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PNG NGO Environment Watch Group

Environment, Human Rights and Mining in Papua New Guinea

Our ref: 30/04
Your ref:

Date: 28/09/01

Catherine Coumans,
Mining Watch Canada,
City Centre,
508-880 Wellington Street,
Ottawa, Ontario K1R 6K7,
Canada.

Dear Catherine,

CSIRO REPORT –PORGERA ENVIRONMENTAL REVIEW

Enclosed please find the long talked-about CSIRO report on the review of Porgera Environmental Review.

I am sorry about the long delay and any inconvenience caused.

Ms. Matilda Koma
Mine campaign Coordinator

Contents

List of plates and maps

Glossary of terms, acronyms and abbreviations used in this review

ANOVA	analysis of variance (a statistical technique)
ANZECC	Australian and New Zealand Environment and Conservation Council
CN	cyanide
CPUE	catch per unit effort
CSIRO CAAC	CSIRO Centre for Advanced Analytical Chemistry
DEC	Dept of Environment and Conservation, PNG
DMP	Dept of Minerals and Petroleum, PNG
ECOWISE	ECOWISE Hydrology & Environmental Services, Canberra
EMMP	*Environmental Management and Monitoring Program.* PJV (1991)
EP	Environmental Plan. Specifically: *Porgera Gold Project Environmental Plan* (1988). NSR Consultants, Melbourne
EQWIN	environmental quality management software from Teck Corp., Canada.
GIS	geographic information system
GPS	global positioning system (use of satellite signals to locate a site accurately)
HYDSYS	a database developed by Hydsys Pty Ltd, Canberra
NAL	National Analytical Laboratory at University of Technology, Lae
NATA	National Association of Testing Authorities
NOEC	no observed effect concentration; during tests for a substance's effects, the highest concentration at which there is no effect on the test organism
NSR	NSR Environmental Consultants, Melbourne
OTML	Ok Tedi Mining Ltd.
pE	electropotential; negative log of the electron, e^-, activity
pH	negative log of the hydrogen ion activity
PJV	Porgera Joint Venture
QA/QC	quality assurance/quality control
SG	code used by the PJV to name streamgauging stations in the Strickland river system
SMEC	Snowy Mountains Engineering Corp.
SPC	statistical process control
TSS	total suspended solids
WAD-CN	weak acid-dissociable cyanide
benthic	relating to the lake or river bottom
bio-	prefix showing that the rest of the word involves living biota
bioassay	a test using living organisms
'control'	unaffected, e.g. a catchment not affected by industrial uses
diagenesis	process involving physical and chemical changes in sediment after deposition
littoral	relating to the lake shore
nano-	prefix representing 10^{-9}
pico-	prefix representing 10^{-12}
risk	the product of exposure and effect
tailings	chemically-altered waste left over after ore extraction

Executive Summary

The Porgera Joint Venture (PJV) contracted CSIRO to select and manage a team of specialists to review effects of the Porgera gold mine on the riverine environment downstream of Porgera, Papua New Guinea.

As five years had passed since operations commenced, the PJV felt it was appropriate to conduct an independent review in accord with its environmental policy. The policy requires an active program of environmental auditing and independent reviews to identify and evaluate potential risks and to ensure environmental performance meets company policies and regulatory requirements. During the past five years community awareness of environmental protection has also increased world-wide, and this was an added incentive for the review. In addition, the PJV sought specific recommendations on how it could improve environmental performance at Porgera.

The report presented here introduces the independent study team and describes the approach used during the study. The Porgera gold mining operations are outlined and aspects of the processing relevant to the mine's riverine impacts are reviewed. The team's assessment of the riverine environment, first in the upper river system and then in the flood plain and Lake Murray area, and the potential effects of mining operations on them, are integrated into two chapters (4 & 5) to give an overall perspective. Chapter 6 discusses the practical aspects of monitoring, including techniques for sampling, analysis, statistics and reporting, with particular reference to the PJV's Environmental Management and Monitoring Program (EMMP). An important component of the review was the health survey of villagers who live along the river system. The survey findings are reported in Chapter 3, together with a review of the potential for mine-derived riverine impacts on the human population of the regions.

The following terms of reference for the review were developed by the PJV and CSIRO:

- ▲ identify and review the riverine impacts associated with the operation of the Porgera mine;
- ▲ assess the accuracy of riverine impact predictions;
- ▲ assess the quality and scientific rigour of the data generated from the present monitoring and research programs;
- ▲ determine whether the monitoring and research programs are adequate for quantifying riverine effects and are able to withstand scientific scrutiny;
- ▲ identify any deficiencies in the present monitoring and research programs and recommend any changes necessary to improve the assessment of existing and future effects;
- ▲ review the operation's compliance with environmental regulations;
- ▲ provide an overview report integrating the findings of the independent review team.

