Programme at present includes ten regions[1] and has over 130 coastal States participating in it. It is conceived as an action-oriented programme having concern not only for the consequences but also for the causes of environmental degradation and encompassing a comprehensive approach to combating environmental problems through the management of marine and coastal areas. Each regional action plan is formulated according to the needs of the region as perceived by the Governments concerned. It is designed to link assessment of the quality of the marine environment and the causes of its deterioration with activities for the management and development of the marine and coastal environment. The action plans promote the parallel development of regional legal agreements and of action-oriented programme activities[2].

The idea for a regional South Pacific Environment Management Programme came from the South Pacific Commission (SPC) in 1974. Consultations between SPC and UNEP led, in 1975, to the suggestion of organizing a South Pacific Conference on the Human Environment. The South Pacific Bureau for Economic Co-operation (SPEC) and the Economic and Social Commission for Asia and the Pacific (ESCAP) soon joined SPC's initiative and UNEP supported the development of what became known as the South Pacific Regional Environment Programme (SPREP) as part of its Regional Seas Programme.

The Conference on the Human Environment in the South Pacific was convened in Rarotonga, from 8 to 11 March 1982. It adopted: the South Pacific Declaration on Natural Resources and Environment; the Action Plan for Managing the Natural Resources and the Environment in the South Pacific Region; and agreed on the administrative and financial arrangements needed to support the implementation of the Action Plan and on the workplan for the next phase of SPREP[3].

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1 Mediterranean, Kuwait Action Plan Region, West and Central Africa, Wider Caribbean, East Asian Seas, South-East Pacific, South Pacific, Red Sea and Gulf of Aden, Eastern Africa and South Asian Seas.

2 UNEP: Achievements and planned development of UNEP's Regional Seas Programme and comparable programmes sponsored by other bodies. UNEP Regional Seas Reports and Studies No. 1, UNEP, 1982.

3 SPC/SPEC/ESCAP/UNEP: Action Plan for managing the natural resources and environment in the South Pacific Region (UNEP Regional Seas Reports and Studies No. 29, UNEP, 1983.

The legal framework of the Action Plan was developed through several meetings of legal and technical exports from the South Pacific Region. It was adopted by the plenipotentiary meeting of the High level Conference on the Protection of the Natural Resources and Environment of the South Pacific Region convened by the Secretary-General of SPC in Noumea, New Caledonia, from 17 to 25 November 1986.

The legal framework adopted by the Conference consists of the following instruments[4].

Convention for the Protection of the Natural Resources and Environment of the South Pacific Region;

Protocol Concerning Co-operation in Combating Pollution Emergencies in the South Pacific Region;

Protocol for the Prevention of Pollution of the South Pacific Region by Dumping.

The convention is a comprehensive umbrella agreement for the protection, management and development of the marine and coastal environment of the South Pacific Region. It lists the sources of pollution which require control: pollution from ships, dumping, land-based sources, seabed exploration and exploitation, atmospheric discharges, storage of toxic and hazardous wastes, testing of nuclear devices, mining and coastal erosion. It also identifies environmental management issues requiring regional co-operation: specially protected areas, pollution in cases of emergency, environmental impact assessment, scientific and technical co-operation, technical assistance, and liability and compensation for damage resulting from pollution.

Considerable support to the implementation of the Action Plan is received from a number of South Pacific research and training institutions. Periodic consultative meetings of these institutions are convened to discuss the environmental problems of the region which may be mitigated or solved through the Action Plan and to identify activites which may contribute toward the goal of SPREP. The present report was commissioned by UNEP as such a contribution. The report has been prepared by a number of scientists from the University of Papua New Guinea and the sponsors of the study would like to express their gratitude to the authors of the report and to their institutions.

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[4] Convention for the protection of the natural resources and environment of the South Pacific Region and related protocols, UNEP 1987.

## EDITORS' NOTE

This volume brings together a number of papers, some of which were originally presented to the 3rd Consultative Meeting of Research and Training Institutions held in Guam in June 1986. Also included are papers derived from related work undertaken by scientists of the University of Papua New Guinea as part of their research programmes. Financial support for these studies was derived from various sources including the United Nations Environment Programme (UNEP via the South Pacific Regional Environment Programme (SPREP), and the University of Papua New Guinea Research Committee.

These papers represent an important contribution in that they document the state of the environment prior to the commencement of mining at the large Ok Tedi gold and copper mine. In particular the papers dealing with the Lakes of the middle Fly region represent the sole base-line data for these systems. Ongoing work as part of the SPREP work programme for 1986-1988 is designed to establish what changes if any are detectable in the Fly River and Delta, following the onset of copper production.

In addition to the pre-mining situation an evaluation of the effectiveness of the current company operated Environmental assessment programme is presented, together with an assessment of the toxicity of mine tailings and some predictions concerning the impacts of mining on this system.

It is to be hoped that this volume will provide useful data not only for the specific project examined here but of more widespread applicability to large scale mining projects throughout the Asia-Pacific Region.

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Chairman, ASPEI.

# THE OK TEDI MINE: ENVIRONMENT, DEVELOPMENT AND POLLUTION PROBLEMS.

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ABSTRACT

One of the largest open-cut copper and gold mines in the world commenced operation in May 1984 in the Star Mountains of Papua New Guinea. Waste rock and tailings are currently dumped into the Ok Tedi, a tributary of the Fly River. Mine development has been surrounded by controversy concerning the potential environmental impacts of this major development. This paper outlines the environment in which the mine is situated; details traditional resource use in the area; reviews the history of mine development and evaluates the current situation with regard to waste disposal. Details of the current concerns expressed both within and outside the country about the long-term impacts of this project are also presented. As such this paper serves as a background to the other papers in this volume, which examine issues such as tailings toxicity; heavy metal levels in fish; the complexing capacity of waters in the drainage basin; and the limnology of lakes associated with the Fly River flood plain.

## INTRODUCTION

The Ok Tedi mine is located in an isolated area of the Western Province of Papua New Guinea (Figure 1). It is based on the exploitation of a porphyry ore body with an overlying gold rich cap. This ore body constitutes Mount Fubilan which on cessation of mining activity will cease to exist. The life expectancy of the mine is some thirty years.

Mount Fubilan and the mine itself are located on the borders of the West Sepik and Western Provinces of Papua New Guinea; whilst the Fly River forms, for a short part of its length, the international boundary between the Indonesian Province of Irian Jaya and the Western Province of Papua New Guinea. In addition at the mouth of the Fly the maritime boundary between Australia and Papua New Guinea reaches within a few kilometres of the coast and discharge from the Fly River enter the Torres Straits area of Australian territorial waters.

The Torres Straits are the northern extension of the Australian Great Barrier Reef system. Development of resources in the Torres Straits and control of land based sources of pollution affecting the area are regulated by the Torres Straits Agreement, an international treaty between Australia and Papua New Guinea. In addition, both Papua New Guinea and Australia are signatories to the recently promulgated SPREP Convention, under which Papua New Guinea has certain obligations to Australia in terms of controlling land based pollution which may have impacts on Australian territorial waters. The mine and its impacts have therefore international as well as national implications.

## THE NATURAL ENVIRONMENT

Mount Fubilan is part of the Star mountains complex which rise to a height of 3,000 m above sea level and form part of the central cordillera of the island of New Guinea. This central chain of mountains forms a major divide separating the drainage basins to the North from those to the South. The Star mountains are located in the divide between the catchments of the Fly River to the South and the Sepik River (the largest river in New Guinea) to the North. The Fly River is the second largest river in New Guinea with a discharge of approximately 200,000 million tonnes of water a year.

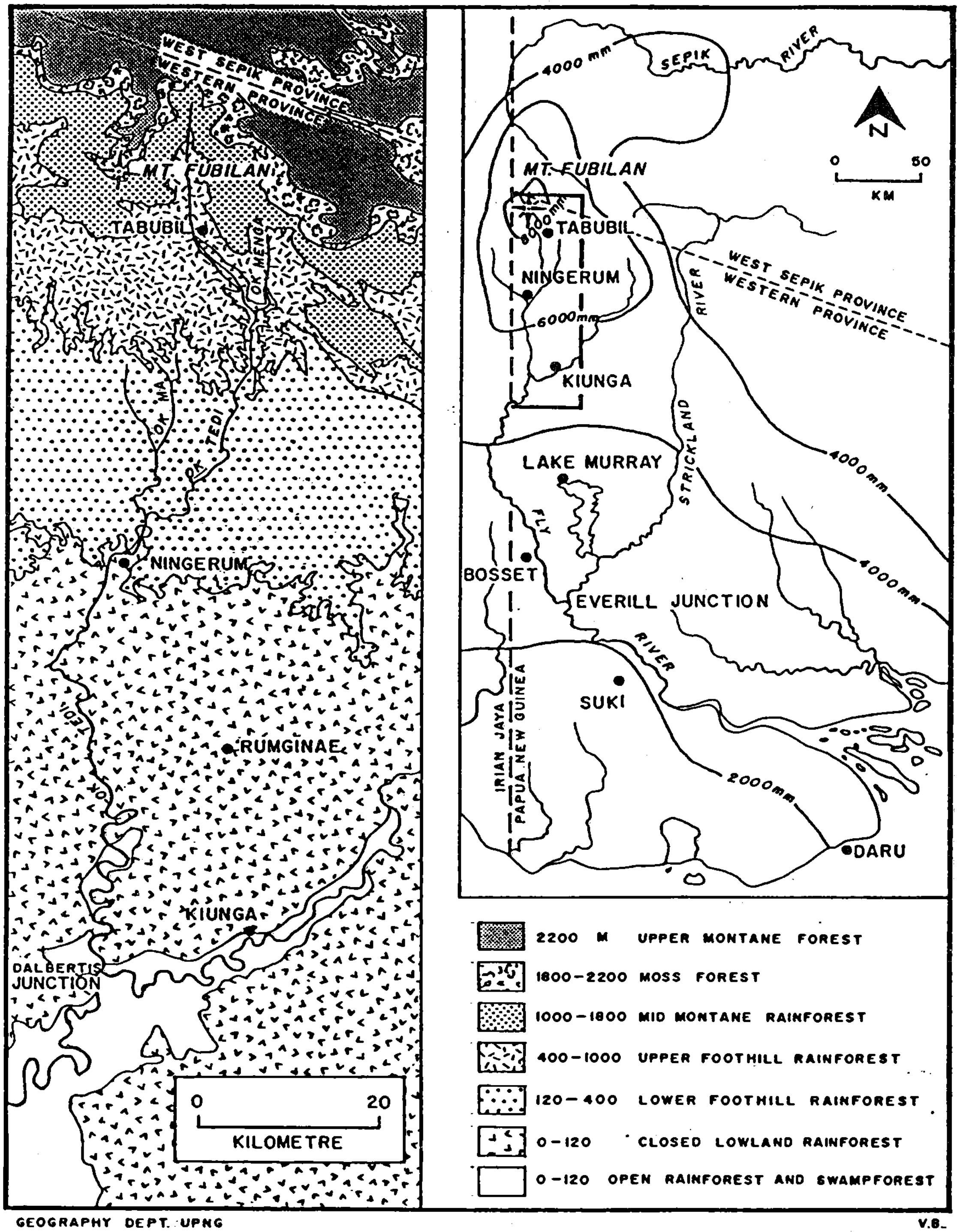


Figure 1. The Fly River area of Papua New Guinea, showing the location of the Ok Tedi Mine at Mt. Fubilan, rainfall and vegetation.

Various aspects of the natural environments and habitats of the Fly River basin and Ok Tedi catchment are summarised in the Ok Tedi Environmental Study (Maunsell, *et al* 1982) which covers vegetation; climate; fauna (both aquatic and terrestrial and the present levels of use); water chemistry and physical limnological parameters; and some data on heavy metal levels in aquatic organisms.

The environs of the mine are humid, tropical with a natural vegetation of moss forest between 1800 and 2200 m and upper montane (cloud) forest beyond. Rainfall is extremely high with over 8 metres/annum being recorded on the mine site, more in the mining town of Tabubil. Mt Fubilan is itself located close to the Ok Tedi and a number of its tributaries. In this region the river is fast flowing with a high natural sediment load. The fish diversity is low (Gwyther, 1980; Roberts, 1978), most fish species in this area are confined to tributaries and branches of the main river and serve as a small but significant protein resource for the people of the area (Hyndman, 1979).

As the Ok Tedi drops towards the mining town of Tabubil the environment changes from the dense tropical rain forests typical of the montane region to a characteristic lower montane forest association of the foothills, still with a closed canopy. At D'Albertis Junction, where the Ok Tedi River joins the Fly, open rain forest and swamp forests commence. These habitats gradually merge with a more open, seasonally flooded savannah vegetation which dominates the middle Fly to the estuary. As one moves down river the climate becomes drier with annual rainfalls at Suki on the lower Fly of under 2000 mm/annum.

The altitude of Kiunga is only around 30 metres above sea level hence for the bulk of its length (800 kilometres of river) the Fly is more slowly moving than the fast flowing Ok Tedi. In this region the river meanders between levees, frequently changing course, forming ox-bow lakes and seasonally flooding the surrounding low-lying land. A major tributary, the Strickland River, joins the Fly below Obo, near Lakes Pangua and Daviumbu. The river finally discharges through its mangrove lined estuary into the Gulf of Papua, an area of extensive commercial prawn and lobster fisheries.

In the middle Fly region the river meanders form a belt around 7 km wide, within an area 16 km wide of low-lying swamp forest and grassland. At Kiunga the main river channel is 200 m wide; at Obo 300 m wide whilst below the junction with the Strickland it spreads to 500 m wide. The lakes of the middle Fly region receive water from the main river channel to varying degrees; in some lakes this may be almost continuously year round; in others only during periods of high water flooding. These lakes have been identified as potentially susceptible to heavy metal pollution from the mine (see Chambers, this volume; Osborne & Polunin, this volume).

## TRADITIONAL RESOURCE USE

Hyndman (1979) and Hyndman and Pernetta (1982) have reviewed traditional terrestrial and aquatic resource use from the headwaters of the Fly to the estuary. In the Ok Tedi region fish, frogs and reptiles form a small portion of the total dietary protein for the Min people. Access to these resources is however, culturally restricted to women and children for whom they form an important component of the diet. Women and children are culturally excluded from eating marsupial mammals which are eaten only by initiated men (Hyndman 1979). This has important implications for the interpretation of the health risk of heavy metal loadings in fish from this area (see Kyle, this volume).

Below Kiunga, the diversity of the fish fauna increases greatly as does the mean size of the species. Fish and aquatic reptiles such as turtles and crocodiles form an important component of the diet of the Ningerum and Boazi peoples (Hyndman & Pernetta, 1982). The Kiwai people of the delta and associated coast rely more on marine fish, turtles and dugong (Hyndman and Pernetta, 1982; Olewale & Sedu, 1979). For the Kiwai peoples, the dugong is an important cultural and trade animal, as well as being a major source of dietary protein (Haddon, 1912). The traditional and commercial exploitation of coastal resources along the coast of Papua are extensively reviewed by Pernetta & Hill (1981).

The Fly River contains five species of turtle, of which two (*Chelodina parkeri* and an unnamed *Elsya* species) are endemic to this river system, and one (*Chelodina siebenrocki* is confined to the Western Province of Papua New Guinea and Southern Irian Jaya. Two crocodiles, *Crocodylus novaeguineae* and *Crocodylus porosus*, occur in the river system: the former is endemic to New Guinea, and both species are on the appendices of the CITES Convention. Crocodiles are farmed commercially at Lake Murray, drained by the Herbert which is a tributary of the Strickland River. Smaller, village based farms are found throughout the area (for a review of crocodile farming in Papua New Guinea see Burgin, 1982). In addition barramundi are fished both commercially (200-250 tonnes/annum) and for subsistence consumption in the lower reaches of the Fly River (for details of this fishery see Anon, 1976).

DEVELOPMENT OF THE MINE

The history and development of the Ok Tedi mine have been reviewed by Jackson (n.d.) in his book "Ok Tedi: the Pot of Gold". The present brief overview is largely based on this masterly review which provides rare insights into the tensions and interactions involved in the development of a multi-national owned mine, from the initial discovery of the ore body.

The first discovery of gold in the Ok Tedi may be attributed to Lawrence Hargreave, captain of the launch Neva who, on its historic exploration of the Fly River, panned some gold flecks from the Ok Tedi above D'Albertis Junction. The Neva was at that time under the direction of the explorer naturalist, Luigi Maria D'Albertis; the date 1876.

Fifty years later in the early 1930s, the area had still been visited by only a few Europeans and an early gold dredging operation near the site of present day Kiunga failed to discover gold. In 1950 the Australian authorities established a permanent patrol post at Kiunga but it was not until 1968 that the first team of field geologists discovered copper anomalies in the sediments of the Ok Tedi system. Late 1968 saw the discovery of ore outcrops, resulting in further work during the succeeding years to "prove" the extent of the ore body. By 1971 the ore body was believed to contain 150 million tonnes of ore with an average grade of 0.9% copper and a cut-off grade of 0.4%. Given the world copper and gold prices at this time Kennecott, the company concerned, estimated that development of the project was marginal, yielding between 14 and 20% return on investment. The company therefore extended exploration in the aıea in an attempt to improve the financial viability of the project by increasing the size of the available ore resources which could be processed through the plant.

Around this time increasing concern was being expressed by prominent Papua New Guineans about the terms of the existing mining agreement under which the Bougainville Copper mine was operating. Under this agreement, Bougainville Copper announced total profits of 158 million Australian dollars in 1973, the largest profits ever made by an Australian listed company to that date. This led to scepticism on the part of Papua New Guineans about Kennecotts claim that Ok Tedi was a marginal development and ultimately to the formulation of a mining policy in the newly independent country of Papua New Guinea which required direct government involvement in the development of major mineral prospects.

Negotiations between Kennecott and its consortium partners on the one hand, and the Papua New Guinean Government on the other, continued through 1974, but by March 1975 negotiations had broken down. At this time world copper prices had slipped and throughout 1976 remained at less than US60 cents per pound. The need for increased Government revenues resulted in the Government deciding to form the Ok Tedi Development Company, to examine the feasibility of developing the resource together with others at Frieda River and Tifalmin. In 1976 the Government signed an agreement with Dampier Mining Company under which Damco would undertake various feasability studies and submit proposals for a mining programme (see Jackson, n.d. for a more detailed evaluation of the terms of this agreement). By late 1976 a consortium, including Amoco (37.5%), BHP (35%) and a group of German Companies (25%), had been put together to underwrite the mine development.

The following four years saw initiation of detailed feasibility studies and intense negotiations between the Government and the mining consortium. These negotiations were ultimately successful due to the explosive rise in mineral prices in 1979 (Copper hit US$1.30/pound and gold US$600/ounce, well above the 90c/pound and $240/ounce considered the lower levels for financial viability of the project.). At the same time the extensive coring had demonstrated that the reserve contained more than 250 million tonnes of ore of copper grades at 0.852%. Additionally these were shown to contain significant quantities of molybdenum and 0.65 grammes of gold per tonne. At least 25 million tonnes of the ore were believed to contain 3 grammes of gold per tonne. In 1980 the Mining (OK Tedi) Supplemental Agreement was signed which allowed construction of the mine infra-structure and paved the way for full-scale development of mining activities.

## ENVIRONMENTAL CONSIDERATIONS

Papua New Guinea is perhaps unique in having environmental management and protection enshrined in its Constitution. The fourth national goal is concerned with natural resources and the environment and reads as follows:

"We declare our fourth goal to be for Papua New Guinea's natural resources to be conserved and used for the collective benefit of us all, and be replenished for the benefit of future generations."

Following from this are a series of directive principles accepted by Parliament in 1977 for application in the development of Papua New Guinea. Such directive principles essentially detail what has become known as "sustainable development" following the production of the Brundtland Commission report in 1987. The state therefore has a recognised role and responsibilities in environmental management, which have been detailed more fully in two acts of Parliament; the Environmental Planning Act and the Environmental Contaminants Act, both passed in 1978.

In any discussion of the environmental impact of this mine it is of interest to note that mine development and operation were specifically exempted from the conditions of these two acts of 1978. Conditions concerning environmental monitoring and regulation of contaminant substances were incorporated into the initial 1976 agreement and reinforced by the 1980 supplemental agreement. The major weakness of the 1976 agreement however was that it specified that the consortium should spend no more than 150,000 Kina on environmental investigations. The pre-construction environmental investigations of the company were therefore totally inadequate. The Government hired its own experts in hydrology, heavy metal pollution and used personnel from its own Bureau of Water Resources and Division of Fisheries to produce additional studies.

Following the 1980 agreement a more extended environmental impact assessment was undertaken by the Company. These investigations were completed by consultants and published as a series of volumes covering aspects of environmental management and recommending programmes for future monitoring (Maunsell, *et al* 1982). Future monitoring was to be restricted to the Ok Tedi system and did not cover investigation of the middle and lower Fly.

Mining was to involve the removal of 30 million tonnes of gold ore, extraction using ferricyanides, and smelting on site to produce gold ingots containing significant quantities of silver. The consortium argued that passing the cyanide residues over a fifty metre weir prior to impoundment in a tailings dam would result in complete oxidation of the cyanide to relatively innocuous compounds. The Government successfully argued that construction of a cyanide destruction tower and monitoring of cyanide levels in the tailings dam should be undertaken.

Copper ore processing was to involve grinding of the ore and mixing with water prior to passing through concentrator systems to form a concentrate of 30% copper. It was calculated that the copper concentrate represented 2.8% of the processed ore. The concentrate was to be piped to Tabubil, partially dried, trucked along 150 kilometres of newly constructed road to Kiunga and barged from there to the mouth of the Fly (870 kilometres), then across the Gulf of Papua to Port Moresby (400 kilometres). The remaining 97.2% of the processed ore, the tailings, (finely ground waste materials from the concentration process) were to be confined in a tailings dam to be maintained in perpetuity by the company (Clause 9.1 of the 1980 supplemental agreement).

All chemicals used in processing the ores are barged from Port Moresby to Kiunga then trucked to the mine site. The accidental loss of 2,700 sixty litre drums of sodium cyanide and a considerable quantity of hydrogen peroxide during 1984 as a result of the swamping of a barge at the mouth of the Fly illustrated the inadequacy of coastal shipping regulations concerning the trans-shipment of hazardous substances. The bulk of the drums of cyanide were never recovered. In addition the accidental release of cyanide rich untreated tailings into the Ok Tedi resulted in fish kills down as far as Kiunga. The environmental accident record of the project is therefore far from good, although the mining company, OTML were quick to argue at the time that the shipping company was responsible for the cyanide loss.

Following its first amendment in 1980 the initial 1976 Ok Tedi agreement has been subject to a series of supplemental agreements (Townsend, 1984). In 1984 the Government agreed to an interim tailings disposal system following a landslide which destroyed the partially built tailings dam in January of that year. This interim disposal scheme involved treating the tailings with hydrogen peroxide to lower cyanide concentration and removal of coarse tailings through hydrocyclones prior to dumping the "fines and slimes" directly into the Ok Tedi river system. Coarse tailings were to be dumped into a nearby river valley, itself a tributary of the Ok Tedi. At this time the costs of the tailings dam, and the unsuitability of the area for dam construction, were both used as arguments by the Company to defer construction. It is interesting to note in this connection that recent television advertising by Ok Tedi Mining Limited states:

"Ok Tedi is one of the worlds largest mines and *lowest cost producers* of copper."

Undoubtedly the failure to construct a tailings dam has contributed to the low costs of production.

On February 28th 1986 the sixth supplemental agreement was signed under which the Company was permitted to proceed with the mining of copper rich ores but to postpone the construction of a permanent tailings dam until 1990. The interim Tailings Disposal Scheme was to continue in operation despite the fact that the state has never set acceptable levels for suspended sediment. In effect the Government has allowed the company to continue unrestricted sediment discharge until January 1990 at which time the state, on the basis of company collected data on the impacts of sediments on the river system, will set the acceptable level for future discharge. The impact of these decisions and evaluation of the Ok Tedi Environmental monitoring programme is presented in the two contributions by Mowbray to this volume.

## CONCLUSIONS

The development of the Ok Tedi mine typifies many projects in developing countries in that environmental and social concerns have been considered secondary to the desire to generate revenue which can be used for development in the fields of education, health and social welfare. Unlike many other such projects however, Ok Tedi's development has involved some consideration of environmental issues; whether enough has been done to safeguard the environment of this unique and fascinating river system remains to be seen. It is clearly the view of some scientists both within and outside Government that greater control measures should have been imposed on the mine operation than have been imposed to date. It is equally clear from a reading of this collection of papers that the absence of adequate base-line data on these tropical ecosystems makes any position vis-a-vis the impacts of this mine open to question and subject to argument. The problem is succinctly summarised by Jackson who writes in connection with this project:

"In our present state of knowledge of the workings of natural systems, it is only on the rarest of occasions that honest environmental experts can 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 which seem to have minimised environmental risks as much as possible in the light of the facts available. But the facts have been very few, casting as much light as might a crescent moon on a man searching a medicine cabinet full of poison for an asprin to relieve a worrisome headache. In the Ok Tedi case, the experts, if they are honest, will be keeping their fingers crossed and their environmental monitoring systems under constant scrutiny." (Jackson, n.d., page 136)

The absence of sound scientific data on potential environmental impacts always favours the developer who can all too easily dismiss the legitimate concerns of scientists as "worst case scenarios for which there exists no supporting data". Interestingly, international mining companies are prepared to accept and defend "worst case scenarios" when projecting ore concentrations, but are not prepared to do the same for environmental considerations, preferring in this instance to take a conservative view of potential impacts.

The financial support of the Universities and of UNEP through SPREP to research and monitoring activities which seek to extend the present knowledge base has resulted in the papers contained in this volume. The issues discussed and the data presented raise serious questions concerning environmental damage; questions which are now being echoed by Australian scientists who fear that the decision to defer construction of a tailings dam may have serious environmental consequences for the Northern Barrier Reef (Wolanski et. al 1984).

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# WATER QUALITY AND SEDIMENT CHEMISTRY OF LAKES BOSSET, PANGUA AND DAVIUMBU

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ABSTRACT

Data concerning the water quality and sediment chemistry of three lakes in the Fly Basin are presented, and compared with Lake Murray a nearby Lake in the catchment of the Strickland River. The three Fly River Lakes are found to have higher trace metal concentrations in their sediments than Lake Murray due to the Porphyry mineralisations in they catchment. The most important difference between the Fly River Lakes and Lake Murray is the relatively high fraction of reducible copper (3.7-8.8% in the Fly River system; 0.8% in Lake Murray). The lakes are nutrient poor, whilst the concentrations of major ions in Lakes Daviumbu and Pangua were found to be higher than those for Lake Bosset, presumably due to less influence of the Fly River in the latter case. Lake Bosset is presumed to show greater seasonal variation in ionic concentrations than the other two lakes due to evaporative concentration.

## INTRODUCTION

Information on the water and sediment chemistry of a lake is important in assessing the biotic status of the water body and how it may be affected by pollution.

This study assesses the water quality of three flood plain lakes and their susceptibility to potential pollution following the operation of the Ok Tedi mine.

Water and sediment samples were collected from Lakes Bosset, Pangua and Daviumbu and the Fly River (Figure 1) on two separate visits to the region from 30 June to 3 July and from 29 November to 1 December, 1984.

## METHODS

Two water samples were collected from open water sites at each lake at a depth of 0.5 m (surface samples) and 0.5 m from the lake bed (bottom samples) (Figure 2). Samples for analysis of nitrogen species (ammonia, nitrite, nitrate and organic nitrogen) were filtered through GFC filters on site. To one 500 mL sample was added 0.5 mL saturated $HgCl_2$ and the other 500 mL sample was acidified with 0.4 mL conc. HCl. Samples for total phosphorus and nitrogen received no treatment. Sediment samples were collected by hand or with an Ekman dredge, transferred using a plastic spoon to plastic bags (Whirlpaks), sealed and frozen.

The following methods of the American Public Health Association (1981) were used for water quality analyses: pH (*in situ*), alkalinity by titration to pH 4.5 with hydrochloric acid (method number 403), chloride by titration with silver nitrate using KSCN indicator (407a), Ca, Mg, Na and K by atomic absorption spectroscopy (303A), sulfate by precipitation with barium chloride (426A), total non-filterable residue by filtration (209A), conductivity at 25 $^{o}C$ by conductivity meter (205) and hardness by titration with EDTA (314B). Bicarbonate concentrations were calculated from the alkalinity. Ammonia, nitrate and nitrite, and soluble reactive phosphorus were measured by the methods of Stainton *et al.* (1977). Total nitrogen, organic nitrogen, and total phosphorus were measured by the methods of Mackereth *et al.* (1978).

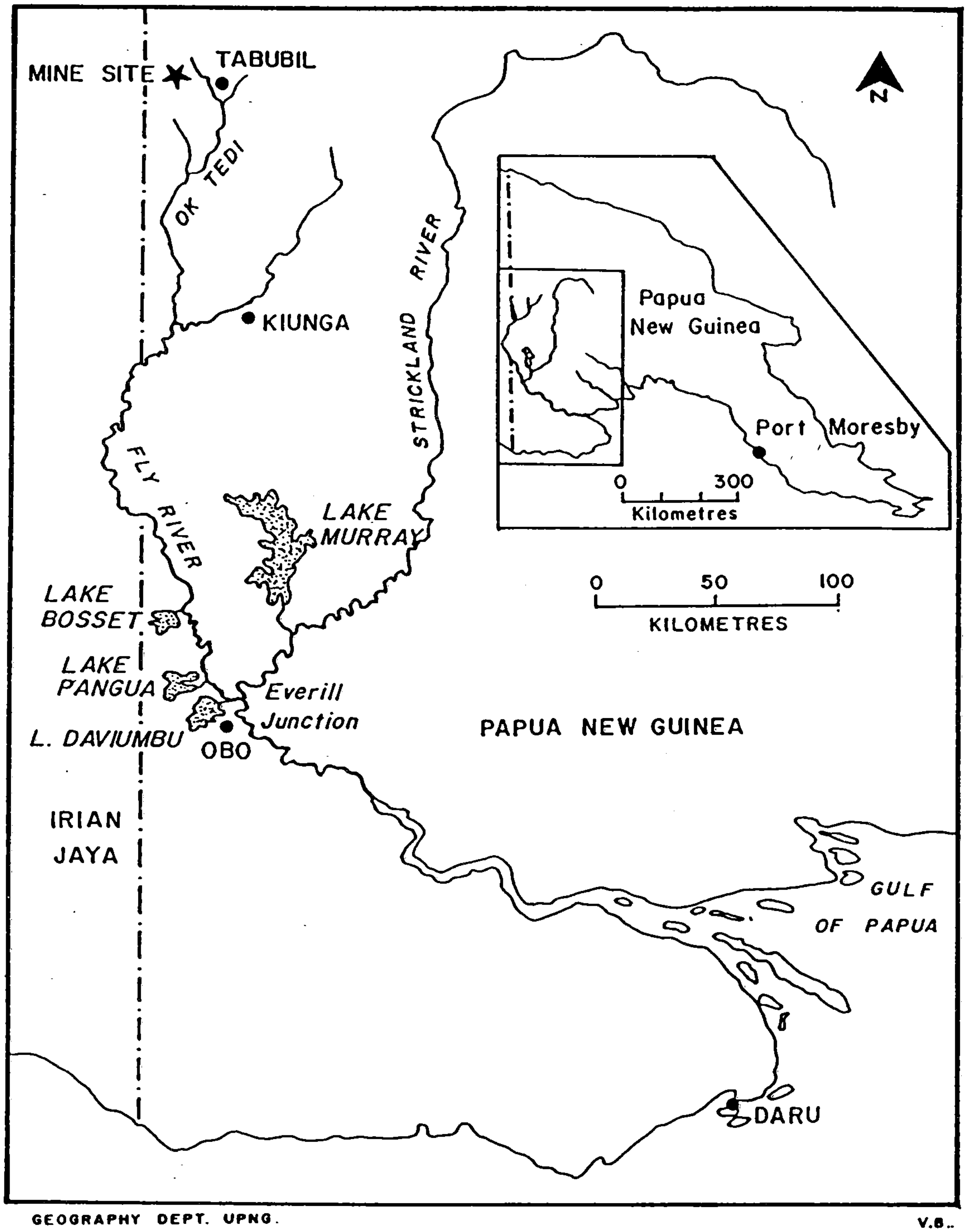


Figure 1. The Fly River Basin, showing the location of the Lakes examined during the present study.

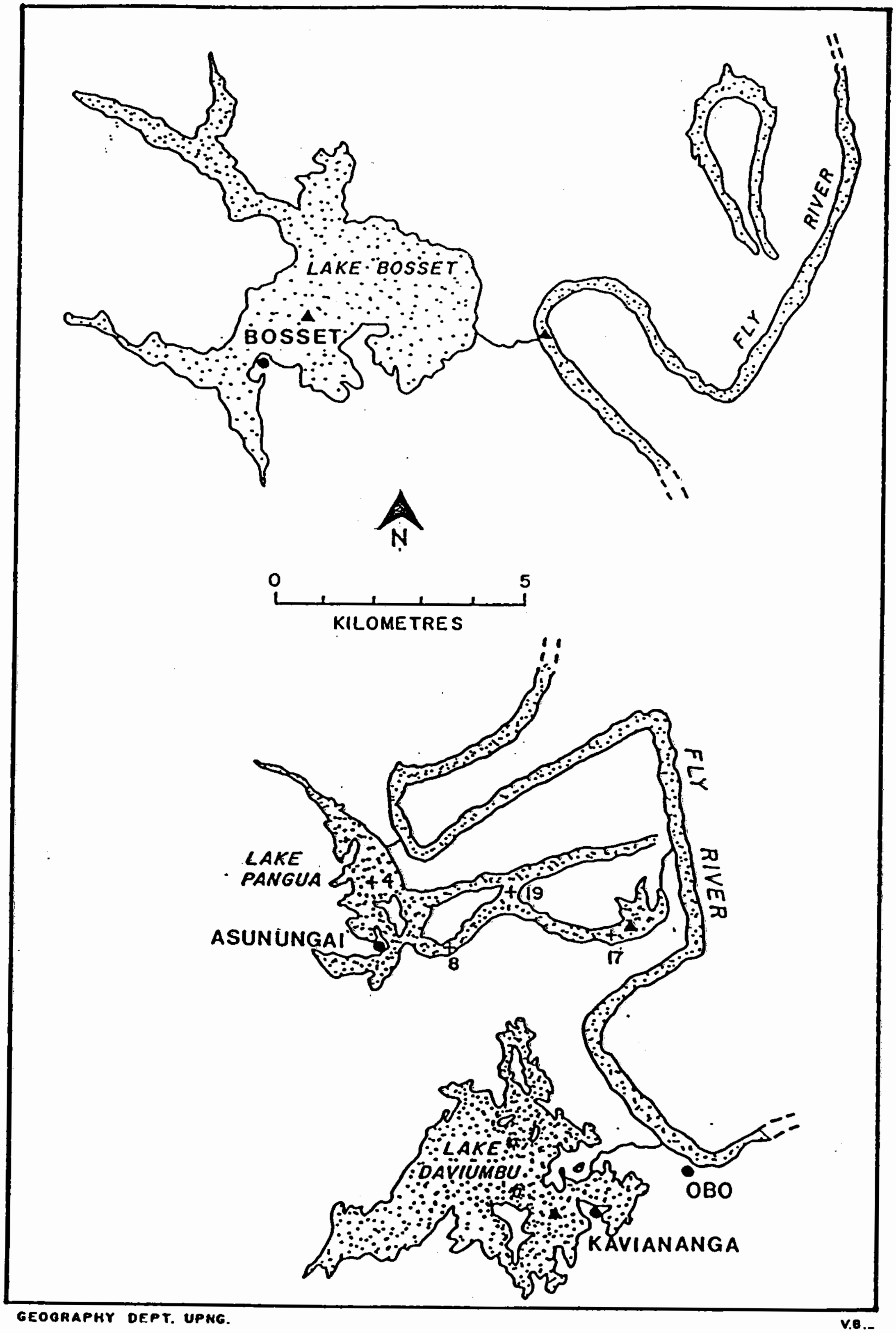


Figure 2. Lakes Bosset, Daviumbu and Pangua showing the location of water and sediment sampling sites.

The sediment samples were analysed for total concentrations of the metals iron, manganese, chromium, zinc, copper, lead and cadmium.

Sediment speciation studies were carried out using the methods of Salomons and Forstner (1980). The sediments were wet-sieved with milli-Q water through a 63 μm nylon sieve prior to analysis, the <63 μm fraction only being used in the speciation studies. The reducible phase was determined by extraction with hydroxylamine hydrochloride ($NH_2OH.HCl$) after adjusting to pH 2 with Aristar nitric acid. This will dissolve amorphous iron oxides/hydroxides and manganese oxides/hydroxides, as well as carbonates. In addition, any exchangeable metal ions will be included in this, the first fraction. Any trace metals that are associated with these sediment phases in any way (e.g. by adsorption, co-precipitation etc.) will be concommittantly released into solution.

The residue from this procedure was then extracted with 30% hydrogen peroxide at 95 °C to isolate the organic fraction. This second residue was used to determine the residual fraction, following digestion with a mixture of hydrochloric, nitric, perchloric and hydrofluoric acids (7:4:7:6).

Total trace metals were determined in the same manner as the residual fraction in the speciation studies. The samples, however, were not sieved to isolate the <63 μm fraction before analysis.

TABLE 1. Physico-chemical characteristics of open water in Lakes Bosset, Daviumbu, Pangua and the Fly River. Data from Ogwa on the Fly River (Maunsell *et al.*, 1982) and Lake Murray (Osborne *et al.*, 1987) are included for comparison. All results expressed in mg $L^{-1}$ except where indicated. n.d. = not detected; - = not analysed).

| | Bosset | Daviumbu | | Pangua | Fly River | | Fly River | Lake |
|---|---|---|---|---|---|---|---|---|
| | June | June | Dec | June | Dec. | Dec. | Ogwa | Murray |
| pH | 6.8 | - | 6.4 | - | 5.8 | 5.5 | 6.4-7.9 | 5.2-9.6 |
| Temperature, °C | 28 | 26 | 31 | 26 | 32 | - | 25-29 | 24-34 |
| Conductivity, μS $cm^{-1}$ | 18.1 | 89.6 | - | 92.9 | - | - | 42-145 | 12-100 |
| Non-Filterable residue | 102 | 134 | 196 | 204 | 302 | 413 | 63-291 | 0-166 |
| Alkalinity (as $CaCO_3$) | 1.75 | 56.5 | 54.6 | 56.3 | 42.2 | 65.2 | 52-92 | 5-50 |
| Hardness (as $CaCO_3$) | 1.60 | 46.6 | 72.0 | 52.0 | 47.0 | 66.5 | 52-112 | 7-42 |
| <u>Major Ions</u> | | | | | | | | |
| Calcium | 0.3 | 21.0 | 21.7 | 21.0 | 15.2 | 30.0 | 16-42 | 4-38 |
| Magnesium | 0.2 | 5.0 | 2.6 | 5.3 | 2.2 | 3.2 | 0.4-7.2 | 0.1-4.3 |
| Sodium | 1.1 | 0.9 | 2.7 | 1.0 | 2.5 | 2.6 | 1.3-1.8 | 0.6-3.8 |
| Potassium | 0.8 | 0.6 | 0.2 | 0.6 | 0.3 | 0.3 | 0.3-0.8 | 0.1-1.0 |
| Bicarbonate | 2.1 | 68.9 | 66.6 | 68.6 | 51.5 | 79.5 | 69-112 | 6-60 |
| Chloride | 2.4 | 0.6 | 0.25 | 2.0 | 0.5 | 1.5 | 0.7-4.4 | 1.0-6.0 |
| Sulfate | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | 1-5 | 1-8 |
| <u>Nutrients (μg $L^{-1}$)</u> | | | | | | | | |
| Nitrate Surface | 1220 | 135 | 320 | 64 | 70 | 130 | - | 4-7 |
| Nitrate Bottom | 2010 | 252 | - | 70 | - | - | - | 9 |
| Nitrite Surface | 6.5 | 45 | n.d. | 10 | n.d. | 5 | - | 5-9 |
| Nitrite Bottom | 3.0 | 5 | - | 10 | - | - | - | 12-28 |
| Ammonia | - | 15 | - | 2 | 5 | 10 | 10-31 | 2-26 |
| Organic Nitrogen | - | - | 112 | - | - | 588 | - | - |
| Total Nitrogen | - | - | 630 | - | 140 | 890 | - | - |
| Total Phosphorus | - | - | 21 | - | 21 | 34 | 10-80 | - |
| Soluble Reactive Phosphorus | 1 | n.d. | - | 2 | - | - | - | n.d. |

## RESULTS

### Water Quality

The results of the water quality analyses are shown in Table 1. Data from the Fly River at Ogwa (near Everill Junction) and Lake Murray (see Figure 1) are included for comparison. Lake Bosset is similar to Lake Murray and has very low concentrations of the major ions. The total concentration of dissolved solids in this lake is estimated as 7 mg $L^{-1}$, in contrast Lakes Pangua and Daviumbu have much higher concentrations of dissolved ions (70-100 mg $L^{-1}$) approaching that of the Fly River (120 mg $L^{-1}$).

The concentrations of ions did not vary significantly between sampling periods in the latter two lakes. Unfortunately, comparative data were not available for Lake Bosset. Since Bosset is different to the other two and is more comparable with Lake Murray, it appears that a greater seasonal variation, due to evaporative concentration, is likely to occur in Lake Bosset as has been recorded for Lake Murray (Osborne, *et al.* 1987).

### Total Metal Concentrations in Sediments

Total concentrations of the metals Fe, Mn, Zn, Cr, Cu, Pb and Cd for Lakes Pangua and Daviumbu and the Fly River are listed in Table 2. Pangua and Daviumbu were sampled in both June-July and November-December 1984 whilst the Fly River was sampled only during December. Data from Lake Murray, collected in April 1981 (Kyle & Gipey, 1987), the Fly River at Obo and all three of the lakes in this study, sampled in July 1981 (Maunsell *et al.*, 1982), are included for comparative purposes.

TABLE 2 Total metal concentrations in sediments from Lakes Pangua and Daviumbu and the Fly River. Data from Lake Murray (Kyle & Gipey, 1987) and Maunsell *et al.*, (1982) are included for comparison.

| Site | Date | Fe % | Mn | Zn | Cr | Cu | Pb | Cd |
|---|---|---|---|---|---|---|---|---|
| | | | mg $kg^{-1}$ dry wt. | | | | | |
| Present Data | | | | | | | | |
| Pangua | June 84 | 5.32 | 504 | 89 | 16 | 41 | 13 | 1.4 |
| | Dec. 84 | 5.17 | 533 | 112 | 30 | 49 | 11 | 1.1 |
| Daviumbu | June 84 | 5.63 | 493 | 98 | 40 | 30 | 7 | 0.6 |
| | Dec. 84 | 5.53 | 508 | 101 | 23 | 21 | 4 | 0.7 |
| Fly River | Dec. 84 | 5.83 | 515 | 120 | 34 | 58 | 15 | 1.7 |
| Previous Data | | | | | | | | |
| Lake Murray | Apr.82 | 5.70 | 680 | 70 | - | 34 | 11 | 0.1 |
| Pangua (Average of 2) | July 81 | - | - | - | - | 43 | 46 | 4.6 |
| Daviumbu | July 81 | - | - | 190 | - | 35 | 36 | 3.5 |
| Boset | July 81 | - | - | 48 | - | 23 | 21 | 2.5 |
| Fly River near Obo | July 81 (Average of 2) | - | - | 85 | - | 28 | 25 | 2.5 |

The sediments are all similar in heavy metal ion composition except for higher concentrations of Zn, Cu and Cd in the Fly River Lakes compared with Lake Murray. These higher concentrations are due to the porphyry mineralisation in the the Star Mountains which contain high levels of Cu, Au, Zn, Pb and Cd. Data on Cu and Zn concentrations from the Ok Tedi Environmental Study (Maunsell *et al.*, 1982) are comparable with the results of this study. The data for the Fly River, collected in December 1984, 7 months after the commencement of mining, show elevated levels of Cu and Zn compared with the 1981 data.