In effect, the terms of reference were formulated to assist the PJV in determining whether:

- ▲ all the riverine effects from the mine had been identified;
- ▲ the Environmental Management and Monitoring Program (EMMP) was adequate to identify effects;

- the data quality (QA/QC) was sufficient and reliable;
- the Environmental Plan and subsequent predictions were accurate;
- the current EMMP needed any improvement to detect effects on the environment.

CSIRO assembled a high-quality team with appropriate expertise to conduct the review:

hydrology — Professor Tom McMahon (University of Melbourne)

sediment transport — Mr John Tilleard and Dr Andrew Markham (ID&A Pty Ltd)

water quality/aquatic biology — Professor Barry Hart (Monash University)

geochemistry/aquatic biology — Professor Peter Campbell (University of Quebec)

health and toxicology — Dr Rick Cardwell (Parametrix Inc., Washington DC)

medical health — Dr Tukutau Taufa (University of PNG);

statistics/sampling design — Dr David Fox (CSIRO, Perth).

The team was co-ordinated by Professor Graham Harris (*aquatic biology*), of CSIRO, Canberra.

None of these people had any direct connection with the Porgera Joint Venture (PJV), or any of its member companies, at the time of this review.

E.1 Review activities

Overall the team adopted a risk assessment methodology; that is, we attempted to assess the environmental risks arising from the transport of tailings and material from the erodible dumps, through the river system. The review also assessed possible effects on organisms exposed to mine-derived materials. Risk is the product of exposure and effect. The team reviewed the PJV's monitoring practices and assessed their capacity to measure these risks.

To do this effectively, the team needed to examine the overall performance of the PJV environmental laboratory and the reliability and historical extent of the data collected. We checked and sometimes re-analysed the chemical, physical and biological data. We looked at how the data were collected, processed and stored, and we considered alternative monitoring techniques.

In the main we relied on reports and data supplied by the PJV staff, and on reports by other independent groups such as NSR Environmental Consultants and CSIRO Centre for Advanced Analytical Chemistry. However, we also inspected the mine operations and the waste dumps, and, after a number of excursions up and down the Lagaip and Strickland rivers, familiarised ourselves with the ecology and measurement systems in the entire catchment down to the junction of the Strickland and Fly rivers.

Meanwhile, Dr Taufa and a team of assistants conducted a survey of the health of villagers living along the river system, from the minesite to the Lake Murray area.

The team had been asked, essentially, to provide a critical assessment of the present status of the PJV Environmental Management and Monitoring Program (EMMP), so we looked for more than just data — we looked also for interpretation and concise management information, for an understanding of the riverine system and of potential risks, and for possible strategies to reduce them.

As we show below, we found, in short, the need for broader monitoring and management focus, taking more account of existing and expected impacts from mine-derived materials, and less account of the need for compliance.

E.2 History

As at December 1996, the Porgera Joint Venture (PJV) consists of five member companies: Placer (PNG) Pty Ltd (25%) which manages the mine, Highlands Gold Properties Pty Ltd (25%), Goldfields Ltd (25%), Mineral Resources Porgera Pty Ltd (10%), and Orogen Minerals Ltd (15%), which is 51% owned by the PNG Government.

Gold was discovered at Porgera in about 1939, and small scale gold panning was carried out during the 1960s and 1970s, as well as some mapping, sampling and drilling by three mining companies. It was not until 1984 that high grade ore was discovered, improving the economics of mining. During the period 1984 to early 1989, exploration and feasibility studies continued, culminating in the granting in May 1989 of the PJV's application for a Special Mining Lease. Construction work started immediately, and the PNG Government took up its 10% entitlement. Gold production began in September 1990 initially from underground mining, and in 1992 from both underground and open pit mining.

Porgera gold mine is near Porgera in the highlands of Papua New Guinea (PNG), about 130 km WNW of Mt Hagen in Enga Province. The terrain is rugged, ranging from 2000–3000 m above sea level, with average annual rainfall of about 3600 mm at Porgera, distributed evenly throughout the year. The mine is in an otherwise sparsely populated region covered in rainforest, near the Porgera River which drains into the Lagaip River and then the Strickland River. The Strickland meets the Fly River downstream of Lake Murray, at Everill Junction.