Metal speciation in sediments

As described above the heavy metal concentration in sediments was determined for three fractions. The first of these, the "reducible" fraction represents that portion of the heavy metals that will become soluble and hence biologically available under mildly reducing conditions (i.e. at low concentrations of dissolved oxygen).

The second fraction isolates any metals that are associated with organic matter, the "organic" fraction. It is believed that metals so bound are more biologically available than those associated with the more stable mineral portion of the sediment (Forstner & Wittman, 1981).

The final or "residual" fraction is the remaining residue which includes less easily reducible iron oxides/hydroxides (poorly crystallised forms) as well as minerals and detrital silicates. This fraction is considered to be unavailable for biological uptake under normal conditions.

The results of this fractionation, presented in Tables 3, 4 and 5, indicate again that in general the composition of all sediments, in terms of reducible, organic and residual fractions, are broadly similar with only minor differences occurring between the two lakes studied here, the Fly River and Lake Murray sediments.

Table 3. Concentrations of trace metals in different sediment phases of the <63 mm sediment from Lakes Pangua, Daviumbu and the Fly River. (n.d. = not detected)

| Phase/Lake | Date 1984 | Fe (%) | Mn | Zn | Cr | Cu | Pb | Cd |
|---|---|---|---|---|---|---|---|---|
| | | | | mg $kg^{-1}$ dry wt. | | | | |
| Reducible | | | | | | | | |
| Pangua | June | 2.80 | 160 | 9.7 | 5.1 | 2.1 | n.d. | n.d. |
| | Dec. | 2.81 | 150 | 14.5 | 9.3 | 3.9 | n.d. | n.d. |
| Daviumbu | June | 3.10 | 139 | 10.4 | 11.4 | 1.3 | n.d. | n.d. |
| | Dec. | 2.84 | 143 | 12.3 | 5.7 | 0.5 | n.d. | n.d. |
| Fly River | Dec. | 3.12 | 160 | 13.6 | 8.2 | 4.7 | n.d. | n.d. |
| Organic | | | | | | | | |
| Pangua | June | 0.24 | 127 | 2.7 | 3.8 | 5.1 | n.d. | n.d. |
| | Dec. | 0.26 | 128 | 4.7 | 7.9 | 6.7 | n.d. | n.d. |
| Daviumbu | June | 0.49 | 103 | 2.3 | 6.3 | 6.4 | n.d. | n.d. |
| | Dec. | 0.47 | 126 | 3.2 | 5.5 | 4.4 | n.d. | n.d. |
| Fly River | Dec. | 0.21 | 147 | 4.8 | 4.9 | 7.6 | n.d. | n.d. |
| Residual | | | | | | | | |
| Pangua | June | 2.01 | 146 | 51.8 | 4.9 | 26.7 | 5.3 | 0.98 |
| | Dec. | 1.98 | 149 | 73.4 | 8.5 | 28.9 | 4.3 | 0.91 |
| Daviumbu | June | 2.24 | 136 | 65.9 | 7.06 | 21.4 | 3.2 | 0.69 |
| | Dec. | 2.07 | 151 | 70.1 | 7.3 | 14.7 | 2.6 | 0.44 |
| Fly River | Dec. | 2.42 | 152 | 83.8 | 9.1 | 41.3 | 7.5 | 1.23 |

Table 4. Total metal concentration in the <63 µm fraction compared to the total metal concentration in the whole sediment (mg $kg^{-1}$ dry wt).

| | Lake Pangua (n = 2) | | Lake Daviumbu (n = 2) | | Fly River (n = 1) | |
|---|---|---|---|---|---|---|
| | <63 µm | Total | <63 µm | Total | <63 µm | Total |
| Fe (%) | 5.05 | 5.25 | 5.61 | 5.58 | 5.75 | 5.83 |
| Mn | 430 | 518 | 399 | 500 | 459 | 515 |
| Zn | 78 | 100 | 82 | 99 | 102 | 120 |
| Cr | 20 | 23 | 22 | 32 | 22 | 34 |
| Cu | 37 | 45 | 24 | 25 | 54 | 58 |
| Pb | 4.8 | 11.6 | 2.9 | 5.5 | 7.5 | 15.3 |
| Cd | 1.0 | 1.2 | 0.6 | 0.6 | 1.2 | 1.7 |

The concentrations of the metals Fe, Mn, Zn, Cr, Cu, Pb and Cd present in the reducible, organic and residual fractions of the <63 µm fraction of the sediment are listed in Table 3. The <63 µm fraction of the sediment was isolated because in general, trace metals are associated with this portion of the sediment (Salomons & Forstner, 1980). In general, the results are similar for all three lakes and the split between the various phases is comparable with that found for Lake Murray (Kyle & Gipey, 1987).

TABLE 5. Percentages of trace metals in different sediment phases for Lakes Pangua, Daviumbu and the Fly River. Data from Lake Murray are included for comparison (Kyle & Gipey, 1987). (n.d. = not detected; - = not analysed)

| Phase | Fe | Mn | Zn | Cr | Cu | Pb | Cd |
|---|---|---|---|---|---|---|---|
| Reducible | | | | | | | |
| Pangua | 55.5 | 36.0 | 15.4 | 36.6 | 8.2 | nd | nd |
| Daviumbu | 52.9 | 35.4 | 13.8 | 38.0 | 3.7 | nd | nd |
| Fly River | 54.3 | 34.9 | 13.3 | 36.9 | 8.8 | nd | nd |
| Lake Murray | 53.0 | 35.0 | 15.5 | - | 0.8 | nd | - |
| Organic | | | | | | | |
| Pangua | 5.0 | 29.7 | 4.7 | 29.1 | 16.1 | nd | nd |
| Daviumbu | 8.6 | 28.6 | 3.3 | 27.3 | 22.1 | nd | nd |
| Fly River | 3.7 | 32.0 | 4.7 | 22.1 | 14.2 | nd | nd |
| Lake Murray | 8.0 | 28.5 | 8.2 | - | 27.2 | nd | - |
| Residual | | | | | | | |
| Pangua | 39.5 | 34.3 | 79.9 | 34.3 | 75.7 | 100 | 100 |
| Daviumbu | 38.5 | 36.0 | 82.9 | 34.7 | 74.2 | 100 | 100 |
| Fly River | 42.0 | 33.1 | 82.0 | 41.0 | 77.0 | 100 | 100 |
| Lake Murray | 39.0 | 36.5 | 76.3 | - | 72.0 | 100 | - |

The sum of the metal concentrations in the different sediment phases is for some metals less than the total metal concentration in the sediment. The data are compared in Table 4. The two results for Fe, Cu and Cd are generally comparable and differences can be explained in terms of experimental error.

The sum of the fraction concentrations for Mn, Zn and Cr are significiantly lower than the metal concentration in the whole sediment. This is probably due to losses during the wet-sieving procedure, as almost all the sediment is <63 µm in size, and the result cannot be attributed to the metal content of the sand fraction (>63 µm). The data for this "lost" fraction have not been included in Table 5. The loss of Pb is not so readily explained since Pb, except for anthropogenic Pb, is normally present almost exclusively in the residual phase (Forstner & Wittman, 1981). Since the detection limit for Pb is reasonably high using flame atomic absorption methods for analysis, the differing results must be put down to experimental error, however further experimental work should be carried out to determine the exact nature of Pb in these sediments. Kyle & Gipey (1987) using a similar wet-sieving procedure, noted losses in the Mn content amounting to about 10%, no losses of Fe, Zn, Cu or Pb occurred.

## DISCUSSION

### Water quality

In common with many lakes in Papua New Guinea the Fly river lakes can be classed as oligotrophic (nutrient-poor) with little open-water, phytoplanktonic, primary production.

The lakes are all subject to seasonal fluctuations in water level, which can be up to 3 - 4 metres in severe droughts; Lake Bosset has been known to dry up completely. These changes in water level affect the extensive littoral vegetation, much of which dies in the dry season. In the following wet season, the dead and decaying vegetation may be presumed to release its nutrients into the water body which then may become productive for a short period until the nutrients are flushed out into the Fly River (see Osborne, *et al.*, 1987).

The concentrations of major ions (Ca, Mg, Na, K, Cl, $HCO_3$, $SO_4$ in Lake Bosset at the times of sampling are lower than for Lakes Daviumbu and Pangua. These ionic concentrations may reflect the influence of the Fly River; Lake Bosset being connected to the Fly River by a single narrow channel has a lower level of total dissolved solids (7 mg $L^{-1}$) than the Fly River (120 mg $L^{-1}$). These data suggest that in contrast Lakes Daviumbu and Pangua are much more influenced by the Fly River. Lake Daviumbu, although only connected to the river by a narrow channel, apparently has a high flow through of river water since the ionic concentration (100 mg $L^{-1}$) is much higher than that of Lake Bosset. This increased ionic concentration must be due to the entry of Fly River water as the lake catchment produces little soluble material. Lake Pangua has relatively high ionic content (*ca* 90 mg $L^{-1}$) again apparently due to a flow through of water from the Fly River.

The most obvious and important difference between the Fly River and its lakes and Lake Murray is the proportion of Cu that is in the reducible fraction. Whereas in Lake Murray it is an insignificant 0.8%, in the Fly River and its lakes, it is an important component at 3.7-8.8%. This fraction of the Cu can become solubilised under mildly anoxic conditions and hence become available for uptake by fish and other aquatic organisms, particularly benthos. Results of the dissolved oxygen studies (see Chambers, this volume) indicate that such conditions are possible, particularly in Lake Pangua.

Proportions of the other toxic metals Zn (13.3-15.4%) and Cr (36.6-38.0%) in the reducible fraction are also significant. Thus solubilisation of these metals may be a problem in anoxic waters, which occur in Lake Pangua.

The organic fractions of the Cr and Cu are also significant in terms of biological availability whereas the Zn concentration in this fraction is low. This is in line with previous studies which tend to show that biologically available Zn is mainly associated with the reducible fraction whereas for Cu the organic fraction tends to predominate. For Cr, previous data are scant and tend to indicate that the organic and residual fractions are the most important (Salomons & Forstner, 1980); however, these data are for rivers and may not be applicable to lakes.

The fractionation of Fe, a major component of the sediment, is typical of other river and lake systems wherein most of the biologically available metal is associated with reducible phase. The behaviour of Mn is usually similar to Fe, however, in this case, a much higher organic component is evident. This unusual behaviour can not be explained at this stage.

## CONCLUSIONS

### Nutrient Status and the influence of the Fly River

In general, nutrient concentrations were low and indicative of oligotrophic (nutrient-poor) lakes with limited phytoplanktonic primary production. The dissolved oxygen data (discussed by Chambers, this volume) support this thesis. Of interest are the high nitrate and nitrite concentrations in Lake Bosset, probably released from the large quantities of decaying vegetation on the lake bed.

The extensive influence of the Fly River on the ionic content of Lakes Pangua and Daviumbu may mean that soluble materials (such as trace metal complexes, cyanides, thickeners and flotation agents) that enter the Ok Tedi - Fly River system will find their way into these lakes. Insoluble fine material will also enter these systems but to a lesser extent due to the slower water speeds in the lakes and the filtering effect of the extensive aquatic plant beds on the flood plains and in the channels (but see Osborne and Polunin, this volume). Lake Bosset is less affected by the river and will be little affected by mining activities except in times of very low water levels when river water may enter the lake.

### Total Metals in Sediments

Sediments from the Fly River and all the lakes have similar concentrations of the metals tested (Table 2). Of particular interest, are the differences in the concentrations of Zn, Cu and Cd, which appear to be higher in the Fly River and associated lakes than in Lake Murray. More data are required to confirm these observations. These three metals are pin-pointed (Maunsell *et al.* (1982) as requiring particular attention due to their presence in the gold and copper mineralisation of the Ok Tedi mine ore. It is possible that these metals may accumulate in the sediments of Lakes Daviumbu and Pangua and the middle Fly River.

The concentrations of Cd reported in Maunsell *et al.* (1982) are substantially higher than in the present study whilst the work of Osborne and Polunin (this volume) suggests that concentrations in sediments are variable and depend upon the relative importance of Fly River inputs compared with the surrounding catchment.

### Metal Speciation in Sediments

The total metal concentrations in sediments, whilst important in themselves, do not indicate the amounts that may be biologically available. In order to estimate the fraction of metal that may become dissolved in the lake waters under different conditions, the total trace metal concentration has been split into three components.

The total ionic content of the lake waters indicates that Lake Bosset is less influenced by the Fly River, than are Lakes Daviumbu and Pangua. Future monitoring should be more concentrated on Lakes Daviumbu and Pangua.

The sediment analyses indicate that at present the sediment composition of the Fly River and the lakes studied are similar to Lake Murray. However, the speciation studies indicated that a significant proportion of the toxic metals Zn, Cr and Cu could become solubilised under anoxic conditions. Future studies should attempt to test this hypothesis by correlating trace metal concentrations in the lake waters with depth and dissolved oxygen data. Methodological studies are also required to more fully define a suitable method for speciation studies that will overcome the uncertainty in the present results, especially with respect to losses during wet-sieving.

Regular monitoring of Lakes Pangua and Daviumbu should continue as they are directly associated with Fly River. Less frequently, Bosset could also be included in the programme.

ACKNOWLEDGEMENT

All experimental work was skillfully and diligently performed by Mr. Jatrepa Tinkerame graduate trainee, whose participation in the research was supported by SPREP.

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# DISSOLVED OXYGEN, TEMPERATURE AND ZOOPLANKTON STUDIES OF LAKES BOSSET, PANGUA AND DAVIUMBU

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ABSTRACT

Oxygen, temperature, zooplankton and other limnological data were collected from Lakes Bosset, Daviumbu and Pangua, typical lakes of the mid-Fly floodplain, in the wet and dry seasons of 1984. In the wet season, water depth was greater by about 3 m and the water much clearer. Temperature and oxygen levels were appreciably lower in the wet season. Temperature and oxygen gradients were present and particularly marked in the cool, wet season. 51 species of zooplankton were recorded from the three lakes. There were major seasonal differences between lakes, with lower diversity and higher density in the dry season. There were also seasonal shifts in zooplankton community composition. The deeper Lake Pangua, an old oxbow lake, had a markedly more diverse fauna than the other lakes. In any future monitoring of the limnology of these lakes, temperature, oxygen and zooplankton should be assessed, although their daily and/or seasonal variations, together with the lack of information on tropical zooplankton, may make interpretation with respect to changes in water quality difficult.

## INTRODUCTION

Information on the oxygen and temperature conditions prevailing within a lake are of importance in understanding the abiotic and biotic interactions which occur within it.

The aim of this study was to describe oxygen, temperature and zooplankton in Lakes Bosset, Daviumbu and Pangua. Two visits were made, one during the wet (June-July) and one during the dry season (December 1984). A number of additional physical factors were recorded.

Compared with temperate regions little is known of the zooplankton of tropical areas. Within the tropics the zooplankton of New Guinea is particularly poorly known. The present state of knowledge of the zooplankton of the tropics was recently summarised by Dussart *et al.* (1984). The aim of the present study was to provide base-line information on the composition of zooplankton in Lakes Bosset, Daviumbu and Pangua. Many zooplankton species are herbivorous and in turn are fed upon by either juvenile or adult fish. As such they occupy a pivotal role in ecosystem processes, converting phytoplankton production into a form accessible to higher trophic levels.

## METHODS

Temperature and oxygen profiles were taken for all three lakes during both visits using a YSI portable oxygen temperature meter. At Lake Bosset 6 sets of wet-season readings were taken from one sampling station over a 26 hours period to measure diurnal changes. A large series of surface temperature readings were made at Lake Daviumbu during the dry season visit. Flow direction in the channels connecting the lakes with the river was noted as were lake water depth, colour, and turbidity.

Total organic carbon was determined as follows: samples were filtered through a 0.45 µm filter, acidified to pH 2 oxidised to carbon dioxide by UV and determined by infra-red absorption using a Barnstead Organic Carbon Analyser.

Zooplankton were collected by vertical hauls from the bed of the lake to the surface using a net (mesh size 47 µm). Five such samples were taken from each lake and mean densities (numbers $L^{-1}$) calculated for each of the major zooplankton groups - Cyclopoida, Calanoida, Cladocera and Rotifera. Lake Bosset was sampled once during the June visit whilst Lakes Daviumbu and Pangua were sampled in both June and November.

## RESULTS

### General lake characteristics

Table 1 records general lake features. During the wet season (June/July), water was flowing from all the lakes into the Fly River. This was also the case at Lake Daviumbu in the dry season (December). At Lake Pangua during the dry season, however, river water was flowing into the lake through the southern channel. The suspended river sediments settled quickly in the lake; At 100 m from the channel entrance the lake water was clear (see Osborne & Polunin, this volume).

TABLE 1. Summary of flow directions, maximum depths (m) water colour and Secchi depths (m) in Lakes Bosset, Daviumbu and Pangua during the wet and dry seasons.

| Lake Bosset | Wet season | Dry Season |
|---|---|---|
| Flow direction | Lake to river | |
| Maximum depth (m) | 4.0 | |
| Water colour | Humic-stained, clear | |
| Secchi depth (m) | 1.8 | |
| Total Organic Carbon | 8.4 mg $L^{-1}$ | |
| Lake Daviumbu | | |
| Flow direction | Lake to river | Lake to river |
| Maximum depth (m) | 4.0 | 1.0 |
| Water colour | Humic-stained, clear | Humic-stained, clear |
| Secchi depth (m) | 3.1 - 4.0 | More than 1m |
| Total Organic Carbon | 3.0 mg $L^{-1}$ | |
| Lake Pangua | | |
| Flow direction | Lake to river | River to lake |
| Maximum depth (m) | 8+ | 5+ |
| Water colour | Humic-stained, clear | Turbid by entrance,otherwise humic-stained, clear. |
| Secchi depth (m) | 2.6 - 3.5 | 1.3-1.8 |
| Total Organic Carbon | 5.3 mg $L^{-1}$ | |

The maximum depths recorded at Lakes Bosset and Daviumbu were 4 m in the wet season, falling to 1 m at Daviumbu in the dry season. The Fly River had also dropped by about 3 m during the same period. At Lake Pangua the maximum depths recorded were 8 m and 5 m during the wet and dry seasons respectively. These readings were taken from the oxbow sections of the lake where depths of up to 19 m have been recorded.

At both sampling times the waters of the lakes were clear and humic stained, except for the small area of turbid water in Lake Pangua in November. The dark brown colouration probably arises both from the decay of vegetation within the lake and from inflows from the surrounding flooded grasslands. Total organic carbon values, however, were only average for lakes.

The Secchi depths of the three lakes varied during the wet season - from a minimum of 1.8 m at Lake Bosset to 4 m at Lake Daviumbu. The only seasonal comparison was at Lake Pangua where the Secchi depth in the dry season was about half its wet season value.

Temperature and oxygen

Temperature and oxygen data recorded from Lake Bosset over a 26 hour period are tabulated in Annex Table 1. Figures 1 and 2 show depth profiles based on these data. Figure 1 demonstrates the presence of some stratification with diurnal temperatures remaining stable below 3 m depth at between 26.8 and 27 °C. The surface water body varies in temperature from around 28 °C in the late afternoon to around 27 °C in the early morning.

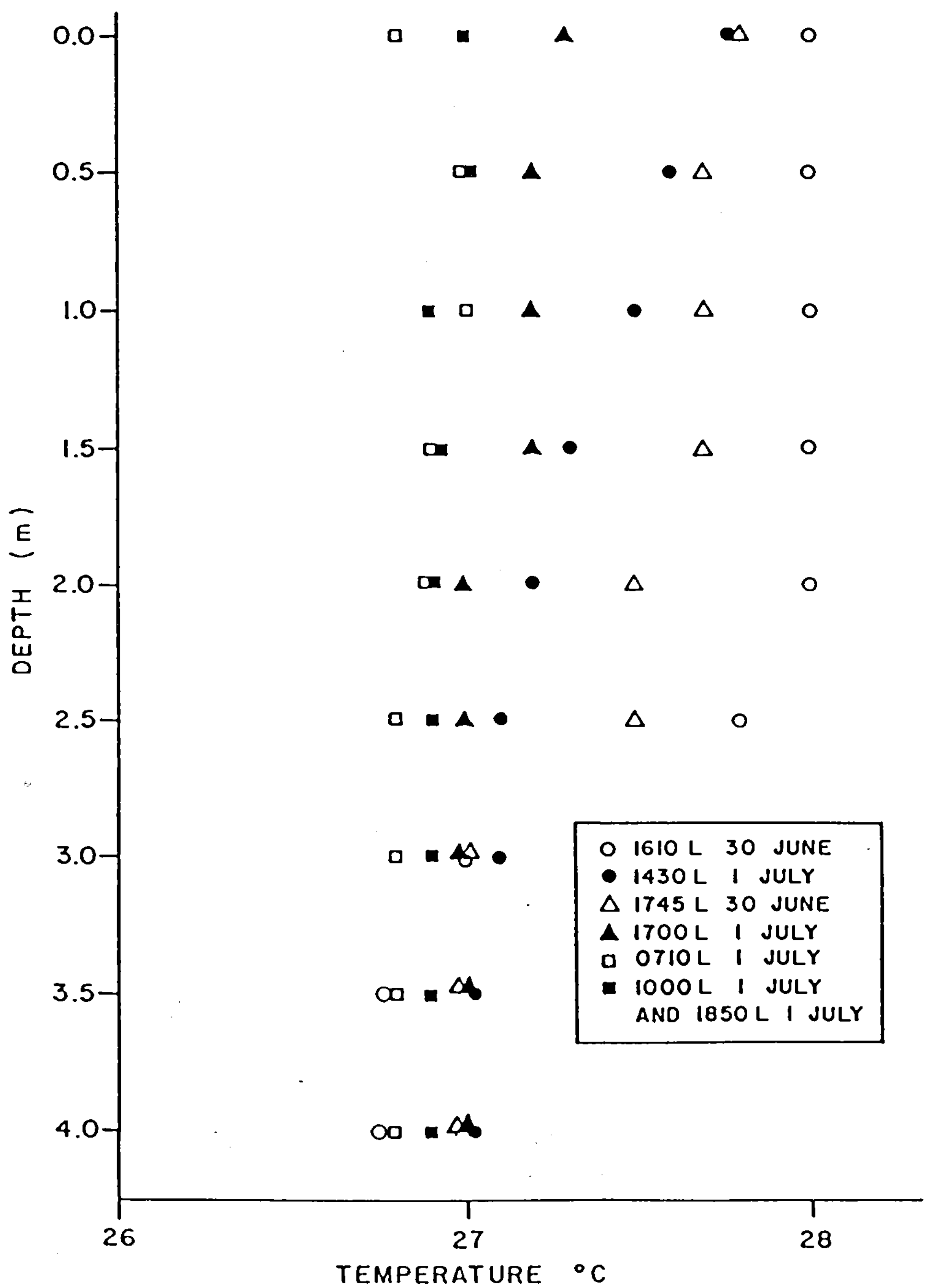


Figure 1. Temperature profiles for Lake Bosset over 26 hours from 30 June to 1 July 1984.

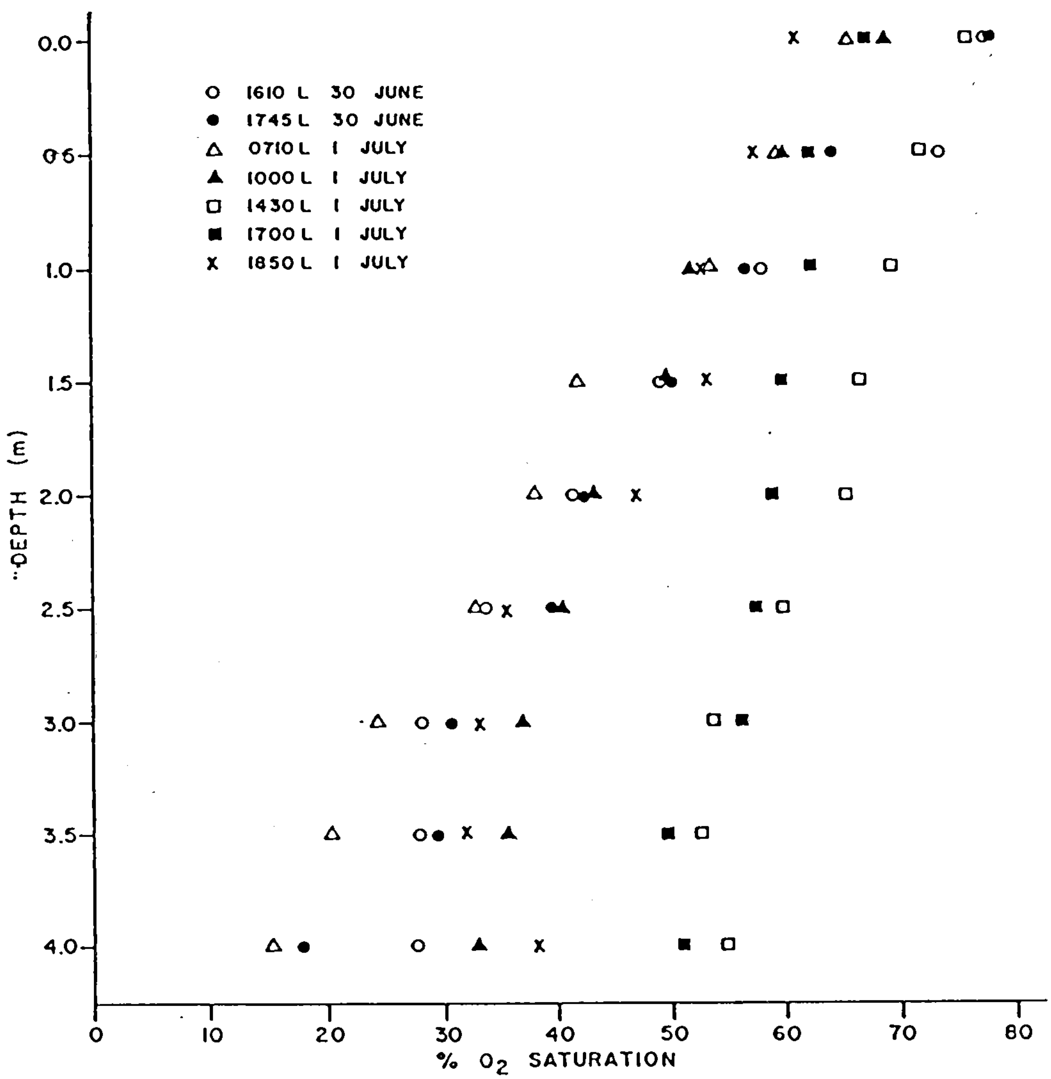


Figure 2. Oxygen saturation profiles for Lake Bosset over 26 hours from 30 June to 1 July 1984.

Figure 2 demonstrates variations in oxygen saturation over depth and time. Maximum saturation values from 75-77% occurred in the afternoon at the surface with minimum values of 15-20% at the bottom in the morning. Such steep gradients reflects little mixing of the water body and high biological oxygen demand at the lake bottom, probably due to the activities of bacterial decomposers. A diurnal pattern is discernable with highest saturation values being recorded in the late afternoon and lower values in the evening and early morning. The two profiles from late afternoon of 30 June correspond more closely to the early morning and early evening profiles of 1 July suggesting an earlier cessation of photosynthetic activity than on the subsequent day.

Table 2 presents oxygen and temperature data for Lake Daviumbu during the wet season. It can be seen that temperature varied little with depth during this period. Oxygen saturation declines with depth and surface values in the late afternoon are higher than in the morning. Annex Table 2 details surface temperature measurements of Lake Davimubu at different times of the day during the dry season. Surface temperatures are generally higher during the dry season (28-33 °C) compared with those of the wet season (26 °C). During the dry season maximum surface temperatures were achieved by late afternoon, and the water column was frequently supersaturated with oxygen at this time, especially on sunny days. Overnight the lake appeared to lose about half its oxygen. Very high saturation values, from 150-190% were recorded in beds of macrophytes.

TABLE 2. Oxygen concentrations, percentage saturations and temperatures for Lake Daviumbu during the wet season.

| TIME | 2 July, 1030 h | | | 2 July, 1445 h | | |
|---|---|---|---|---|---|---|
| Depth m | Temp. °C | Oxygen mg $L^{-1}$ | Saturation % | Temp. °C | Oxygen mg $L^{-1}$ | Saturation % |
| 0 | 25.9 | 5.7 | 71.3 | 26.2 | 6.4 | 80.5 |
| 0.5 | 25.8 | 5.3 | 66.2 | 26.2 | 6.0 | 75.5 |
| 1.0 | 25.8 | 4.8 | 59.9 | 26.2 | 5.9 | 74.2 |
| 1.5 | 25.8 | 4.4 | 54.9 | 26.2 | 5.6 | 70.3 |
| 2.0 | 25.8 | 4.1 | 51.2 | 26.1 | 5.5 | 69.0 |
| 2.5 | 25.8 | 4.1 | 51.2 | 26.0 | 4.9 | 61.3 |
| 3.0 | 25.8 | 3.4 | 42.4 | 26.0 | 4.4 | 55.1 |
| 3.5 | 25.8 | - | - | 26.0 | 3.5 | 43.8 |

Wet season temperatures in Lake Pangua (Annex Table 3) were lower than in Lake Bosset; maximum recorded surface temperature was 26.0 °C at 15.00 h. The temperature at 8 m depth was only 0.7 °C lower. Dissolved oxygen, however, showed a steep decline between surface and bottom - from around 60% to 10% saturation. Most of this decline occurred within the top 2-3 m of the water column.

In the dry season recordings at Lake Pangua, both water temperatures and oxygen levels were higher. Surface temperatures were up to 32.2 °C with no stratification. Oxygen levels up to 98.5% were recorded at 1100 h. The entire water column was well oxygenated to with in 1 m of the lake bottom and then declined to 26-28% saturation.

Zooplankton

A total of 51 species of zooplankton were recorded and their seasonal and distributional occurrences are shown in Annex Table 4. These data are summarised in Table 3. Only 3 of the 51 species occurred in each lake on each occasion; *Bosminopsis dietersi, Chydorus eurynotus* and *Calamoecia ultima.*

Of the remaining 48 species, five were recorded only from Lake Daviumbu and 20 were confined solely to Lake Pangua. Of the latter, 16 were rotifers present only during the wet season.

Lakes Daviumbu and Pangua had higher species diversity than Lake Bosset in the wet season. For these two lakes the number of species found in the wet season was about twice that present in the dry season.

Table 4 shows the density of zooplankton from which it can be seen that Lakes Daviumbu and Pangua had higher densities of zooplankton in the dry season that in the wet. At Lake Daviumbu the density was nearly 5 times higher whereas at Pangua it was dry season density was 19 times greater than that of the wet season.

Lake Bosset had the highest wet season density, exceeding Daviumbu and Pangua by 1.7 and 8.1 times respectively. It also displayed the lowest species diversity at this time.

In all lakes during the wet season, the different zooplankton groups occurred in the same relative densities: Cyclopoida > Cladocera > Rotifera > Calanoida. This relationship also held good for Lake Daviumbu. In Lake Pangua the dry season, abundance of rotifers was 144 times greater than that in the wet.

Table 3. Numbers of zooplankton species in 4 major taxa from the Fly River lakes.

| | WET SEASON | | | DRY SEASON | |
|---|---|---|---|---|---|
| | Bosset 30:6:84 | Daviumbu 2:7:84 | Pangua 3:7:84 | Daviumbu 28:11:84 | Pangua 29:11:84 |
| Cladocera | 8 | 15 | 16 | 8 | 9 |
| Cyclopoida | 1 | 3 | 2 | 0 | 2 |
| Calanoida | 1 | 1 | 1 | 1 | 1 |
| Rotifera | 2 | 6 | 20 | 2 | 3 |
| Total | 12 | 25 | 39 | 11 | 15 |

Table 4. The zooplankton densities (numbers $L^{-1}$) in Lakes Bosset (June 1984) and Daviumbu and Pangua (July and November 1984). P = Present in very small numbers.

| Zooplankton Category | Bosset June 84 | Daviumbu July 84 | Daviumbu Nov. 84 | Pangua July 84 | Pangua Nov. 84 |
|---|---|---|---|---|---|
| Cyclopoida | 21.6 | 11.7 | 41.6 | 3.1 | 22.7 |
| Calanoida | P | P | P | P | P |
| Cladocera | 7.9 | 4.9 | 25.7 | 0.4 | 6.3 |
| Rotifera | 1.1 | 1.3 | 16.7 | 0.3 | 43.2 |
| Total Zooplankton | 0.6 | 17.9 | 84.0 | 3.8 | 72.2 |

DISCUSSION

All three lakes were virtually isothermal on the occasions on which they were sampled. Temperatures varied little between the surface and the lake bottom and evidence of thermal stratification was recorded only for Lake Bosset during the wet season (July). Stratification might be expected to occur under calm conditions particularly during the wet season. In the shallower conditions of November/December thermal stratification would be less likely.

Diurnal variations in temperature and oxygen saturation occur, with the lakes generally having highest values for these parameters in the late afternoon.

The markedly higher water temperatures of the dry season may be due to a combination of circumstances - increased solar radiation, shallower water depths and reduced flow rates through the lakes.

All three lakes showed pronounced oxygen undersaturation during the comparatively high water levels and cooler temperatures of June/July. This in turn suggests that either phytoplankton and macrophyte photosynthesis was comparatively low at these times or that decomposer activity in the sediments resulted in an oxygen demand exceeding the rate of photosynthetic production. This is suggested by the steep oxygen gradients in all lakes, although this varied from day to day. In the deeper Lake Pangua conditions were nearly anoxic at the bottom even in late afternoon indicating little mixing with the upper water layers.

Surface oxygen levels were much higher in the dry season, and the entire water column was well oxygenated at this time for most of its depth in both Lakes Daviumbu and Pangua. Seasonal variation in biomass and productivity of the macrophytes and phytoplankton is unknown. Therefore it is not possible to quantify the varying contributions of these plants to oxygen levels within the lakes. During the dry season, however, photosynthetically produced oxygen was sufficient to keep the smaller water volumes of the lakes well oxygenated. During the wet season such was not the case. At this latter time, therefore, respiration by plants, animals and decomposers may be greater than the rate of oxygen production from photosynthesis, leading to the marked undersaturation levels recorded.

In Lakes Daviumbu and Pangua the diversity and density of zooplankton were inversely related with higher dry season densities occurring at the times of lowest diversity. Although density differences varied considerably between sampling times (up to 19 times at Pangua) overall numbers were always low with the maximum density recorded being only 84 $L^{-1}$. Compared with other localities, the zooplankton populations of the Fly River lakes appeared to be sparse.

Higher wet season diversity in both Lakes Daviumbu Pangua may be attributable at least in part to littoral species being flushed into the open water of the lakes by stronger currents. The lower overall density at these times may in part reflect a higher flushing rate of the lakes with populations being unable to maintain themselves. Low diversity in the dry season may be due to poor water quality; such as higher water temperatures, and lower transparency. Many rotifers are known to be stenothermic (able to live only within narrow temperature ranges), and therefore the temperature fluctuations between the seasons may affect diversity. Other rotifers (*Lecane* and *Brachionus*) are sensitive to pH changes.

The change between wet and dry season populations was most pronounced in the Lake Pangua rotifer communities. The 20 species present in July had a total density of only 0.3 $L^{-1}$. None of these species were found in November and the three additional species found at this time had a density of 43.2 $L^{-1}$. Thus although conditions may favour fewer species in the dry season those that can survive exist in comparatively high numbers.

The zooplankton community of Lake Pangua was the most variable; the ratio for wet:dry season density was 1:19 while rotifer diversity decreased 7 times between the two seasons compared with 3 times in Lake Daviumbu. More species were recorded in Lake Pangua (44) than from Lake Daviumbu

(30). Lake Pangua was the only lake to show dominance of rotifers (both in terms of diversity and density) over the other plankton groups. The low abundance and diversity of cyclopoids and calanoids appears to be a characteristic of tropical lakes of low nutrient status.

## CONCLUSIONS

Oxygen levels of the three lakes varied considerably from season to season; from day to day and from each other. In any extensive study of oxygen levels within the Fly River system, such variations would have to be taken into consideration in the design of the sampling programme.

Although zooplankton have a pivotal role in the food chains and webs of the Fly River lakes it is the least known part of these ecosystems. This paucity of data is due both to lack of study in the area and in the tropics in general. Thus there is little detailed information available on either the ecology or likely response of this section of the food chain to the changes in water quality which may result from mining activities at Ok Tedi.

This lack of knowledge combined with difficulties of identification pose difficulties in the use of zooplankton in long-term monitoring studies. Despite this it would be of value to continue and expand the monitoring of zooplankton as a component of any long-term monitoring programme.

## ACKNOWLEDGEMENT

I am grateful to Professor C.H. Fernando for identifying the zooplankton collections.

## REFERENCE

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# ANNEX 1

Table 1. Oxygen concentrations, percentage saturations and temperatures for Lake Bosset over a 26 hour period from 30 June to 1 July, 1984. B = lake bottom.

| TIME | 30 June, 1610 h | | | 30 June, 1745 h | | | 1 July, 0710h | | | 1 July, 1000 h | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth m | Temp. oC | Oxygen mg L-1 | Saturation % | Temp. oC | Oxygen mg L-1 | Saturation % | Temp. oC | Oxygen mg L-1 | Saturation % | Temp. oC | Oxygen mgL-1 | Saturation % |
| 0 | 28.0 | 6.0 | 77.4 | 27.8 | 5.6 | 77.4 | 26.8 | 5.2 | 65.9 | 27.0 | 5.4 | 68.7 |
| 0.5 | 28.0 | 5.7 | 73.5 | 27.7 | 5.0 | 64.3 | 27.0 | 4.77 | 59.8 | 27.0 | 4.7 | 59.8 |
| 1.0 | 28.0 | 4.5 | 58.0 | 27.7 | 4.4 | 56.6 | 27.0 | 4.2 | 53.4 | 26.9 | 4.1 | 52.0 |
| 1.5 | 28.0 | 3.8 | 49.0 | 27.7 | 3.9 | 50.1 | 26.9 | 3.3 | 41.9 | 26.9 | 3.9 | 49.5 |
| 2.0 | 28.0 | 3.2 | 41.3 | 27.5 | 3.3 | 42.3 | 26.9 | 3.0 | 38.1 | 26.9 | 3.4 | 43.1 |
| 2.5 | 27.8 | 2.6 | 33.5 | 27.5 | 3.1 | 39.7 | 26.8 | 2.6 | 33.0 | 26.9 | 3.2 | 40.6 |
| 3.0 | 27.0 | 2.2 | 28.0 | 27.0 | 2.4 | 30.5 | 26.8 | 1.9 | 24.1 | 26.9 | 2.9 | 36.8 |
| 3.5 | 26.8 | 2.2 | 27.9 | 27.0 | 2.3 | 29.3 | 26.8 | 1.6 | 20.3 | 26.9 | 2.8 | 35.5 |
| 4.0-B | 26.8 | 2.2 | 27.9 | 26.8 | 1.4 | 17.7 | 26.8 | 1.2 | 15.2 | 26.9 | 2.6 | 33.0 |

| TIME | 1 July, 1430 h | | | 1 July, 1700 h | | | 1 July 1850 h | | |
|---|---|---|---|---|---|---|---|---|---|
| Depth m | Temp. oC | Oxygen mg L-1 | Saturation % | Temp. oC | Oxygen mg L-1 | Saturation % | Temp. oC | Oxygen mg L-1 | Saturation % |
| 0 | 27.8 | 5.9 | 75.9 | 27.3 | 5.3 | 67.6 | 27.0 | 4.8 | 61.1 |
| 0.5 | 27.6 | 5.6 | 71.9 | 27.2 | 4.9 | 62.5 | 27.0 | 4.5 | 57.3 |
| 1.0 | 27.5 | 5.4 | 69.1 | 27.2 | 4.9 | 62.5 | 26.9 | 4.2 | 53.3 |
| 1.5 | 27.3 | 5.2 | 66.4 | 27.2 | 4.7 | 59.9 | 26.9 | 4.2 | 53.3 |
| 2.0 | 27.2 | 5.1 | 65.1 | 27.0 | 4.6 | 58.5 | 26.9 | 3.7 | 47.0 |
| 2.5 | 27.1 | 4.7 | 59.9 | 27.0 | 4.5 | 57.3 | 26.9 | 2.8 | 35.5 |
| 3.0 | 27.1 | 4.2 | 53.5 | 27.0 | 4.4 | 56.0 | 26.9 | 2.6 | 33.0 |
| 3.5 | 27.0 | 4.1 | 52.2 | 27.0 | 3.9 | 49.6 | 26.9 | 2.5 | 31.7 |
| 4.0-B | 27.0 | 4.3 | 54.7 | 27.0 | 4.0 | 50.9 | 26.9 | 3.0 | 38.1 |

**Table 2. Surface temperatures for Lake Daviumbu during the dry season.**

| Date Time | Temp. °C | Oxygen mg $L^{-1}$ | Saturation % | Date Time | Temp. °C | Oxygen mg $L^{-1}$ | Saturation % |
|---|---|---|---|---|---|---|---|
| 28 Nov. (sunny) | | | | 1 Dec. (cloudy) | | | |
| 1420 | 33.3 | 8.0 | 111.1 | 0900 | 28.8 | 4.0 | 52.2 |
| 1510 | 33.5 | 8.1 | 112.8 | 0920 | 29.7 | 7.0 | 92.6 |
| 1620 | 33.7 | 8.4 | 117.3 | 1010 | 29.2 | 6.6 | 86.7 |
| 1800 | 33.5 | 8.4 | 117.0 | 1145 | 29.9 | 7.1 | 94.2 |
| | | | | 1300 | 30.2 | 6.5 | 86.6 |
| 30 Nov. | | | | 2 Dec. | | | |
| 0930 | 29.7 | 4.7 | 62.1 | 0940 | 29.9 | 5.9 | 78.2 |
| 1100 | 31.3 | 5.9 | 79.8 | 0955 | 30.0 | 7.0 | 93.3 |
| 1145 | 32.3 | 8.1 | 111.1 | 1020 | 30.1 | 7.0 | 93.1 |
| 1325 | 33.1 | 8.1 | 112.3 | 1240 | 32.1 | 7.9 | 108.1 |
| | | | | 1310 | 33.0 | 7.8 | 108.1 |

**Table 3. Oxygen concentrations, percentage saturations and temperatures for Lake Pangua (a) during the wet season (3 July 1984 and (b) the dry season (29 November 1984) (B=Lake bottom).**

(a) TIME 1400 / 1500

| Depth m | Temp. oC | Oxygen mg L-1 | Saturation % | Depth m | Temp. oC | Oxygen mg L-1 | Saturation % |
|---|---|---|---|---|---|---|---|
| 0 | 25.6 | 4.6 | 57.2 | 0 | 26.0 | 5.0 | 62.6 |
| 0.5 | 25.5 | 4.8 | 59.6 | 0.5 | 26.0 | 4.2 | 52.6 |
| 1.0 | 25.5 | 4.2 | 52.2 | 1.0 | 26.0 | 3.7 | 46.3 |
| 1.5 | 25.5 | 3.1 | 38.5 | 1.5 | 26.0 | 3.5 | 43.8 |
| 2.0 | 25.5 | 2.2 | 27.3 | 2.0 | 26.0 | 3.2 | 40.1 |
| 2.5 | 25.5 | 1.8 | 22.4 | 2.5 | 25.9 | 2.7 | 33.8 |
| 3.0 | 25.4 | 1.3 | 16.1 | 3.0 | 25.9 | 2.5 | 31.3 |
| 3.5 | 25.1 | 1.1 | 13.6 | 3.5 | 25.8 | 2.3 | 28.7 |
| 4.0 | 25.1 | 1.0 | 12.3 | 4.0 | 25.8 | 1.2 | 15.0 |
| 4.5 | 25.0 | 1.0 | 12.3 | 4.5 | 25.5 | 1.0 | 12.4 |
| 5.0 | 25.0 | 1.0 | 12.3 | 5.0 | 25.5 | 0.9 | 11.2 |
| 5.5-B | 25.0 | 0.9 | 11.1 | 6.0 | 25.3 | 0.8 | 9.9 |
| | | | | 7.0 | 25.3 | 0.8 | 9.9 |
| | | | | 8.0-B | 25.3 | 0.8 | 9.9 |

(b) TIME 1000 / 1100

| Depth m | Temp. oC | Oxygen mg L-1 | Saturation % | Dept m | Temp. oC | Oxygen mg L-1 | Saturation % |
|---|---|---|---|---|---|---|---|
| 0 | 32.1 | 5.9 | 80.7 | 0 | 32.2 | 7.2 | 98.5 |
| 0.5 | 32.1 | 5.8 | 79.3 | 1.0 | 32.2 | 6.8 | 93.2 |
| 1.0 | 32.1 | 5.7 | 78.0 | 2.0 | 32.2 | 6.5 | 89.0 |
| 1.5 | 32.1 | 5.7 | 78.0 | 3.0 | 32.2 | 6.4 | 87.7 |
| 2.0 | 32.1 | 5.7 | 78.0 | 4.0 | 32.2 | 6.3 | 86.3 |
| 2.5 | 32.1 | 5.6 | 76.7 | 5.0-B | 31.2 | 2.0 | 28.2 |
| 2.8-B | 32.1 | 1.9 | 26.0 | | | | |

Table 4. The zooplankton of Lakes Bosset (June 1984), Daviumbu (July and November 1984) and Pangua (July and NOvember 1984).

| Species | Bosset June | Daviumbu July | Daviumbu Nov. | Pangua July | Pangua Nov. |
|---|---|---|---|---|---|
| Cladocera | | | | | |
| *Acroperus alonoides* | + | | | + | |
| *Alona affinis* | | + | | | |
| *Alona guttata* | | + | + | + | |
| *Alona (Indialona) globulosa* | | + | | + | |
| *Alona karua* | + | + | | + | |
| *Alona monocantha* | + | + | | + | |
| *Alona pulchella* | | | | + | + |
| *Alona rectangula* | + | + | | | |
| *Alonella nana* | | | + | | |

| | | | | | |
|---|---|---|---|---|---|
| *Bosmina meridionalis* | | | + | + | |
| *Bosminopsis dietersi* | + | + | + | + | + |
| *Ceridodaphnia cornuta* | | + | | + | + |
| *Ceriodaphnia dubia* | | + | | | |
| *Chydorus eurynotus* | + | + | + | + | + |
| *Chydorus of faviformis* | + | | + | + | + |
| *Diaphanosoma unguiculatum* | | + | | + | + |
| *Dunhevedia crassa* | | + | | | |
| *Ilyocryptus spinifer* | + | + | | | |
| *Kurzia longirostris* | | | | + | |
| *Latonopsis australis* | | + | | + | |
| *Leydigia australis* | | + | + | + | |
| *Macrothrix triserialis* | | | | + | + |
| *Oxyurella sinhalensis* | | | + | + | + |
| Cyclopoida | | | | | |
| *Ergasilus sp.* | + | | | | |
| *Mesocyclops thermocyclopoides* | + | + | | + | + |
| *Microcyclops varicans* | | + | | + | |
| *Thermocyclops sp.* | | | | | + |
| Calanoida | | | | | |
| *Calamoecia ultima* | + | + | + | + | + |
| Rotifera | | | | | |
| *Asplanchna brightwelli* | + | + | | | + |
| *Asplanchnopus multiceps* | | | | + | |
| *Brachionus falcatus* | | | + | | + |
| *Brachionus patulus* | | | | + | |
| *Brachionus quadridentatus* | | | | + | |
| *Cephalodella sp.* | | | | + | |
| *Dicronophorus robustus* | | | | + | |
| *Dipleuchlanis propatula* | | | | + | |
| *Eothenia elongata* | | | | + | |
| *Keratella tropica* | | + | + | | + |
| *Lecane bulla* | + | + | | + | |
| *Lecane leontina* | | | | + | |
| *Lecane luna* | | + | | + | |
| *Lecane papuana* | | | | + | |
| *Lecane stichtaea* | | | | + | |
| *Lecane unquitata* | | | | + | |
| *Macrochaetus collinsi* | | | | + | |
| *Notommata avenna* | | | | + | |
| *Platyias quadricornis* | | + | | + | |
| *Scaridium longicaudatum* | | | | + | |
| *Testudinella patina* | | | | + | |
| *Trichocerca rattus* | | + | | + | |
| *Trichotria tetractis* | | | | + | |
| Total No. of Cladocera species | 8 | 15 | 8 | 16 | 9 |
| Total No. of Cyclopoida species | 1 | 3 | 0 | 2 | 2 |
| Total No. of Calanoida species | 1 | 1 | 1 | 1 | 1 |
| Total No. of Rotifera species | 2 | 6 | 2 | 20 | 3 |
| Total No. of Species | 12 | 25 | 11 | 39 | 15 |

# PROGRESS IN ELUCIDATING THE SEDIMENT RECORD OF TWO SHALLOW LAKES IN PAPUA NEW GUINEA.

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ABSTRACT

Lake sediments usually contain a vertical record of the ecological history of the lake basin and its catchment area. Furthermore, surface sediment samples collected from a number of sites may reveal interesting patterns of current sediment deposition within the lake's basin. The distribution of zirconium in Lake Daviumbu adjacent to the Fly River indicates that sediment from the river enters the lake and is deposited in it. Similarly, the distribution of photosynthetic pigments in the surface sediments of Waigani Lake, near Port Moresby, are clearly related to the source of sewage input. Analysis of sediment layers in short cores taken from these lakes has permitted interpretations of their ecological history and demonstrates that sediment deposition in shallow lakes is sufficiently chronological to make this possible.

## INTRODUCTION

Lake sediments usually contain a vertical record of the ecological history of the lake basin and its catchment area. This history maybe recorded in the remains of organisms or parts of organisms that once lived there; the remains being deposited serially in the sediment. In addition temporal variations in the loading rates of nutrients and pollutants such as heavy metals can often be detected by different concentrations in successive sediment layers. By analysing the layers in a lake's sediment some details of its history can be elucidated. A prerequisite for the establishment of a good sediment record is calm conditions for sediment deposition and the absence of marked sediment bioturbation. These conditions are less likely to be met in shallow lakes, where there is a greater likelihood of physical disturbance of sediments and colonisation of the entire sediment by both plants and animals. Despite these potential problems a number of paleolimnological studies have indicated that the sediments of some shallow lakes do contain an interpretable record (see Osborne & Moss, 1977; Moss, 1980; Osborne & Polunin 1986). In addition to this vertical record, analysis of surface sediments collected from a number of sites may reveal interesting patterns of current sediment deposition within the lake's basin.

This sediment record is particularly useful in lakes in which major ecological changes have occurred and need to be explained but for which ecological studies do not span the time-scale concerned. Alterations in community structure can often be correlated with changes in environmental factors and this may provide some insight into the nature of the causal agent, especially if the changes have resulted from some action by man. In pristine lakes, the record can also be used to establish baseline levels of pollutants which may increase as a result of environmental change from proposed developments in the lake's catchment area. These data can be provided at a fraction of the cost of routine monitoring programmes and, in addition, sediment core studies may be used to explain past environmental changes in the absence of sampling over extended time periods. It is essential, however, that adequate sampling is carried out to encompass the variation in spatial distribution of sediments, both horizontally and vertically.

The points made above are illustrated by results of studies of the sediments from two shallow lakes in Papua New Guinea: Lake Daviumbu, Western Province and Waigani Lake near Port Moresby, National Capital District.

## LAKE DAVIUMBU

### Study Area

Lake Daviumbu is a shallow lake filling a depression adjacent to the Fly River, to which it is connected by a narrow channel. The lake is approximately 3 m deep when full, but has marked seasonal fluctuations in water level and may almost dry out completely. Morphometric data are given by Kyle and Chambers (this volume) and information on the bathymetry of the lake is given in Maunsell *et al.* (1982). Dense beds of aquatic plants cover all but the deeper parts of the lake and the diverse aquatic flora includes the following dominant species: *Blyxa aubertii*, *Blyxa novoguineensis*, *Ceratophyllum demersum*, *Echinochloa praestans*, *Eleocharis dulcis*, *Hanguana malayana*, *Hymenachne acutigluma*, *Ischaemum polystachyum*, *Leersia hexandra*, *Limnophila aromatica*, *Limnophila indica*, *Nelumbo nucifera*, *Nymphaea macrosperma*, *Nymphaea violacea*, *Oryza rufipogon*, *Pistia stratiotes*, *Sacciolepis myosuroides* and *Utricularia aurea* (see Leach and Osborne, 1985).

### Surface sediment surveys

Osborne *et al.* (in press) were concerned about the potential impact of the Ok Tedi mine on the lakes of the middle Fly region and used Lake Daviumbu as an example of one of the shallow depression lakes on the floodplain of this large river. They collected samples of surface sediments by hand from 32 sites and analysed them for 27 elements by X-ray fluorescence (see Osborne *et al.*, in press); amongst these elements were zirconium and phosphorus. Zirconium is concentrated in the heavy mineral fraction and its distribution correlates with sediments deposited rapidly. Figure 1 demonstrates the importance of the Fly River as a source of sediment input to lakes connected to the river by even a narrow channel such as Lake Daviumbu. This impact is undoubtedly due to the very large and rapid rises in river level that occur following heavy rainfall in the Fly River catchment area. Although flooding occurs across the levees as well as through the channel, the clays containing much zirconium are deposited primarily along the central axis of the lake. Phosphorus, by contrast, is more associated with biological activities such as peat accumulation, and its distribution in Daviumbu is approximately the inverse of zirconium (Figure 2). Maunsell *et al.* (1982) concluded from hydrological evidence that flows from the main river to the backswamps rarely occur. We suggest that, given the clear patterns of sediment deposition obtained, ingress of Fly River water to backswamps such as Lake Daviumbu may be an annual, or even more frequent, occurrence.

Table 1. Mean concentrations and ranges of iron, manganese, zinc, chromium, copper and lead recorded in 32 surface sediment samples collected in December 1984 from Lake Daviumbu, Western Province, Papua New Guinea. For comparison, the results of Kyle and Chambers (this volume) and those of Maunsell *et al.* 1982 are given.

| | Fe | Mn | Zn | Cr | Cu | Pb |
|---|---|---|---|---|---|---|
| Mean | 4.43 | 362 | 182 | 69 | 62 | 16 |
| Range | 2.4-10.8 | 200-1400 | 36-309 | 30-94 | 28-167 | 3-27 |
| Maunsell *et al.* 1982 | | | | | | |
| July | - | - | 190 | - | 35 | 36 |
| Kyle 1984 | | | | | | |
| June | 5.63 | 493 | 98 | 40 | 30 | 7 |
| Dec | 5.53 | 508 | 101 | 23 | 21 | 4 |

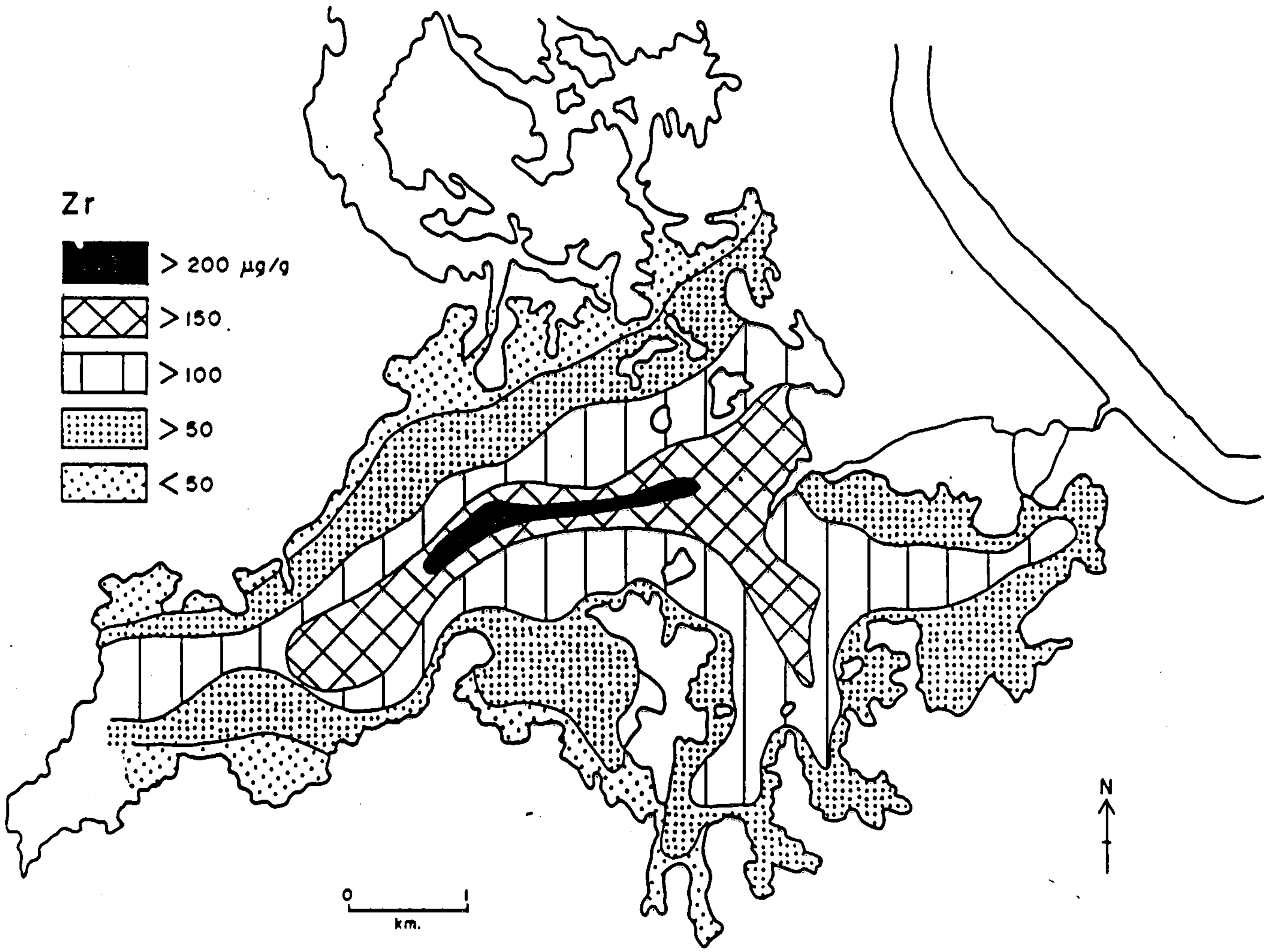


Figure 1. Distribution of zirconium in surface sediments collected from 32 sites in Lake Daviumbu, Papua New Guinea. (Reproduced with permission from Osborne *et al.*, (in press). Geochemical traces of riverine influence on a tropical lateral lake. Verh. Internat. Verein. Limnol., 23.)

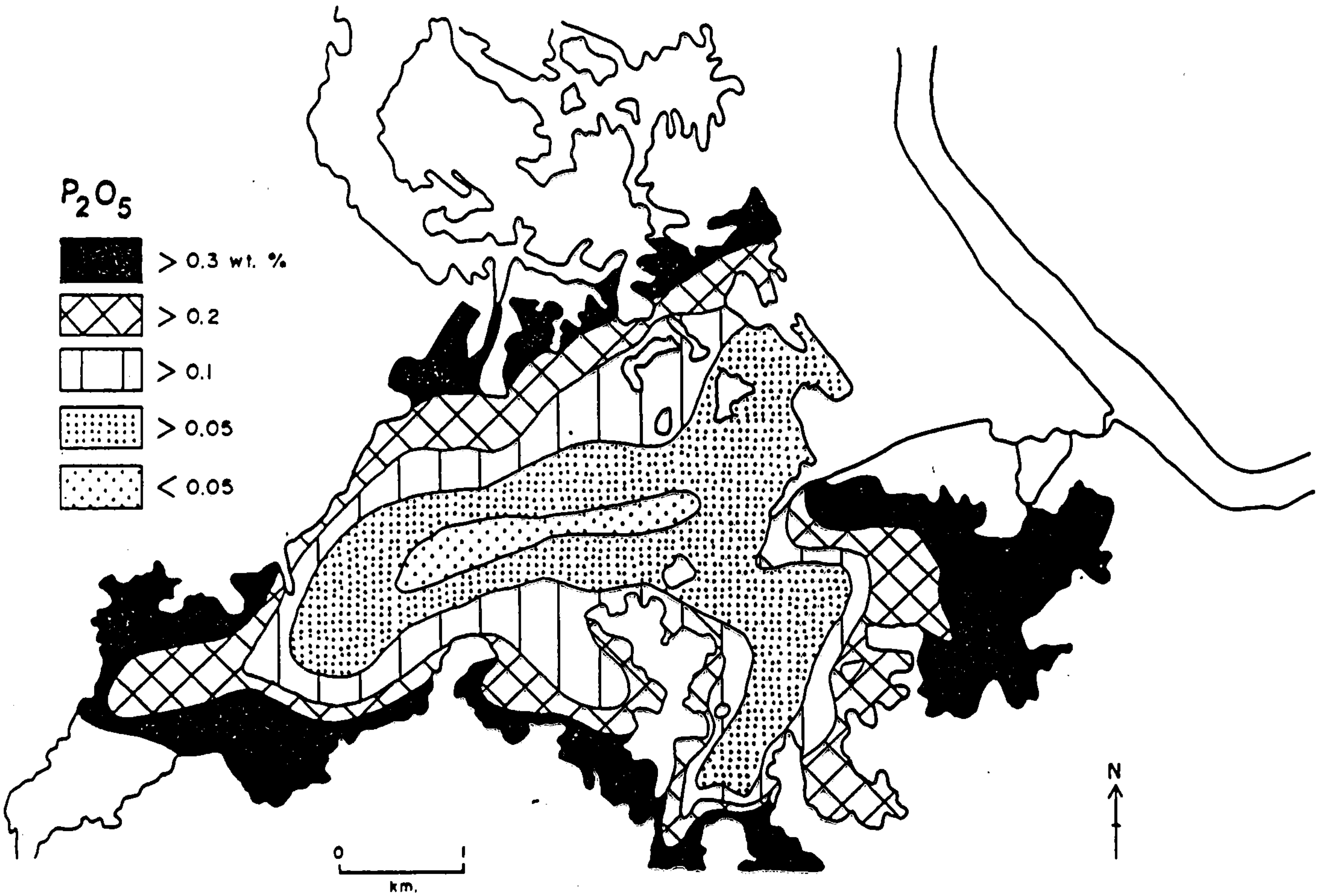


Figure 2. Distribution of phosphorus in surface sediments collected from 32 sites in Lake Daviumbu, Papua New Guinea. (Reproduced with permission from Osborne *et al.*, (in press). Geochemical traces of riverine influence on a tropical lateral lake. Verh. Internat. Verein. Limnol., 23.)

Table 1 gives the mean values and ranges for the concentrations of Fe, Mn, Zn, Cr, Cu and Pb recorded in the 32 surface sediment samples collected from Lake Daviumbu. These figures are compared with those reported by Kyle and Chambers (this volume) and Maunsell *et al.* (1982). These results indicate the importance of adequate sampling to account for the variations in element concentrations resulting from differential rates of sediment deposition. Kyle and Chambers (1986) suggested that the high value recorded for Zn by Maunsell *et al.* (1982) was erroneous. However, our study records Zn concentrations of over 200 ppm in 14 samples from Lake Daviumbu. The concentrations of Zn and Cu recorded by Kyle and Chambers (this volume) for Fly River sediments sampled in December 1984 show elevated levels compared with the results recorded by Maunsell *et al.* (1982) for samples collected in 1981. Even these elevated values, however, are lower than most of the values recorded by us in the surface sediments of Lake Daviumbu.

Sediment core samples

Short sediment core samples collected in 1983 showed variations in physical appearance (Osborne *et al.*, in press). The surface layer of all cores was soil-like and this was underlain in one core by a peaty layer but in others by an organic-rich clay layer. Peat layers were recorded beneath the clay layers in two cores (Osborne *et al.*, in press). Longer cores (up to 4 m) were collected in 1986 and analyses are in progress. Future investigations should include measurements of actual deposition rates and the monitoring of a flood event to see if predictions regarding sediment deposition are correct. Furthermore, the study should be extended to other lakes associated with the Fly River to see if the results obtained for Daviumbu are more generally applicable.

## WAIGANI LAKE

Study area

Waigani Lake is shallow (*c.* 1 m) and occupies a valley in which much of the urban development of Port Moresby has taken place. Sewage disposal into the lake began in 1965 and quantities have increased with the urbanisation of the catchment. Major changes in the aquatic flora of the lake have occurred over the last forty years and these have been documented through interpretation of a series of aerial photographs by Osborne and Leach (1983). The main lake is now devoid of submerged and floating-leaved plants. It is surrounded by emergent swamp dominated by *Phragmites karka* and *Typha orientalis*. In the late 1960s and early 1970s nymphaeids (*Nymphoides indica, Nymphaea pubescens* and *Nymphaea dictyophlebia*) dominated the area which is now open water. Aerial photographs taken in 1942 and 1956 both show the central area of Waigani Lake covered with emergent vegetation (Osborne and Leach, 1983). Recently, it has been shown that the emergent swamp surrounding the lake is declining in area (Osborne, unpublished).

Osborne and Polunin (1986) made a detailed study of the sediment record of Waigani Lake and produced distribution maps of sediment accumulation rates and photosynthetic pigments. The photosynthetic pigment concentration pattern obtained was related to the source of sewage input (Figure 3). Osborne and Polunin (1986) also collected short cores from the lake and through analyses of phosphorus and nitrogen concentrations, diatoms and plant remains were able to reconstruct the ecological history of the lake. The timing of changes in the features measured suggested sewage effluent disposal was a possible cause of the marked changes observed but the effects of possible changes in water level could not be ruled out (Osborne and Polunin, 1986). An analysis of the heavy metal content of core sections from Waigani Lake again demonstrates the usefulness of sediments as archives of environmental change (Polunin *et al.*, in press). Future work should investigate the pre-urbanisation human impacts and relate changes in the sediment record to changes in the vegetation history of the catchment area, particularly in regard to the replacement of forest by savanna.

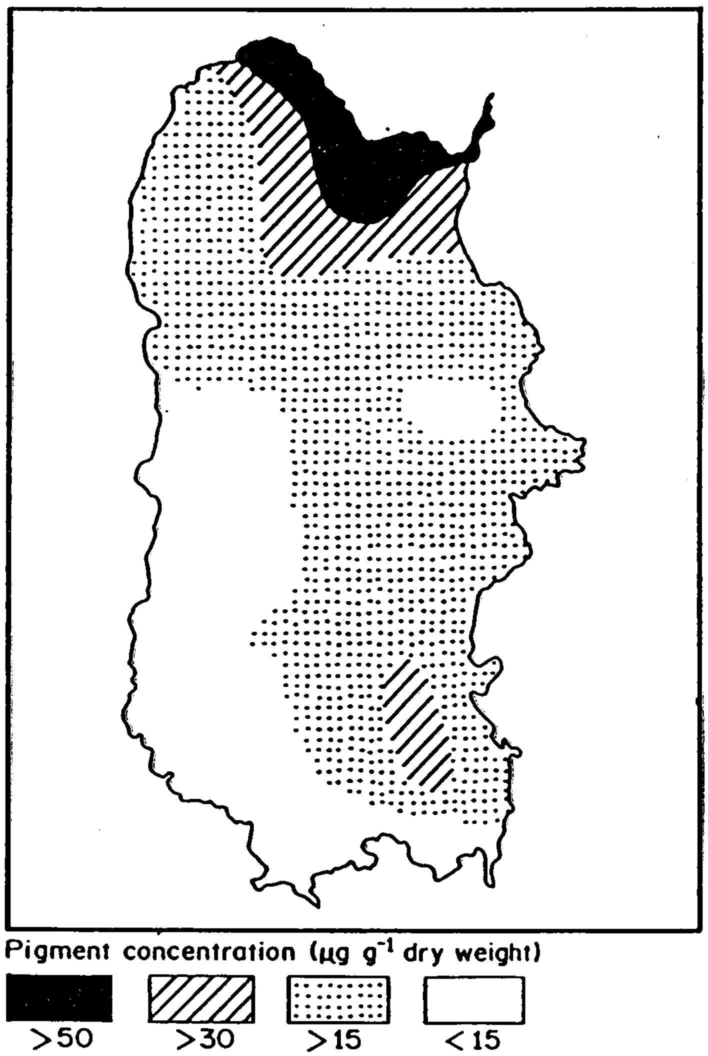


Figure 3. Distribution of plant pigment products in sediment samples collected from Waigani Lake, Papua New Guinea. (Reproduced with permission from Osborne and Polunin (1986). From swamp to lake: Recent changes in a lowland tropical swamp. Journal of Ecology, 74, 197-210.)

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# THE COMPLEXING CAPACITY OF FLY RIVER LAKE WATERS

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## ABSTRACT

The complexing capacity as determined by anodic stripping voltammetry of lake waters from the Fly River is reported. Results indicated higher concentrations of "dissolved" or fine colloidal copper in Lake Daviumbu than in the other two lakes, hence suggesting a greater influence of the Fly River in the case of this lake. Data from billabongs in the Northern Territory of Australia indicate comparable complexing capacities to the lakes examined from the middle Fly. Data indicate that at a plating potential of -0.3v to -0.6v, Fly River lakes may be capable of complexing 0.5 μM of added copper (0.2 μM at potentials of -0.9v to 1.2v). These data suggest that complexation may be a potentially significant mechanism for detoxification of copper ions in these lakes. The total capacity of the lakes may be insufficient however, to cope with large influxes of trace metals into these ecosystems.

## INTRODUCTION

Trace metals in natural waters are present in several different physio-chemical forms which may have quite different effects on aquatic organisms (Florence & Batley 1980). It is now known that the free metal ions of trace metals such as zinc, copper and cadmium are much more toxic than complexed forms of the metal ions (Lake *et al.* 1979; Petersen 1982). The metal ions may be complexed by dissolved organic matter in the water or by colloidal or particulate matter. The extent to which this occurs in a natural water sample is known as the complexing capacity. It is an important parameter in trace metal toxicity studies as it governs the amount of toxic free metal ion in the water body.

The results of complexing capacity studies of filtered water samples from Lakes Bosset, Pangua and Daviumbu using the Anodic Stripping Voltammetry (ASV) technique are presented. The experiments were performed at four different potentials (-0.3v, -0.6v -0.9v, and -1.2v). Standard Calomel Electrode (SCE) and the total ligand concentrations and metal-ligand stability constants were evaluated at each potential.

## METHODS (after Hart & Jones 1984)

The complexometric titration method can be used to evaluate the complexing capacity of a natural water sample. The water sample is titrated with ionic copper. After each addition of the metal ion, a short equilibration time is allowed, and then the concentration of unreacted copper (or free copper ions left in solution) is determined using ASV. Initially, the concentration of 'free' copper is very small because most of the added copper is being complexed. However, once the complexing capacity of the water has been exceeded, the amount of 'free' copper increases sharply. Hence a graph of 'free' copper, or an experimental parameter related to this (e.g. peak current) versus total added copper (Figures 1 - 3) show initially a small slope changing to a steep slope when the complexing ligands become saturated with copper ions.

If it is assumed that only one type of bonding ligand (L) is present in the water body, the reaction between the added metal ion (M) and the ligand is as shown below. The conditional stability constant (K*) is defined by equation (1) (charges have been omitted for clarity):

$$M + L = ML \qquad \text{where } K^* = \frac{[ML]}{[M][L]} \qquad (1)$$

The total ligand concentration, $[L_t]$, is equal to the sum of the complexed and uncomplexed forms, i.e. [ML] plus [L], and is related to the free concentration and the conditional stability constant by equation (2):

$$[ML] = \frac{K^*[M][L_t]}{1 + k^*[M]} \qquad (2)$$

This equation can be rearranged to:

$$\frac{[M]}{[ML]} = \frac{[M]}{[L_t]} + \frac{1}{K^*[L_t]} \qquad (3)$$

The parameters $[L_t]$ and K* can then be evaluated from a straight line plot of [M]/[ML] versus [M] which has a slope $l/[L_t]$ and an intercept $l/K^*[L_t]$. The conditional stability constant is only applicable for the conditions of pH and ionic strength under which it was evaluated.

Water samples were collected from each of the three lakes, filtered on site through acid-washed 0.45 µm millipore filters, and stored at 4 °C in acid-washed polyethylene bottles until required. The samples were re-filtered through 0.45 µm filters, adjusted to pH 6.0 with sodium acetate/acetic acid buffer (0.1 ml of 4M), de-aerated for 16 minutes and titrated with Cu(II) ion at constant pH. After each addition of Cu(II) solution, 10 minutes equilibration time was allowed before stripping currents were measured by ASV using a PAR 174A polarographic analyser fitted with a PAR model 303A static mercury drop electrode. The solution temperature was 26.0 ± 0.5 °C.

Instrument settings used were: plating time, 5 min; scan rate, 5 mV $s^{-1}$; modulation amplitude, 25 mV; initial potential, -0.3, -0.6 -0.9 or -1.2 vs SCE; clock 0.5 s. The initial concentrations of Cu(II) in the water samples were also determined by ASV after digestion of the sample in 1% nitric acid.

## RESULTS

The sets of titration curves of peak current, i, versus the total concentration of copper added, [Cu], for each of the lakes studied are shown in Figures 1 to 3. The slope of the steep portion of each titration curve was used to calculate the free copper, Cu(II), concentration at each experimental point and hence the concentration of complexed copper. These data were plotted as required by equation (2) to determine values of the total ligand concentration or complexing capacity, $[L_t]$, and the conditional stability constant, K*, which are displayed in Table 1, together with the initial total concentration of copper present in the unspiked water (determined on separate samples). The values of K* and $[L_t]$ for each of the three lakes were determined at four different initial plating potentials by the ASV technique; The different values obtained for the terms $[L_t]$ and K* at each of these potentials are displayed visually in Figure 4.

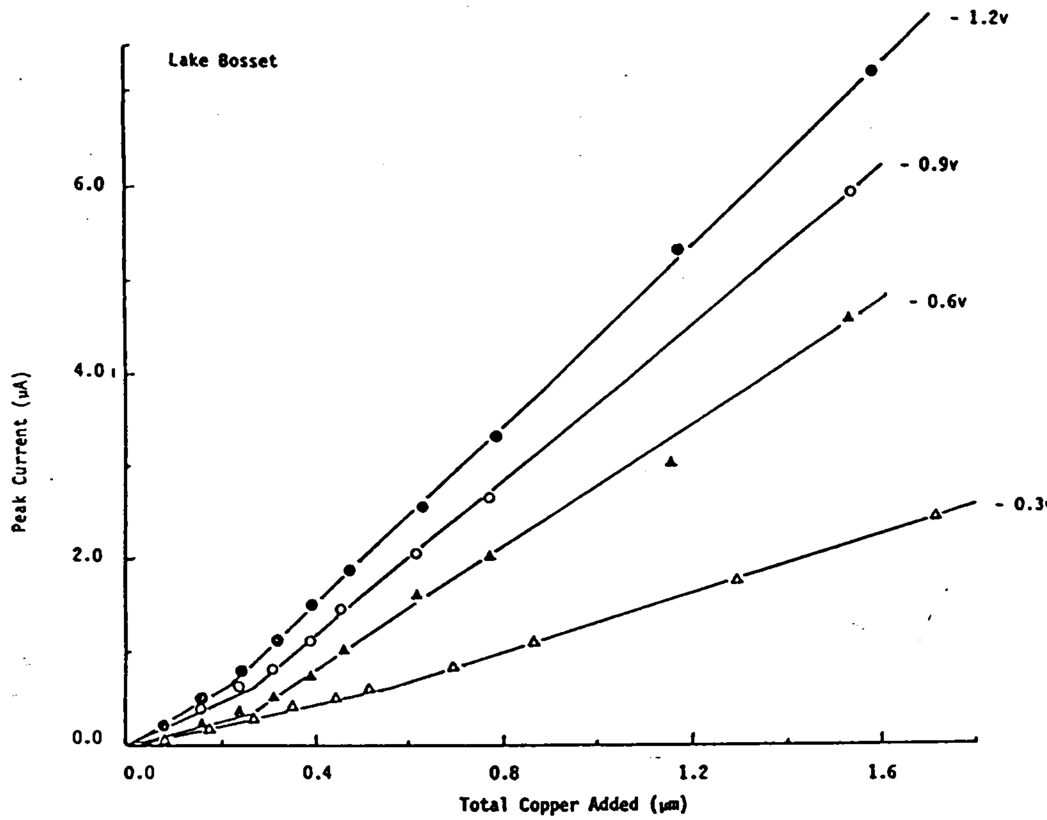


Figure 1. Peak Current vs. Total Copper Added at four different plating potentials.

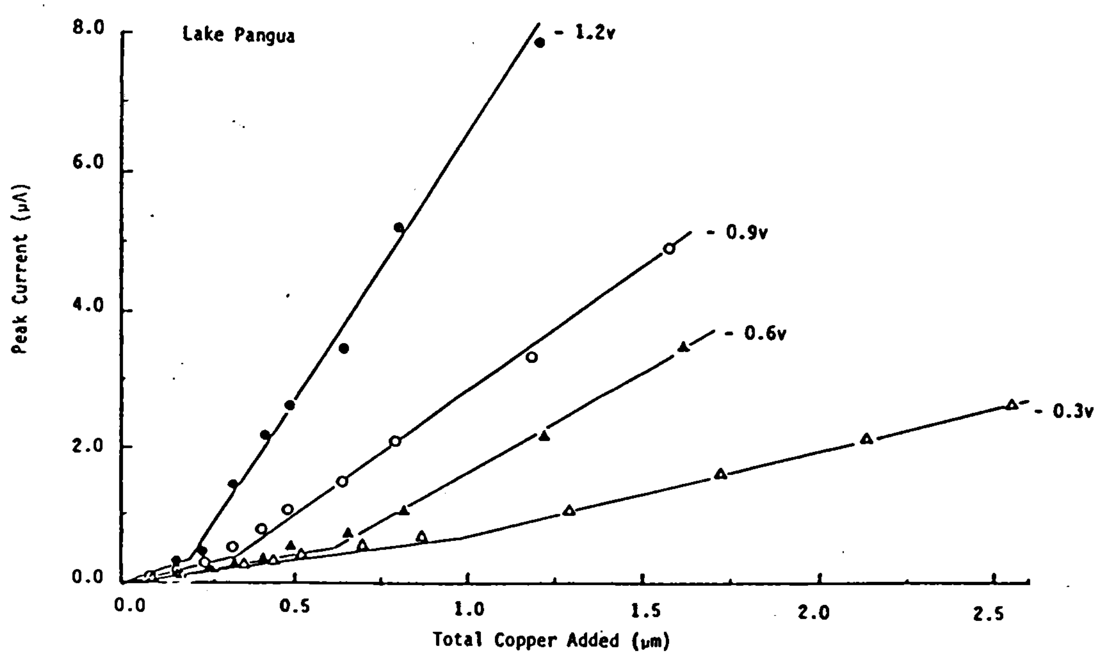


Figure 2. Peak Current vs. Total Copper Added at four different plating potentials.

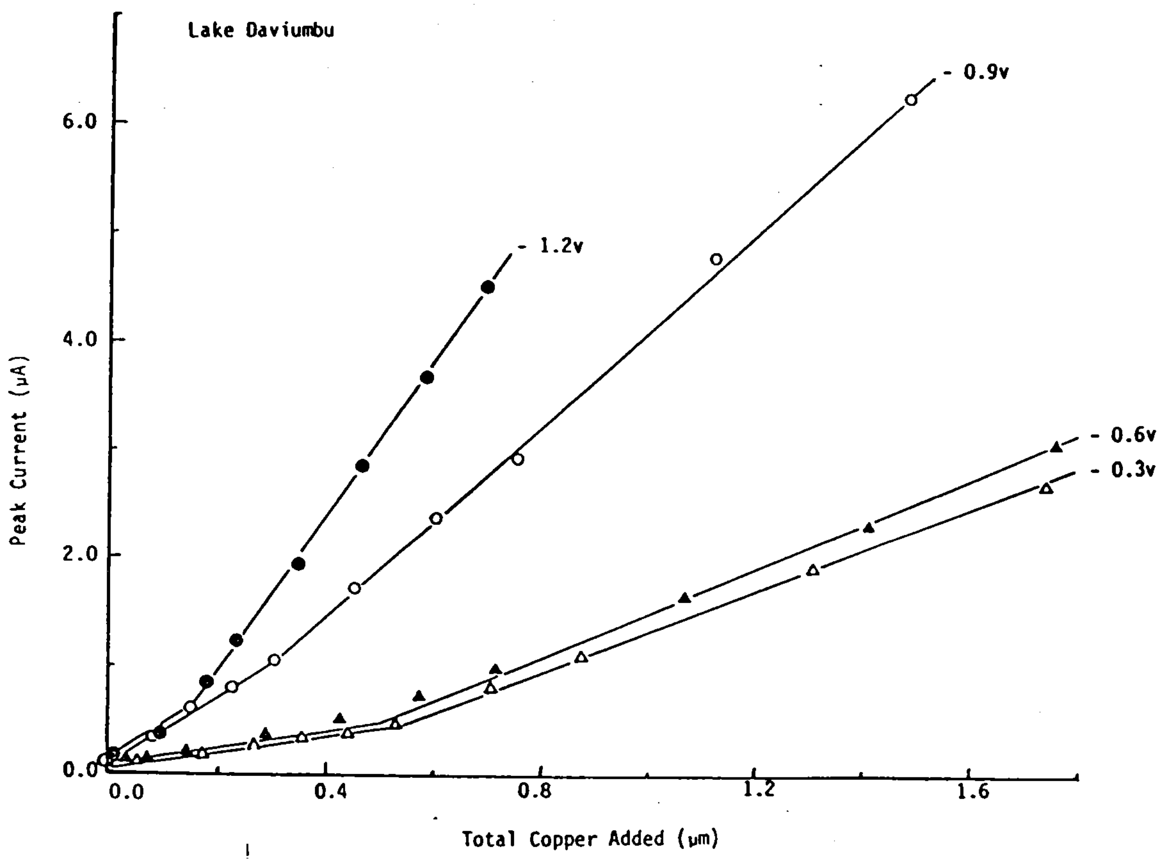


Figure 3. Peak Current vs. Total Copper Added at four different plating potentials.

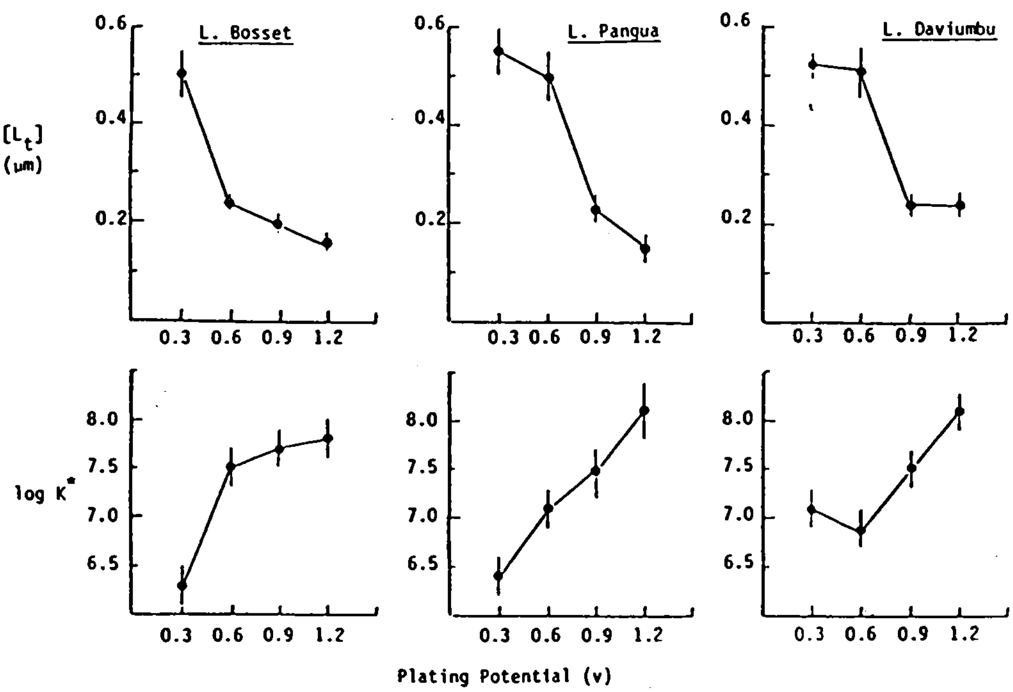


Figure 4. The variation of apparent total ligand concentration $[L_t]$, and the apparent conditions stability constant K* with the initial plating potential (-ve vs. SCE).

TABLE 1. Total ligand concentrations, $[L_t]$ in µm, and conditional stability constants, K* (expressed as log K*), obtained for Lakes Bosset, Pangua and Daviumbu at four different plating potentials. Standard deviations are given and the initial concentration of total copper in the water $[Cu]_O$ is included (µm).

| | Planting Potential (vs SCE) | Bosset | Pangua | Daviumbu |
|---|---|---|---|---|
| $[L_t]$ | -0.3v | 0.50 ± 0.05 | 0.55 ± 0.05 | 0.52 ± 0.02 |
| (µM) | -0.6 | 0.24 ± 0.01 | 0.65 ± 0.05 | 0.51 ± 0.05 |
| | -0.9 | 0.20 ± 0.02 | 0.23 ± 0.02 | 0.24 ± 0.02 |
| | -1.2 | 0.16 ± 0.02 | 0.15 ± 0.02 | 0.24 ± 0.02 |
| log K* | -0.3v | 6.3 ± 0.2 | 6.4 ± 0.2 | 7.1 ± 0.2 |
| | -0.6 | 7.5 ± 0.2 | 6.8 ± 0.2 | 6.9 ± 0.2 |
| | -0.9 | 7.7 ± 0.2 | 7.5 ± 0.2 | 7.5 ± 0.2 |
| | -1.2 | 7.8 ± 0.2 | 8.1 ± 0.3 | 8.1 ± 0.2 |
| $[Cu]_O$ (µm) | | 0.057 | 0.008 | 0.170 |

There was a large variation in the initial concentrations of copper in the lakes from 0.008 µM in Pangua to 0.170 µM in Daviumbu. All analyses were performed in duplicate and matching results were obtained. The extremely high concentration of "dissolved" copper in Daviumbu was verified by independent analysis about the same time by the Department of Minerals and Energy (unpublished data).

## DISCUSSION

### Initial Copper Concentration

It must be assumed that most of the "dissolved" copper in the Daviumbu sample was very fine colloidal copper that would pass through a 0.45 µm filter, rather than true dissolved copper ions. This result is further evidence of the effect of the Fly River water on the chemical composition of Lake Daviumbu, since the very fine colloidal copper must have come into the lake from the mining area via the Fly River.

### Effect of Plating Potential

In the ASV method for measuring free or uncomplexed copper, the water sample is electrolysed for a fixed time, at a given negative potential, so that the "free" copper is reduced into the static mercury drop electrode. The potential is then changed so that the plated copper is "stripped" back into the solution, i.e. it is reoxidised to copper ions. The current produced by this oxidation reaction is proportional to the concentration of free copper ions in solution.

The present experiments have shown that the actual amount of "free" copper measured, and hence the values of the conditional stability constant K*, and the total ligand concentration, $[L_t]$, depend on the potential chosen to electrolyse the sample. As this potential decreased with respect to SCE, the amount of free copper measured increased. Hence the value of $[L_t]$ decreased and K* increased. This behaviour of the "constants" $[L_t]$ and K* with changing initial potentials can be explained as follows. The natural water system contains a number of different types of ligands or binding sites that bond to copper with varying strengths (inorganic ligands, colloidal hydrous oxides, organic matter). The copper complexes formed between ions and these ligands are reducible at given negative potentials - the more negative the potential, the more types of complexes are reducible. The reducible copper complexes, as well as the free copper ions, will contribute to the peak stripping current, and hence increase the apparent concentration of free copper ions and decrease the apparent concentration of ligands, $[L_t]$. Generally speaking, the complexes that reduced at a given potential have lower stability constants than the unreduced complexes. Hence, as the range of ligands decreases, the average stability constant of the remaining ligands increases.