Treated tailings may be discharged, up to a nominal rate of 17,700 tonnes per day (t/d), into a tributary of the Porgera River, although the mine has yet to reach that capacity. The PNG Government also permits the PJV to allow incompetent waste rock to wash into the river system from the erodible dumps.

The river naturally carries a large load of sediment derived from weathering and landslides of the marine sediments that dominate the regional geology, mostly in the upper catchment.

On the basis of earlier environmental studies, NSR Environmental Consultants (Melbourne) prepared an Environmental Plan for the PJV in 1988. A 'baseline' sampling program was carried out in May and June 1989. In 1991, the PJV finalised its Environmental Management

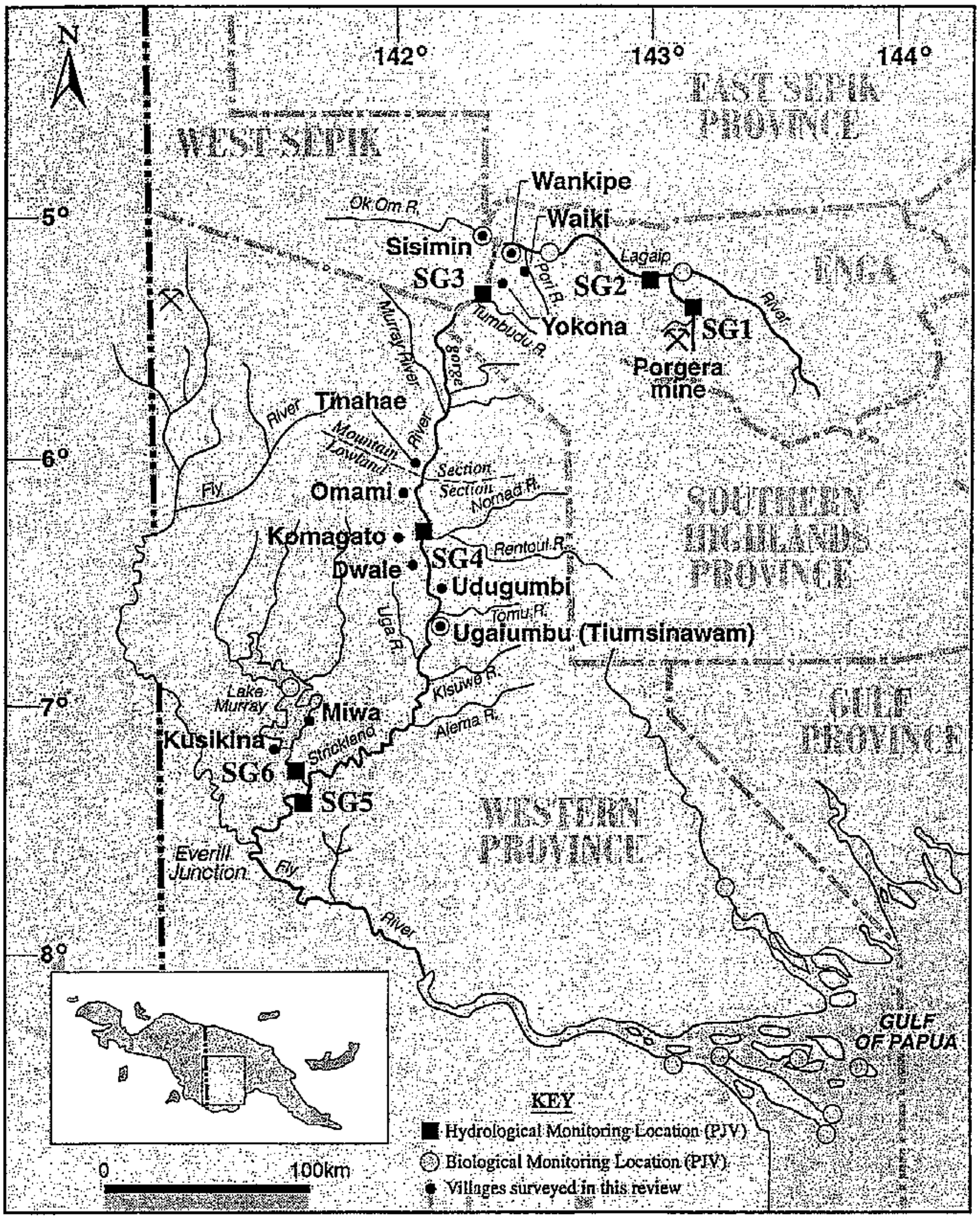
Plate 1. View across the mine site

and Monitoring Program (EMMP), which was approved, after independent review, by the PNG Dept of Environment and Conservation (DEC) as a condition of development approval.