Comparison with Other Data

The most comparable data have been collected by Hart and co-workers (1980, 1984) for a number of billabongs in the Alligator River region of the Northern Territory of Australia (Table 2). These workers used both ASV (initial plating potential -0.9v) and ion selective electrode (ISE) techniques. The latter method only measures free copper ions and no complexes at all. Hence values for free copper are lower than by ASV, which means that values of $[L_t]$ are larger and K* are smaller. The ASV data of Hart and co-worders (1980; 1984 a, b) are in general agreement with present results, showing comparable values of $[L_t]$ and K*.

TABLE 2. Complexing capacity, $[L_t]$, and conditional stability constants, K*, measured at pH 6.0 for Lakes Bosset, Pangua and Daviumbu compared with data for some billabongs in the Northern Territory, Australia. All Australian results determined by ASV at -0.9v except Island (determined by both ASV and ISE at pH = 6.0).

| | $[L_t]$ (μM) | logK* (-0.9v) |
|---|---|---|
| Lakes | | |
| Bosset | 0.20 | 7.7 |
| Pangua | 0.23 | 7.5 |
| Daviumbu | 0.24 | 7.5 |
| Billabongs | | |
| Gulungul | 0.46 | 7.6 |
| Island ASV | 0.18 | 8.0 |
| Island (ISE) | 1.47 | 5.7 |
| Georgetown | 0.24 | 7.6 |
| Leichhardt | 0.15 | 8.0 |
| Jabiluka | 0.07 | 8.1 |

CONCLUSION

It is now generally agreed that the measurement of complexing capacity by ASV underestimates the true total ligand concentration in the water body. The current results show that by using a plating potential less than -0.9v, that normally used in previous studies, higher values of the complexing capacity are obtained that may be closer to a realistic result. Other workers (Hart & Jones 1984) have used a combination of ASV and ISE to obtain a better idea of the total complexing capacity of a system. How these data relate to biological availability of copper ions is a question that requires further investigation. Complexing capacity data indicate that the Fly River lakes may complex up to about 0.5 μM of added copper at a plating potential of -0.3 to -0.6v or 0.2 μM at a plating potential of -0.9 to -1.2v. This is a substantial amount and hence complexation will be a significant mechanism in the detoxification of Cu(II) ions that may enter the lakes from the Fly River or be formed *in situ* from copper minerals in the sediment. The total quantity of complexing material in the lakes will not be sufficient to cope with a large influx of trace metals into these systems; constant monitoring is therefore needed to ensure that levels of total trace metals do not increase to 0.5 μM in the lake waters.

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# ASSESSMENT OF THE BIOLOGICAL IMPACT OF OK TEDI MINE TAILINGS, CYANIDE AND HEAVY METALS

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## ABSTRACT

Tailings were sampled from the Ok Tedi Mine in the first six months of gold production. Toxicity tests showed that the tailings were more toxic to freshwater shrimps than fish, LC50's being 0.1% and 0.4 respectively.

Acute toxicity tests were conducted to determine the toxicity of heavy metal ions and cyanide to both fish and shrimps. The fish were most sensitive to copper then cyanide, whilst the shrimps were most sensitive to cadmium, then copper then cyanide.

On the basis of results of toxicity tests, a consideration of tailings production, water quality parameters and river flow conditions, predictions were made on how far acute and chronic effects on aquatic life would extend downstream on the Ok Tedi and Fly Rivers. It was predicted that acute effects would be confined to the upper Ok Tedi close to the mine but chronic effects could extend down the Fly River.

It was predicted that with increased production and under conditions of low river flow the acute effects of the tailings, of the heavy metals, cyanide and the sediment, would be confined to the upper Ok Tedi close to the mine but chronic effects could extend down the Fly River.

## INTRODUCTION

Prior to the construction of the Ok Tedi mine the PNG Government required Ok Tedi Mining Limited (OTML) to submit a detailed environmental impact statement (Maunsell *et al.* 1982). Much useful biological, chemical, hydrological, geological and sociological data were reported by the study, which proposed an environmental monitoring program to include regular monitoring of heavy metals, suspended solids and other water quality parameters. Such monitoring has since been undertaken by OTML's Environmental Section (OTML,1984a); periodic monitoring was also carried out by the Bureau of Water Resources (BWR) which contracted the Australian company Australian Mineral Development Laboratories (AMDEL) to do their analyses. Buckley (1984a) reviewed the monitoring program and suggested some changes.

The Government approved development plan required the company to construct a tailings dam to minimise pollution of the Fly River System. Cyanides used in the extraction processes were to be passed through a cyanide destruction tower and it was anticipated that residual cyanides would break down whilst held in the dam. Most particulate matter containing heavy metals was expected to settle in the dam. On 7 January, 1984 a massive landslide destroyed the proposed site of the tailings dam, and the government then agreed that mining could proceed using an interim tailings disposal scheme (ITDS). This scheme involved treating tailings with hydrogen peroxide to lower the concentration of cyanide; coarse tailings were to be removed by hydrocyclones and dumped into a nearby valley; and fine tailings were to be discharged into the Fly River System. From 1984 to 1986, the interim means of disposal of tailings continued with between 17500 and 22500 tonnes of ore being processed per day; however, the operation resulted in a higher proportion of the finer tailings being dumped into the Ok Tedi River than originally anticipated.

The Government has always insisted that a permanent tailings dam be built as quickly as possible, while The Company has continually reaffirmed that it would indeed build a permanent tailings dam. Following the 1984 landslide, details of the new location and design were to be provided by OTML. On 18 March 1986, at the company's request, the Government deferred the construction of a permanent tailings dam until 1990. It simultaneously gave approval for increased gold production, and for the commencement of copper production. The result has been that up to 60,000 tonnes or more of tailings are dumped into the river system each day.

Considerable concern has been expressed about the possible effects of the tailings on aquatic life in the Ok Tedi and Fly River systems (Dent,1985; Jackson,1985; Mowbray,1986). The toxicity of the tailings, and their constituent parts, and their possible biological impacts need to be evaluated.

This study, which commenced in June, 1984, aimed at determining how toxic the fine tailings are to fish and freshwater crustacea. These data are then evaluated in the light of: heavy metal toxicity tests performed at UPNG since 1980; and residue data and water quality parameters collected by the Government and by the OTML Environmental Section. An evaluation of the possible biological effects of the treated tailings on the Ok Tedi and Fly Rivers and relevant tributaries, is provided.

This report does not consider the impact of the tailings on subsistence fisheries or resource use, which was the subject of a recent consultancy by Dr P. Guo of WHO/PEPAS who studied pollution control measures undertaken by Ok Tedi, and briefly discussed the likely impact of the ITDS on resource use, concluding that it would be minimal (Guo,1985).

## METHODS

### Toxicity Testing

Animals were dosed with mine tailings, heavy metals or cyanide, and exposed to a geometric series of concentrations of the toxicant for a specified period of time. Mortality was measured, and using probit analysis a log dose-mortality curve was then calculated. The dose required to kill 50% of the animals was determined, giving the LC50. The method used in these experiments is similar to that given in Mowbray (1978). Twenty four hour to two hundred and sixteen hour (1-9 day) LC50's were determined under static conditions.

Little work has been done to determine the suitability of using any of the animals which occur in the Ok Tedi and Fly River systems as laboratory test animals. Some tests were commenced on the rainbow fish, *Melanotaenia splendida*, by OTML, but results have never been published. It was considered logistically impractical to transport large numbers of animals (or large amounts of water) to Port Moresby, and accordingly, suitable animals from Port Moresby were chosen for testing.

Only four species of freshwater animals, suitable for toxicity testing, are found in sufficient numbers in freshwater creeks around Port Moresby throughout the year. These are the mosquitofish, *Gambusia affinis* , the guppy, *Poecilia reticulata* , tilapia, *Oreochromis (Sarotherodon) mossambicus* and the freshwater shrimp, *Caridina nilotica*. Mosquitofish and shrimp were used in the present tests.

### Sampling Methods: Animals

All fish were collected with fine mesh dipnets from Boroko Creek between Gordons Market and Jackson's Airport, and placed in plastic garbage bins with about 60 litres of creek water. The bins containing the fish were then taken to the laboratory. Water containing the fish was aerated and left until the temperature changed to that of the tap water in the laboratory tanks. Aquarium water was aerated to remove chlorine.

Up to 200 fish were then placed into each holding aquarium of about 50 litres each and dosed with 2-4 capsules of antibiotic to reduce bacterial and fungal infection. Each capsule contained

Mysteclin-V (250 mg of tetracyclin HCl and 250,000 units of nystatin) or Amphicillin (250 mg of penicillin). Tanks were aerated and fish were left for a minimum of 2 days. During this period dead and moribund fish were removed.

One day prior to the commencement of the experiment 20-30 female fish of size range 20-40 mm (mean 28 mm; standard deviation 4 mm), were randomly selected and placed in 40 litre experimental tanks and left in the aquaria for 24 hours prior to dosing with the toxic test materials; dead and moribund fish were removed and not replaced, during the test period.

In the first two tailings tests and some of the early tests with heavy metals guppies, *Poecilia reticulata* , were included inadvertently, with the mosquitofish. The precise proportion is not known but is considered to have been low. Tests 3 and 4 used only mosquitofish. Subsequent trials showed that mosquitofish and guppies did not differ significantly in susceptibility to tailings.

Shrimps were collected with dipnets from a creek at the rear of the University adjacent to Gerehu Stage 1, and placed in 10 litre plastic buckets containing creek water. In the laboratory, after the water temperature had reached that of the tap-water in the laboratory tanks, 15-25 shrimps of size range 12.5-30 mm (mean 22 mm; standard deviation 3 mm), were randomly placed in 1.5 litre containers.

The 1981-1982 tests (for heavy metals) were done in an airconditioned room at 25 $^oC$. In 1980, 1984-1985 the test room was not airconditioned but ceiling fans remained on, keeping the water temperature in the tanks relatively constant; temperature varied between 22-28 $^oC$ during different experiments but within any one experiment the absolute range was $\pm$ 1.5 $^oC$.

Sampling Methods: Tailings

Samples of fine tailings (overflow slimes) from the ITDS discharge point were collected on 13 and 30 June, 4 October and 28 November, 1984 and placed in 2 litre plastic containers.

Prior to sampling, all containers had been washed sequentially in detergent, distilled water, 10% nitric acid and distilled water. After sampling all containers were air freighted to Port Moresby within 24 hours and placed in a cold room (at 5 $^oC$) until required.

Experimental Vessels

Aquaria used for the fish experiments were all glass, jointed with silicone sealant. The appropriate amounts of tailings were poured into each tank containing the test animals in 10-20 litres (experiment 1) and 10 litres (experiments 2-4) of Port Moresby tapwater; in the first experiment 100% tailings was placed in a 2 litre container. For tests involving heavy metals and cyanide 40 litres of tapwater were placed in the aquaria. All tanks were continuously aerated. Before and after the tests, aquaria were washed with a strong solution of laboratory detergent and disinfectant (Pyroneg), and then thoroughly rinsed at least twice with tapwater. All air stones used were either new or washed thoroughly in detergent and distilled water in an ultrasonic bath.

Containers used for shrimp experiments were made by removing the tops of used 2 litre glass wine flagons, washed as above. The appropriate amounts of tailings or heavy metals were poured into each container, and made up to 1.5 litres with Port Moresby tapwater. All tanks were continuously aerated.

Dosing

In tests 1 and 2 (June) measured quantities of tailings were poured directly from individual collection containers. It was assumed that the tailings in each plastic container were similar; subsequent measurement of density and percent sediment revealed that this was not the case. Thus for tests 3 and 4 (October and November) tailings from all plastic containers were 'pooled' and mixed before any dosing. Tailings were then poured directly into the aquaria containing the fish or shrimps.

For toxicity testing with heavy metals and cyanide, stock solutions of chemicals and appropriate dilution series were prepared in volumetric flasks. For the most part, the appropriate amounts of diluted chemical were pipetted directly into aquaria. In a few cases, weighed amounts of some metal salts were placed directly into the aquaria. All concentrations used are expressed as ug $L^{-1}$ (ppb) or mg $L^{-1}$ (ppm) of the ion. Chemicals used were $CuSO_4.5H_2O$ ($Cu^{2+}$), $Pb(NO_3)_2$ ($Pb^{2+}$); $ZnSO_4.7H_2O$ ($Zn^{2+}$); $FeSO_4.7H_2O$ ($Fe^{2+}$); $CdCl_2$ ($Cd^{2+}$) and NaCN ($CN^-$).

Test Design

Tests were conducted under static conditions, with a single randomly assigned dose being added to the water in each experimental vessel at the beginning of the test. The animals were not fed during tests, and were recorded as dead when movement ceased and the individual did not respond to mechanical stimulation.

Statistical procedures follow those given by Finney (1971), and as out-lined by Mowbray (1978). The computer programme was taken from Mowbray (1978) modified by Salter-Duke (pers. comm.), run on a Prime 250 computer.

Physical Analyses of Tailings

The density and percent sediment* of the tailings were determined by passing the tailings through a Gallenkamp No.2 sieve of pore size 40-50 mm, or through Whatman No.8 Filter Paper of pore size 10 mm.

Chemical Analyses of Tailings

Tailings collected in June, 1984, were analysed by Dr J. Kyle of UPNG for total metals using the method specified by Meshach (1984) for mineral phase. Tailings collected in both October and November, 1984, were analysed for free cyanide ($CN^-$) and heavy metals (Cu, Pb, Zn, Fe, CD) by AMDEL of South Australia using EPA methods outlined in USA, EPA (1979).

Samples collected for cyanide analyses were fixed by adding 2.0 ml 10N NaOH to 2 litres of tailings; tailings collected for heavy metal analysis were fixed by the addition of 2.0 ml concentrated $HNO_3$. Both Moresby water and diluted tailings used in the series of toxicity tests were also analysed; samples were fixed with addition of 1.0 ml of either alkali or acid. Total recoverable metals (TRM) (Buckley, 1984b) and free cyanide levels were determined for all samples. Samples from the toxicity experiments were also passed through a 0.40-0.50 mm sieve, and filterable (soluble) residues were also determined.

RESULTS

Toxicity of Ok Tedi Tailings

LC50's and associated statistics determined for each test using both organism are given in Appendix Tables 1 and 2. A summary of results is given in Table 1 below:

Tailings were much more toxic to shrimps than to mosquitofish and tailings became significantly more toxic to both species as mining proceeded (Table 1).

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*percent sediment = $\frac{\text{dry mass of solids g}}{\text{100ml volume of tailings}}$

TABLE 1. Four and Nine day LC50's of Ok Tedi Tailings to mosquitofish, *Gambusia affinis*, and freshwater shrimps, *Caridina nilotica*. Tailings concentration is expressed as: percent of original tailings by volume.

| Tailings Date | Exposure (days) | Fish | Shrimp |
|---|---|---|---|
| 13.6.'84 | 4 | 17 | 5 |
| 30.6.'84 | 4 | 9 | 0.5 |
| 4.10.'84 | 4 | 1.5 | 0.3 |
| 4.10.'84 | 9 | 0.8 | 0.2 |
| 28.11.'84 | 4 | 1.2 | 0.1 |
| 28.11.'84 | 9 | 0.4 | 0.1 |

In the first two tests, mortality was measured only over a 96 hour period. In the tests on *C. nilotica* with tailings collected on 30 June, and on mosquitofish with tailings collected on 13 June, animals were still dying after 96 hours. Consequently the tests using tailings collected on 4 October and 28 November ran for 216 hours (or 9 days). Control mortality of mosquitofish was too high at 216 hours for tests of tailings collected on 4 October. Fish mortality due to tailings seemed to cease after 144 hours in both tests. Shrimp mortality ceased after 96-120 hours.

Control mortality

The control mortality at 96 hours in the first two fish tests was greater than 10%, being 25% and 17% for the testing of samples collected on 13.6.'84 and 30.6.'84 respectively. These mortalities were unacceptably high, due to tailrot (either bacterial or fungal infection). Subsequent tests resulted in effective control of this mortality by dosing the fish with 4 capsules of Mysteclin or 4 capsules of Amphicillin, or two of both, for 2 days before the commencement of the toxicity tests. Control mortality at 96 hours was reduced to 9% and 3% for Mysteclin and Amphicillin respectively, and to 2% for a mixture of both. Consequently in experiments 3 and 4, fish were treated with both antibiotics for 2 days before the trials began. Control mortality in experiment 3 was less than 1% at 96 hours, still 1% at 144 hours but rose to 9% at 196 hours. All fish in two control tanks were dead by 216 hours. In experiment 4 control mortality was 10% at 96 hours but had risen to 48% at 216 hours. In all experiments shrimp control mortality remained below 10%. Corrections were made for control mortality in the calculation of LC50's (Finney, 1971).

Toxicity of Heavy Metals and Cyanide to Test Animals

LC50's and associated statistics are given in Tables 3 and 4 of the Appendix. A summary of test results is given in Table 2. Although the LC50's of heavy metals determined at different times may differ significantly, such differences are small when compared to the differences in LC50's between the individual heavy metals and cyanide.

The relative toxicity of heavy metals and cyanide to mosquitofish was found to be:

copper > cyanide > cadmium > zinc > iron > lead.

The relative toxicity of heavy metals and cyanide to shrimps was found to be:

cadmium > copper > cyanide > zinc > iron > lead.

Differences in LC50's are all significant: Mosquitofish being more susceptible to copper and zinc than the shrimps: Shrimps were more susceptible to iron, cyanide and cadmium, while lead was equally toxic to both organisms.

TABLE 2. 4-day LC50's of soluble heavy metals and free cyanide to mosquitofish, *Gambusia affinis* and freshwater shrimps, *Caridina nilotica*. ($\mu g\ L^{-1}$ or ppb) (*24 hour LC50).

| Chemical | Date of test | Fish | Shrimp |
|---|---|---|---|
| copper ($Cu^{2+}$) | 05:'80 | 175 | |
| | *05:'81 | 157 | |
| | 12:'81 | 57 | 194 |
| | 05:'82 | 77 | |
| | 11:'84 | 128 | |
| Geometric mean | | 100 | |
| lead ($Pb^{2+}$) | 11:'84 | 56500 | 53500 |
| zinc ($Zn^{2+}$) | 07:'84 | 4350 | 4650 |
| | 08:'84 | 2900 | |
| | 11:'84 | 3300 | |
| Geometric mean | | 3500 | |
| iron ($Fe^{2+}$) | 09:'84 | 20000 | 8450 |
| | 10:'84 | 34000 | |
| Geometric mean | | 2600 | |
| cadmium ($Cd^{2+}$) | 11:'84 | 1700 | 19 |
| cyanide ($CN^{-1}$) | 01:'85 | 792 | 316 |

Data given in Appendix Tables 1-4 indicate that although heterogeneity was significant in most of the sets of data, it was never excessively high. Values of the statistic 'g' were greater than 0.4 in only 5 instances out of 99 sets of data, indicating that the data are statistically secure.

Physical Analysis of Tailings

The physical properties of the tailings differed significantly, (Table 3); a summary of overall data is given in Appendix Table 5. Tailings produced at the end of November, 1984 were the most dense and contained the highest mass of particulate matter.

TABLE 3. Density and percentage sediment of Ok Tedi tailings. (different superscripts indicate significantly different values).

| Date of sample collection | Density of tailings $g\ mL^{-1}$ | % Sediment $g\ mL^{-1}\ 10^{-2}$ |
|---|---|---|
| 13.06.'84 | $1.07^{a}$ | $14^{a}$ |
| 30.06.'84 | $1.29^{b}$ | $42^{b}$ |
| 04.10.'84 | $1.28^{b}$ | $44^{b}$ |
| 28.11.'84 | $1.42^{c}$ | $51^{c}$ |

TABLE 4. Results of analyses of heavy metal levels (µg $L^{-1}$) and free cyanide (mg $L^{-1}$) from samples collected in 1984. (* estimated from data provided by Townsend pers.com.) (location of sampling sites in given in Mowbray, this volume).

| Date | Sampling Site | Sample No | Heavy metal/cyanide Pb | Zn | Cd µg $L^{-1}$ | Cu | Fe mg $L^{-1}$ | CN(free) | Analyst |
|---|---|---|---|---|---|---|---|---|---|
| Total particulate | | average | 52500 | 6000 | 500 | 250000 | 62500* | 0.50 | OTML |
| June - September | | minimum | 20000 | 4500 | 5 | 146000 | | | |
| | | maximum | 67500 | 37500 | 4950 | 1175000 | | | |
| 13.6 | Moscow Tunnel (Tailings)b | 1 | 3500 | 3600 | 100 | 50000 | | | KYLE,UPNG |
| 30.6 | Moscow Tunnel (tailings):b | 1 | 29500 | 8400 | 400 | 274000 | | | KYLE,UPNG |
| 4.10 | Moscow Tunnel | 1 | 15 | 350 | 3.9 | 345 | | | AMDEL |
| | (tailingl) | 2 | 30 | 240 | 3.5 | 135 | | 0.20 | |
| | | 3 | 9 | 1190 | 5.5 | 880 | 79000 | 0.20 | |
| Total recoverable | | | | | | | | | |
| | Ok Mani | 1 | 30 | 200 | 0.8 | 385 | | 0.01 | AMDEL |
| | Ok Tedi | 1 | 180 | 185 | 1.9 | 215 | | 0.02 | AMDEL |
| | Bridge (RB) | 2 | 315 | 250 | 3.3 | 220 | | 0.02 | |
| | Ok Tedi | 1 | 95 | 315 | 5.5 | 250 | | 0.07 | AMDEL |
| | Bridge LB | 2 | 315 | 270 | 3.4 | 225 | | 0.02 | |
| 3.10 | Ok Tedi Ningerum | 1 | 35 | 165 | 1.5 | 75 | | 0.02 | AMDEL |
| | | 2 | 25 | 205 | 1.0 | 95 | | 0.03 | |
| 27.11 | Moscow Tunnel | 1 | 120 | 4050 | 11.0 | 19600 | | 0.26 | AMDEL |
| 28.11 | (tailings) | | | | | | | | |
| 27.11 | Ok Mani | 1 | 150 | 490 | 1.0 | 2040 | | 0.02 | AMDEL |
| 28.11 | | 2 | 84 | 250 | 9.0 | 1250 | | 0.02 | |
| 27.11 | Ok Tedi, Bridge (LB) | 1 | 23 | 170 | 0.6 | 130 | | 0.01 | AMDEL |
| 28.11 | | 2 | 28 | 220 | 1.5 | 170 | | 0.02 | |
| 27.11 | Ok Tedi, Ningerum | 1 | 18 | 110 | 0.9 | 46 | | 0.01 | AMDEL |
| 28.11 | | 2 | 32 | 210 | 0.5 | 150 | | 0.03 | |
| 27.11 | Fly (just upstream of Ok Tedi Jnct.) | 1 | 6.5 | 200 | 0.7 | 96 | | 0.01 | AMDEL |
| 27.11 | Fly River 20k Tedi Junction | 1 | 14 | 120 | 1.5 | 34 | | 0.01 | ADMEL |
| 27.11 | Fly River at | 1 | 12 | 180 | 0.45 | 140 | | 0.02 | AMDEL |
| | Kuambit. | 2 | 11 | 130 | 2.0 | 40 | | 0.01 | |

Chemical Analysis of Tailings in the River Water

Results of analyses of heavy metals from river water samples collected in 1984 are shown in Table 4. Heavy metal analyses performed by Kyle are total metals; those by AMDEL are total recoverable metals. The level of total recoverable metal is estimated by Kyle (1984) to be 60-100% of the total particulate level, but exact values depend upon metal speciation. In this report it is assumed to be 50%. Results supplied by Kyle were based on dry weight (mg $kg^{-1}$) of sediments, but were converted into values based on volume (μg $L^{-1}$); total particulate levels reported by Higgins (1984) for June-September have been adjusted to a volumetric basis and are included for comparison.

The data given in Table 4 show results of analyses of water samples taken from the ITDS downstream to Kuambit on days when tailings samples were collected for toxicity tests. The values for tailings sampled on 4.10.84 and 27-28.10.84 seem very small compared to values reported by Higgins and Kyle. The number of samples collected was inadequate for statistical analysis. Despite this, it would seem that levels of heavy metals (as total recoverable metals) in the water decrease as tailings are diluted downstream. The free cyanide level drops immediately.

Chemical Analyses of Tailings in Experimental tanks dosed with LC50.

Data from analyses of water samples collected on 4 October and used in toxicity tests are given in Table 5. Some samples were fixed immediately in the field, but most samples were transported to Port Moresby then frozen and were fixed at the time of the toxicity experiments.

TABLE 5. Heavy metal levels (μg $L^{-1}$) and free cyanide (mg $L^{-1}$) in tailings used for toxicity testing, November-December 1984 (Tailings collected on 4.10.'84 Analyses by AMDEL). (TRM = total recoverable metal; FR = filterable or soluble residues)

| Samples | | No | Pb | Zn | Cd | Cu | Fe | CN(free) |
|---|---|---|---|---|---|---|---|---|
| | | | | | μg $L^{-1}$ | | mg $L^{-1}$ | |
| Tailings 4.10 | TRM | 1 | 15 | 350 | 3.9 | 345 | - | - |
| (fixed immediately) | 2 | 30 | 240 | 3.5 | 135 | - | 0.20 | |
| Tailings 4.10 (frozen, fixed 3.12) | TRM | 3 | 9 | 1190 | 5.5 | 880 | 79000' | 0.20 |
| 1.5% tailings TRM | 1 | 59 | 250 | 2.5 | 730 | 8920 | 0.02 | |
| LC50 fish FR | 1 | 0.5 | 28 | 0.5 | 24 | 10 | - | |
| 0.27% tailings | TRM | 1 | 350 | 280 | 67 | 280 | 3160 | 0.08 |
| LC50 shrimps FR | 1 | 40 | 19 | 3.0 | 13 | 10 | - | |
| Moresby tap-water | TRM | 1 | 18 | 150 | 0.8 | 26 | 100 | 0.01 |
| Control fish | FR | 1 | 0.5 | 22 | 0.7 | 4.5 | 10 | - |
| Moresby tap-water | TRM | 1 | 29 | 250 | 3.0 | 96 | 0.02 | |
| Control shrimp | FR | 1 | 1.5 | 9.0 | 0.9 | 7.0 | 10 | - |

On the basis of toxicity tests performed on 4 November, the 96 hour LC50 of the October tailings were determined to be 1.5% and 0.27% for mosquitofish and shrimps respectively. Approximately 25 fish were then placed in four dosed tanks and four control tanks. After 96 hours mortality averaged 51% for fish in the dosed tanks and 8% for fish in the control with little variation. Approximately 20 shrimps were placed in each of 8 dosed tanks and 8 control tanks. Mortality was variable within the treatments, but averaged 58% for dosed shrimps and 6% for control shrimps. Samples of water in these tanks were then fixed. Results of analyses showed that diluted tailings still contained relatively high levels of heavy metals, particularly of total recoverable Pb, Zn, Cu and Fe. The high level of cadmium (TRM) 0.27% tailings is inexplicable.

## DISCUSSION

### Validity and relevance of the experimental data to the Ok Tedi environment.

The fundamental question under consideration is how toxic tailings might be to the animals that live in the Ok Tedi and Fly River systems. In this study mosquitofish and freshwater shrimps were used as test organisms, their susceptibility to tailings, needs to be compared with that of animals occurring in the Ok Tedi and Fly River system; unfortunately data for such species are not available.

In Table 6 a comparison is made between 96 hour LC50's for heavy metals and cyanide of the present test animals with the LC50's of the most sensitive fish and arthropods recorded (Skidmore and Firth, 1983), (Leduc et al, 1982; Mowbray, 1984).

TABLE 6. 96 hour LC50's of soluble heavy metals (μg $L^{-1}$) and free cyanide to mosquitofish, freshwater shrimp, and other fish and freshwater arthropods.

| Pollutant | Fish | | | Arthropods | | |
|---|---|---|---|---|---|---|
| | Least Sensitive | Mosquitofish | Most Sensitive | Least Sensitive | Shrimp | Most Sensitive |
| copper | >100,000 | 100 | 15 | 100,000 | 194 | 5 |
| lead | 540,000 | 56,500 | 1,200 | 64,000 | 53,500 | 28 |
| zinc | 200,000 | 3,500 | 93 | 32,000 | 4,650 | 40 |
| cadmium | 74,000 | 1,700 | 1 | 32,000 | 19 | 3 |
| cyanide | ? | 790 | 28 | ? | 316 | 400 |

It is clear that except for the effects of cadmium on the shrimp neither test species is as sensitive to the test pollutants as the most sensitive species examined to date. Skidmore and Firth (1983) report that mosquitofish and guppies are more sensitive to copper than many other fish; and *Paratya*, a close relative of *Caridina*, is more sensitive to copper (LC50 = 120 μg $L^{-1}$) than many other Australian crustaceans and molluscs.

One can speculate that animals in the Ok Tedi/Fly River system may be tolerant of heavy metals. Data from Maunsell *et al.*, (Vol. 2, 1982) gives the following range of values of soluble copper (expressed as filterable residues) at various sites before the main construction work began.

TABLE 7. Filterable residues of copper in waters around Ok Tedi Mine in 1981-1982, in μg $L^{-1}$.

| Site | Range of Median | Range of levels recorded |
|---|---|---|
| Ok Mani | 0.8 - 5.0 | 0.5 - 10.0 |
| Tabubil Ford | 2 - 5.0 | 1 - 20 |
| Ok Tedi at Worongbin | 3 | 0.5 - 31 |
| Fly at Kiunga | 2 - 5 | 0.25 - 15 (1600?) |

One seemingly anomalous value of 1600 μg $L^{-1}$ was recorded at Kiunga apart from that, levels of soluble copper recorded prior to mining are similar to levels commonly found in unpolluted waters in Australia and the U.S.A. Maunsell *et al.* (1982) and Buckley (1984a) believe there is no reason to suppose that aquatic species in the Ok Tedi have a naturally high tolerance to copper; or to any other heavy metal. To date no toxicity tests have been performed on fish, crustaceans or other arthropods, from the Ok Tedi River system.

Skidmore and Firth (1983) concluded that, at present, reliable generalisations about the order of sensitivity of aquatic animals to heavy metals cannot be made. Large differences in susceptibility to heavy metals exist between all species. Under the circumstances, the best evaluation of toxicity can only be made using the mosquitofish and shrimps as 'indicator species', and relating the results to available data. Single species of fish or arthropods from the Ok Tedi region would probably be no more 'representative' of all species in the river system than are the mosquitofish and shrimps.

River water samples from the Ok Tedi and upper Fly River systems before construction of the mine commenced gave sediment levels ranging from 0.5 - 2929 mg $L^{-1}$ with median ranging from 29 - 185 mg $L^{-1}$. Prior to the construction of the mine only those species that could tolerate levels of suspended solids above 200 mg $L^{-1}$ for extended periods, could have survived in the mainstream of the Ok Tedi system.

Maunsell *et al.* (1982) state that healthy fisheries were maintained at Ningerum during mine construction under conditions of high suspended solids. Limited data are available on the toxicity of 'inert' suspended solids, although no precise data exist concerning levels of "inert' suspended solids which can be tolerated by animals. Maunsell *et al.* (Vol. 6 1982) reported that concentrations of suspended solids lethal to fish range from 100 to 20,000 mg $L^{-1}$. OTML (1984c) report survival of fish at levels of suspended solids from 300 to 100,000 mg $L^{-1}$ for periods ranging from 3 days to 5 weeks. Mosquitofish are known to tolerate higher levels of suspended solids and lower oxygen levels than many other fish.

For many toxic substances, susceptible animals exposed to a lethal dose in toxicity tests will die within 4 days. For some toxins however, it takes 9 days or even 30 days and longer. It is important to determine the time after which no further death occurs due to the toxic substance (the 'incipient period'). In those tests where all susceptible animals die within 4 days, the 96 hour LC50 is also the incipient LC50. For heavy metals, it has been found that mortality occurs up to 9 days, hence the 9 day LC50 is also determined (and is the incipient LC50).

All tests were done by pouring the tailings into Port Moresby tap-water. Toxicity of heavy metals is known to vary enormously under different experimental conditions, e.g. pH, temperature and water hardness. OTML Environment Laboratory regularly monitors these factors at many locations both upstream and downstream of the mine (Table 8). A comparison of water quality data for locations downstream of the mine, Port Moresby tapwater and in the experimental tanks is given in Table 8.

Although temperature and pH are approximately the same, for test and field conditions, hardness differs. Port Moresby tapwater is soft, whereas water in the river downstream of the mine is usually of medium hardness, though at times it varies from soft at low river flow to hard at medium or high river flow. Brown (1968, cited in Skidmore and Firth, 1983), Hart (1982) and Maunsell *et al.* (1982) show that there is a logarithmic relationship between total hardness and toxicity for heavy metals, though it varies depending on the metal; as hardness increases toxicity decreases, it is therefore possible to

Table 8: Values of pH, temperature and hardness of Ok Tedi and Port Moresby waters. (*data derived from OTML).

| | WATER QUALITY PARAMETERS | | | |
|---|---|---|---|---|
| FIELD* Locality | Measure | pH | Temperature | Hardness mg $L^{-1}$ $CaCO_3$ |
| Ok Mani | Median | 7.7-8.2 | 22 | 76-80 |
| | range | 7.5-8.7 | 20-24 | 36-100 |
| Tabubil | Median | 7.5-7.6 | 20 | 127 |
| | range | 7.2-7.9 | 17.5-21.5 | 75-156 |
| Ningerum | Median | 7.7-7.9 | 25 | 90-122 |
| | range | 6.5-8.5 | 21-26 | 48-314 |
| Konkonda | Median | 7.2 | | 58 |
| | range | 5.6-8.3 | 23-29 | 17-88 |
| Kuambit | Median | | | 64 |
| | range | 6.8-8.1 | 25-27 | 24-94 |
| EXPERIMENTAL TANKS | | | | |
| Port Moresby tapwater | range | 6.9-7.5 | 22-26.5 | 40 |
| Tailings | range | 8.9-9.0 | | |
| Fish Tanks | | | | |
| 0.5%-17.8% Tailings | range | 7.3-8.0 | 22-28.5 | |
| 23.7% Tailings | range | 7.8-8.6 | 22-28.5 | |
| Shrimp Tanks | | | | |
| 0.1%-6.3% Tailings | range | 7.3-7.8 | 22-28.5 | |

adjust the LC50 values for hardness. Tests were done by pouring tailings into water of hardness of 40 mg $L^{-1}$ $CaCO_3$. Median hardness at Ningerum is 90 mg $L^{-1}$ $CaCO_3$ (Buckley, 1984b). In this study it is assumed that the hardness of river water varies between 40 mg $L^{-1}$ and 100 mg $L^{-1}$ $CaCO_3$.

Under the latter conditions most heavy metals are probably about half as toxic as in the former. Hardness probably does not affect the toxicity of cyanide (Leduc *et al.*, 1982); and its effect if any on toxicity of the suspended solids is unknown.

Significance of results

The present tests clearly show that Ok Tedi tailings are quite toxic, their acute effects occurring at dilutions of up to 250 times for mosquitofish and 1000 times for shrimps.

It is not possible to state categorically whether heavy metals, or particulate matter, or suspended solids alone, or an interaction of one or more constituents were responsible for the observed mortality.

From a comparison of LC50's of heavy metals and cyanide to fish and shrimps (Table 2), and the concentrations of the soluble chemicals in experimental tanks dosed with LC50 amounts of tailings filterable residues (FR) (Table 5), one can postulate possible causes of mortality. The concentration of copper in the fish tanks was approximately 0.14 to 0.42 of the lethal dose. Concentrations of lead, zinc, cadmium, iron and cyanide were insignificant. The concentration of dissolved copper, cadmium and cyanide in shrimp jars were 0.07, 0.16 and 0.25 of the lethal dose respectively. No one heavy metal appears to be the sole cause of death; although copper was possibly the major contributor to fish death, copper, cadmium and cyanide could all have contributed to shrimp mortality.

Even though the total recoverable levels of heavy metals seem high in the test tanks, they are probably of no biological significance in these tests, since metal complexes almost certainly existed in the tailings changing the toxicity of the metal ions present. Recent studies relating metal toxicity to speciation have shown that toxicity is a function of free metal ion concentrations, and that metal complexes are generally less toxic (Borgmann and Ralph, 1984). Copper and cyanide ions are both more toxic than most copper cyanide complexes (Gawne, 1986). Interactions (including synergistic or antagonistic effects) of heavy metals and cyanides, and their complexes, could also possibly occur (see Mowbray 1978). It has been argued by Evesson (pers. comm.) that residual chlorine from the tapwater if present may have reacted with thiocyanate, a relatively nontoxic cyanide complex, to form highly toxic cyanogen chloride. This is unlikely given the 2 day aeration of the tapwater prior to its use in the tests.

In the tests being reported here, the concentrations of suspended solids at the LC50 values, for trials with mosquitofish were estimated to range from 400 to 7500 mg $L^{-1}$; for shrimps, 200 to 2800 mg $L^{-1}$.

Table 9. Correlation coefficients for density, percentage suspended solids and 96 hour LC50 of tailings. (n.s = not significant at 0.05 level).

| | suspended solids | LC50 fish | LC50 shrimp |
|---|---|---|---|
| density | +0.96<br>$p<0.05$ | -0.82<br>n.s | -0.97*<br>$p<0.05$ |
| suspended solids | | -0.84<br>n.s | -0.99*<br>$p<0.05$ |
| LC50 fish | | | +0.89<br>n.s |

The correlation between LC50 of shrimps and both density and percentage suspended solids is significant, suggesting that the physical properties of the tailings may have caused the death of the shrimps. Although the correlation between LC50 of fish and the physical proper- ties of the tailings is high, it is not significant.

One can tentatively conclude that copper was a contributing factor to fish mortality, suspended sediment causing shrimp mortality. Although heavy metals and cyanide could also have been contributing factors in the latter case.

Mortality Effects of Ok Tedi Tailings in the river system

Using data supplied by the Department of Minerals and Energy (DME), BWR and OTML (1985a,b), calculations have been made to determine the dilution by river water and the concentration of tailings in the river system at various sites downstream of the mine to the Fly River (D'Albertis Junction) (Figure 1). These values are then compared with the LC50 values obtained for mosquitofish and shrimps for tailings collected in November, 1984.

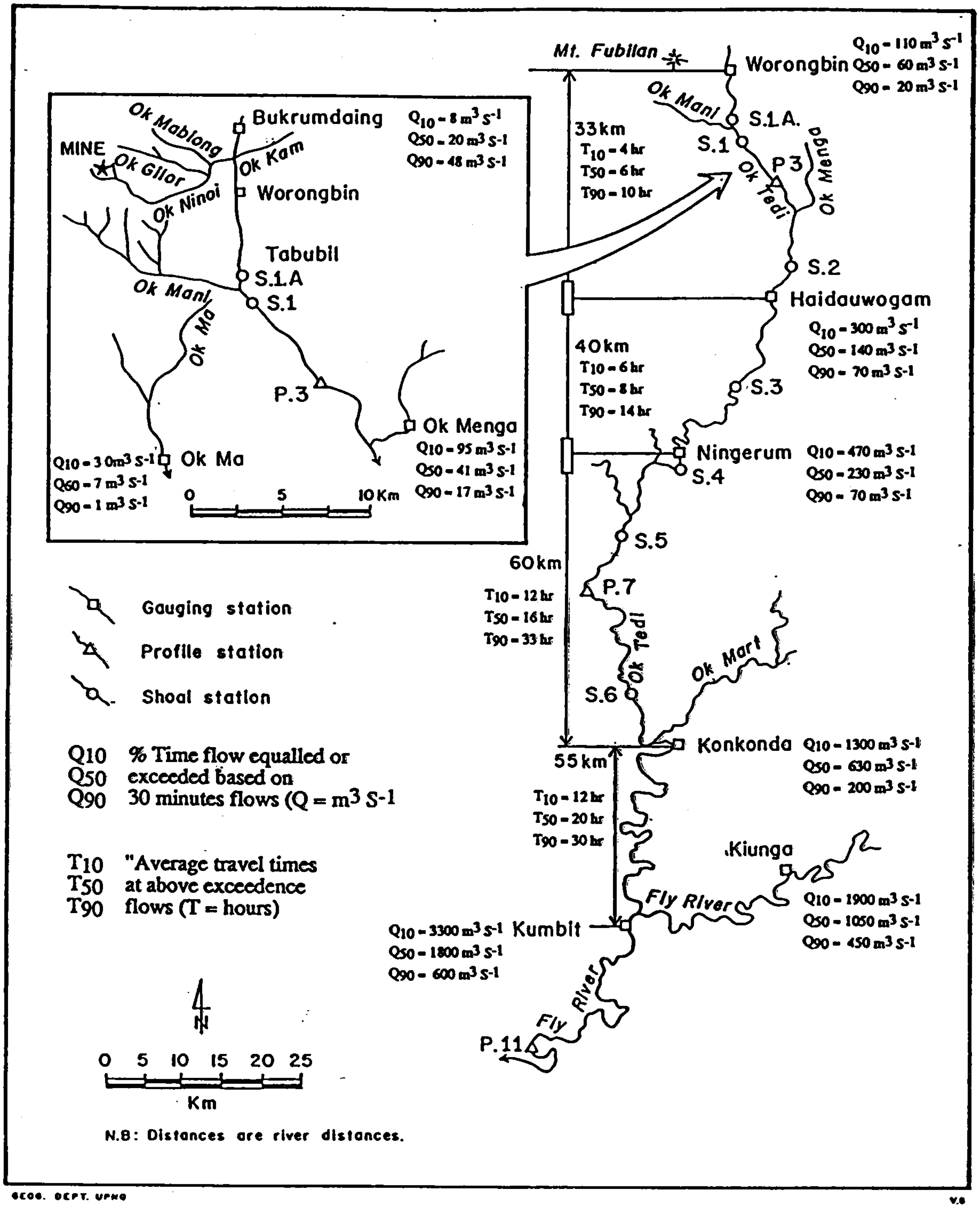


Figure 1. Monitoring locations on Ok Tedi River and river flow conditions (Data from the Bureau of Water Resources.

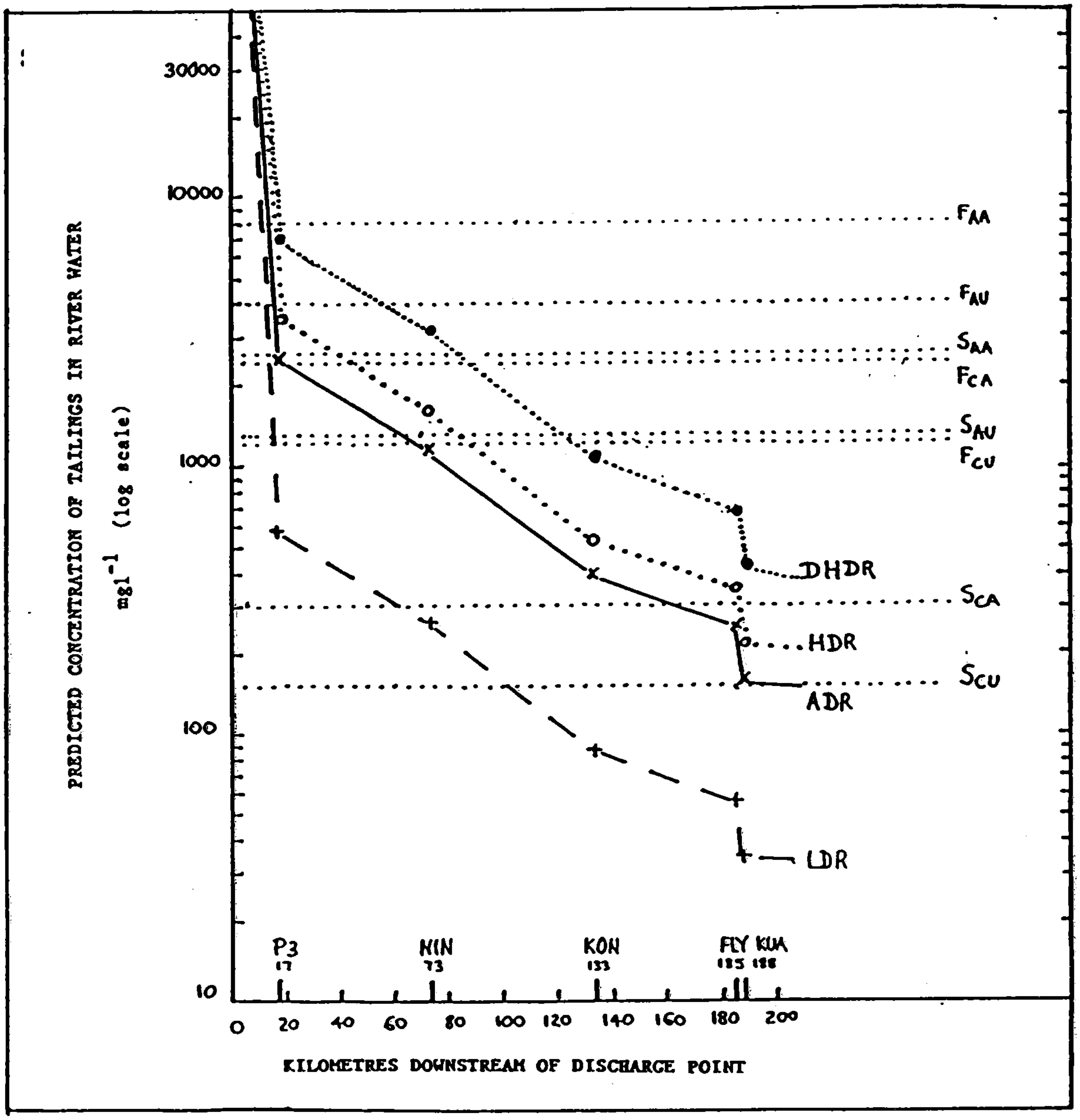


Figure 2. Predicted concentrations of tailings in river water at sites downstream of the discharge point (Moscow Tunnel), under long term mean daily flow conditions, in mg $L^{-1}$, plotted on a log scale.

OTML (1984c) estimated that the total discharge rate of fine tailings into the river system would be 0.28 $m^3$ $sec^{-1}$. Information was requested from BWR and DME on total discharge rates of tailings into the river system for 1984, to include both tailings slimes through the Moscow Tunnel into the Ok Mani and the sandpile underflow into the Ok Ningi. Specifically requested were data on cyclone performance, i.e. the cyclone split between slimes and sands for the periods June-July 1984, November-December 1984, and March 1986; and on average percent solids in tailings which entered the Moscow Tunnel for the period July 1984-June 1985 and for March 1986.

This request was not met; no information was made available to the author on discharge rates in 1984. Information available to the BWR in January, February, November and December, 1985 and subsequently provided to the author shows that the discharge rate from the plant varied greatly, from 60 $m^3$ $h^{-1}$ to 2160 $m^3$ $h^{-1}$. Assuming a typical low discharge rate (LDR) of 300 $m^3$ $h^{-1}$; an average discharge rate (ADR) of 1250 $m^3$ $h^{-1}$; and a high discharge rate (HDR) of 1700 $m^3$ $h^{-1}$; that 80% (by volume) of the tailings enters the river system; that most enter as fine tailings (slimes) via the Ok Mani; that a smaller fraction enters as leachate (sandpile-underflow), from the coarse tailings dump, via the Ok Ningi; that most of the suspended solids, heavy metals and cyanide are discharged in the fine tailings, then it is estimated that LDR is 0.06 $m^3$ $sec^{-1}$, ADR is 0.28 $m^3$ $sec^{-1}$; and HDR is 0.38 $m^3$ $sec^{-1}$. Thus the actual discharge rates approximated what was predicted.

OTML (1984b, 1985a, b) give data on the long term mean daily flow rates (in $m^3$ $sec^{-1}$) for various stations along the Ok Tedi and Fly Rivers. Using these data together with discharge rate data, values are derived for dilution factors and predicted concentrations of tailings. Tailings are assumed not to settle out due to their small size (150 µm) and the fast flowing nature of the river. Predicted river dilutions and tailings concentrations are given in appendix Table 6 together with the extent of tailings dilution by the river system.

The Bureau of Water Resources also provided data on river flow rates at median flow ($Q_{50}$) and low flow ($Q_{90}$) (Figure 1). Tables 7 and 8 in the appendix give river dilutions and predicted tailings concentrations under these conditions.

Tailings concentrations at sites downstream of the mine are plotted in Figures 2-4, together with the 9-day LC50 of tailings to both animals. An adjusted 9 day LC50 is also given, using corrections for water hardness. The 9-day LC50 of tailings to mosquitofish and shrimp are 4000 mg $L^{-1}$ and 1300 mg $L^{-1}$ respectively. The adjusted 9-day LC50's are 8000 and 2600 mg $L^{-1}$ respectively. In the figures the tailings concentrations between data points are approximate. Large dilution occurs where main tributaries enter the Ok Tedi, and at its confluence with the Fly River which contributes 60 - 70% of the total flow below D'Albertis Junction, depending upon river conditions.

The dilution of tailings and their concentrations at long term mean and median daily flow conditions are similar. Under low flow conditions dilutions downstream are much less, and concentrations of tailings are much higher; river water is also generally softer.

Under conditions of average discharge rates (ADR), low discharge rates (LDR) and high discharge rates (HDR); zones of acute effects may be predicted, Table 10.

To check the validity of these predictions, comparison can be made between data in appendix tables 6-8 with data in Table 16. Precise data on the average percent solids in tailings discharged into the Moscow Tunnel are needed to improve the accuracy of these predictions. DME estimates percentage solids to be up to 55%; assuming that tailings

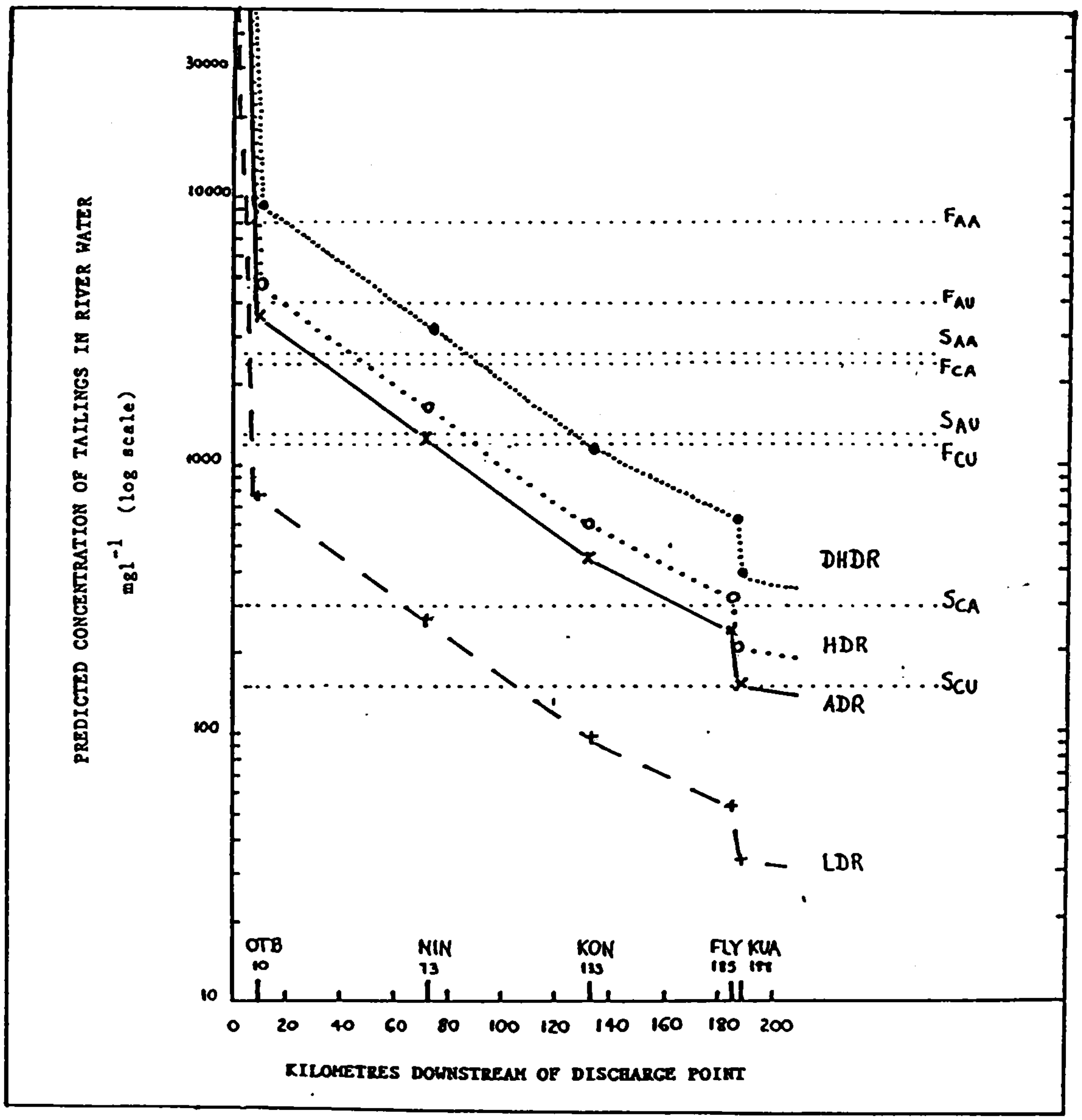


Figure 3. Predicted concentrations of tailings in river water at sites downstream of the discharge point (Moscow Tunnel), under median flow conditions, in mg $L^{-1}$, plotted on a log scale.

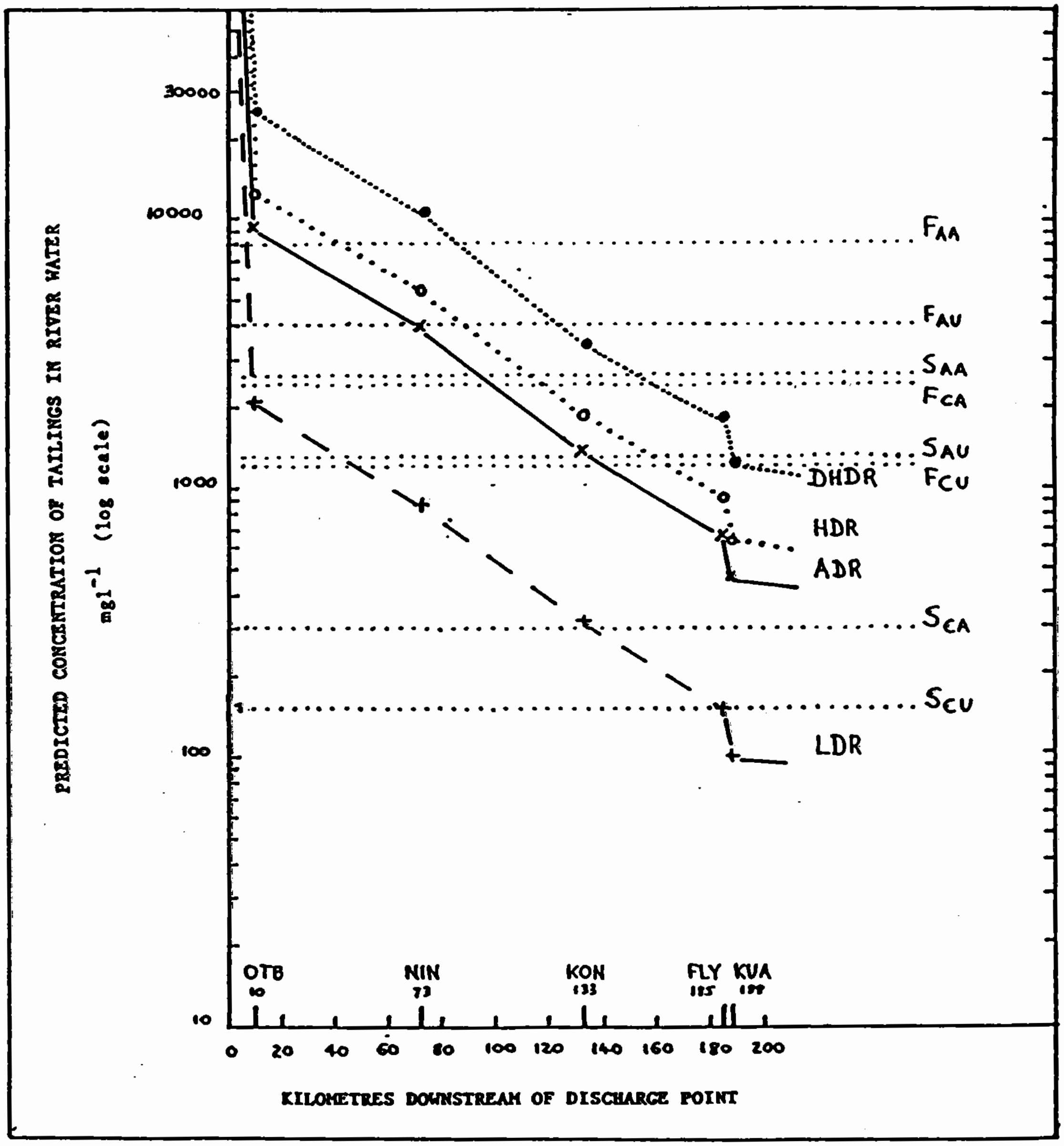


Figure 4. Predicted concentrations of tailings in river water at sites downstream of the discharge point (Moscow Tunnel), under low flow conditions, in mg $L^{-1}$, plotted on a log scale.

**Table 10: Zone of acute effects on fish and shrimps under different tailings discharge rates and river flow conditions.**

| FISH | ADR (0.28 $m^3 sec^{-1}$) | LDR (0.06 $m^3 sec^{-1}$) | HDR (0.38 $m^3 sec^{-1}$) |
|---|---|---|---|
| mean flow | above Tabubil Bridge | well above Tabubil Bridege | to around Tabubil Bridge. |
| median flow | above Tabubil Bridge | well above Tabubil Bridge | just below Tabubil Bridge |
| low flow | between Tabubil Bridge to Ningerum | well above Tabubil Bridge | below Tabubil Bridge to below Ningerum |
| **SHRIMPS** | **ADR (0.28 $m^3 sec^{-1}$)** | **LDR (0.06 $m^3 sec^{-1}$)** | **HDR (0.38 $m^3 sec^{-1}$)** |
| mean flow | above Tabubil Bridge or to above Ningerum | well above Tabubil Bridge | below Tabubil Bridge or to below Ningerum |
| median flow | below Tabubil Bridge or to just above Ningerum | well above Tabubil Bridge | below Tabubil Bridge or to below Ningerum |
| low flow | well below Ningerum to Konkonda | above Tabubil Bridge to half way to Ningerum | well below Ningerum to well below Konkonda |

are 50% suspended solids, then the predicted concentrations of tailings in appendix tables 5 - 6 would be twice the suspended solid concentrations given in table 2 in Mowbrary (other article in this volume). Despite enormous variablity and small number of samples involved, the higher values are probably a better appreciation of the actual situation. This appears to be true at least downriver to Ningerum. Below Ningerum, the levels of suspended solids decrease rapidly suggesting that settling out is occurring.

Tailings production is thought to have varied from 17,500 to 25,000 tonnes per day in late 1984 and 1985 (except for the one month when the mine was temporarily closed). It was expected to reach 30,000 tonnes per day in 1986; and it was projected to reach 60,000 tonnes per day by the end of 1988. Consequently the rates of discharge of tailings will increase, dilutions downstream of the mine will be less and tailings concentrations greater. Acute effects could reach further down the river, as shown in Figure 1 - 3 under what is termed 'double high discharge rates' (DHDR). Assuming that constituents remain similar, then at low flow, acute effects to fish would extend downstream from Ningerum to above Konkonda; and to shrimps from below Konkonda to Kuambit.

Factors not considered above include the changing composition and characteristics of the ore body as mining proceeds. Background levels of suspended solids and heavy metals also need to be considered, as these may increase the 'toxicity' of the riverwater. On the other hand, tailings and sediment may settle out, leaving the riverwater less toxic; the heavy metals may be reduced due to adsorption and ion-exchange and other physical/chemical processes so removing components from river water rendering it less toxic. Furthermore, extraction of the copper from the gold cap should also reduce the amounts of copper and cyanide in the tailings and so reduce the amounts released into the river system.

The actual toxicity of the tailings and the extent of their effects downstream could, in fact, be tested by bioassay tests using samples of riverwater and local species.

Possible chronic effects of Ok Tedi Tailings on the river system

The relationship between LC50 and the levels when chronic effects become significant, are adequately discussed and summarised in the Ok Tedi Environmental Statement (Maunsell Vol 6, 1982), in Hart (1982) and in Skidmore and Firth (1983).

In the absence of data on the levels at which heavy metals cause chronic effects an 'application factor' is used, being the fraction of the 'acceptable safe level' of a short term (96 hour) LC50 value. Application factors may be used as a rough guide to what are safe concentrations of pollutants. The following criteria have been adopted by EPA (1977, as reported in Skidmore and Firth, 1983) by AWRC (from Hart, 1982) and AWRC (from Hart,1974; reported in Maunsell, 1982, vol 6) respectively.

TABLE 11. Application factors for heavy metals, and free cyanide.

| Heavy Metal | EPA Criteria (USEPA, 1977) | AWRC Criteria (Hart, 1982) | AWRC Criteria (Hart, 1974) |
|---|---|---|---|
| Cu | 0.1 | 0.05 | 0.05 |
| Pb | 0.01 | 0.01 | 0.01 |
| Zn | 0.01 | 0.01 | 0.005 |
| Cd | - | 0.01 | - |
| Cyanide | - | - | 0.1 |

In order to determine, 'maximum acceptable toxic concentrations' both water quality data and detailed toxicity data, are required. The latter are totally lacking for aquatic animals from the Ok Tedi and Fly River Systems; to obtain them one would need to determine the most sensitive species from acute bioassay tests, followed by chronic studies.

For the purposes of this study, it is 'conservatively' assumed that the chronic effects of tailings occur at concentrations above 0.1 x 96 hour LC50, this being the highest application factor (for copper) listed above (using the EPA criteria). In addition it is assumed that the suspended solids, in association with the heavy metals and cyanide could cause chronic effects, through interactions. On this basis the concentrations of November, 1984, tailings which may cause chronic effects would be estimated to be 1200 mg $L^{-1}$ (0.1 x 12000 mg $L^{-1}$) for fish, and 150 mg $L^{-1}$ (0.1 x 1500 mg $L^{-1}$) for shrimps with no adjustment for hardness. Maunsell *et al.*, (1982) suggests that chronic toxicity is not affected by hardness, this view is open to question and if adjustments were made, concentrations would be 2400 mg $L^{-1}$ and 300 mg $L^{-1}$ for fish and shrimps respectively, one can predict that chronic effects on would occur along stretches of river as detailed in Table 12.

These predictions are not all that different from those of the original EIS for fish (Maunsell, *et al.*, (1982), Vol.1: p70 Fig. 3.6). Effects on susceptible animals (with similar sensitivities to the shrimp) would

**Table 12 : Zone of chronic effects on fish and shrimp under different tailings discharge rates and river flow conditions.**

| FISH | ADR (0.28 $m^3$ $sec^{-1}$) | LDR (0.06 $m^3$ $sec^{-1}$) | HDR (0.38 $m^3$ $sec^{-1}$) |
|---|---|---|---|
| mean flow | below Tabubil Bridge or to Ningerum | well above Tabubil Bridge | well below Tabubil Bridge to below Ningerum |
| median flow | well below Tabubil Bridge to Ningerum | well above Tabubil Bridge | well below Tabubil to below Ningerum |
| low flow | well below Ningerum to below Konkonda | well above Tabubil Bridge to halfway to Ningerum | above Konkonda to well below Konkonda |
| **SHRIMPS** | **ADR (0.28 $m^3$ $sec^{-1}$)** | **LDR (0.06 $m^3$ $sec^{-1}$)** | **HDR (0.38 $m^3$ $sec^{-1}$)** |
| mean flow | well below Konkonda to Kuambit | above Ningerum to well below Ningerum | Fly River confluence to well below Kuambit |
| median flow | below Konkonda to Kuambit | above Ningerum to well below Ningerum | Fly River confluence to well below Kuambit |
| low flow | well below Kuambit | Konkonda to Fly River confluence | well below Kuambit |

extend further downstream than originally predicted. If discharge rates were to double (eg DHDR), then at low flow rates the chronic effects to fish could extend from below Konkonda to Kuambit; and shrimps many km downstream of Kuambit.

Since chronic effects of heavy metals on aquatic organisms are well known to occur at levels one hundredth of acute levels (where application factors equal 0.01), one could predict that profound biological effects may well occur for many km further downstream, than originally envisaged.

The tailings which travel below Ningerum and enter the Fly, contain high levels of particulate heavy metals. Some of this many well reach the lake ecosystems of the middle Fly and the Fly Delta. (See also Kyle; Osborne & Polumin; Chambers; this volume). Of this a fraction may well be mobilised later, becoming soluble and producing concentrations which may exert chronic effects. Dent (1985) believes this may be one of the principle long-term effects. The lethal effects of heavy metals in the tailings are due only to the soluble fraction (and probably the ionic fraction of this).

Field studies are as yet too little advanced to accurately predict the long term chronic effects of the tailings on the river system, (OTML 84c, 85a, b, see Mowbray this volume). Hart and Lake (1984) state that it is very difficult to predict effects of heavy metals on ecosystems, very little is known of the processes controlling the behaviour of heavy metals in natural environments. Factors such as speciation, transportation, transformation between compartments and their ultimate fate, are unquantified.

Other Consequences

It has been publicaly argued by OTML that the above effects will be confined to the main river channel, it is also argued that many animals may well migrate to side streams away from the main river, and so avoid the high sediment levels, and associated concentrations of heavy metals. The species composition in side streams is different from that of the main Ok Tedi as reported by Roberts (1978) and Maunsell, *et al.*, (1982: Vol. 6). Many river fish that cannot tolerate the new riverine conditions will disappear and not migrate to the side streams. Furthermore some of the fish species need to migrate from the side streams to the lower reaches of the river and the swamps for breeding (Roberts, 1978) and hence will be affected during certain phases of their life cycle. Populations are probably maintained by repeated recolonisation from other side streams; the condition of the main river may well prevent such events from occuring and may lead to 'isolated' populations in side streams which will be more susceptible to extinction. Species diversity in the side streams will therefore be decreased.

Recently Australian scientists (Wolanski *et al*, 1984; Heinsohn and Wolansk, 1985; McGhee, 1985) have expressed concern that the increased sediment and heavy metals in the Fly River water may effect organisms particularly phytoplankton and coral in the Northern sector of the Great Barrier Reef. While such impacts are less likely to occur than impacts on the Middle and Lower Fly river systems, they represent a real concern which may influence Australian scientists concerned with the implementation of the Joint PNG/Australian Torres Strait Treaty.

Summary of predicted effects of Tailings on Ok Tedi and Fly River (based on Tailing Toxicity Tests)

The areas of effect of toxic tailings predicted by this study are shown in Tables 10 and 12, are similar to those predicted by Manusell *et al.*, (Vol 1, 1982) though a more extensive impact could result if species are more sensitive to tailings than assumed. It is assumed that the animals in the river system have similar sensitivities to tailings as the test organisms.

The most critical situations will arise when large volumes of tailings are discharged under low river flow conditions, at which time the water tends to be softer. If such conditions lasted for around 9 days the impact could well be biologically significant to the Fly River and beyond. It is under these conditions that tailings discharge rates must be reduced to lessen the zone of impact.

## CONCLUSIONS

1. Toxicity tests have shown that the tailings produced in November, 1984, are very toxic, having 9-day LC50's as low as 0.4% and 0.1% for freshwater fish and shrimps respectively.

   Tailings collected in October and November,1984, just after gold production had commenced, were found to be significantly more toxic than those collected in June, 1984. These tailings were also significantly more toxic to shrimps than to mosquitofish.

2. It is not possible to conclude what toxic factors in the tailings killed the animals; it is suggested that an interaction of all the constituents may have killed the fish, and that the suspended solids probably killed the shrimps.

3. On the basis of the tests done on mosquitofish and shrimps, and taking into account the amount of tailings presently produced, water quality parameters and river flow conditions, it is predicted that the acute effects of the tailings on fish under mean (or median) flow conditions will extend to Tabubil Bridge, but at low flow could extend down towards Ningerum, and on shrimps under mean (or median) flow conditions will extend to Ningerum, but at low flow to beyond Konkonda. Chronic effects on fish under median flow conditions will extend to Ningerum, but at low flow could extend to Konkonda. Chronic effects on shrimps under both median and low flow conditions will extend below Kuambit. With increased production both acute and chronic effects could well extend much further downstream. Species with similar susceptiblities as mosquitofish and shrimps would be similarly effected. Effects below Ningerum could be reduced due to sedimentation. Chronic effects could extend down the Fly due to remobilisation and accumulation of the heavy metals bound in the suspended solids. How far downstream the effects will actually reach cannot be predicted.

ACKNOWLEDGEMENTS

The Department of Minerals and Energy through the Bureau of Water Resources (now a part of the Department of Environment and Conservation) provided the funds to do many of the toxicity tests (Mowbray, this volume), paid for one set of chemical analyses of tailings and funded a field trip by the author to the Ok Tedi Mine and the Ok Tedi and Fly Rivers in November 1984. Dr William Townsend, Dr David Sargeant, Mr Jim Dent, Mr Mike Patchett, and Mr Kepas Wali assisted in sampling tailings, initial comment and providing the author with data provided to them by OTML Environment Section.

Dr Jim Kyle of UPNG analysed tailings collected in June, 1984. My Vagi Raula and his Cartography Unit in the Geography Department at UPNG drew all the figures, including the map.

The following students assisted in conducting the toxicity tests: Mr Nasan Balat, Mr Misimoa Lam, Mr Mulo Kapush, Mr Palisa Walhos and Mr Lawong Balun. Work by Mr Balat (1982) and Mr Lam (1984) was part of their course programes, however the data was reanalysed using the computer programme, for this review.

Ms Bligh Mowbray, Dr John Pernetta and Dr Lance Hill criticised the final draft. Ms Bligh Mowbray, Hilda Petrus and Mary George assisted with typing the script onto the word processor.

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APPENDIX

Table 1. LC50's (percent) for Ok Tedi tailings together with upper and lower 95% confidence limits (UCL and LCL), regression constants (y = a+bx), "g" statistics and heteroyeneity factor (For full explanation see Mowbray, 1978) derived from probit analysis of mortality of female mosquitofish, *Gambusia affinis*

| Date of collection | Date of Test | Hours of exposure | 95% UCL | LC50 | 95% LCL | a | b | g | HF | Significance heterogeneity p |
|---|---|---|---|---|---|---|---|---|---|---|
| 13.6.84[b] | 21.6.84 | 24 | 424.35 | 109.75 | 67.49 | 0.98 | 1.97 | 0.355 | 0.36 | ns |
| | | 48 | 115.39 | 54.01 | 34.13 | 1.94 | 1.76 | 0.263 | 1.55 | ns |
| | | 96 | 26.26 | 16.68 | 9.58 | 2.69 | 1.89 | 0.221 | 0.95 | ns |
| 30.6.84[b] | 3.7.84 | 24 | 12.55 | 11.52 | 10.61 | -0.49 | 5.17 | 0.039 | 1.48 | ns |
| | | 48 | 11.81 | 9.98 | 8.48 | 1.45 | 3.55 | 0.086 | 1.86 | 0.05 |
| | | 96 | 10.62 | 8.70 | 6.94 | 1.68 | 3.54 | 0.136 | 2.22 | 0.05 |
| 4.10.84 | 4.11.84 | 24 | 12.25 | 10.31 | 8.68 | 1.27 | 3.68 | 0.069 | 2.04 | 0.05 |
| | | 48 | 7.16 | 5.67 | 4.45 | 2.63 | 3.14 | 0.098 | 3.35 | 0.05 |
| | | 72 | 3.22 | 2.53 | 1.98 | 3.59 | 3.49 | 0.118 | 4.35 | 0.05 |
| | | 96 | 2.00 | 1.50 | 1.09 | 4.11 | 5.07 | 0.275 | 7.84 | 0.05 |
| | | 120 | 1.28 | 1.19 | 1.10 | 4.49 | 6.80 | 0.039 | 1.25 | ns |
| | | 144 | 1.10 | 0.97 | 0.58 | 5.10 | 6.86 | 0.119 | 2.19 | 0.05 |
| | | 168 | 0.99 | 0.84 | 0.69 | 5.59 | 7.55 | 0.282 | 2.98 | 0.05 |
| | | 192 | 1.38 | 0.97 | 0.85 | 6.30 | 10.38 | 0.336 | 2.24 | 0.05 |
| | | 216 | | (control mortality too high) | | | | | | |
| 28.11.84 | 12.12.84 | 24 | 39.61 | 20.66 | 14.13 | 3.13 | 1.42 | 0.117 | 2.40 | 0.05 |
| | | 48 | 8.18 | 5.72 | 4.21 | 4.01 | 1.30 | 0.056 | 2.85 | 0.05 |
| | | 72 | 3.42 | 2.70 | 2.12 | 4.32 | 1.57 | 0.037 | 2.11 | 0.05 |
| | | 96 | 1.57 | 1.19 | 0.88 | 4.87 | 1.74 | 0.064 | 1.74 | 0.05 |
| | | 120 | 0.93 | 0.74 | 0.58 | 5.30 | 2.31 | 0.075 | 2.33 | 0.05 |
| | | 144 | 0.73 | 0.55 | 0.39 | 5.70 | 2.70 | 0.147 | 3.88 | 0.05 |
| | | 168 | 0.61 | 0.46 | 0.30 | 6.13 | 3.34 | 0.251 | 4.04 | 0.05 |
| | | 192 | 0.72 | 0.53 | 0.14 | 7.01 | 7.32 | 0.823 | 4.62 | 0.05 |
| | | 216 | 0.60 | 0.40 | 0.17 | 6.32 | 3.26 | 0.575 | 3.845 | 0.05 |

Table 2. LC50's (percent) for Ok Tedi tailings together with associated statistics derived from probit analyses of mortality of shrimps, *Caridina nilotica*

| Date of collection | Date of Test | Hours exposured | 95% UCL | LC50 | 95% LCL | a | b | g | HF | Significance of heteroyeneity p |
|---|---|---|---|---|---|---|---|---|---|---|
| 13.6.84 | 21.6.84 | 24 | 6.79 | 5.81 | 4.95 | -1.56 | 8.58 | 0.368 | 2.72 | 0.05 |
| | | 48 | 5.45 | 5.16 | 4.82 | -4.57 | 13.43 | 0.103 | 1.31 | ns |
| | | 96 | 4.87 | 4.57 | 4.24 | -1.30 | 9.54 | 0.076 | 1.26 | ns |
| 30.6.84 | 3.7.84 | 24 | 5.12 | 4.26 | 3.64 | 3.36 | 2.60 | 0.058 | 2.38 | 0.05 |
| | | 48 | 2.88 | 2.45 | 2.09 | 4.09 | 2.35 | 0.048 | 2.15 | 0.05 |
| | | 96 | 0.59 | 0.47 | 0.34 | 6.03 | 3.12 | 0.112 | 3.63 | 0.05 |
| 4.10.84 | 4.11.84 | 24 | 5.02 | 3.98 | 3.30 | 3.60 | 2.34 | 0.076 | 2.28 | 0.05 |
| | | 48 | 1.08 | 0.93 | 0.80 | 5.09 | 2.83 | 0.035 | 1.90 | 0.05 |
| | | 72 | 0.45 | 0.37 | 0.31 | 6.75 | 4.08 | 0.117 | 4.21 | 0.05 |
| | | 96 | 0.30 | 0.27 | 0.24 | 8.76 | 6.58 | 0.075 | 2.31 | 0.05 |
| | | 120 | 0.28 | 0.23 | 0.19 | 9.86 | 7.56 | 0.354 | 8.55 | 0.05 |
| | | 144 | 0.23 | 0.21 | 0.18 | 11.32 | 9.22 | 0.227 | 3.99 | 0.05 |
| | | 168 | 0.23 | 0.20 | 0.18 | 11.82 | 9.86 | 0.249 | 3.79 | 0.05 |
| | | 192 | 0.21 | 0.20 | 0.18 | 13.36 | 11.91 | 0.192 | 2.58 | 0.05 |
| | | 216 | 0.21 | 0.20 | 0.18 | 13.48 | 12.02 | 0.172 | 2.40 | 0.05 |
| 28.11.84 | 12.12.84 | 24 | 2.37 | 1.84 | 1.46 | 4.48 | 1.96 | 0.042 | 2.86 | 0.05 |
| | | 48 | 0.38 | 0.31 | 0.25 | 6.64 | 3.23 | 0.107 | 5.12 | 0.05 |
| | | 72 | 0.20 | 0.17 | 0.15 | 9.54 | 5.95 | 0.111 | 5.81 | 0.05 |
| | | 96 | 0.17 | 0.15 | 0.14 | 11.00 | 7.37 | 0.141 | 6.99 | 0.05 |
| | | 120 | 0.16 | 0.15 | 0.13 | 12.17 | 8.60 | 0.164 | 7.48 | 0.05 |
| | | 144 | 0.16 | 0.14 | 0.12 | 11.98 | 8.24 | 0.215 | 9.55 | 0.05 |
| | | 168 | 0.16 | 0.14 | 0.12 | 12.66 | 9.00 | 0.235 | 10.35 | 0.05 |
| | | 192 | 0.14 | 0.14 | 0.12 | 12.09 | 8.22 | 0.194 | 8.31 | 0.05 |
| | | 216 | 0.15 | 0.13 | 0.12 | 10.98 | 6.83 | 0.147 | 6.58 | 0.05 |

Table 3: LC50's of heavy metals and cyanide together with associated statistics derived from probit analyses of mortality of mosquitofish, *Gambusia affinis*

| | Date of test (month) | Hours exposure | 95% UCL | LC50 | 95% LCL | a | b | g | HF | Significance of p |
|---|---|---|---|---|---|---|---|---|---|---|
| copper $\mu g\ L^{-1}$ (ppb) | 5.80a | 96 | 518.46 | 174.73 | 103.59 | 3.23 | 0.79 | 0.223 | 0.43 | ns |
| | 5.81a | 24 | 254.83 | 157.02 | 90.86 | 1.79 | 1.46 | 0.191 | 3.12 | 0.05 |
| | 12.81a | 24 | 207.19 | 124.88 | 67.21 | -2.12 | 3.40 | 0.584 | 3.43 | 0.05 |
| | | 48 | Regression not significant | | | | | | | |
| | | 96 | 13.10 | 56.95 | 42.11 | -2.19 | 4.10 | 0.218 | 2.40 | 0.05 |
| | 5.82a | 48 | 232.84 | 169.02 | 125.86 | 0.30 | 2.11 | 0.108 | 2.76 | 0.05 |
| | | 96 | 94.03 | 77.11 | 61.10 | -3.33 | 4.41 | 0.217 | 3.22 | 0.05 |
| | 11.84 | 24 | 834.35 | 344.44 | 239.36 | -1.14 | 2.42 | 0.428 | 7.31 | 0.05 |
| | | 48 | 236.31 | 181.95 | 136.32 | -1.17 | 2.73 | 0.160 | 4.66 | 0.05 |
| | | 96 | 161.31 | 127.68 | 94.99 | -0.18 | 2.46 | 0.106 | 3.50 | 0.05 |
| lead $mg\ L^{-1}$ (ppm) | 11.84 | 24 | 71.04 | 65.93 | 61.73 | -23.59 | 15.72 | 0.214 | 4.53 | 0.05 |
| | | 48 | 67.24 | 61.57 | 56.29 | -24.81 | 16.66 | 0.321 | 7.17 | 0.05 |
| | | 96 | 60.65 | 56.46 | 51.08 | -24.04 | 16.58 | 0.302 | 5.37 | 0.05 |
| zinc $mg\ L^{-1}$ | 7.84a | 24 | 8.48 | 6.91 | 5.61 | 1.95 | 3.63 | 0.083 | 0.22 | ns |
| | | 48 | 8.73 | 5.20 | 2.46 | 2.55 | 3.42 | 0.458 | 2.65 | 0.05 |
| | | 96 | 5.31 | 4.34 | 3.55 | 1.60 | 5.34 | 0.133 | 0.51 | ns |
| | 8.84a | 24 | 7.77 | 6.30 | 5.52 | -5.27 | 12.86 | 0.626 | 4.57 | 0.05 |
| | | 48 | 4.91 | 4.24 | 3.52 | 1.60 | 5.42 | 0.147 | 2.61 | 0.05 |
| | | 96 | 3.51 | 2.97 | 2.36 | 2.94 | 4.36 | 0.118 | 2.16 | 0.05 |
| | 11.84 | 24 | 6.91 | 6.11 | 5.50 | -3.45 | 10.75 | 0.271 | 3.07 | 0.05 |
| | | 48 | 5.42 | 4.87 | 4.41 | 0.74 | 6.20 | 0.084 | 2.22 | 0.05 |
| | | 96 | 3.75 | 3.29 | 2.85 | 2.98 | 3.90 | 0.079 | 2.05 | 0.05 |
| iron $mg\ L^{-1}$ (ppm) | 9.84a | 24 | 635.00 | 135.09 | 83.64 | -3.66 | 4.06 | 0.728 | 2.42 | 0.05 |
| | | 48 | 71.69 | 61.58 | 52.59 | -16.19 | 11.84 | 0.334 | 0.61 | ns |
| | | 96 | 25.50 | 20.03 | 11.42 | -0.76 | 4.43 | 0.297 | 0.19 | ns |
| | 10.84 | 24 | 131.49 | 122.07 | 113.24 | -6.28 | 5.41 | 0.047 | 1.61 | ns |
| | | 48 | 56.02 | 53.73 | 51.55 | -19.76 | 14.31 | 0.063 | 1.19 | ns |
| | | 96 | 37.87 | 33.92 | 30.36 | -6.34 | 7.41 | 0.135 | 2.29 | 0.05 |
| cadmium $mg\ L^{-1}$ | 11.84 | 24 | 7.42 | 6.08 | 5.32 | -0.16 | 6.58 | 0.190 | 3.07 | 0.05 |
| | | 48 | 3.64 | 3.09 | 2.62 | 2.78 | 4.53 | 0.122 | 4.17 | 0.05 |
| | | 96 | 1.83 | 1.71 | 1.58 | 3.45 | 6.68 | 0.038 | 1.56 | ns |
| cyanide $\mu g\ L^{-1}$ (ppb) | 1.85 | 24 | 889.23 | 801.58 | 720.43 | -12.07 | 5.88 | 0.084 | 4.10 | 0.05 |
| | | 48 | 873.35 | 781.63 | 691.93 | -10.41 | 5.33 | 0.097 | 0.81 | 0.05 |
| | | 96 | 894.98 | 792.23 | 684.31 | -10.40 | 5.31 | 0.131 | 3.88 | 0.05 |

a Fish included some guppies, *Poecilia reticulata*

Table 4. LC50's of heavy metals and cyanide together with associated statistics derived from probit analyses of mortality of shrimps, *Caridina nilotica*.

| | | Date of Test (month/ year) | Time of exposure | 95% UCL | LC50 | 95% LCL | a | b | g | HF | Significance of heterogeneity (p=0.05) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| copper | | 12.81 | 24 | 286.68 | 225.31 | 191.97 | -2.83 | 3.33 | 0.148 | 1.85 | 0.05 |
| $\mu g\ L^{-1}$ | (ppb) | | 48 | 251.18 | 208.61 | 181.20 | -3.12 | 3.50 | 0.117 | 1.65 | 0.05 |
| | | | 96 | 215.20 | 193.59 | 176.25 | -3.68 | 3.79 | 0.054 | 1.50 | ns |
| lead | | 11.84 | 24 | 90.87 | 71.04 | 61.23 | -5.37 | 5.60 | 0.292 | 4.61 | 0.05 |
| $mg\ L^{-1}$ | (ppm) | | 48 | 78.08 | 62.68 | 53.09 | -2.49 | 4.17 | 0.208 | 3.81 | 0.05 |
| | | | 96 | 65.62 | 53.46 | 44.11 | -1.49 | 3.76 | 0.186 | 4.00 | 0.05 |
| zinc | | 8.84 | 24 | 10.01 | 7.95 | 6.37 | 3.23 | 1.96 | 0.072 | 2.91 | 0.05 |
| $mg\ L^{-1}$ | (ppm) | | 48 | 7.86 | 6.31 | 5.01 | 3.45 | 1.94 | 0.070 | 2.84 | 0.05 |
| | | | 96 | 5.54 | 4.65 | 3.81 | 3.51 | 2.23 | 0.048 | 2.23 | 0.05 |
| iron | | 9.84 | 24 | 16.07 | 13.12 | 10.86 | 0.55 | 3.98 | 0.138 | 2.21 | 0.05 |
| $mg\ L^{-1}$ | (ppm) | | 48 | 12.05 | 10.99 | 10.01 | -0.66 | 5.44 | 0.057 | 1.72 | ns |
| | | | 96 | 10.14 | 8.47 | 6.56 | -1.12 | 6.60 | 0.315 | 3.62 | 0.05 |
| cadmium | | 11.84 | 24 | 140.88 | 108.94 | 87.93 | 1.59 | 1.67 | 0.017 | 1.36 | ns |
| $\mu g\ L^{-1}$ | (ppb) | | 48 | 38.21 | 30.69 | 24.55 | 0.92 | 2.74 | 0.087 | 2.14 | 0.05 |
| | | | 96 | 23.41 | 19.48 | 15.88 | 1.61 | 2.63 | 0.063 | 1.70 | 0.05 |
| cyanide | | 1.85 | 24 | 383.18 | 342.07 | 306.23 | -8.33 | 5.26 | 0.063 | 3.20 | 0.05 |
| $\mu g\ L^{-1}$ | | | 48 | 379.93 | 323.92 | 276.77 | -7.00 | 4.78 | 0.105 | 5.51 | 0.05 |
| | | | 96 | 365.48 | 316.06 | 270.61 | -6.95 | 4.78 | 0.106 | 4.26 | 0.05 |

Table 5. Results of analyses of physical properties of Ok Tedi tailings. Means with different superscripts are significantly different, using ANOVA and Student-Newman-Keuls test at 5% level of significance.

| Date of Sample Collection | no | Density of tailings gm $L^{-1}$ mean | standard deviation | method | gm $L^{-2}$ no | % Sediment $10^{-1}$ mean | standard deviation |
|---|---|---|---|---|---|---|---|
| 13.06.84 | 2 | $1.07^a$ | 0.01 | 40.50 mμ sieve | 5 | $13.9^a$ | 2.2 |
| 30.06.84 | 19 | $1.29^b$ | 0.05 | 40.50 mμ sieve | 6 | $42.1^b$ | 5.6 |
| 4.10.84 | 5 | $1.28^b$ | 0.09 | 10 mμ filter | 5 | $45.8^b$ | 2.8 |
| | | | | 40.50 mμ sieve | 5 | $44.1^b$ | 4.2 |
| 28.11.84 | 5 | $1.42^c$ | 0.03 | 10 mμ filter | 6 | $51.4^c$ | 3.2 |
| | | | | 40.50 mμ sieve | 5 | $50.9^c$ | 2.1 |

1. Method using Gallenkamp No. 2 sieve (40-50mμ)
2. Method using Whatman No. 1 Filter Paper (10mμ).

Table 6. Values of river dilution and predicted concentrations of tailings in river water at different rates of tailings discharge based on long term mean daily flow rates. Also included for comparison is the toxicity of the tailings (dilution faction are determined for average (ADR), low (LDR) and high (HDR) discharge rates of tailings).

| Site | River dilution factors ADR | LDR | HDR | Predicted concentration of tailings in river-water mg $L^{-1}$ ADR | LDR | HDR | Toxicity of Tailings 9 day LC50 mg $L^{-1}$ UNADJUSTED fish | shrimp | ADJUSTED fish | shrimp |
|---|---|---|---|---|---|---|---|---|---|---|
| Tabubil Bridge Profile 3 | 394 | 1760 | 289 | 2541 | 568 | 3460 | | | | |
| Ningerum | 845 | 3770 | 620 | 1184 | 265 | 1611 | | | | |
| | | | | | | | 4000 | 1300 | 8000 | 2600 |
| Konkonda | 2592 | 11580 | 1901 | 386 | 86 | 526 | | | | |
| Kuambit | 6386 | 28530 | 4683 | 157 | 35 | 214 | | | | |

Table 7. Values of river dilution and predicted concentrations of tailings in river water at different rates of tailings discharge based on median flow rates. Also included for comparison is the toxicity of the tailings.

| Site | River dilution factors | | | Predicted concentration of tailings in riverwater mg $L^{-1}$ | | | Toxicity of Tailings 9 day LC50 mg $L^{-1}$ UNADJUSTED | | ADJUSTED | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ADR | LDR | HDR | ADR | LDR | HDR | m'fish | shrimp | m'fish | shrimp |
| Tabubil Bridge[a] | 289 | 1290 | 212 | 3460 | 775 | 4721 | | | | |
| Ningerum | 828 | 3710 | 609 | 1208 | 270 | 1642 | 4000 | 1300 | 8000 | 2600 |
| Konkonda | 2269 | 10161 | 1668 | 441 | 98 | 600 | | | | |
| Kuambit | 6480 | 29032 | 4765 | 154 | 34 | 210 | | | | |

a. Flow rate at Tabubil Bridge estimated from flow conditions at Worongbin to be 80 $m^3$ $sec^{-1}$.