Since operations commenced, the PJV's Environment Dept staff have monitored aspects of the management of process tailings, waste rock, hazardous chemicals, waste oil and garbage, sewage, spills, drinking water supplies, and the use and discharge of water. Rainfall and streamflow have been measured reasonably regularly at a number of sites along the river system, in some cases since 1983. The PNG Dept of Environment and Conservation requires that water quality, monitored at gauging station SG3, approximately 160 km downstream of the mine below the confluence of the Tumbudu and Strickland rivers, complies with defined limits. Criteria are set for riverine concentrations of cyanide, ammonia, dissolved metals, and for pH, while mercury and sulfide concentrations are also monitored.

As well, though not required by regulatory conditions, the PJV Environment Dept staff monitor total metal concentrations and suspended solids in the river system, in an effort to understand the rivers' water chemistry and the potential effects of mine-derived inputs.

To monitor factors of concern for human health, the PJV measures metal concentrations in fish caught along the river system, and compares the results with the maximum



Map 1. The location of the mine in the Strickland/Fly river system, and the gauging stations (SGs), and the villages surveyed

residue limits set by the Australian Health & Medical Research Council, though the standards are not entirely relevant as PNG villagers eat more parts of a fish than the Australian regulations take into account. Fish abundance and health are monitored. The PJV also undertakes periodic checks of mercury levels in villagers' scalp-hair, especially in the vicinity of Lake Murray.

Results of the monitoring are reported in the PJV's quarterly and annual Environmental Reports to the PNG National and Provincial Governments.

E.3 Review findings

The PJV has made considerable effort to collect and analyse data to assess the effect of the mine on the Strickland river system since the inception of the mine. No-one should underestimate the trials involved in maintaining equipment in, and collecting samples from, a large and remote river system, and in performing these complex and difficult analyses.

However, as outlined below, this review team finds that the EMMP could be enhanced through revision to focus on the potential environmental effects of the riverine disposal of tailings and incompetent rock. We assess the possibility of sedimentation problems in the Strickland river system as moderate to low, but the PJV needs more data to determine if there is potential for low-level, long-term riverine effects from the mine-derived metals. Monitoring should be adaptive in response to potential impacts, and comprise three components: (a) compliance monitoring; (b) broad scale monitoring for issue detection and for record; (c) campaign monitoring to gather intensive data to address a specific potential issue.

We find that the present EMMP is too narrowly focused on compliance monitoring and reporting. The data, in numerous annual and consultants' reports, appendices and tables, contain much good information, but overall there is too little interpretation and a general lack of concise management information. The review team considers the Environment Dept must develop its abilities at analysing and interpreting data, to assess existing impacts, detect potential impacts, adapt monitoring programs, and determine long-term prognoses.

We recommend the PJV aim for a more detailed understanding of the riverine system and how it functions, so it can better identify potential risks and strategies needed to reduce them. All aspects of the environmental monitoring effort must be integrated effectively in the decision making process: field work and sampling, logistics, chemical analysis, databases and management, statistical analysis, information generation and reporting. Overview reports, reviews and reports to management could be improved by incorporating simple graphs to ensure that trends over time are obvious to the casual reader. When outsiders examine the broader environmental effects they need to see management information (not data) and an assessment of risks.

The review team concludes the PJV should develop environmental overview and risk assessment methodologies, to reduce the possible false sense of security associated with environmental compliance. There should be a decided shift towards monitoring for impact.

We strongly recommend that the PJV Environment Dept be provided with additional staff to carry out the more rigorous and refocused EMMP we are advocating.

E.3.1 Statistical issues, data quality and management

The review team identified a number of statistical issues: for example the appropriateness of averages and the need to incorporate measures of variability. In a new EMMP*, there must be full agreement (between the PJV, DEC and appropriate consultants) on statistical approaches, and the compliance limits need to be defined accordingly. Staff need extra training in statistical methods.

* The review team understands the PJV is currently (December 1996) preparing a revised, updated EMMP.

We note and applaud the use of three databases, HYDSYS, EQWIN and ACCESS, which are improving the standards of data archiving and retrieval. Access to sophisticated software systems does not, of itself, ensure adequate information is generated. However, a secure and well managed database is essential for the delivery of useful management information which can enable the PJV to assess risks to the environment.

The review team suggests the PJV upgrade the security of its computer systems to ensure the integrity of the data. Data should be supported by full audit trails, an effective backup policy and suitable computer hardware.