Table 8. Values of river dilution and predicted concentrations of tailing in river water at different rates of tailings discharge based on low flow rate. Also included for comparison is the toxicity of the tailings.

| Site | River dilution factors | | | Predicted concentration of tailings in riverwater mg $L^{-1}$ | | | Toxicity of Tailings 9 day LC50 mg $L^{-1}$ UNADJUSTED | | ADJUSTED | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ADR | LDR | HDR | ADR | LDR | HDR | m'fish | shrimp | m'fish | shrimp |
| Tabubil Bridge[a] | 108 | 480 | 79 | 9259 | 2067 | 12658 | | | | |
| Ningerum | 252 | 1129 | 185 | 3968 | 886 | 5405 | 4000 | 1300 | 8000 | 2600 |
| Kondonda | 720 | 3226 | 529 | 1389 | 310 | 1890 | | | | |
| Kuambit | 2167 | 9860 | 1588 | 462 | 103 | 630 | | | | |

a. Flow rate at Tabubil Bridge estimated from flow conditions at Woronbin to be 80 $m^3$ $sec^{-1}$.

# EVALUATION OF THE OTML MONITORING PROGRAMME AND HEAVY METAL RESIDUES IN OK TEDI AND FLY RIVER SYSTEM - 1981-1985

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## ABSTRACT

A review of both chemical monitoring and biological studies conducted up to December 1985 was conducted. This included studies done before mining activity commenced, during the construction phase and for the first eighteen months of gold processing.

Levels of suspended solids increased greatly in the Ok Tedi and at times exceeded allowable levels. Their biological effects are unknown but it is likely that intolerant species have disappeared from these areas. Levels of soluble metals have remained lower than initially predicted, but high levels of particulate copper, often exceeding the "PNG standard" could have an impact, and flushes of "higher than acceptable" amounts of soluable copper and cyanide are frequent. One extensive fish kill has been confirmed. Biological studies show that some fish and invertebrate populations have been affected in the Ok Tedi River. Lead concentrations have increased in some fish sampled. The biological data available is insufficient and difficult to interpret.

No conclusion could be made concerning the magnitude of the impact to date.

## INTRODUCTION

To evaluate the impact of the tailings on organisms in the river system it is important to compare actual levels of heavy metals, cyanide and suspended solids in the river system at different times and to draw conclusions concerning possible changes in concentration since mining activity commenced. This review relates the levels occurring to generally recognised 'acceptable safe levels' for aquatic ecosystems; to standards set by the Government and to known 'no-effect levels'. Levels of suspended solids, heavy metals and cyanide are compared to the PNG standards set at Ningerum; to LC50's'; to concentrations in the toxicity test experimental tanks (Mowbray this volume), and to estimated chronic levels. Adjustments have been made for hardness. The concentrations which cause no chronic toxicity in the more sensitive species can be regarded as a 'no effect threshold'.

Dissolved metals are those from water samples passed through a 0.45 μm filter. Dissolved forms include free metal ions and complex and colloidally bound metal species all of which are generally biologically available. Comparison with toxicity data assumes soluble metals are mainly in ionic forms; particulate metals are those retained by a 0.45 μm filter.

### Data sources

The data that is available on residue levels, either in water or animal tissues, comes from the sources listed in Table 1.

Ok Tedi Mining Limited (OTML) regularly evaluates changes in concentrations of suspended solids and heavy metals plus other hydrological, water quality, biological and health data in each 'six monthly environment report' (OTML 1983, '84b, '84d, '85a, '85b, '86a). OTML (1984c) and Buckley (1984b) reviewed likely biological impact of the Interim Tailings Disposal Scheme (ITDS). OTML predicted that the ITDS would cause the greatest impact on the upper reaches of the Ok Tedi; a moderate impact on the river between Tabubil and Ningerum; a minimal impact downstream of Ningerum; and no significant nor unacceptable impact on the aquatic resources of the Fly river. Buckley predicted a large impact that would be environmentally "totally unacceptable", estimating much higher levels of copper than actually occur at present. The following is a review of the present situation regarding residues together with criticisms and recommendations.

TABLE 1. List of sources consulted in obtaining data for this review, and in in evaluation of the present monitoring programme.

| | |
|---|---|
| Before mining activity commenced, 1982 | Boyden et al., 1974.<br>Maunsell (1982) OTES: Vols 1,2,6 |
| During the construction phase, July-June 1984 | OTML (1983)<br>OTML (1984a)<br>OTML (1984b)<br>OTML (1984c)<br>OTML (1984d) |
| During the processing phase, under ITDS | Higgins (1984)<br>OTML (1984e)<br>OTML (1984f)<br>OTML (1985a)<br>OTML (1985b)<br>OTML (1985c)<br>OTML (1986a) |
| Predicted impact of ITDS | Buckley 1984a<br>Buckley 1984b |

Sampling sites for which data are available are indicated in Figure 1 of Mowbray (this volume). The number of samples made at most locations, were generally few (as for January - June 1985); and results may not be representative of the site. An additional problem with most of the OTML data is that the water is only sampled at each site once per month. There is no guarantee that the sample is representative of the entire time period. Regular daily (or two hourly) monitoring at one or two locations (Ok Tedi Bridge and Ningerum) show enormous fluctuations within and between consecutive days, which may depend in part upon river flow conditions, discharge rates and the grade of ore (high or low copper) being processed at the time.

Daily (and even two hourly) sampling occurs only at two locations due to financial and manpower constraints. Concentrations of dissolved and particulate heavy metals (copper, zinc, lead and cadmium) and cyanide have been monitored a number of times a day at the lower Ok Tedi Bridge, Tabubil. Except for cyanide levels such data, have been published (OTML 1985b). Concentrations of free cyanide levels and dissolved copper levels at Ningerum have also been monitored since July 1985. Results for 1985 have been published as 'figures' in OTML (1986a). Since levels appear to regularly exceed criteria (see below), it is important that these results be published in full or in tables summarising results in each 'six monthly environmental report'.

The mine did not operate during the period 18 February, 1985 to 21 March, 1985, due to closure by the Government, resulting in reduced levels of tailings discharge into the river for this six-monthly period. Most data have not been analysed statistically since little of the raw data have been made available. The following review is based on comparison of means (or medians) and ranges only, except where otherwise stated.

TABLE 2. Mean (or median) and maximum concentrations of suspended solids (mg $L^{-1}$) and estimated total sediment load (million tones/year at sampling stations on Ok Tedi and Fly River systems from 1981 to 1985.

| Phase | Period | OKTEDI at BUKRUMBAING | | OKTEDI below OK MANI OKTEDI BRIDGE | | OKTEDI above NINGERUM | | ALICE RIVER at KONKONDA | | FLY RIVER at KUAMBIT | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mean (median) | max | mean | max | mean | max | mean | max | mean | max |
| PRE MINING | 1981 | (51) | 366 | (94) | (910)* | (85) | 244 | (37) | 258 | (76) | 162 |
| CONSTRUCTION PHASE | July-Dec 1982 | | | | 501 | 1875 | 69 | 164 | 44 | 180 | |
| | Jan-Jun 1983 | | | | 1919 | 9488 | 532 | 2001 | 178 | 430 | |
| | July-Dec 1983 | 96 | 1522 | | 720 | 2391 | 198 | 578 | 129 | 305 | |
| | | | (24) | | | (642) | | (143) | | (125) | |
| PROCESSING PHASE | July-Dec 1984 | 33 | 99 | 1201 | 9117 | 956 | 6230 | 412 | 1498 | 271 | 955 |
| | | | (22) | | (736) | | (458) | | (140) | | (114) |
| | Jan-Dec 1985 | 64 | 167 | 1982 | 69079 | 668 | 5613 | 318 | 1088 | 137 | 199 |
| | | | (33) | | (1109) | | (442) | | (252) | | (153) |
| | July-Dec 1985 | 83 | 259 | 2357 | 25351 | 752 | 9092 | 327 | 681 | 153 | 319 |
| | | | (42) | | (1692) | | (457) | | (224) | | (147) |
| BUCKLEY (1984b) | | | | | | | | | | | |
| | | | | | | | 1000 | | | | |
| Recommended Standard: 95 percentile | | | | | | (200) | | | | | |
| TOTAL SEDIMENT ($mta^{-1}$) | | | | | | | | | | | |
| PRE MINING | 1981 | 0.05 | - | | 2.1 | | 2.1 | | 5.2 | | |
| CONSTRUCTION PHASE | July-Dec 1982 | 0.01 | - | | 4.3 | | 1.7 | | 2.6 | | |
| | Jan-June 1983 | 0.20 | - | | 16.3 | | 13.1 | | 10.4 | | |
| | July-Dec 1983 | 0.08 | - | | 6.1 | | 5.0 | | 7.5 | | |
| | Jan-June 1984 | 0.10 | 11.1 | | 6.4 | | 13.7 | 9.7 | | | |
| PROCESSING PHASE | July-Dec 1984 | 0.03 | 4.7 | | 8.1 | | 10.3 | 15.9 | | | |
| | Jan-June 1985 | 0.05 | 7.8 | | 5.7 | | 7.9 | 8.0 | | | |
| | July-Dec 1985 | 0.07 | 9.3 | | 6.4 | | 8.1 | 9.0 | | | |

* OTML (1985b) estimates median to be 45 mg $L^{-1}$ pre-construction.

## RESULTS

### Suspended solids and sediment load

Levels of suspended solids below the junction of Ok Mani to just below the junction with the Fly River have remained much higher than was the case before construction commenced. Increased levels of suspended solids in the first half of 1985 compared to before construction at Profile 3 were 12 fold; though OTML (1985b) states that increases were 25 fold. For the second half of 1985 these were 18 fold (my estimate) and 36 fold (Ok Tedi's estimate). Throughout 1985, at Ningerum the increased level was 6 fold; Konkonda 7 fold; at Kuambit 2 fold. Maximum levels at Ningerum were 40 times higher than before mining, and maximum levels at Ok Tedi Bridge probably even higher (75 times). This increase in suspended solids, due to tailings discharge and mine wastes, is also reflected in the total sediment load which has increased by 2 to 4 times its preconstruction levels. During the construction phase levels were even higher (See Table 2).

Levels of suspended solids at Ningerum regularly exceed the standard of 1000 mg $L^{-1}$ recommended by Buckley (1984b); the mean for 1985 was three to four times the 95 percentile level and the 1985 median twice the 95 percentile level recommended by Buckley (1984b).

Before mining commenced the river alternated between periods of high and low sediment levels. The ITDS effectively ensures a continuously high level of suspended solids, with possible consequent loss of organisms which cannot tolerate such conditions. Possible effects of the increased sediment are discussed by OTML (1984c).

### Cyanide spill from Ok Tedi Mine

On 19 June, 1984, 1080 $m^3$ of free cyanide of about 300 $\mu g\ L^{-1}$ were released into the Ok Mani. This was estimated to be diluted to 500 $\mu g\ L^{-1}$ when it reached the Ok Tedi (i.e. 600 fold dilution), and 200 $\mu g\ L^{-1}$ at Ningerum (1500 fold dilution). Over the period 21 June to 28 June, 1984, dead fish and prawns were observed in the Ok Tedi River down to Ningerum (confirmed by OTML) and according to newspaper reports local villagers reported many dead fish and tortoises and a dead crocodile. People stopped fishing in the Ok Tedi and Fly Rivers for a short while, only returning to fishing in the river with some fear and reservations. Another small cyanide spill was alleged to have occurred in late 1984, killing numbers of the freshwater prawns, but this has never been confirmed.

### Mercury

Lamb (1977), Kyle (1981) and Kyle and Ghani (1982) analysed mercury residues in fish species from the Fly and Strickland Rivers. They found higher residue concentrations (occurring naturally) than in most fish sampled elsewhere in PNG. Buckley (1984a) recommended that mercury levels should be monitored with high priority since natural levels are high. This has not been done (or data never published) to date, and the effects of mining on mercury levels are not known. Maunsell *et al.* (1982) reported that mercury levels in ore are low, and that operations should not affect natural levels.

### Copper residues (Table 3)

Slight increases in dissolved copper levels seem to have occurred when construction of the mine commenced; increases have persisted with use of the ITDS, the highest on the Ok Tedi being recorded in the second half of 1985. All levels were well below levels known to be acutely toxic; were generally always below the levels found in the toxicity test experimental tanks (Mowbray, this volume); and were nearly always below the accepted PNG standards at Ningerum. Mean levels at Ningerum and occasional maxima at Haidauwogam, Ningerum, Kokonda and Kuambit have all reached levels at which chronic effects are known to occur (Hart, 1982, Maunsell Vol 6, 1982).

TABLE 3. Soluble and particulate copper residues in water samples at sites during the period 1981-1985, compared to possible 'toxic concentrations' (see Mowbray, this volume) and PNG standards, $\mu g\ L^{-1}$.

| Period | | Ok Tedi at Bukr-umbaing | | Ok Tedi Haidau-wogam | | Ok Tedi above Ningerum | | Alice River at Konkonda | | Fly River at Kuambit | | Toxic Concentration LC50 Acute | | Tailings | | Chronic | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mean | max | mean | max | mean | max | mean | max | mean | max | f. | sh. | f. | sh. | f. | sh. |
| SOLUBLE LEVELS | | | | | | | | | | | | | | | | | |
| Pre-mining | | | | | | | | | | | | | | | | | |
| 1981 | | 3 | 12 | 1 | 4 | 1 | 7 | 2 | 13 | 2 | 8 | | | | | | |
| | | | | | | | | | | | | 100 | 194 | 24 | 13 | 10 | 19 |
| Construction Phase | | | | | | | | | | | | | | | | | |
| Jan-June | 1983 | 2 | 5 | 5 | 7 | 7 | 11 | 7 | 23 | 4 | 8 | | | | | | |
| July-Dec | 1983 | 3 | 5 | 4 | 7 | 5 | 9 | 8 | 33 | 7 | 14 | | | | | | |
| Jan-June | 1984 | 3 | 6 | 3 | 6 | 4 | 8 | 3 | 7 | 9 | 26 | | | | | | |
| Processing Phase | | | | | | | | | | | | | | | | | |
| July-Dec | 1984 | 4 | 8 | 5 | 7 | 11 | 22 | 4 | 14 | 3 | 4 | | | | | | |
| Jan-July | 1985 | 3 | 5 | 7 | 11 | 6 | 7 | 5 | 11 | 3 | 4 | | | | | | |
| July-Dec | 1985 | 4 | 12 | 18 | 41 | 26 | 52 | 7 | 21 | 7 | 16 | | | | | | |
| PNG Standard | | | | | | | 50 | | | | | | | | | | |
| Pre Mining | | | | | | | | | | | | | | | | | |
| | 1981 | 2 | 10 | 5 | 25 | 4 | 20 | 3 | 12 | 4 | 11 | | | | | | |
| Construction Phase | | | | | | | | | | | | | | | | | |
| Jan-June | 1983 | 5 | 15 | 253 | 610 | 1577 | 4780 | 176 | 640 | 52 | 125 | | | | | | |
| July-Dec | 1983 | 5 | 10 | 53 | 150 | 104 | 305 | 47 | 150 | 83 | 280 | | | | | | |
| Jan-June | 1984 | 2 | 6 | 420 | 1438 | 207 | 410 | 119 | 400 | 107 | 500 | | | | | | |
| Processing Phase | | | | | | | | | | | | | | | | | |
| July-Dec | 1984 | 42 | 220 | 144 | 300 | 50 | 120 | 44 | 91 | 30 | 56 | | | | | | |
| Jan-July | 1985 | 13 | 25 | 247 | 375 | 255 | 420 | 35 | 50 | 46 | 75 | | | | | | |
| July-Dec | 1985 | 10 | 37 | 330 | 615 | 189 | 330 | 56 | 120 | 48 | 85 | | | | | | |
| PNG standard[a] | | | | | | 115 | | | | | | | | | | | |
| Adjusted PNG Standard[b] | | | | | 230 | | | | | | | | | | | | |

a. Total Recoverable

b. Assuming total recoverable - 50% total particulate.

TABLE 4. Soluble and particulate lead residues in water samples at sites during the period 1981-1985, compared to 'toxic concentrations' (see Mowbray, this volume and PNG standard, $\mu g\ L^{-1}$

| Period | | Ok Tedi at Bukr-umbaing mean | max | Ok Tedi at Haidau-wogam mean | max | Ok Tedi above Ningerum mean | max | Alice River at Konkonda mean | max | Fly River at Kuambit mean | max | Toxic Concentrations LC50 Acute f. | sh.[c] | Tailings f. | sh. | Chronic f. | sh. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SOLUBLE LEVELS | | | | | | | | | | | | | | | | | |
| PRE-MINING | | | | | | | | | | | | | | | | | |
| | 1981 | 0.5 | 6 | 1 | 9 | 0.5 | 8 | 0.5 | 9 | 0.5 | 9 | | | | | | |
| | | | | | | | | | | | | 56500 | 53500 | 0.5 | 40 | 565 | 535 |
| CONSTRUCTION PHASE | | | | | | | | | | | | | | | | | |
| Jan-June | 1983 | 1 | 3 | 6 | 14 | 4 | 8 | 4 | 6 | 2 | 3 | | | | | | |
| July-Dec | 1983 | 1 | 3 | 2 | 4 | 3 | 7 | 2 | 5 | 2 | 4 | | | | | | |
| Jan-June | 1984 | 5 | 18 | 3 | 5 | 6 | 15 | 5 | 14 | 2 | 3 | | | | | | |
| PROCESSING PHASE | | | | | | | | | | | | | | | | | |
| July-Dec | 1984 | 5 | 18 | 3 | 9 | 14 | 80 | 3 | 10 | 3 | 11 | | | | | | |
| Jan-July | 1985 | 1 | 2 | 1 | 2 | 2 | 2 | 1 | 3 | 1 | 2 | | | | | | |
| July-Dec | 1985 | 2 | 5 | 4 | 8 | 4 | 7 | 5 | 8 | 5 | 9 | | | | | | |
| PNG standard | | | | | | 20 | | | | | | | | | | | |
| PARTICULATE LEVELS | | | | | | | | | | | | | | | | | |
| PRE MINING | | | | | | | | | | | | | | | | | |
| | 1981 | 8 | 19 | 3 | 86 | 4 | 29 | 0.5 | 4 | 0.5 | 9 | | | | | | |
| CONSTRUCTION PHASE | | | | | | | | | | | | | | | | | |
| Jan-June | 1983 | 19 | 40 | 336 | 837 | 1080 | 4000 | 187 | 620 | 40 | 80 | | | | | | |
| July-Dec | 1983 | 9 | 30 | 61 | 120 | 94 | 250 | 39 | 120 | 22 | 50 | | | | | | |
| Jan-June | 1984 | 6 | 20 | 427 | 2300 | 192 | 394 | 50 | 140 | 30 | 84 | | | | | | |
| PROCESSING PHASE | | | | | | | | | | | | | | | | | |
| July-Dec | 1984 | 56 | 278 | 66 | 190 | 63 | 160 | 49 | 190 | 38 | 160 | | | | | | |
| Jan-July | 1985 | 22 | 30 | 67 | 90 | 99 | 180 | 31 | 60 | 39 | 60 | | | | | | |
| July-Dec | 1985 | 19 | 43 | 110 | 285 | 77 | 195 | 22 | 54 | 23 | 53 | | | | | | |
| PNG standard[a] | | | | | | 220 | | | | | | | | | | | |
| Adjusted PNG standard[b] | | | | | 440 | | | | | | | | | | | | |

There has been a massive increase in particulate copper levels downstream of the mine since construction began. PNG standards for Ningerum are regularly exceeded. According to Buckley (1984b) the Water Resources Act has been breached many times.

The biological significance of these levels is unknown. The immediate effects are probably minimal, but these residues could become solubilised and later lead to an increased rate of remobilisation and bioaccumulation of the copper, particularly further downstream (see Kyle, this volume). Such particulate copper could cause a major environmental impact in the long term.

Lead residues (Table 4)

The concentration of soluble lead seemed to have returned by early 1985 to preconstruction levels after an initial increase during the construction phase, although it was also high during the initial period of gold processing. Levels seemed to have increased again in late 1985. It is interesting to note that in 1984, levels at Bukrumdaing also inexplicably increased. Occasionally in 1984, the levels at Ningerum exceeded the PNG standards. The level in one experimental tank was higher than in nearly all river samples but even this probably caused no effect.

The amount of particulate lead is still well above preconstruction levels. Except for periods in the early construction phase, levels have remained below the PNG standard. These residues probably have no immediate effect on animals in the river, but bioaccumulation may occur.

Zinc residues (Table 5)

There has been no apparent change in soluble zinc residues, although at times even before mining construction commenced concentrations have exceeded levels likely to cause chronic effects. There has been an increase in particulate zinc concentration since mining construction commenced, but the immediate effect is unknown, other than possible bioaccumulation. Levels have remained below the PNG standard.

Cadmium (Table 6)

There has been no apparent change in dissolved cadmium since before mining activities commenced. Cadmium, like zinc, has episodically occurred at levels known to cause chronic effects. Eisler (1985) reported that concentrations as low as 0.8 $\mu g\ L^{-1}$ can cause both acute and chronic effects on freshwater animals and that effects are most probable where concentrations exceed 3 $\mu g\ L^{-1}$. The shrimp, *Caridina nilotica* seems to be particularly susceptable to cadmium (Mowbray, this volume). One might predict that animals living in the Ok Tedi system are more tolerant than the shrimp. No obvious increase has occurred in particulate cadmium levels during 1984 except possibly at Haidauwogan and Ningerum. There are no PNG standards for cadmium; one needs to be set, possibly 3.0 $\mu g\ L^{-1}$.

## DISCUSSION

Residues at lower Ok Tedi bridge at Tabubil

OTML (1985b) states that over the first twelve months of operation of the ITDS, there was a decrease in dissolved lead concentration, but an increase in particulate copper concentration. Overall, a comparison with PNG standards shows that levels of dissolved copper, zinc and lead at times exceeded the PNG standards; although means are well below the standards. (Table 7). The observed 'flushes' of high concentrations of dissolved copper could be acutely toxic to many of the organisms in the river if they persisted for a few days.

TABLE 5. Soluble and particulate zinc residues in water samples at sites from 1981-1985, compared to possible 'toxic concentrations' (see Mowbray this volume) and PNG standards, in $\mu g\ L^{-1}$.

| Period | | Ok Tedi at Bukr umbaing | Ok Tedi Haidau-wogam | | Ok Tedi above Ningerum | | Alice River at Konkonda | | Fly River Kuambit | | | Toxic Concentration LC50 Acute | | Tailings | | Chronic | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | mean | max | mean | max | mean | max | mean | max | mean | max | f. | sh. | f. | sh | f. | sh. |
| SOLUBLE LEVELS | | | | | | | | | | | | | | | | | |
| PRE-MINING | | | | | | | | | | | | | | | | | |
| | 1981 | 10 | 75 | 11 | 143 | 19 | 75 | 15 | 118 | 10 | 90 | | | | | | |
| | | | | | | | | | | | | 3500 | 4650 | 28 | 19 | 35 | 47 |
| CONSTRUCTION PHASE | | | | | | | | | | | | | | | | | |
| Jan-Dec | 1984 | 19 | 57 | 10 | 15 | 8 | 15 | 14 | 39 | 23 | 96 | | | | | | |
| PROCESSING PHASE | | | | | | | | | | | | | | | | | |
| July-Dec | 1984 | 6 | 9 | 5 | 9 | 6 | 14 | 5 | 8 | 4 | 13 | | | | | | |
| Jan-July | 1985 | 16 | 17 | 15 | 19 | 21 | 32 | 20 | 24 | 18 | 24 | | | | | | |
| July-Dec | 1985 | 7 | 16 | 8 | 19 | 18 | 52 | 16 | 32 | 10 | 24 | | | | | | |
| PNG standard | | | | | | | 100 | | | | | | | | | | |
| PARTICULATE LEVELS | | | | | | | | | | | | | | | | | |
| PRE MINING | | | | | | | | | | | | | | | | | |
| | 1981 | 26 | 67 | 18 | 68 | 11 | 120 | 10 | 300 | 28 | 132 | | | | | | |
| CONSTRUCTION PHASE | | | | | | | | | | | | | | | | | |
| Jan-June | 1984 | 25 | 40 | 836 | 4500 | 348 | 744 | 104 | 349 | 66 | 118 | | | | | | |
| July-Dec | 1984 | 36 | 185 | 55 | 134 | 63 | 155 | 44 | 155 | 42 | 150 | | | | | | |
| PROCESSING PHASE | | | | | | | | | | | | | | | | | |
| Jan-July | 1985 | 16 | 25 | 65 | 118 | 139 | 308 | 40 | 75 | 29 | 34 | | | | | | |
| July-Dec | 1985 | 14 | 42 | 125 | 355 | 76 | 165 | 34 | 54 | 30 | 54 | | | | | | |
| PNG standard[a] | | | | | | | 400 | | | | | | | | | | |
| Adjusted PNG standard[a] | | | | | 800 | | | | | | | | | | | | |

a. Total Recoverable
b. Assuming total recoverable - 50% total particulate.

TABLE 6. Soluble and particulate cadmium residues in water samples at sites from 1981-1985, compared to possible 'toxic concentrations' (see Mowbray this volume) and PNG standards, $\mu g\ L^{-1}$.

| Period | | Ok Tedi at Bukru-mbaing | | Ok Tedi at Haid-uwogam | | Ok Tedi above Ningerum | | Alice River at Konkonda | | Fly River at Kuambit LC50[a] | | Toxic Concentration | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Acute | | Tailings | | Chronic[b] | |
| | | mean | max | mean | max | mean | max | mean | max | mean | max | f. | sh.[c] | f. | sh | f. | sh. |
| SOLUBLE LEVELS | | | | | | | | | | | | | | | | | |
| PRE-MINING | | | | | | | | | | | | | | | | | |
| | 1981 | 3.0 | 4.0 | 0.5 | 1.0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | | | | | | |
| | | | | | | | | | | | | 1700 | 19 | 0.5 | 3.0 | 17 | 0.2 |
| CONSTRUCTION PHASE | | | | | | | | | | | | | | | | | |
| Jan-June | 1984 | 0.5 | 1.2 | 0.3 | 0.8 | 0.3 | 0.7 | 0.3 | 0.4 | 0.3 | 0.6 | | | | | | |
| PROCESSING PHASE | | | | | | | | | | | | | | | | | |
| July-Dec | 1984 | 0.5 | 1.4 | 0.4 | 0.7 | 0.5 | 1.5 | 0.3 | 0.8 | 0.3 | 1.1 | | | | | | |
| Jan-July | 1985 | 0.2 | 0.4 | 0.2 | 0.3 | 0.4 | 0.5 | 0.4 | 0.4 | 0.3 | 0.5 | | | | | | |
| July-Dec | 1985 | 0.4 | 0.8 | 0.5 | 0.9 | 0.5 | 0.7 | 0.5 | 0.8 | 0.5 | 0.9 | | | | | | |
| PNG standard | | | | | None | | | | | | | | | | | | |
| PARTICULATE LEVELS | | | | | | | | | | | | | | | | | |
| PRE MINING | | | | | | | | | | | | | | | | | |
| | 1981 | 0.5 | 9.0 | 0.5 | 2.0 | 0.5 | 0.5 | 0.5 | 0.6 | 0.5 | 1.0 | | | | | | |
| CONSTRUCTION PHASE | | | | | | | | | | | | | | | | | |
| Jan-June | 1984 | 0.9 | 2.5 | 3.8 | 14.0 | 2.6 | 6.0 | 1.7 | 3.0 | 1.3 | 2.5 | | | | | | |
| PROCESSING PHASE | | | | | | | | | | | | | | | | | |
| July-Dec | 1984 | 0.9 | 3.2 | 1.9 | 9.0 | 1.2 | 2.0 | 0.5 | 1.0 | 0.8 | 2.0 | | | | | | |
| Jan-July | 1985 | 0.7 | 0.7 | 1.4 | 2.1 | 2.1 | 3.5 | 0.4 | 0.4 | 0.9 | 1.1 | | | | | | |
| July-Dec | 1985 | 1.4 | 4.0 | 1.8 | 6.0 | 1.3 | 4.0 | 1.0 | 2.0 | 1.0 | 2.0 | | | | | | |
| PNG standard[a] | | | | | 10 | | | | | | | | | | | | |
| Adjusted PNG standard[b] | | | | 20 | | | | | | | | | | | | | |

a. Total recoverable

b. Assuming total recoverable = 50% total particulate.

TABLE 7. Concentrations of dissolved and particulate metal measured at lower Ok Tedi Bridge at Tabubil for period July 1984-July 1985 (from OTML, 1985b), in μg $L^{-1}$ (PNG Standard: Determined by multiplying Ningerum standard by 2.5. Total particulate, Standard assumes total recoverable = 50% total particulate).

| | DISSOLVED | | | | PARTICULATE | | | |
|---|---|---|---|---|---|---|---|---|
| Element | Number | Mean | Max | PNG Standard[a] | Number | Mean | Max | Adjusted PNG Standard[ab] |
| Cu | 930 | 11.6 | 355 | 125 | 935 | 453 | 7565 | 576 |
| Zn | 926 | 11.1 | 285 | 250 | 934 | 199 | 9999 | 2000 |
| Cd | 925 | 0.5 | 1.77 | 12.5 | 934 | 1.4 | 50 | 50 |
| Pb | 925 | 4.0 | 136 | 50 | 935 | 119 | 2620 | 1100 |

The mean for particulate copper is close to the PNG standards, indicating that the standards are often exceeded. Levels of zinc, cadmium and lead have also exceeded the standards.

More detailed data were given by OTML (1984f) and summarised in Higgins (1984)) for the four month period from June-September 1984. For this period concentrations of soluble residues at the Ok Tedi Bridge were determined, and are given in Table 8, together with PNG water quality standards. PNG standards are set at Ningerum, but are multiplied by 2.5 to give standards for the Ok Tedi Bridge at Tabubil. Similar data are given in Table 9 for total metal concentrations for suspended solids and free cyanide.

These data demonstrate that the acceptable residue levels (as determined by PNG standards) are not often exceeded. Medians and 90% percentile values for the heavy metals, except for particulate copper, are well below the acceptable levels. Occasionally levels of soluble copper and lead, and of all particulate metals however, do exceed the allowable levels: 7% of all particulate copper readings are above this level: Dissolved cyanide levels have occasionally exceeded the mean daily allowable level, but not the maximum allowable level. There are at present no standards for suspended solids, but 10% of readings are greater than 1570 mg $L^{-1}$; this is a very high level. 5 readings exceeded the level of 2500 mg $L^{-1}$. Buckley (1984b) recommends that the 95% percentile standard should be 500 mg $L^{-1}$ at Tabubil Bridge (2.5 x 200 mg $L^{-1}$). In fact, Townsend (pers. comm.) contends that levels of suspended solids in the river are generally indicative of discharge rates, i.e. when the mine was operating at high or low capacity, suspended solids were high or low.

Figures 1 and 2 illustrate that average daily levels of particulate copper and suspended solids exceeded standards (or recommended standards) in the period from 13 June to 9 September 1984. However the mean values for the period are significantly less than the standards (t-test). Data were not log transformed so results could be compared to those OTML, presented by geometric means for these data are smaller than the arithmetic means. Monthly readings are not representative of the real situation.

Residues at Ningerum (Table 9)

The PNG standards for acceptable safe levels for residues emanating from the Ok Tedi tailings are set at Ningerum. which is about 73 km downstream of the mine.

The company has performed regular analyses of soluble copper and free cyanide levels at Ningerum from July 1985 to check compliance with Government standards. The data

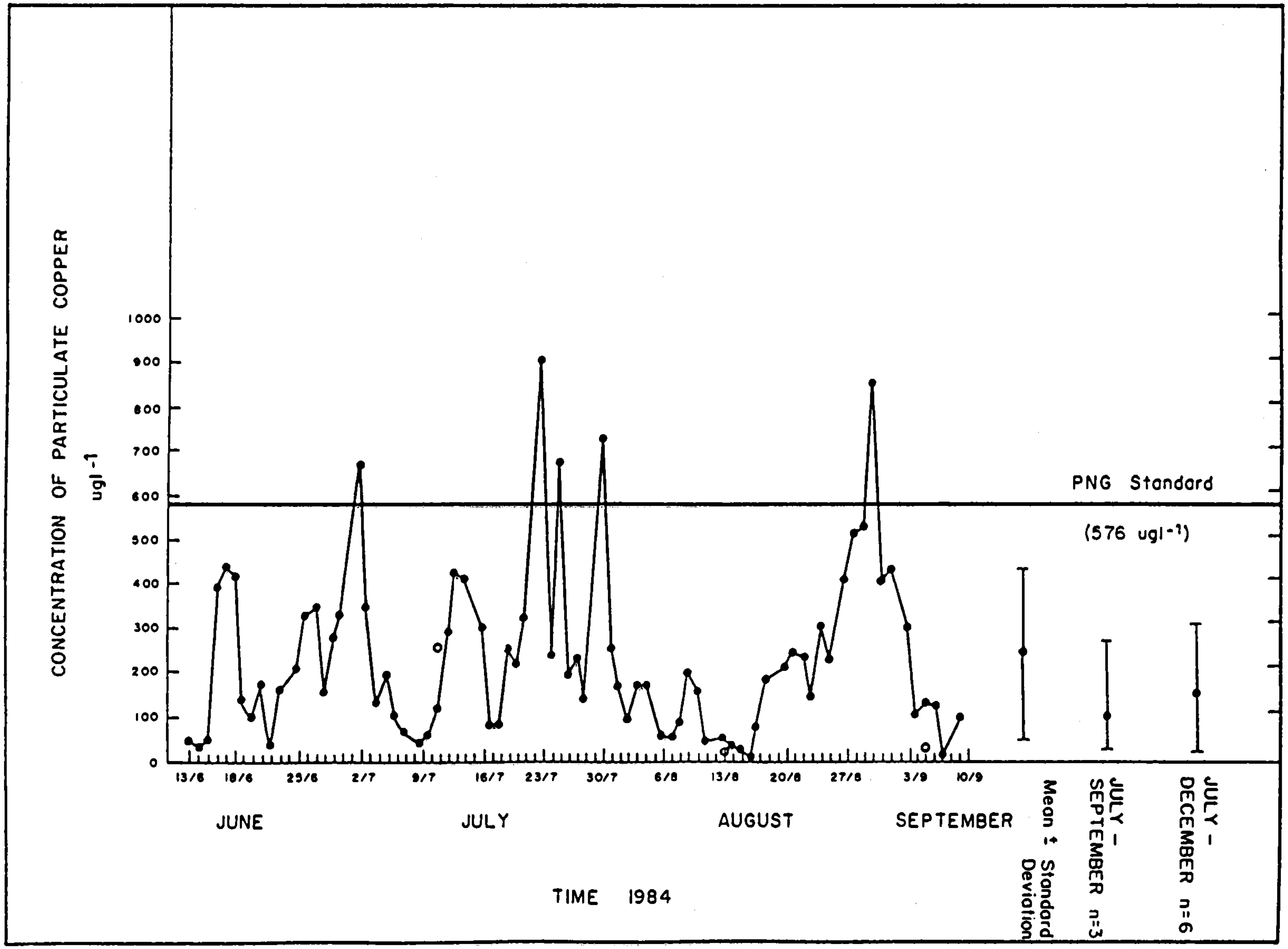


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Figure 1. Average daily concentrations of particulate copper at Ok Tedi Bridge, Tabubil, from 13 June - 9 September; compared to monthly analyses done July - December, 1984, at Haidauwogam; and compared to PNG standard (assuming total recoverable metal = 50% total particulate; derived as x 5 standard at Ningerum).

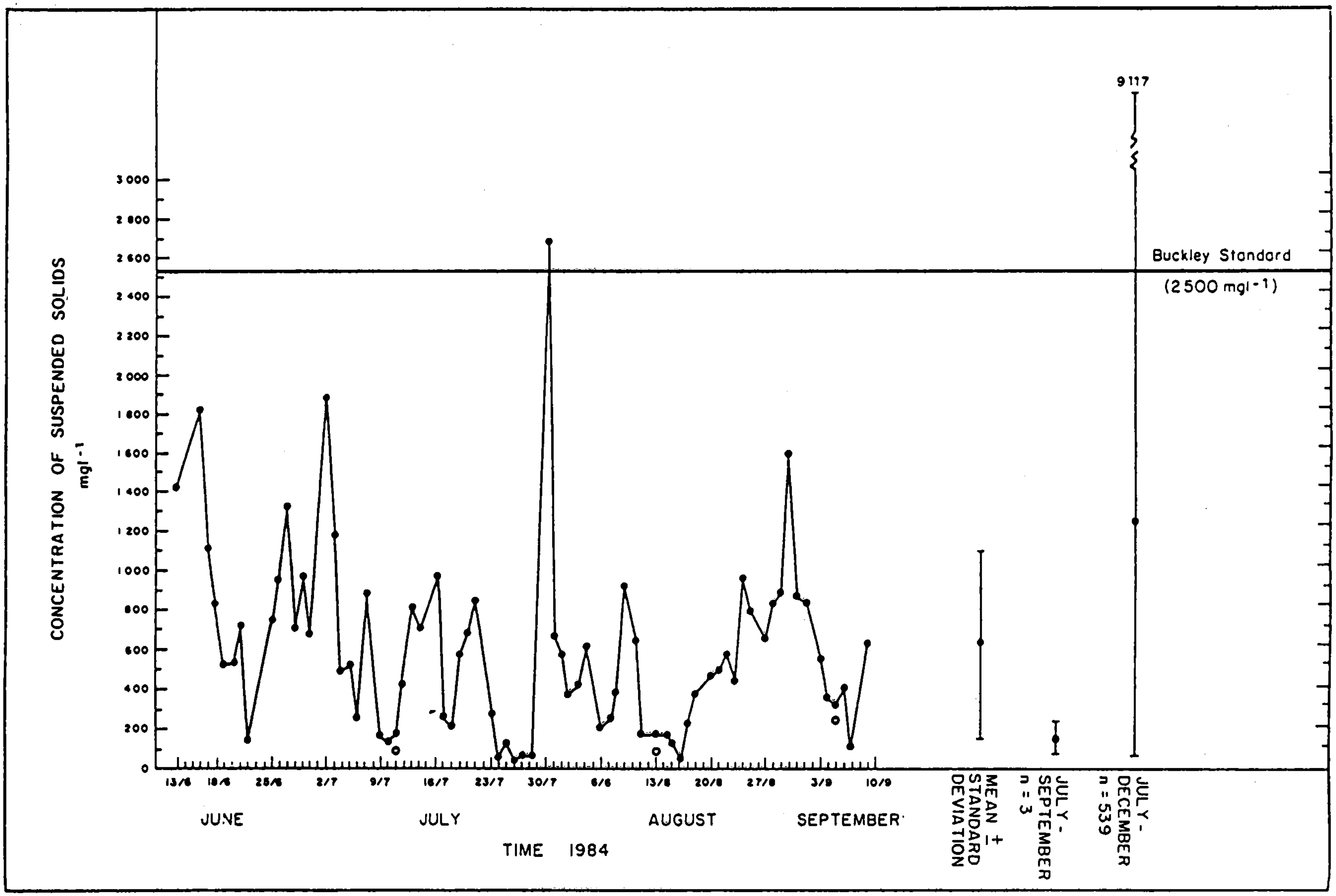


Figure 2. Average daily concentration of suspended solids at Ok Tedi Bridge, Tabubil, from 13 June - 9 September, 1984, in mg $L^{-1}$; compared to monthly analyses done for Haidauwogam from July - September 1984; compared to average and range for analyses done at Profile 3 From July - December 1984; and compared to the standard recommended by Buckley (derived as x 2.5 recommended maximum at Ningerum).

made available was for the period July-November, 1985. These data are summarised in Table 9 and Figures 3 and 4 which include the mean and range given in Table 8.

TABLE 8. Soluble and total residues of heavy metals (µg $L^{-1}$) total cyanide (µg $L^{-1}$) and suspended solids mg $L^{-1}$ in the river water at Tabubil Bridge (from 217 samples).

| | Heavy Metal | Median | 90 Percentile | Range | PNG standards | Times standards exceeded |
|---|---|---|---|---|---|---|
| S | | | | | | |
| O | copper | 6 | 16 | 2 -218 | 125 | 1 |
| L | lead | 4 | 15 | 0.1 -136 | 50 | 4 |
| U | zinc | 6 | 23 | 0.3 -176 | 250 | 0 |
| B | cadmium | 0.2 | 2.7 | 0.02 - 40 | - | - |
| L | | | | | | |
| E | | | | | | |
| T | copper | 175 | 536 | 1 -2320 | 288 | 16 |
| O | lead | 94 | 357 | 10 -2620 | 550 | 5 |
| T | zinc | 104 | 482 | 15 -4230 | 1000 | 5 |
| A | cadmium | 2.1 | 7.7 | 1 -50 | 25 | 1 |
| L | | | | | | |
| Suspended solids mg $L^{-1}$ | | 538 | 1570 | 18 -4168 | (2500) | 5 |
| Cyanide µg $L^{-1}$ | | 1 | 2.5 | 1 -27 | 8.8 | 3 |
| | | | | 500 | 130 | 0 |

Estimated levels from June 1984 accident

Table 9 shows that: the mean concentration of soluble copper was 30 µg $L^{-1}$, and mean of mean daily average was 26 µg $L^{-1}$. Both the mean and mean of mean daily concentrations of free cyanide were 4.2 µg $L^{-1}$. The standards for soluble copper and free cyanide are regularly exceeded; 19% of readings exceeded the acceptable standards of 50 µg $L^{-1}$ for soluble copper; (the maximum reading being 215 µg $L^{-1}$). 33% of the individual readings exceeded the mean daily standards of 3.5 µg $L^{-1}$ for free cyanide. The maximum instantaneous level of 52 µg $L^{-1}$ was never exceeded, (the highest reading being 47 µg $L^{-1}$); the mean daily standards were exceeded 38% of the time. Cyanide levels are much higher than originally predicted. It seems cyanide is being released from the metal complexes more readily than was originally thought would be the case. Cyanide levels at Ningerum often reach those which can cause chronic effects (See below).

Dent (1985) also reported that between June and November 1984 there were numerous occasions when the water quality criteria for copper, lead, cadmium and cyanide were all exceeded either at the Ok Tedi Bridge or at Ningerum or both. OTML (1986a) showed that for the six monthly period from July to November 1985 the mean dissolved copper concentration was 36 µg $L^{-1}$ compared to 26 µg $L^{-1}$ (for July to October). In fact Figure 33 of OTML (1986) shows that for late October through November the PNG standard of 50 µg $L^{-1}$ was regularly exceeded with a maximum at the end of October/early November of approximately 225 µg $L^{-1}$. Dissolved copper levels frequently exceeded the PNG standard in 1986 (D.E.C. pers. comm.). The mean free cyanide concentration for July to November was reported by OTML to be 3.6 µg $L^{-1}$ (compared to 4.2 µg $L^{-1}$). This reflects lower cyanide levels in November 1985. High cyanide levels also were recorded througout 1986 (D.E.C. pers. comm.).

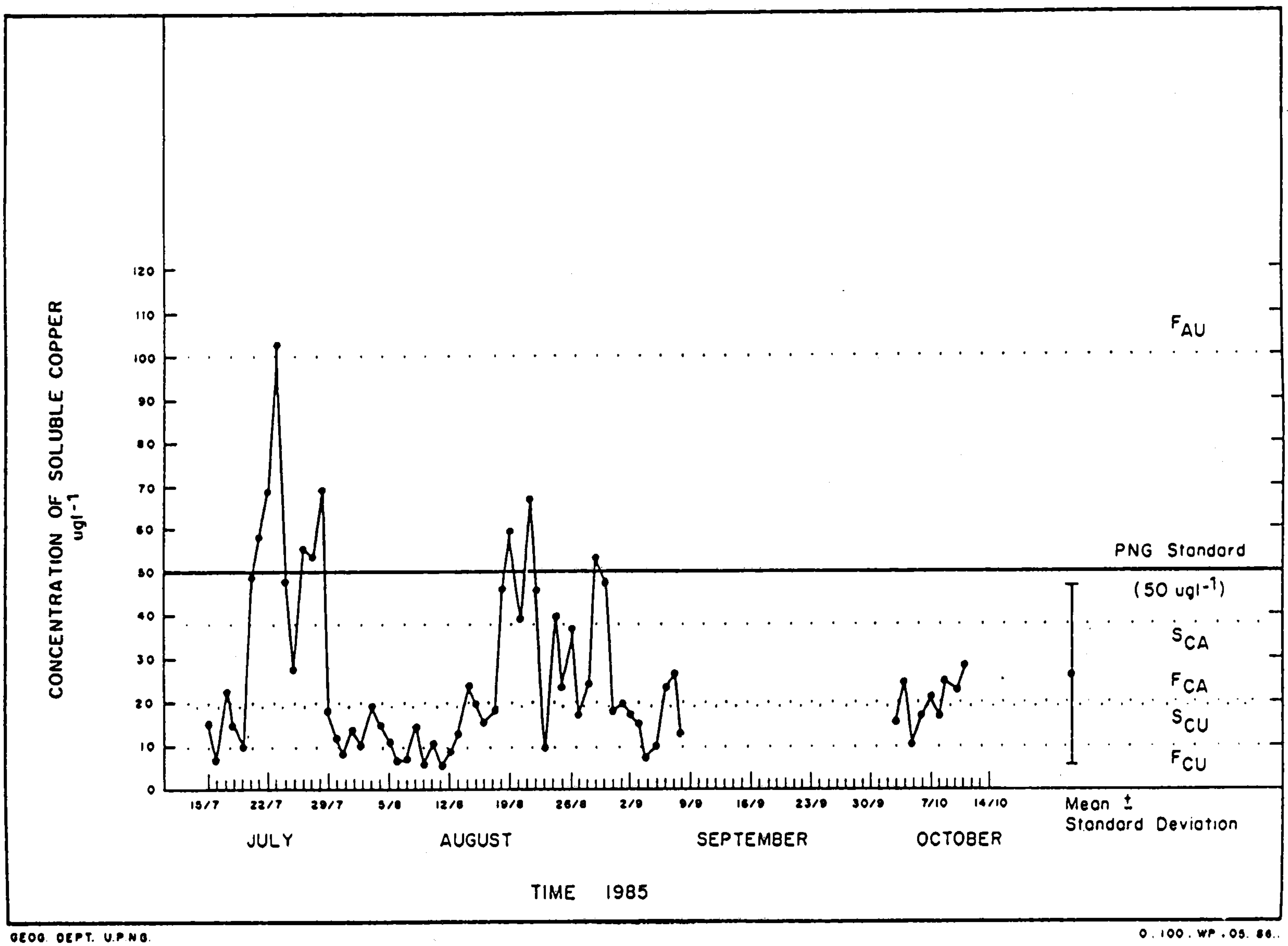


Figure 3. Average daily concentration of soluble copper at Ningerum, from 15 July - 11 October 1985, in μg $L^{-1}$; compared to PNG Standard; and compared to concentrations toxic to mosquitofish and shrimps.

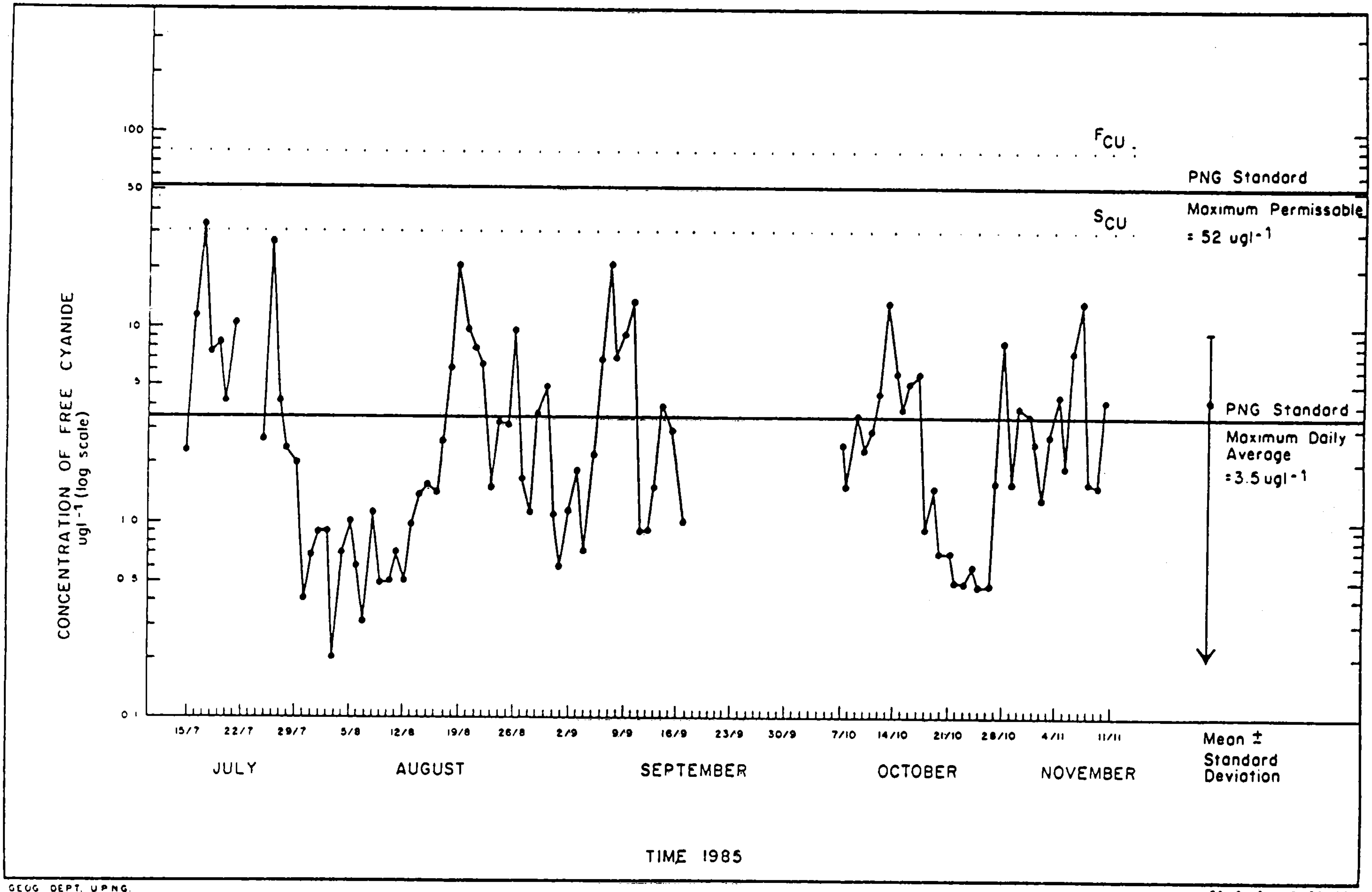


Figure 4. Average daily concentration of free cyanide at Ningerum from 15 July - 10 November, 1985, in µg L-1, plotted on a log scale; compared to PNG Standards; and compared to concentrations toxic to mosquitofish and shrimps.

TABLE 9. Soluble residues of copper and free cyanide ($\mu g\ L^{-1}$) at Ningerum, from July-November 1985, (data taken from daily reports supplied by OTML to BWR). Compared with PNG standards (soluble copper = 50 $\mu g\ L^{-1}$; free cyanide = 3.5 $\mu g\ L^{-1}$ maximum daily average)

| by | Month | No of days | No of samples | Maximum recorded $\mu g\ L^{-1}$ | Daily average $\mu g\ L^{-1}$ mean | standard deviation | Individual samples mean | standard deviation | No of times standard exceeded daily average | individual samples |
|---|---|---|---|---|---|---|---|---|---|---|
| copper | | | | | | | | | | |
| | July | 17 | 166 | 215 | 38 | 28 | 6 | 54 | | |
| | August | 31 | 181 | 124 | 24 | 17 | 3 | 24 | | |
| | September | 8 | 46 | 57 | 16 | 7 | 0 | 1 | | |
| | October | 9 | 51 | 86 | 20 | 5 | 0 | 4 | | |
| | Total | 65 | 444 | - | 26 | 20 | 30 | 329 (14%) | | 83 (19%) |
| cyanide | | | | | | | | | | |
| | July | 14 | 78 | 47 | 8 | 10 | 8 | 43 | | |
| | August | 31 | 145 | 38 | 3 | 4 | 8 | 47 | | |
| | September | 16 | 95 | 40 | 5 | 6 | 6 | 29 | | |
| | October | 25 | 150 | 26 | 3 | 3 | 10 | 36 | | |
| | November | 10 | 56 | 37 | 4 | 4 | 4 | 18 | | |
| | Total | 96 | 524 | - | 4 | 5 | 4 | -36 (38%) | | 173 (33%) |

Heavy metals in river and lake bottom sediment

A few analyses have been performed on heavy metal residues in surface and bottom sediment and core samples in the lower Fly river and lake systems. Some sampling was done before mining construction commenced (Maunsell Vol. 6 1982) around Bosset and Obo and downstream to the mouth; and Gipey (1983) sampled Lake Murray. Polunin and Osborne (this volume) sampled Lake Daviumbu near Obo in late November 1984. Studies of trace metal speciation by Kyle (this volume) showed that a significantly high proportion of the trace metals manganese, chromium, zinc, copper and iron (but not lead and cadmium) were 'biologically available'.

Dent (1985) reported that Delft Hydraulics Laboratory has predicted that sediments reaching the sea will contain 320 mg $L^{-1}$ of copper, and that over a mine life of 30 years, the result of sediment disposal into the river will cause the deposition of 1m depth of polluted sediments over an area of 1000 $km^{-2}$ in the offshore delta. Potential pollution of the Torres Straits area has led to some concern being expressed by Australian scientists (McGhee, 1985; Dent, 1985; Heinnhn & Wolanski, 1985; Wolanski *et al.* 1984).

Further samples should be collected over the next few years to determine the heavy metal content of the bottom sediment. This will indicate if significant amounts of heavy metals are accumulating in flood plain lakes and if animals face possible increased exposure to heavy metals. Studies to determine both heavy metal residues (copper, cadmium, lead, zinc and cyanide) in freshwater, estuarine water and sediments of the Ok Tedi/Fly river system proposed by researchers at PNG University of Technology for 1987 and 1988 (as well as similar studies of the Bulolo and Jaba Rivers) are underway. Such studies should also include chemical speciation; its importance in bioaccumulation has been stressed (Nelson and Donkin, 1985; Gawne, 1986).

EVALUATION OF IMPACT ON BIOLOGICAL COMMUNITIES

OTML (1985a, b) state that the effects of discharging the tailings into the river system appear to be less damaging on aquatic communities than was previously perceived, presumably in the OTES (Maunsell *et al.* Vol 1, 6, 1982). They claim this despite the higher than predicted amounts of suspended solids and particulate heavy metals in the river, and occasional high levels of soluble copper and free cyanide.

It is argued that the impact due to mining is small compared to natural calamities. Jackson, (n.d.) stated that the Ok Tedi ecosystem is capable of dealing with huge inputs of natural sediments and chemicals. This was demonstrated after the massive collapse of part of the Hindenburg Wall in 1977; he stated that between three and a half and five million tonnes of rock entered the Ok Tedi system within a matter of days. Large fish kills were reported, however within three months, the fish populations had returned to normal (Jackson, n.d.). Although obviously great, the magnitude of the impact of the land slide will never really be known.

The argument by OTML that the mine impact is small in comparison, and that the river ecosystem is resilient is at best tenuous. 6.4 million tonnes of sediment are entering the Ok Tedi river system, over a year of which most are derived from the mine. The present situation is therefore quite different, OTML continuously discharges large amounts of suspended solids and chemicals into the river system and will continue to do so for up to five years (or more). The impact of the mining activities may not be so quickly reversible, as that of "one-off" natural catastrophes.

A large amount of early biological data have been summarised in Maunsell *et al.* 1982); some of the more recent data have been summarised in the six-monthly reports. Interpretation of the available data is often difficult, due to seasonal effects, time of sampling, location effects lack of replicates and effects of flooding. It appears from the data available (OTML 1984d; 1985 a, b; 1986a) that some fish and invertebrate populations have been affected down to Ningerum (lower fish catches at Ningerum, increased physiological stress - as reflected by high kidney and liver indices on catfish at Ningerum; lower invertebrate diversity at Lower Ok Tedi Bridge, reduced capture rates of prawns at Sawmill). At present no tangible proof seems evident of effects on biological communities below Ningerum, but comparisons often do not predate the mining construction which commenced in 1983. Long term trends may take a few years to become evident.

Data on heavy metal residues in fish tissue and in prawns has been collected (OTML, 1985b) and partly published in OTML (1984b, d; 1986a). Much data on heavy metal residues in animals sampled before mining construction commenced are recorded in Boyden et al. (1974) and Maunsell *et al.* (Vol. 6 1982). Kyle (this volume) and Kyle *et al* (1986) also analysed heavy metal residues in whole fish collected in the Ok Tedi in 1981 prior to construction of the mine. All found higher levels of Cu, Zn, Cd in animal tissue than reported in most unpolluted waters elsewhere. In the 1986 six-monthly report (OTML, 1986a) a comparison is made of residue levels in three fish species sampled before and after mining construction commenced. Unfortunately no proper statistical analysis of data seems to have been done; absolute ranges merely seem to have been compared (except for lead residues). Also errors or omissions have been made in summary tables both in the Maunsell report (Vol 6, p 111) and in the OTML report (1986, Tables 12A - 12C ). Despite this a comparison of means and ranges of residue in fish tissue is given in Table 10. It seems from these data that no differences exist in residue concentrations in tissues in either location or time, except possibly for lead in flesh of all three species. Lead residues appear to be increasing. All residue levels are still well below the Australian NHMRC Standards, again except for lead. These standards are: cadmium 1.0 mg $kg^{-1}$; copper 50 mg $kg^{-1}$; lead 7.5 mg $kg^{-1}$; and, zinc 750 mg $kg^{-1}$.

TABLE 10. Comparisons of the concentrations of heavy metals (mg $kg^{-1}$ dry weight) in muscle or flesh (F) and liver (L) of three species of fish in the Fly/Ok Tedi River System between before mining construction commenced (EIS-1981 in Maunsell *et al* (1982), and after mining contruction commenced (OTML 1986). (nd = not detectable <0.1 mg $kg^{-1}$).

| Metal Species | Tissue | AFTER MINING CONSTRUCTION COMMENCED LOCALITY | | | | | | 'CONTROL AREA' | | | BEFORE MINING | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Ok Tedi - Ningerum Oct.'83 - Jan.'85 | | | Ok Tedi - Atkamba Dec.'83 - April '85 | | | Ok Birim Oct'83 - Jan'85 | | | EIS 1981 (Maunsell vol 6 pII) | | |
| | | no | mean | range | no | mean | range | no | mean | range | no | mean | range |
| Cadmium | | | | | | | | | | | | | |
| *Arius acrocephalus* (forktailed | F | 71 | 0.6 | nd-1.9 | 23 | 0.1 | nd-1.0 | 21 | 0.1 | nd - 0.4 | 6 | 0.4 | 0.3-0.6 |
| catfish) | L | 55 | 2.0 | nd-14.7 | 23 | 0.8 | nd-1.7 | 18 | 4.4 | 0.2- 77 | 6 | 1.6 | 0.7-3.0 |
| *Parambassis gulliveri* (perchlet) | F | 53 | 0.1 | nd-0.5 | 114 | 0.1 | nd-4.1 | 112 | 0.3 | nd-0.6 | 9 | 0.26 | 0.25-0.30 |
| *Melanotaenia splendida* (rainbowfish) | F | 51 | 0.7 | nd-1.3 | 59 | 0.7 | nd-1.5 | 73 | 0.9 | nd-1.5 | 3 | 0.25 | 0.25 |
| Copper | | | | | | | | | | | | | |
| *Arius acrocephalus* | F | 71 | 4.6 | 0.6-19.9 | 23 | 1.2 | 0.5-1.5 | 21 | 3.7 | 0.6-8.8 | 36 | 1.8 | 0.5-4.5 |
| | L | 55 | 12.6 | 9.1-18.8 | 23 | 11.1 | 1.1-37.2 | 18 | 15.5 | 8.1-25.8 | 20 | 34.8 | 7.0-461.5 |
| *Parambassis gulliveri* | F | 53 | 1.6 | 0.6-5.1 | 114 | 1.7 | 0.7-6.2 | 112 | 0.9 | 0.4-2.6 | 15 | 1.9 | 1.0-3.5 |
| *Melanotaenia splendia* | F | 51 | 3.6 | 2.1-6.9 | 59 | 3.4 | nd- 9.7 | 73 | 4.0 | 0.1-6.5 | 43 | 2.6 | 1.0-3.5 |
| Lead | | | | | | | | | | | | | |
| *Arius acrocephalus* | F | 71 | 2.8 | nd-6.9 | 23 | 3.9 | nd-37.6 | 21 | 3.0 | nd-4.9 | 36 | 1.0 | 1.0-6.0 |
| | L | 55 | 3.0 | nd-37.2 | 23 | 3.2 | nd-6.2 | 18 | 7.7 | nd-16.4 | 20 | 3.2 | 1.0-16.0 |
| *Parambassis gulliveri* | F | 53 | 2.8 | nd-6.3 | 114 | 2.4 | nd-3.3 | 112 | 1.4 | nd-3.3 | 14 | 1.4 | 0.5-2.5 |
| *Melanotaenia splendida* | F | 51 | 5.0 | nd-24.3 | 59 | 9.3 | nd-24.3 | 73 | 6.8 | nd-10.8 | 43 | 2.2 | 0.5-4.5 |
| Zinc | | | | | | | | | | | | | |
| *Arius acrocephalus* | F | 71 | 45 | 6-172 | 23 | 25 | 12-36 | 21 | 53 | 16 -150 | 36 | 69 | 20-363 |
| | L | 55 | 1692 | 348-22353 | 23 | 1018 | 116-1845 | 18 | 1487 | 23-2594 | 20 | 1089 | 370-2390 |
| *Parambassis gulliveri* | F | 53 | 32 | 19-70 | 114 | 32 | 9.7-91 | 112 | 32 | 20-51 | 15 | 55 | 36 - 74 |
| *Melanotaenia splendida* | F | 51 | 69 | 50-122 | 59 | 85 | 49-162 | 73 | 76 | 28-117 | 43 | 88 | 56-163 |

These conclusions are highly suspect due to the absence of proper statistical analysis; all residue data need to be analysed, and monitoring needs to be reassessed. Proper analysis should give some indication of whether the animals are accumulating excessive levels of heavy metals; give some indication of actual exposure, and indicate whether tailings have significantly increased exposure to unacceptable levels.

No sampling has been done to date to monitor heavy metal residues in bivalve species in the delta, in the Gulf of Papua or in the nearby Torres Strait. Such a program would provide a valuable assessment of the heavy metals reaching these areas and their levels of biological availability (Phillips, 1980). Denton (1985) proposed such a program using the giant clam, *Tridacna maxima* for the Torres Strait (and Great Barrier Reef). SPREP (1986) has also funded a study by UPNG researchers (including the author) to monitor heavy metal residues in suitable bivalve species, in the Fly River Delta which commenced in 1987.

<u>Sixth supplemental agreement</u>

The initial Ok Tedi Agreement was signed by the PNG Government in 1976 (PNG, 1976), but since then it has been subject to a series of ammendments (Townsend, 1984).

On 28 February, 1986, the Government of PNG signed the Sixth Supplemental Agreement (PNG, 1986), which was later ratified by Parliament on 18 March, 1986.

Basically this supplemental agreement allows for the postponement of construction of a permanent tailings dam until 1 January, 1990. It ratifies the acceptable levels of heavy metals and cyanide at Ningerum; it decrees that an environmental study will be done to determine the impact of suspended solids on the Fly River. However the acceptable levels of such suspended solids will not be determined until after the study is completed, i.e. by not later than 1 January, 1989.

The 'acceptable levels' of heavy metals (at Ningerum on the Ok Tedi River) might be considered high and much less stringent than overseas standards. Compared to criteria recommended by USEPA, AWRC (Hart, 1982) and American Fisheries Society (AFS) (Skidmore and Firth, 1983) standards set at Ningerum are high; but are considered reasonable under the circumstances (Buckley,1984a,b).

Buckley (1984a) reported that a maximum acceptable level of free cyanide of 5 $\mu g\ L^{-1}$ was set for the Tabubil Bridge, EPA standards were later set at Ningerum to be 3.2 $\mu g\ L^{-1}$ (mean daily average) and 52 $\mu g\ L^{-1}$ (maximum allowable level) (SHA/EPA, 1979). Under the new agreement the levels of free cyanide allowable have been increased to 30 $\mu g\ L^{-1}$ (mean daily average), and to 70 $\mu g\ L^{-1}$ (maximum allowable level). This was done on the recommendation of OTML and a WHO consultant, Mr P. Guo, (Guo, 1985) who recommended that the water quality criteria for the Ok Tedi should be based on resource use. These criteria are inadequate for protection of aquatic ecosystems, and the EPA standards for freshwater of 3.2 $\mu g\ L^{-1}$ and 52 $\mu g\ L^{-1}$ should be retained. Levels of below 70 $\mu g\ L^{-1}$ are acutely toxic (and fast acting) to some fish; Levels of 5-40 $\mu g\ L^{-1}$ are known to cause chronic or sublethal effects (OTML, 1984c; Mowbray, 1984). An excellent summary of the effects of cyanide on aquatic organisms is that by Leduc *et al* (1982), who state that in general, concentrations greater than 100 $\mu g\ L^{-1}$ of $CN^-$ can be expected to kill sensitive fish species; invertebrates are generally less sensitive. Concentrations of below 50 $\mu g\ L^{-1}$ cause chronic effects. Leduc *et al.* (1982) states that at high concentrations cyanide is more toxic at high temperatures, but at low concentrations it is more toxic at lower temperatures. Cyanide is more toxic at low levels of dissolved oxygen, Hart (1974). Accordingly, acceptable levels of cyanide, i.e. the PNG standard, should not be increased but should be maintained at EPA recommended levels.

Buckley (1984b) recommended to the Government that the maximum allowable levels of suspended solids at Ningerum be 1000 $mg\ L^{-1}$. This was not accepted by the State and acceptable levels of suspended solids have never been set. In fact, the Sixth Supplemental Agreement gives the company until 1 January, 1989 before the State will determine acceptable levels of suspended particulate matter. With increased production, this in effect means that the concentrations of suspended solids, particularly in the Ok Tedi, will remain very high with consequent environmental impact. The magnitude of this impact is a matter of debate. Acceptable levels at Ningerum must be set immediately and should be done in consultation with recognised authorities not employed by either DME nor OTML. These standards could later be amended in the light of the proposed "Environmental Study".

When changes are made to standards (i.e. standards or allowable levels of chemicals in the river), such changes should be published and justified publicly. It appears that the company would like the acceptable levels to be higher since they are currently often exceeded (as is the case for copper and cyanide). Furthermore, since the levels for suspended solids recommended by Buckley (1984b) could be often exceeded it is 'convenient' not to set an acceptable level. Implicit in the Sixth Supplemental Agreement is the inference that no guarantee can be given that the lower Ok Tedi would not be greatly affected, and that this is the 'cost' that needs to be tolerated for the economic viability of the project.

The terms of reference of the Environmental Impact Study under the Sixth Supplemental Agreement were forwarded to OTML on the 24th July 1986 (PNG, DME 1986). The study is concerned both with the total impact of the mining operations on the Fly River and with a re-evaluation of all effluent and environmental monitoring data so far collected. Hopefully this has included an assessment of the impact on the lower Ok Tedi River, though this is not definitely stated, only implied.

The "Environmental Study" is not only concerned with the impact of suspended solids - but includes a critical re-evaluation of the impact of suspended solids, cyanide and the heavy metals, particularly copper. This must involve a critical evaluation by independent bodies of the present biological studies.

## CONCLUSIONS

The River levels of suspended solids produced by the tailings are very high having increased 18 fold at Profile 3 below Tabubil and 2 fold at Kuambit compared to background levels. Sediment loads have increased, levels greater than 1000 $\mu g\ L^{-1}$ have been exceeded a number of times at Ningerum. The biological effect of these high levels is unknown; it is likely that some species which cannot tolerate the continuously high sediment levels will disappear.

Levels of soluble metals have remained lower than was initially predicted, but high levels of particulate copper, often exceeding the PNG standard, could have an impact. Flushes of river water containing 'above acceptable' amounts of soluble copper and free cyanide are frequent. One reported kill of freshwater animals occurred when a very high level of free cyanide was accidentally released into the river system.

Biological studies to date show that tailings have affected some fish and invertebrate populations down river as far as Ningerum. To date there is no tangible evidence that effects extend beyond Ningerum. Much of the available biological data is difficult to interpret. To date it seems that residue concentrations of lead, but not copper, zinc and cadmium, have increased in some fish. On the basis of data published to date, it is not possible to predict the magnitude of the impact of mine development on the lower Ok Tedi and Fly Rivers.

## RECOMMENDATIONS

These recommendations were originally submitted to Government in 1985. Since then a number of reports have been published in line with recommendation 4. Recently OTML has published further reviews of their hydrological (OTML, 1985b) water quality monitoring (OTML, 1986c) and biological sampling programmes (OTML, 1986d).

1 It is strongly recommended that OTML Environment Section commence regular bioassay tests to determine the toxicity of the tailings. They should use at minimum two local species which can be easily handled and transported, are small and are readily available in large numbers. One species should be relatively tolerant of tailings, the other sensitive. On the basis of these tests measures should be found to reduce the toxicity of the tailings.

2 It is recommended that the present standards for heavy metals and the original standards for free cyanide in water be adhered to and that standards for suspended solids be set immediately. These standards should always be subject to revision in the light of new data - but should not be changed for 'convenience'. Any changes to standards should be published and justified. The "Environmental Study" proposed under the Sixth Supplemental Agreement should include an evaluation by *independent scientists* of the effects of both suspended solids and heavy metals of the further 3 years of discharging tailings.

3 Ways must be found to reduce levels of suspended solids immediately and to ensure high levels of copper and free cyanide in the tailings are also reduced. Discharge of tailings into the river must be reduced at times of low river flow rates.

4 All data on heavy metal residues in animals should be published as soon as possible. Analyses should be done to determine concentrations of heavy metals in bottom sediments in the lower Fly River and lake systems.

5 It is recommended that an independent scientist assist in evaluating the biological studies done to date and have access to all 'in-house' data.

6 It is recommended that an 'Evaluation Committee' be immediately established by Government. Initially, it should assist in implementing the environmental study under the sixth supplemental agreement. It should assist in reassessing the total environmental sampling and data collection programme to date, and determine the likely impacts of continuing, at increased production, the interim tailings disposal scheme. This committee should include independent scientists and a representative of the peoples living on the Ok Tedi and Fly Rivers. It should at all times have access to 'in-house' data.

Postscript:

Since these papers were written reviews covering the period to mid 1986 by Ok Tedi, its consultants and Government consultants have all been published, although no "independent review" has been done. Copper production has commenced, production levels and consequently tailings have both increased.

## ACKNOWLEDGEMENTS

The Department of Minerals and Energy through the Bureau of Water Resources (now a part of the Department of Environment and Conservation) funded this evaluation and funded a field trip by the author to the Ok Tedi Mine and the Ok Tedi and Fly Rivers in November 1984. Dr William Townsend and Mr Mike Patchett, provided the author with data and information given to them by OTML Environmental Section.

Ms Bligh Mowbray, Dr John Pernetta and Dr Lance Hill criticised the final draft. Ms Bligh Mowbray, Hilda Petrus and Mary George assisted with typing the script onto the word processor.

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# PRE-MINING TRACE METAL LEVELS IN FISH FROM THE FLY RIVER

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## ABSTRACT

Concentrations of the trace metals, zinc, copper, lead and cadmium in fish from the Ok Tedi river prior to the onset of mining are reported. Concentrations were determined for whole specimens rather than the flesh alone since whole fish are consumed in this region. Three species were analysed during the present study and the results compared with data for other species examined during the course of the Ok Tedi Environmental Study. Variation within species was found to be greater than variation between species and the order of concentration was found to be zinc, copper, lead and cadmium. Concentrations of cadmium were found to exceed the Australian National Health Standards whilst those for copper, lead and zince were below these standards.

## INTRODUCTION

Roberts conducted an extensive ichthyological survey of the Ok Tedi - Fly River system in 1978 describing 11 new species (Roberts, 1978), while The Papua New Guinea Department of Primary Industry Fisheries Research Division has subsequently carried out a number of surveys of the region (Gwyther 1980; Eremu 1980; La'a 1980; Robertson and Baidam 1983). In order to obtain information on pre-mining subsistence fisheries in the area, a number of studies were performed prior to the commencement of mining in May, 1984. Hyndman (1979) and Welsch (1979) reported information on the role of aquatic biota in village nutrition while Lamb (1974), Boyden et al. (1975) and Kyle & Ghani (1982a, 1982b) determined concentrations of heavy metals in various aquatic plants and animals. In addition, the mining company has continued to monitor fish populations and trace metal concentrations in fish since 1982. These data are at present unpublished.

All of the above studies have helped to provide some baseline knowledge of the condition of pre-mining subsistence fisheries in the region. Because of the low-levels of fish abundance in the area (Robertson and Baidam 1983), any one study can only contribute a small amount to the total knowledge of fisheries in the region.

The aim of the present study was to assess the pre-mining concentrations of the trace metals zinc, copper, lead and cadmium (Zn, Cu, Pb and Cd) in some Ok Tedi fish species. Results are reported for 42 specimens comprising three of the most common species found in the area. The fish were caught by Robertson and Baidam during a visit to the region between 31 March and 14 May 1981; details of their methods of capture are reported elsewhere (Robertson & Baidam 1983), while the sampling sites are indicated in Figure 1.

## METHODS

### Sample Preparation

All fish specimens were caught with gill nets and handlines. Weight and length data were recorded in the field before the fish were stored in plastic bags on ice for return to the laboratory. For long term storage, whole or partial fish specimens were macerated in a stainless steel homogeniser, oven dried at 105 $^{o}C$, ground to a powder in a porcelain mortar and stored frozen in plastic topped polythene vials. The percentage moisture in each specimen was determined during the drying process.

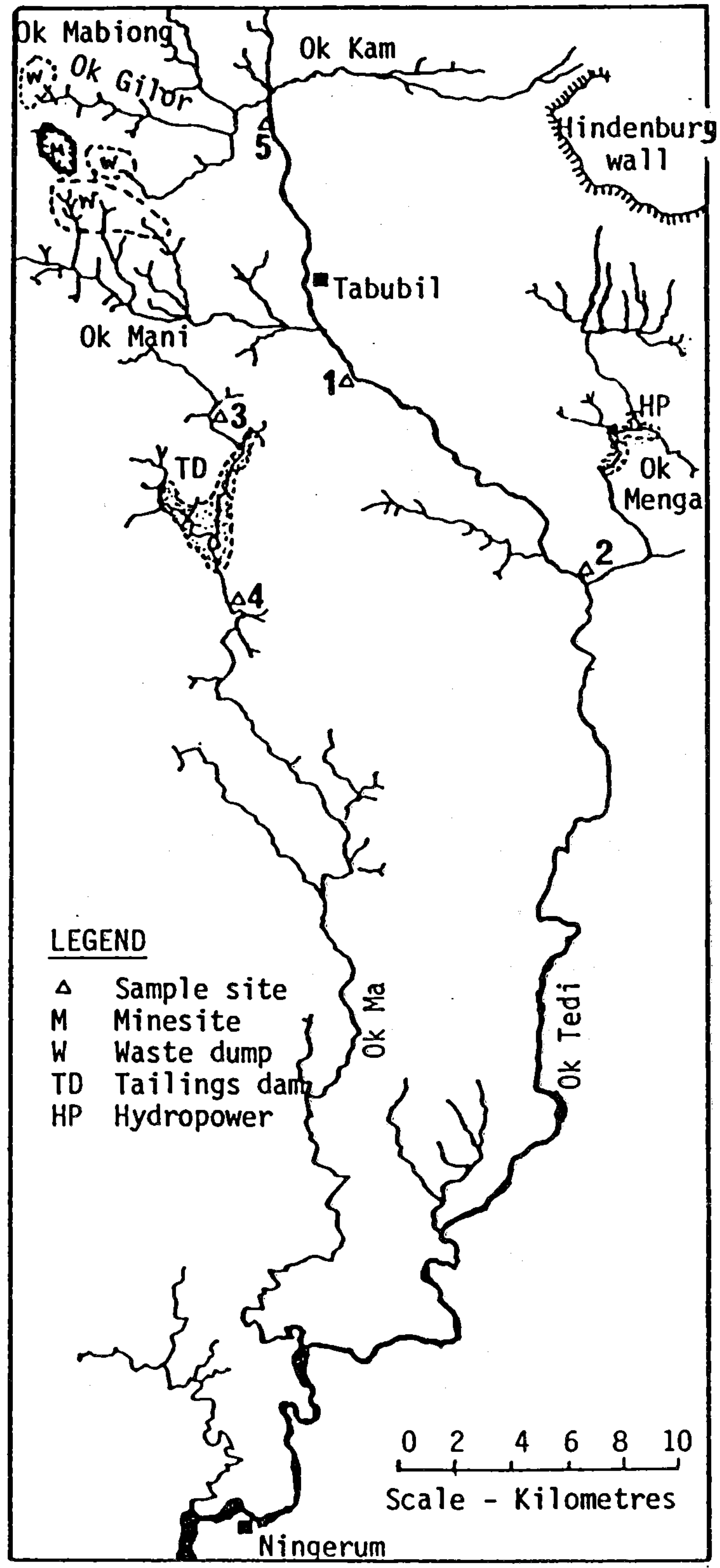


Figure 1. Map of the study area showing the sampling sites, minesite, waste dumps and formerly proposed tailings dam and hydropower sites.

It should be noted that all results are for the whole fish specimen (except where indicated) whereas much previous data has been for dorsal muscle tissue only or different organs. Since the people in the Ok Tedi region tend to consume the whole fish, rather than just the muscle tissue, and since many of the fish collected were very small, it was considered appropriate to analyse the whole fish.

Sample Digestion

Approximately 1.0 g samples of the dried fish specimens were weighed into 100 ml glass erlenmeyer flasks fitted with air condensers and digested with 10 ml nitric acid for 12 hrs then cooled. Perchloric acid (70%, 5 ml) was added and the solution digested for a further 7 hours or until the digest solution became colourless. The air condenser was then removed and the solution evaporated to near dryness (1-2 ml). Hydrochloric acid (2 ml) was added and the sample dissolved in milli-Q water and made up to 50 ml. One reagent blank was included for each five samples.

Reagents and Glassware Preparation

Nitric acid (analytical reagent grade) was twice distilled before use. Perchloric acid (70%) and hydrochloric acid (35%) were analytical reagent grade used as received. All glassware was soaked in 10% nitric acid for at least 24 hours before use. All sample handling and digestion was carried out in a clean air cabinet.

Atomic Absorption Analyses

Zinc and copper were determined by conventional flame Atomic Absorption Spectroscopy using a Varian AA 175 Spectrophotometer with deuterium lamp background correction. Standard solutions were prepared by dilution of spectroscopic grade 1000 ppm standards.

Anodic Stripping Voltammetry (ASV)

The concentrations of lead and cadmium were too low to be determined by the above method. Hence, they were determined by ASV using a Princeton Applied Research (PAR) Model 174A polarographic analyser coupled with a PAR Static Mercury Drop Electrode (Model 303A).

A 10 ml aliquot of sample was pipetted into the electrolytic cell and de-aerated for 12 minutes with high purity nitrogen. The sample was then electrolysed for 5 minutes at a potential of -1.2 v versus SCE (Standard Calomel Electrode). The stirrer was stopped for the last 15 seconds of the plating time. The voltammogram was then recorded. The concentrations of Pb and Cd in the original sample were then determined by the method of standard additions, using 20 µl aliquots of a standard containing 1.00 p pm and 0.4 ppm Cd.

RESULTS

The raw data giving the concentrations of the trace elements Zn, Cu, Pb and Cd in the 42 fish specimens, are given in Annex 1. The data are reported as mg $kg^{-1}$ based on the dry weight of the whole fish specimens. So that the data can be compared with other results quoted on a wet weight basis, the percentage moisture in each specimen has been included.

It will be noted that for a number of specimens, no result is recorded for zinc. This was due to the fact that the analytical results were extremely high (in excess of 1000 mg/kg) and were considered to be due to contamination. Unfortunately, time constraints did not permit repetition of these analyses.

A summary of these data is given in Table 1. including means and standard deviations for all specimens grouped by species and by sample site. Table 2 presents a comparision of the present data with the ranges reported by Maunsell *et al.* (1982) while Table 3 presents a comparision with the Australian Foodstuff standards.

TABLE 1. Means and standard deviations (in brackets) for the data in Annex Table 1 for each species of fish examined by site and by species. The mean trace metal concentrations are mg $L^{-1}$ kg based on the dry weight of the fish.

| FAMILY and species | Sampling Site | No. of Specimens | Mean Weight (g) | Mean Length (mm) | Mean % Moisture | Mean Metal Concentration Zn | Cu | Pb | Cd |
|---|---|---|---|---|---|---|---|---|---|
| PLOTOSIDAE | | | | | | | | | |
| *Neosilurus gjellerup* | 1 | 4 | 86 | 225 | 78.4 | 238 | 23.4 | 1.08 | 1.56 |
| | | | (31) | (23) | (0.5) | (19) | (17.7) | (2.05) | (1.82) |
| | 2 | 3 | 144 | 247 | 79.6 | 297 | 21.5 | 2.46 | 2.52 |
| | | | (222) | (152) | (2.8) | (97) | (10.6) | (4.02) | (0.90) |
| | 3 | 3 | 61 | 205 | 75.4 | 290 | 13.2 | 2.21 | 0.70 |
| | | | (26) | (30) | (5.0) | (23) | (5.2) | (3.75) | (0.81) |
| Species mean | | 10 | 116 | 226 | 77.8 | 269 | 19.6 | 1.84 | 1.59 |
| | | | (115) | (76) | | (59) | (12.7) | (2.92) | (1.41) |
| ELEOTRIDAE | | | | | | | | | |
| *Oxyeleotris fimbriatus* | 3 | 7 | 25 | 127 | 76.5 | 231 | 24.0 | 4.20 | 0.81 |
| | | | (12) | (20) | (2.3) | (124) | (19.9) | (2.93) | (0.51) |
| | 4 | 7 | 41 | 151 | 77.7 | 196 | 41.4 | 2.25 | 1.09 |
| | | | (8) | (8) | (1.2) | (109) | (16.6) | (0.47) | (0.49) |
| | 5 | 7 | 7.1 | 83 | 77.8 | 111 | 9.86 | 3.55 | 0.89 |
| | | | (3.4) | (16) | (0.6) | (67) | (5.58) | (4.23) | (0.84) |
| Species mean | | 21 | 25 | 120 | 77.3 | 186 | 25.1 | 3.32 | 0.93 |
| | | | (16) | (32) | | (112) | (19.5) | (2.87) | (0.61) |
| *Mogurnda mogurnda* | 1 | 6 | 19 | 121 | 77.5 | 243 | 15.0 | 0.88 | 1.58 |
| | | | (4) | (9) | (0.5) | (191) | (4.1) | (2.09) | (1.43) |
| | 4 | 5 | 27 | 119 | 77.8 | 198 | 51.6 | 2.48 | 0.63 |
| | | | (23) | (37) | (1.3) | (55) | (21.3) | (1.74) | (0.47) |
| Species mean | | 11 | 23 | 120 | 77.6 | 221 | 31.6 | 1.60 | 1.15 |
| | | | (15) | (24) | | (134) | (23.6) | (2.03) | (1.16) |

## DISCUSSION

The most complete study published to date on trace metal concentrations in fish from the Ok Tedi - Fly RIver is that of the Ok Tedi Environmental Study (Maunsell *et al.* 1982). Liver and/or muscle samples were examined from 562 specimens comprising 27 species from 21 sites in the river system. The metals determined were Zn, Pb, Cu, As, Hg, Cd and Mo. No data were included for the three species of fish examined in this study, even though they are commonly caught and consumed by subsistence fishermen in the OK Tedi region (Robertson and Baidam 1983). The present results, are generally comparable with data from the Environmental Study (see Table 2).

Table 2. Concentration of trace metals in fish from the Ok Tedi region (mg $kg^{-1}$ wet weight). The present data for whole fish are compared with the overall species mean ranges obtained in the Ok Tedi Environmental Study (Maunsell *et al* 1982).

| Species | Mean Zn | Trace Cu | Metal Pb | Concentration (mg $kg^{-1}$) Cd |
|---|---|---|---|---|
| *N. gjellerup* | 60 | 4.3 | 0.41 | 0.35 |
| *O. fimbriatus* | 42 | 5.7 | 0.75 | 0.21 |
| *M. mogurnda* | 49 | 7.1 | 0.36 | 0.26 |
| Ok Tedi Study | | | | |
| Muscle Tissue | 6.4-29 | 0.23-0.71 | 0.130-0.15 | 0.05-0.10 |
| Liver | 19-800 | 2.4-49 | 0.15-2.0 | 0.09-0.74 |

In the data provided by Maunsell *et al.* (1982) and that from the present study, there was wide variation within species with the standard deviation in most cases being high in relation to the mean. In addition, Maunsell *et al* (1982) found a wide variation between different species (Table 2). Variation between species was not found in the present study (the means are not statistically different presumably because all the fish examined were in a similar size range and from the same region of the river system, whereas in the Maunsell study they were of different sizes and from different locations.

Even though these wide variations occurred, the present data are comparable with those of Maunsell *et al.* (1982). The trace metal concentrations are in the same order (Zn > Cu > Pb > Cd) and the whole fish analyses of the present study are generally higher than muscle tissue but less than liver concentrations. This is to be expected since trace metals tend to accumulate to a greater extent in internal organs such as the liver and kidney than in muscle tissue (Forstner & Wittman 1979). In general, the concentrations of lead may be considered to be of the same order as those reported in Maunsell *et. al.* (1982) whereas zinc, copper and cadmium concentrations are generally higher. The concentrations of cadmium are sufficiently high to be of concern.

Table 3. Comparision of trace metal concentrations in whole fish (mg/kg wet weight) with Australian National Health and Medical Research Council Standards (1980) for muscle tissue.

| | AUSTRALIAN STANDARD mg $kg^{-1}$ Wet Weight | PRESENT DATA Mean Range |
|---|---|---|
| Zinc | 150 | 42-60 |
| Copper | 10 | 4.3-7.1 |
| Lead | 1.5 | 0.36-0.75 |
| Cadmium | 0.2 | 0.21-0.35 |

The Australian National Health and Medical Research Council, (NHMRC, 1980) have recommended standards for trace metals in foods (including fish). These standards refer to the muscle tissue of the fish as this is the portion that is usually consumed. The Fly River people however normally consume the whole fish. It is important, therefore when considering health standards for these people, that the whole fish analyses should be compared with health criteria rather than just muscle tissue analyses (Maunsell *et al.* 1982); this is done in Table 3. From an inspection of these data, it is immediately evident that the fish analysed do not meet the NHMRC standard for cadmium. This does not mean that the fish should never be eaten. Health standards are normally conservative estimates of the concentrations of trace metals that may be harmful if the fish are eaten in reasonable quantities (say 500 g per week), with the application of a safety factor of ten. Hence, harmful effects would be noticeable if 500 g per week of fish containing 2.0 mg $kg^{-1}$ Cd or 5000 g per week of fish containing 0.2 mg $kg^{-1}$ Cd were consumed.

The Ok Tedi people do not rely heavily on fish for their food, unlike the people in the middle to lower Fly River (Kyle and Ghani 1982a). Robertson and Baidam (1983), when they collected the present specimens, noted that fish consumption was generally low, with consumption ranging from one meal per week to one meal every three weeks. Hyndman (1979) noted however that fish, frogs and reptiles are culturally "womans food" and consumed more by young children and women more than by men. The concentrations of trace metals observed in the fish should be of no major concern assuming consumption remains low. Increasing quantities of mine waste in the rivers will probably lead to increases in these base level metal concentrations and continued monitoring is therefore vitally important. Such monitoring should be of analyses of trace metals in the whole fish specimen, rather than the muscle or liver, to give a better indication of what is actually being consumed by the local people than do the separate tissue and/or liver analyses, currently being performed.

ACKNOWLEDGEMENTS

The fish specimens were collected by Mr. C. H. Robertson and Mr. C. Baidam, Fisheries Research Division, Department of Primary Industry. Mrs E. Lacanienta and Mrs N. Ghani helped with the preparation of the fish specimens, for analysis. Mr J. Tinkerame and Mr. P. Haei SPREP supported trainees performed the analyses.

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Annex 1. Weight, length, percent moisture and trace metal concentrations in mg kg$^{-1}$ dry weight for all fish specimens analysed. The sample sites are indicated in Figure 5.1. The whole fish was analysed except where indicated.

| FAMILY and Species (Date of sampling) | Sampling Site | Weight (g) | Length (mm) | Moisture Content % | Metal Concentrations mg kg$^{-1}$ dry weight Zn | Cu | Pb | Cd |
|---|---|---|---|---|---|---|---|---|
| PLOTOSIDAE | | | | | | | | |
| *Neosilurus gjellerup* | 1 | 125 | 225 | 78.1* | 211 | 24.5 | 0.175 | 1.65 |
| (11 April 1981) | | 92 | 230 | 78.1* | 249 | 10.5 | 0 | 0.20 |
| | | 51 | 200 | 79.2* | 237 | 10.5 | 0 | 4.10 |
| | | 76 | 215 | 78.3* | 255 | 48.0 | 4.15 | 0.30 |
| (27 April 1981) | 2 | 400 | 359 | 81.5+ | 408 | 29.0 | 7.10 | 1.95 |
| | | 220 | 307 | 81.0+ | 231 | 14.0 | 0 | 2.05 |
| | | 10 | 74 | 76.4 | 252 | - | 0.28 | 3.55 |
| (22 April 1981) | 3 | 91 | 239 | 74.2 | 307 | 13.0 | 0.10 | 0 |
| | | 46 | 194 | 80.9 | 274 | 18.5 | 6.55 | 1.60 |
| | | 46 | 183 | 71.1 | - | 8.1 | 0 | 0.50 |
| ELEOTRIDAE | | | | | | | | |
| *Oxyeleotris fimbriatus* | 3 | 34 | 138 | 79.0 | 220 | 19.0 | 2.25 | 0.70 |
| (20 April 1981) | | 16 | 111 | 76.9 | 390 | 25.0 | 2.50 | 1.55 |
| | | 16 | 116 | 76.0 | 195 | 65.5 | 0.85 | 0.43 |
| | | 12 | 99 | 77.8 | 220 | 25.0 | 2.25 | 0.37 |
| (22 April 1981) | 3 | 45 | 159 | 77.0 | 108 | 10.0 | 7.45 | 0.23 |
| | | 26 | 128 | 77.0 | 83 | 8.8 | 8.25 | 1.15 |
| | | 29 | 135 | 71.7 | 400 | 14.4 | 5.85 | 1.25 |
| (23 April 1981) | 4 | 47 | 153 | 79.1 | 306 | 20.0 | 3.00 | 1.45 |
| | | 35 | 146 | 77.8 | 105 | 52.0 | 2.10 | 0.98 |
| | | 42 | 145 | 78.8 | - | 15.0 | 1.70 | 0.70 |
| | | 52 | 164 | 77.8 | 155 | 55.0 | 2.40 | 1.25 |
| | | 32 | 151 | 77.9 | 130 | 51.0 | 2.25 | 0.55 |
| | | 32 | 142 | 77.3 | 360 | 46.0 | 2.60 | 0.75 |
| | | 47 | 156 | 75.4 | 120 | 51.0 | 1.70 | 1.93 |
| (4th April 1981) | 5 | 8.1 | 90 | 78.1 | 46 | 4.7 | 1.88 | 0.65 |
| | | 5.3 | 71 | 77.9 | 109 | 5.3 | 0.85 | 1.05 |
| | | 2.0 | 55 | 77.7 | - | 5.6 | - | 0.20 |
| | | 13 | 106 | 77.3 | 192 | 20.6 | 10.5 | 2.55 |
| | | 8.5 | 92 | 78.2 | 164 | 12.2 | 7.10 | 0.15 |
| | | 7.0 | 86 | 78.6 | 44 | 10.3 | 0.30 | 1.25 |
| | | 5.6 | 92 | 76.7 | - | 10.3 | 0.70 | 0.35 |
| ELEOTRIDAE | | | | | | | | |
| *Mogurnda mogurnda* | 1 | 17 | 115 | 76.7 | 316 | 19.5 | 0 | 3.93 |
| (11 April 1981) | | 15 | 111 | 77.3 | 502 | 13.4 | 0 | 0.05 |
| | | 17 | 115 | 77.5 | 49 | 19.5 | 5.15 | 1.45 |
| | | 22 | 125 | 77.2 | - | 9.0 | 0 | 0.23 |
| | | 26 | 135 | 78.3 | 288 | 15.5 | 0.10 | 2.30 |
| | | 19 | 20 | 77.8 | 59 | 13.0 | 0 | 1.50 |
| (23 April 1981) | 4 | 43 | 148 | 79.8 | 200 | 48.5 | 2.25 | 0.30 |
| | | 59 | 162 | 77.6 | 150 | 51.0 | 2.00 | 0.98 |
| | | 17 | 118 | 78.0 | 215 | 61.5 | 2.95 | 0.48 |
| | | 10 | 90 | 76.3 | 280 | 71.5 | 5.00 | 0.15 |
| | | 6 | 75 | 77.5 | 147 | 19.5 | 0.20 | 1.25 |

0 = Not detected - = Not analysed * body w/o head, tail or gut analysed

+ Dorsal muscle tissue only analysed

# GIVING AWAY THE RIVER: ENVIRONMENTAL ISSUES IN THE CONSTRUCTION OF THE OK TEDI MINE, 1981-84*

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ABSTRACT

The role of the State in the development of the Ok Tedi mine is reviewed and conclusions drawn concerning reasons for the failure to implement adquate environmental safeguards. The administrative and organisational pathways through which the States financial and environmental interests were incorporated into project planning and implementation are outlined and it is concluded that problems of management and co-ordination resulted in environmental considerations being ignored or playing a secondary role to financial concerns. The adoption of a "fast track" approach to development has resulted in significant financial losses through abandonment of engineering projects such as the hydro-dam only after significant expenditures had already been made. The project is judged to have a poor environmental and accident record.

## INTRODUCTION

The Ok Tedi gold and copper deposit, located in the Star Mountains near the Indonesian border, was discovered in 1968. Initial proving of the ore deposit and setting up the project was done by the Kennecott Mining Company, who considered the project to be primarily a copper mine (Jackson, n.d.). After Kennecott dropped the project on March 12, 1975, Papua New Guinea continued development of the mine with technical advice from Behre Dolbear, a mining consultant from New York City. As this project was being developed it was considered by many to be the cornerstone of the Papua New Guinea economy.

After further drilling and the dramatic increase in gold prices in 1980 the mine was considered as an excellent example of staged development, with the gold ore at the top of the deposit and copper ore underneath. In Stage I the ore at the top of Mount Fubilan would be processed to extract gold. Stage II included two processing lines; one for gold and one for high grade copper ore. Finally, Stage III involved processing relatively large quantities of low grade copper ore. With this staged mining procedure shown to be feasible, a new company was formed with three private partners: BHP of Australia, AMOCO Oil Company of Indiana, and a German consortium of companies. Papua New Guinea, with a 20 per cent share, became the fourth partner and plans were developed to begin construction of the mine. Bechtel and Morrison Knudson International (B-MKI) were selected as the prime contractor and the pre-construction work began in May, 1981.

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*This paper was made available only after the other contributions had been edited and compiled for publication. It is included since it provides significant insights into the organisation and administration of Government involvement in the Ok Tedi project. Dr Townsend was employed by MRDC from March 1981-December 1984 with primary responsibility to advise the State on technical matters and to co-ordinate the activities of the State's technical personnel working on the OTML Project. Recognising the problems of a conflict of interest within the Department of Minerals and Energy the Government later transferred the Bureau of Water Resources to the Department of Environment and Conservation. Hence much of the technical advice which was ignored during the development of the Ok Tedi project is now available to the National Executive Council and Government via an independent Ministry. Hopefully this will lead to more careful consideration of environmental issues in future mining projects within the country. Editor's footnote.

Construction of the Stage I infrastructure, containing the facilities and support systems necessary to mine gold, was authorised in mid-1981. The agreement between OTML and the State is contained primarily in the Mining (Ok Tedi Agreement) Act 1976 dated 22 March 1976, the Mining (Ok Tedi Supplemental Agreement) Act dated 26 June 1980, and the Construction Feasibility Study, ten volumes which give details about the transportation systems, townsites, power supply, process plant, ore reserves, and waste disposal. In general the 1976 Ok Tedi Act specified the components which the mining company would build and the Feasibility Study listed quantities and the construction sequence. The Supplemental Agreement, Schedule B, described the requirements of the Environmental Impact Study and the environmental management program which were to be carried out by OTML.

This paper will discuss construction of the Ok Tedi project and agreements that relate to protection of the river system in order to show specifically what happened to the environmental programme during Stage I construction. It will not discuss the thinking and negotiations that led to the agreed environmental programme (Pintz, 1984). Nor will it discuss the anticipated impact of the mine on the local peoples environment, both social and physical (Jackson, n.d.). Others have studied the actual social impact of Stage I construction and mine operation (Hyndman, 1988; Ulijaszek *et al.*, 1987).

## PAPUA NEW GUINEA'S GOAL FOR ENVIRONMENTAL PROTECTION.

It was understood by the State that mining and development of the townsite, mine, hydro-electric facility, and waste disposal system would have a major environmental impact on the immediate area of the mine. What the State wanted was to limit the mine impact to the area adjacent to the upper Ok Tedi River. In order to do this is was necessary to control the impact of the mine on the river system. Thus, the State's commitment to environmental protection was centered on limiting the impact the Ok Tedi River, in order to avoid the environmental disaster which accompanied the Bougainville Copper Mine (Hyndman, 1988).

From 1975 until 1979 while the project was still considered to be economically marginal because of low copper and gold prices and inadequate ore reserves, the mining company was not agreeable to the State's requirement to contain the incompetent waste material which was scheduled for disposal in dumps adjacent to the mine on the South side (the "Southern dumps"). The material originally planned for disposal there is made up of about 130 million tonnes of soil and soft rock which will decompose quickly and enter the Ok Tedi river system very soon after being deposited. The agreement ended up at the arbitrary figure of 60 million tonnes of incompetent waste which could be disposed of in the Southern Dumps. When metal prices rose to relatively high levels in 1979 the mining company finally agreed to this condition.

The planned protection of the environment consisted primarily of the tailings dam on the Ok Ma which was on the critical path for construction. This meant that any delay in beginning or completing construction would delay operation of the completed plant. Transportation of the tailings from the Process Plant, originally at Teranaki, to the Ok Ma reservoir was to be by pipe-lines, a completely closed system. In the event of major storms or malfunction of the principal system, the cyanide would be neutralized by chemical treatment of the tailings. Functioning of the tailings dam to neutralize the cyanide by natural decay and retention of the tailings fines by settling out of the particles was not considered to be automatic. It was considered necessary by both the State and the Mining company that the effluent from the reservoir be monitored in order to ensure the desired protection of the river system in the event of major storms or other conditions that could reduce the effectiveness of the tailings pond.

Environmental monitoring and an Environmental Impact Statement (EIS) were defined in the Supplemental Agreement. Jackson, (n.d. page 85), doubts that OTML was serious about environmental protection because of the small sum that was specified for the Study. The Environmental Impact Statement presented by OTML has serious shortcomings, including a limited time span of measured rainfall and stream flow records, limited information about the chemical and physical properties of the tailings, and a sketchy survey of the natural environment. These factors were severely criticized by the State's environmental consultant (Buckley, 1984). Nevertheless, in spite of its limited scientific rigour the EIS does contain a lot of useful information and sets down guidelines which would provide a level of protection to the river system. The EIS written by OTML's consultants gives criteria for chemical and particulate pollution of the Ok Tedi River from the tailings dam effluent.

There is uncertainty and a great deal of debate concerning the level of damage caused by various pollutions to specific plants and animals that live in and adjacent to a river system. An environmentalist will interpret data so that the grey area of uncertainty is considered unacceptable or at least risky. An entrepreneur, on the other hand, will be searching for the limit beyond which damage will occur and thus will tend to consider the grey area of uncertainty as acceptable. That is, there is no damage if it cannot be clearly proven. In order to prevent stalemate in negotiations it was decided not to address this issue until after mine operations had begun (Pintz 1984 p.90). The problem with this deferral is that resolving the conflict between the environmentalist and entrepreneurial interpretation of data is no easier after mining has begun than it was before mining started.

The agreement to postpone the decision on acceptable environmental impact put the burden of decision and enforcement on the State in 1983, when OTML requested approval of the Interim Tailings Scheme. As a practical issue, all of the staff who negotiated the agreement had left government by the time that decisions needed to be made.

During construction and commencement of mining operations, (from 1982 through 1984), OTML gathered much data, as required by the agreement, and talked to many technical specialists on environmental issues. This gave OTML a great deal of time and information to develop and support its viewpoint. The State, on the other hand, had all new staff and more limited resources and support for presenting the other side of the environmental argument. Meanwhile, reduced profitability of the mine hardened OTML's resolve not to spend the money necessary to build the tailings dam.

TABLE 1. Sequence of Events for Stage I Construction

| | |
|---|---|
| February 1981 | First MRDC staff hired |
| May 18, 1981 | Begin Pre-construction phase |
| August 18, 1981 | Authorization given for Stage I construction |
| September 1981 | Second MRDC staff hired |
| January 1982 | Re-organize MRDC |
| November 17, 1982 | State informed project is eight months behind schedule |
| January 1983 | Terminate Ok Menga hydro construction |
| March 1983 | OTML Task Force |
| March 1983 | Re-organize MRDC |
| August 1983 | OTML presents Interim Tailings scheme |
| November 1983 | Visit Malaysian minesite |
| January 7, 1984 | Landslide at Ok Ma dam site |
| January 25, 1984 | State approves Interim Tailings scheme |
| February 1984 | MRDC receives 1982 environmental monitoring report from OTML |
| May 1984 | Begin operation of process plant |
| December 31, 1984 | Deadline for OTML to let contracts for half of tailings dam construction |
| March 18, 1986 | Parliament ratifies Sixth Supplemental Agreement |
| January 1, 1989 | Environmental study due on impact on Fly River |
| January 1, 1990 | Permanent tailings dam construction to begin |

GOVERNMENT ORGANISATION

As both an active shareholder and the owner of the natural resource, Papua New Guinea recognised that there would be decisions to make. In order to co-ordinate its role on the Ok Tedi Project the National Executive Council set up a three-level organisation; a small group of senior ministers to control political discussions, a committee of public servants to co-ordinate the government departments involved in the project, and a separate company (Mineral Resources Development Company) to manage the State's interest in the project.

Originally the State's negotiators who wrote the project agreement were public servants working at the First Assistant Secretary level. The departments of Minerals and Energy, Finance, Justice, and the National Planning Office were most active at this time and formed the working core of the Ok Tedi Management Committee. Many of the individuals who were active in the negotiations were personally committed to protection of the environment but none of the core departments had environmental protection as a primary departmental responsibility. The Water Resources Bureau is charged with protection of the country's rivers but they were not active in planning the project. During negotiations and planning, there was no one present who was primarily concerned with protection of the environment.

In order to manage and co-ordinate the State's interest on the Ok Tedi project it was planned to set up a separate company for the project. This was considered necessary because many of the government departments were not organised to support the project in an effective way, particularly considering that there would be unusual demands made by the project. This company, Mineral Resources Development Company (MRDC), was never completely established after the initial appointment of a manager in September 1981 was a failure; nor was MRDC ever given authority to represent the State. The intention, in 1981, was that MRDC would co-ordinate and manage the activity of governmental departments on the project and would thus be working at the secretarial level. By 1983 when the original tailings scheme was being abandoned by OTML, MRDC had been re-organized to function as a division within Minerals and Energy. At this time MRDC reported to the Ok Tedi Co-ordinator who reported to the First Assistant Secretary. Thus, following re-organization the State's co-ordination team was now functioning well below the secretary level with a correspondingly weakened ability to influence policy decisions and to co-ordinate the States role on the project. All reports and recommendations from MRDC went through Minerals and Energy and were supported or vetoed depending on the Department's programme.

At the same time that Ok Tedi project matters were being more deeply buried within Minerals and Energy, the mining company was building an active management organization which was based primarily in Port Moresby. (Bechtel had a central office in Melbourne and, of course, the construction activity was centered at Tabubil.) The management of OTML tried to gain as complete control of the project as possible by making contact with key ministers and providing information about the project to the State. In order to keep information flowing between the State and OTML, weekly briefings were held in the Department of Minerals and Energy between OTML management and representatives of the State. These meetings were useful for communicating detailed information, however, major issues and decisions about the project did not go through this channel. OTML Management found it expedient to go directly to the decision-makers, the Secretary of Finance, and the Secretary of Minerals and Energy as well as government ministers.

The State's designated representation on the OTML board was the Secretary of Finance and the Secretary of Minerals and Energy. Both Secretaries Morata and Agonia, however, who were major forces for the State in defining the Ok Tedi Agreement, had left their government positions by the time that the environmental issues came up in 1983 and had been replaced by new appointees. The Ok Tedi Act designates the Secretary of Minerals and Energy as the point of contact for OTML and in 1981 the Secretary used MRDC as his designated agent for this liasion. By 1983 MRDC had been completely bypassed as the point of contact.

Ministers of the various departments who sit on the National Executive Council are the principal decision-makers for the State. The normal procedure for communication with these Ministers is a well established part of government which is very cumbersome, particularly in comparison with a fast-moving mining project. In order for the project co-ordination team to make a recommendation to the Minister for Minerals and Energy it was necessary to get the approval of the Department's Ok Tedi Co-ordinator, the First Assistant Secretary, and then the Secretary. Because of this cumbersome procedure, rarely did MRDC brief any Minister and never did MRDC appear before the National Executive Council. OTML, on the other hand, could talk to anyone who would listen. It was easy for OTML personnel to get an audience with ministers who were frustrated with departments that could not give them timely briefings about this large and exciting project. Unlike government departments, OTML was quick to give up-to-date information, especially when important issues were at hand. OTML's General Manager often escorted key Ministers around the project and often discussed issues with the State's Directors. Never once did the General Manager attend the State briefing sessions that had been set up for communication with the State. The cumbersome procedure established for the State's departments doing business in combination with OTML's direct access to Ministers and key personnel undercut the State's project management team and effectively removed technical considerations from the decision-making process.

The weakness of the State's decision-making process is illustrated by the Task Force which was established by the OTML Board on March 8, 1983. The Board was concerned about construction lagging behind schedule and incurring massive cost overruns. The Task Force was set up to review the whole project management and the construction program. All shareholders were represented on the Task Force including the State, which was represented by MRDC's Assistant Manager Technical. This appointment seemed a major breakthrough, this being the first time the government had been given an equal role on technical matters.

The terms of reference were "The study should determine the required course of action to achieve gold production at the earliest practicable date and at the lowest possible cost. The study should consider all alternatives, including alternatives which do not accord with existing agreements, and should consider deferral of any expenditure that can be practicably deferred". The Task Force interviewed senior management of B-MKI and OTML at Tabubil and at Melbourne. Construction was reviewed for the whole project and all schedules and alternatives were reviewed. Several things became clear to the Task Force:

1. The project was far behind schedule with little chance of making up lost time. With construction of the Ok Menga hydro-electric facility permanently stopped and the Tailings Dam construction temporarily stopped all resources could be diverted to constructing the Process Plant. It appeared that the plant could be operating by June 1984, only a small slippage in the original schedule of operation by May 18, 1984.

2. OTML management and B-MKI were openly hostile toward each other and the situation had developed where each party seemed to be actively concerned with defending its position. Although B-MKI had made mistakes, the Task Force felt that B-MKI was the project's builder and ways should be sought to ease their work. The Task Force observed that OTML management was developing an organisation which was ineffective and duplicated the function of B-MKI. The Task Force felt that OTML management should be reduced so as not to duplicate B-MKI's function and that the construction tasks be clarified.

The Task Force completed its report on March 25, 1983 and gave it to OTML's General Manager for his review and discussion. The major difficulty which the Task Force faced was in recommending measures to correct the deteriorating management situation which OTML had developed. After reviewing the report, the General Manager sent it, along with his rebuttal to the Board. Each of the representatives from the three private shareholders discussed that Task Force report with their own Board members. The State's decision-makers, however, did not seek input from the State's representative. Instead the Prime Minister was briefed by OTML management about topics where its own failings were being reviewed. The Prime Minister then instructed the State's two directors what position to take regarding the report. At no time did any minister or departmental secretary, including the State's board members, discuss the report or the findings of the Task Force with the State's representative who had been involved in a concentrated two-week review of the project which included interviews with Bechtel, Morrison and Knudson International, and OTML management at Tabubil, Port Moresby, and Melbourne, Australia. By this time OTML management had developed such good communications with the top levels of government that the State in this case had less independence than the private shareholders.

A critical factor in the State's organization on the Ok Tedi project was the conflict of interest of some key individuals and departments on the project. The most serious case of this was within the Department of Minerals and Energy, the State's point of contact with OTML. Minerals and Energy had the interest of OTML in mind through the Secretary who was a member of the Board. As a director, the Secretary is primarily responsible for the efficient implementation of the mining project. As Secretary of Minerals and Energy, his responsibilities are different and come into conflict with his responsibilities as Director. The Department of Minerals and Energy includes the Mines Division, charged with safety on mining projects around the country, and the Water Resources Bureau, charged with safe and effective use of the country's water resources. The Chief Inspector of Mines and the Director of the Water Resources Bureau both needed to function freely under their own statutory regulations. Positions relating to the shareholder role were usually formulated by the Division of Policy and Planning while positions relating to standards and regulations were formulated by the department's technical staff: the Mines Division, the Water Resources Bureau, and the Geological Survey.

Often on the Ok Tedi project the Department's position as shareholder conflicted with its position as enforcer of standards and regulations. When in conflict, the Department almost always took the position of the State as shareholder. This meant that when the Department found itself in conflicting roles it usually chose the position which was not supported by its own technical staff. This was clearly the case when on January 25, 1984 the National Executive Council accepted OTML's request to stop construction of the Ok Ma tailings dam and start construction of the Interim Tailings scheme.

The State's decision to stop construction on the Ok Ma dam and start construction of the Interim Tailings scheme was made in the face of contrary technical input and recommendations from technical staff. Technical staff and institutions who recommended against the Interim Tailings scheme include:

1. The Australian Mineral Development Laboratories (AMDEL), who had been hired by the State to advise on environmental issues including the Interim Tailings scheme, advised that the mine not be allowed to operate using the proposed scheme (AMDEL Report No 1541).

2. The Chief Inspector of Mines recommended that OTML and the State concentrate all efforts on efficient construction of the agreed tailings system.

3. The Director of the Bureau of Water Resources was adamantly opposed to dumping tailings directly into the river system.

4. MRDC considered the system ineffective for protection of the environment and recommended that the original system be built as quickly as possible.

In spite of unanamous opposition to the proposed scheme by the State's technical advisors NEC decided to accept OTML's recommendations on environmental protection.

## CONSTRUCTION

Although construction of Stage I began in mid-1981, the State never did establish its organisation for managing its role in the construction project. As a result, the State was barely able to produce the required land lease agreements and then only after a monumental effort. The project's management team, Mineral Resources Development Company (MRDC), never reached its authorized staff level of seven. Only two professional staff were hired. (This compares poorly with the State's full time project management team of four for the Bougainville project). Even so the two staff that were hired were severely limited in that they were given no authority to make decisions or direct activities. These two were able to accomplish significant tasks only because of the good will of departments that wanted to support the project.

In addition to not setting up an adequate management team, the State was ineffective in using the staff which it did have on the project. For example, in May 1981, before Stage I construction was formally authorized, MRDC's Assistant Manager Technical, a Civil Engineer, recommended that the State employ an internationally established geo-technical engineer as a consultant to advise the State and project on soil stability problems. This request was prompted by his observation that there were many visible landslides in the upper Ok Tedi basin, particularly near the Ok Menga gorge which was being developed for hydro-electric power. The proposal requested the minimum of outside consultation which would be centered on the Ok Menga hydroelectric dam and the Ok Ma tailings dam. The request was turned down, primarily by staff from the National Planning Office who commented that the cost of US$ 50,000 was too high.

In early 1983 construction of the Ok Menga hydroelectric facility was stopped because of a massive block of land that was moving as a result of the power house construction. The tunnel had been completed through the right bank to gain access to the Ok Menga basin and the turbines had been ordered and shipped to Kiunga for storage. Construction of the Ok Menga facility has never been resumed, but before it was stopped OTML had spent US$ 89,178,084 on it.

Later in 1983, construction began on the Ok Ma tailings dam in a frantic attempt to have it on line in time for production even though the design had not been completed and geological features of the site had not even been mapped. The well-published landslide of January 7, 1984, resulted in the termination of construction of the tailings dam. This event was not unpredictable in that a minor slide in the same area occurred two weeks earlier and the construction of the decant tunnel on the right bank produced a continuously moving land mass that was carefully controlled. Even so the aborted construction of the tailings dam had cost the project US$ 64,319,158.

The State's 20 per cent share of the OTML expenditure on the two aborted dam construction projects is more than US$ 30 million. This is more than 500 times the funds requested to advise the State on this aspect of the project. Much more serious than the immediate financial loss to the State is the long term impact on the project of not having hydroelectric power or the environmental protection offered by the tailings dam. One cannot say what would have happened if the proposed consultant had been hired however, the probability of failure on either one of these projects would have been greatly reduced if the State had made a proper technical review.

Another example of the State's ineffective use of staff on the Ok Tedi project is the construction progress report MRDC presented on November 17, 1982, to the Ok Tedi Management Committee (made up of representatives from the departments of Finance, Minerals and Energy, Justice and the National Planning Office). The report indicated that construction was eight months behind schedule, a delay which would produce massive cost overruns that would reduce the profitability of the project. One should remember that when the project was considered economically marginal OTML was not willing to include the environmental protection which the State required. Further, the report stated that since the tailings dam was the last major component scheduled for construction in Stage I, it was in the State's interest to monitor this portion of the project carefully. The Management Committee agreed with the report and recommendation. Minerals and Energy had taken over the direction of MRDC however, and was acting as the co-ordinator for the State's activities in construction of the mine. Minerals and Energy had its own agenda of reducing the cut-off grade for gold ore as well as activities on other mining projects so that the warning about cost overruns was ignored and the direction to actively monitor OTML's implementation of the tailings dam was not pursued.

The State's ineffective use of staff is further illustrated by the history of the design of the Ok Ma Dam. The Ok Tedi Task Force was set up in March 1983 with representation from all four shareholders. One of the recommendations of the Task Force was that the Ok Ma Tailings Dam design be finalized immediately so that construction could be properly planned. The State's representative wrote two separate memos to Minerals and Energy with the strong recommendation that the State push for a meeting of interested parties to convene until the design was finalized. The State's Chief Inspector of Mines took a similar position, however, the department decided against taking the recommended action.

On January 7, 1984 a massive earth movement caused OTML to stop construction of the Ok Ma tailings dam. A number of facts should be pointed out about conditions associated with the Ok Ma Dam failure.

1. Construction had begun on the dam foundation even though the dam design had not been completed at the time of the failure.

2. Construction had begun on the dam foundation even though the geological features of the dam site had not been mapped at the time of the failure.

3. Immediately after the landslide, Bechtel stated that the dam could be built on the same site with the dam moved 200 meters upstream.

4. In the Ok Ma "Post Mortem" by Hollingsworth and D'Applonia it was stated that the dam could be built on the same site by moving it 150 meters upstream.

5. The decision to terminate construction of the Ok Ma Dam and the National Executive Council's decision to approve the Interim Tailings Scheme was done with no technical input from the State. The whole exercise was handled in the administrative and political arena.

The impact of the January 7, 1984 landslide on the Ok Ma dam site was that the State's chances of meaningful protection of the river system were reduced to nearly zero. In this regard implementation of the Ok Tedi project by the State duplicated the experience of the Bougainville project: that is, tailings are dumped into the river with no effective treatment.

<u>OTML's Management of the Environmental Program</u>

Ok Tedi Mining Limited consistently followed a simple strategy during Stage I Construction to undermine the State's position on environmental protection. This strategy consisted of three parts:

1. Keeping the State's technical staff as far away from meaningful discussion of project components as possible.

2. Removing the 60 million tone limit on incompetent waste agreed for the Southern Dumps.

3. Proposing a highly visible but inadequate mode of tailings disposal after the failure to construct the agreed tailing dam.

OTML's intention to keep the State out of technical review and significant discussion was made very clear at the beginning of the project. The company's General Manager said more than once that he did not want the State to get involved in technical issues. When early planning of the Ok Menga Dam was started, Bechtel sent some of their technical experts to the site for visits and review of the data. This required that all visitors to the project pass through Port Moresby both coming to and leaving the project. These people were instructed by OTML Management not to visit or talk to the State's project management team (Memo dated August 7, 1981). This action effectively undermined the State's technical position by keeping information away from key staff. Unfortunately it also tended to undermine the whole project. It was agreed that the project would be built by the 'Fast Track' approach where the engineer and construction company are the same. This eliminated one technical review of the design which occurs in typical projects where the engineer and contractor are separate. When OTML successfully undermined the State's technical review of specific project designs, they effectively eliminated a second review which occurs in typical projects. If OTML had an adequate staff of technical personnel then these two short-circuits in the review process would not have seriously affected the project. OTML's technical limitations on the project and lack of commitment to technical rigour became painfully obvious through State I construction. The expenditure of over US$ 200 million on dams that are useless and/or abandoned was a very high price to pay on a project that is now considered marginal.

At the beginning of Stage I construction OTML expressed concern about the limitation of dumping only 60 million tonnes of incompetent waste in the Southern Dumps. When it became clear that the State intended to uphold the agreement, OTML Management looked for an alternate method of confining the waste. The plan that was actually pursued was to build the Ok Mani diversion weir to collect both the material from the Southern Dumps as well as the tailings that were proposed to be dumped into the Ok Mani watershed. The river plus all of these mine wastes were to be diverted through a 4 meter diameter tunnel into the Ok Ma reservoir. The State's technical staff immediately expressed concern about whether or not the scheme would work. The size and frequency of flood peaks on the Ok Mani was questioned and eventually OTML increased the design flood peaks on the Ok Mani which meant that a second tunnel would be required to handle the floods up to the annual peak flow. Of greater concern was the envisioned movement of the material down the Ok Mani valley. The State's technical staff as well as OTML's consultants who wrote the Environmental Impact Statement envisioned the incompetent waste moving down the valley in sudden uneven movement, which is how natural systems usually work. The concern by the State was that these surges could easily bury or clog up the tunnel, making the whole system inoperative. After commissioning a model study at Manly Vale in Australia and then later a separate technical review by Kloen Leonhoff late in 1984, OTML finally conceded that the system would not work. In the meantime US$ 20 million U.S. was spent on driving the tunnel from the Ok Mani basin through to the Ok Ma basin.

It became obvious that the tailings dam was far behind schedule in August 1983 and that it was unlikely that tailings impoundment would be possible when the process plant was ready for operation. At this time OTML made a lot of noise about protecting the environment, held special meetings at Tabubil, and sent a delegation to Malaysia to observed a tailings impoundment project that was being used at the Mamut mine. There were several important differences between the observed Mamut disposal system and the one which Ok Tedi was proposing. First of all, the rainfall at the Malaysian site was a fraction of the rainfall at the Ok Tedi site. More importantly the system at the Malaysian site was completely contained, with no significant waste entering the watershed. At Ok Tedi, the proposal was to discharge most of the wastes directly into the river with only superficial treatment. The State's technical staff recommended rejection of the interim tailings scheme for several reasons:

1. Construction was far behind schedule and the last thing the project needed was an additional demand on already overloaded construction staff.

2. The proposed scheme would do very little to protect the environment. It was felt that tailings with fine particles and a high concentration of heavy metals would cause substantial damage to the river system.

3. OTML, with its hit-and-miss construction record, was proposing to build a large pile of sands which could easily fail in a catastrophic manner.

It is enlightening to consider OTML's explanation of the Interim Tailings environmental impact. The argument for using cyclones to split off the course fraction of tailings for storage on the downstream face of the Ok Ningi Dam was that it is the coarse particles that damage fish gills. When the State expressed concern about the impact of cyanide and other chemicals on the marine life in the rivers the response was "fish exhibit avoidance behavior". That is, fish don't like to live in rivers that have high levels of particulate pollution so they migrate to the side streams. This means that since the chemicals are confined to the main stream they won't hurt the fish. The State responded with "If the fish are in the side streams to avoid the fines then why should the project spend money to remove the coarse particles from the tailings?" This argument was never answered by OTML.

## OTML'S COMMITMENT TO ENVIRONMENTAL PROTECTION

Three separate incidents are described briefly here to show the level of OTML's commitment to environmental protection. The first one has to do with the river monitoring which OTML is required to report to the State at six-month intervals. Water samples are collected at a number of stations from the mine down the Ok Tedi and Fly Rivers and analysed once a month for heavy metals and particulate pollution. The first report period, from July 1982 through December 1982, corresponded with a severe drought. This interval also corresponded with the major construction effort to build the access road to the mine and develop the site for the process plant construction. This construction location and effort put massive amounts of heavy metals into the river system. Unfortunately for the State the results of the river sampling were not reported until more than one year later so that all consideration of the Interim Tailings scheme and approval were completed before the results were reported. Also, because of the severe drought, water holes which are preferred for drinking water dried up and local people moved to the rivers for drinking water. In particular, the village of Bosset moved several miles to camp adjacent to the Fly River to get drinking water from the Fly River. This delayed environmental report was the State's first clear indication that heavy metal pollution would be a serious problem.

On June 14, 1984, a barge being towed across the Gulf of the Papua leaned far enough to one side that 15 containers of sodium cyanide and some stainless steel containers of hydrogen peroxide slid off the barge into the water. This accident caused one of the containers to burst open, setting free 180 60-liter drums which had a specific gravity of approximately one, depending on the amount of sodium cyanide in each of the drums. This meant that they would float near the surface where they were carried towards shore by the wind and current. There was considerable discussion about recovering the 14 intact containers as well as the 180 drums that were set free from the broken container. Most of the 180 drums were found but none of the 14 containers were found. It was speculated that the drums in these containers imploded as they sank, spilling the sodium cyanide. A barge was prepared with the cranes and hoists necessary to salvage any containers that were found. Meanwhile, it was discovered that the stainless steel hydrogen peroxide tanks lost in the same incident were not economically salvageable. Upon discovering this, OTML immediately dropped the salvage operation and dismantled the barge.

On June 19, 1984, approximately 1000 cubic meters of untreated tailings were dumped into the Ok Tedi River. These tailings contained free cyanide at a concentration of between 100 and 400 PPM which, when diluted, would produce concentrations of cyanide at Ningerum, 73 km downstream from the mine, of about 200 PPB. This concentration is considerably higher than the agreed criterion of 5 PPB and is considerably higher than levels which fish can tolerate. Hundreds of fish and prawns and several crocodiles were killed. It is reported that at least one villager collected and ate dead fish and one tortoise was eaten by villagers. Two days after the spill, on June 21, OTML environmental staff found ten dead fish and one crocodile at Ningerum. OTML said that their upper management because aware of the seriousness of the situation on June 27. The incident was not reported to the Department of Minerals and Energy until July 3, two weeks after it occurred.

From these critical incidents in which the mining company failed to release information or take action one can judge that environmental safety has been a very low priority in the project.

## ENVIRONMENTAL DAMAGE FROM INTERIM TAILINGS DISPOSAL

The original Ok Tedi agreement included a pipeline to transport tailings from the plant to the Ok Ma Reservoir. Capacity of the reservoir was calculated such that there would be adequate time for the fine tailings particles to settle out and the free cyanide, which is quite unstable, to decompose from exposure to natural sunlight and oxygen while in the reservoir. Even with such a large reservoir it was not certain that the effluent would be sufficiently clean. Therefore, a programme to monitor the levels of free cyanide, heavy metals and particulate concentrations was proposed. The clear intention of the agreement was that there would be no significant impact on the Ok Tedi River from operation of the mine. It was always understood that the Ok Ningi and Ok Mani tributaries would have significant impact from the mine and that during construction there would be an unavoidable impact. However, the agreement and the Environmental Impact Statement included levels of contamination that would assure the continuance of aquatic life in the Ok Tedi River itself. Certainly the Fly River, into which the Ok Tedi flows, would experience no serious impact from the mine operating as originally planned.

With the construction of the Interim Tailings Scheme it was obvious that the project could not stay within the agreed maximum levels of contamination. The State was faced with the problem of what criteria to adopt for heavy metal, particulate, and cyanide pollution. OTML insisted that with the cyanide detox system operating the cyanide was neutralized and the tailings rendered totally inert. That is, there would be no chemical impact because the tailings were supposedly non-toxic.

The government's project management team and Director of the Water Resources Bureau felt that professional advice should be sought and measurements of heavy metals in the river system determined independently from OTML. In order to do this water samples were taken from the Ok Mani, Ok Tedi, and Fly River for analysis. In addition tailings from the operating plant were collected and sent to the University of Papua New Guinea for toxicity testing. AMDEL, The Australian Mineral Development Laboratories, was employed under the direction of the Director of the Water Resources Bureau to review the reports prepared by OTML on the environmental impact of the interim tailings scheme and to advise the State on criteria for acceptable contamination of the river system. AMDEL was highly critical of the Interim Tailings scheme and OTML's presented information (or lack of it). AMDEL recommended levels of cyanide, heavy metal, and particulate pollution of the Ok Tedi River for adoption (Buckley, 1984). This recommendation formed the basis for criteria established for the project by the Bureau of Water Resources. It is clear that these criteria were exceeded several times by Stage I process rates. Obviously if the mining rates were increased even more to accommodate Stage II or Stage III then there would be more and larger breaches of the criteria (see Mowbray this volume).

Perhaps the best way to express the impact of tailings on the Ok Tedi and Fly Rivers is to project the impact expected on acquatic life (Mowbray, this volume). Mowbray conducted toxicity tests at UPNG on live mosquito fish and shrimps collected near the University. He used samples of tailings collected in June and November 1984 to determine the concentrations which would kill half of the animals in 9 days, a standard measure of toxicity. The result found was that tailings concentrations of .004 and .001 would kill half the mosquito fish and shrimps respectively. Using these results and calculating the concentration of tailings in the Ok Tedi and Fly Rivers it was determined how far down the river the tailings would be toxic enough to poison the animals tested. It was calculated that for high production levels and low river flow the shrimps would be affected for all of the Ok Tedi River and a major portion of the Fly River (Mowbray, 1986).

In order to consider the impact of mine wastes on the Ok Tedi River system several things must be considered. First of all particulate pollution and heavy metals are not introduced into the Ok Tedi by tailings alone. A substantial input will come from the stable Northern Dumps and the unstable Southern Dumps. Because of the pollution from the dumps as well as the residual tailings particles which have settled out to the river bed, impact from the mine will continue long after mining has stopped. This of course means that stress on biological systems is expected to continue after mining operations have ceased.

Another way to consider the impact of tailings on the river system is to use OTML's own assessment of the Interim Tailings Scheme (OTML, October, 1984, Addendum No.1). This document was prepared in October, 1984, five months after the ITS began operation. For 30,000 tonnes per day processing rate, from 1985-1990, OTML predicts that suspended sediment concentrations will reduce the fisheries status in the Lower Ok Tedi from good to one of between poor and extremely poor. That is, OTML project a 'moderate to severe biological impact on the Lower Ok Tedi and a minor impact on the Fly River'. For increased mine process rates scheduled for Stage III with no tailings dam OTML says that 'excessive concentrations of suspended solids will decimate the fish populations in the Lower OK Tedi'. The impact of this tailings disposal on the Fly River at Kuambit, the first large settlement on the Fly River below the mouth of the Ok Tedi River, would be to reduce it from a good fishery to between poor and extremely poor. OTML's projection of impact on the Middle Fly is that there would be reduced

**numbers of fish species and individuals. In both cases OTML says that local people should be compensated for expenses incurred by having to go by motor boat to swamps for subsistence fishing.**

THE STATE'S OPTIONS

During Stage I construction OTML successfully changed the level of environmental protection to its own benefit. In 1981, at the beginning of Stage I construction, the State's position, which OTML agreed to, was that there would be no significant pollution of the Ok Tedi river from operation of the process plant. By 1984, at the end of Stage I construction, the discussion was 'what is an acceptable level of pollution of the Ok Tedi and Fly Rivers?' Thus, the State had retreated from the position that there was to be no pollution of the river system to a position of uncertainty about exactly what level of pollution to accept.

In order to determine how much toxic waste can be discharged into the Ok Tedi and Fly Rivers an environmental study is being done. However, OTML is making the major expenditure on the study and directing the collection of data. The State has been unwilling to make major expenditures on environmental protection and is poorly staffed to direct such a study. One can be sure that staff wishing to stay employed by OTML will be looking for data to support OTML's position on the environmental impact of mining operations.

A careful and thorough study of the impact of the Ok Tedi mine on the environment should assess the bodies of water adjacent to the Fly River. These include Lakes Bosset and Murray which have some commercial fishing value as well as the swamps adjacent to the Fly River. Also, the Fly river delta area and Torres Strait should be considered for possible impact. A short-term load of tailings is not likely to produce a significant impact on these larger bodies of water, however, over the life of the mine the build-up of heavy metals could be enough to produce impacts on sensitive plants and animals. The approach to environmental monitoring and analysis used by OTML is not likely to be adequate to predict this impact reliably. They simply are not taking enough samples for analysis. If OTML is careful with their work and reporting then they should be able to assess the impact of mining and tailings disposal on the Fly River itself.

CONCLUSIONS

Everybody wants to protect the environment and have safe fishing industries and other by-products of a healthy river system. The crucial question is how much a company or country is willing to spend to attain a particular level of environmental quality or protection. For the mining company the answer is to do as little as possible because it reduces profits. A country, on the other hand, has responsibilities other than profit. Quality of life for its citizens becomes a factor as well as development of human resources so that the country is more able to control its future. In the case of the Ok Tedi project the State, under two successive governments, was not willing to spend the money necessary to set up the project management team. Further, the staff that were hired were not given adequate authority to represent the State. In the original agreement the State did not require an appropriate funding level to do an adequate environmental impact study. When the project deviated from the original agreement the State was not willing to fund environmental monitoring which its consultants recommended. In January 1984, after the Ok Ma landslide, when OTML petitioned the National Executive Council to drop the agreed environmental protection programme the State capitulated without even consulting its own technical advisors.

Finally the State agreed on March 18, 1986 to postpone construction of the tailings dam until January 1, 1990. This is essentially the end of Stage II, which means that most of the gold ore and high-grade copper ore will have already been mined. What the project was scheduled to face in 1990 was Stage III, mining of a large quantity of lower grade copper ore. The revenues from Stage III in today's metals market will not come even close to paying for the construction of the proposed tailings dam. Thus, by agreeing to postpone construction of the tailings dam until 1990, the State agreed to conditions under which the possibility of constructing the dam were nearly zero. One can conclude that in the case of the Ok Tedi project the Government of Papua New Guinea did not take the necessary steps to produce the environmental protection which it claimed as one of its initial goals.

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