The rainfall station network was adequate at the time of this review, and the recovery of hydrological data at the compliance point, SG3, was satisfactory. Overall the hydrological stations require upgrading, as already recognised by the PJV, and stream gauging should be carried out more frequently and regularly. We concur with the PJV's decision to retain ECOWISE hydrological consultants to oversee the upgrade and operation of the network. For data storage, the HYDSYS database is satisfactory for reviewing and archiving the data and is well understood by the PJV staff.

E.3.2 Baseline data

When assessing the mine's effects we found that the 'baseline' data for the Strickland river system, collected during the special sampling program in 1989, were incomplete and did not form a sound basis for comparison with data collected more recently. This was partly due to the short period of data collection (albeit under difficult conditions) in relation to known variability of sediment load and rainfall from place to place and from year to year in these mountain catchments.

Deficiencies in the baseline data complicate the detection of riverine changes and effects related to the mine's activities. *Therefore, we recommend the PJV employ a better-designed sampling program and select other 'control' catchments nearby, unaffected by upstream land uses, for comparison with the Strickland river system.* Detection of riverine effects in a spatially and temporally variable environment is difficult and requires a sophisticated approach. Much has been achieved to date, but more could be done.

Plate 2. Landslip on the Strickland River

E.3.3 Assessment of the mine's effects

Potential effects from mine-derived sediments are increasingly understood. As well as a strong effect of sediment load upstream and downstream of gauging station SG1 on the Porgera River, impacts are possible in the meander zone of the Strickland River, adjacent to Lake Murray, and in Lake Murray itself. Actual and potential riverine effects from mine-derived materials can be immediate or long term.

Upper river

In the upper-river environment, we judge there is little risk to humans of chemical effects from mine-derived materials, because villagers have limited exposure to them. The Environmental Plan predictions in this respect are reasonable, but should be confirmed by a formal risk analysis. Nevertheless it may be necessary to upgrade mine performance and to reassess the tailings disposal strategy to ensure ecosystem protection.

The Porgera and Lagaip rivers receive massive sediment inputs from the mine; however, there is little evidence of long term aggradation of the river bed. Sand and cobbles can build up temporarily, but the deposits are flushed through by subsequent high flows. Erosion of the valley walls can occur and total suspended solid (TSS) content is increased dramatically above natural levels.

Further downstream in the Lagaip River, input from tributaries progressively reduces the significance of the mine contribution. TSS content remains high and there is potential for deposit of sediment in the river channel.

Tailings

Treated tailings and incompetent waste rock are discharged from the mine predominantly as fines (more than 80% is <65 µm in diameter) and these fines are transported to the lower Strickland River, the Strickland/Fly flood plain and to the Fly River estuary. Tailings are the most metal-enriched fine fraction, so riverine transport of tailings is the major source of environmental risk.

With the increase in processing to an instantaneous maximum* of 17,700 t/d, the efficiency of treating tailings effluent may be reduced as a result of shorter residence time and increased flow rate in the final neutralisation treatment. *The review team recommends that the PJV carefully assess: (i) the effect of increased production on these residence times; (ii) the probability of accidental discharges of incompletely-treated materials; and (iii) the response mechanisms required to manage such eventualities.* The levels and role of residual process chemicals (e.g. xanthates) in the tailings effluent should also be examined because such compounds may increase the bioavailability of metals in the riverine environment.

Close to the mine there appears to be little opportunity for immediate human health impacts associated with discharge of tailings, because the local population does not currently use these rivers for food and water. People who pan for alluvial gold in the tailings stream and the discharges from the erodible dumps are exposed through activities such as wading.

It is possible to detect an effect of the mine in the enrichment of the TSS by metals measured at the compliance point, SG3. Particulate metals (As, Pb, Ag, Cd, Hg, Ni on a per gram TSS basis) are steadily increasing and may now exceed concentr-ations that have been shown elsewhere to have long-term ecosystem effects, particularly when the river is at low flow. There is some indication that dissolved metals are diluted as the volume of flow increases.

Nevertheless, concentrations of dissolved metals do not exceed the compliance criteria set by the PNG Government. Also, scalp-hair contains little mercury in the people of the upper river system.

Sediments

At SG3, the compliance point, data collected since the mine has been in operation show that the effects of mine-derived sediment are small. However, the various catchments above SG3 export quantities of sediment that differ markedly with time and location, so it is difficult to quantify how much of the TSS measured at SG3 relates to mine-derived sediment. Major sedimentation problems are not expected because the Strickland River carries much more naturally-derived sediment than the contribution expected from the mine (10–12 Mt/yr TSS from the mine at SG3 compared with 35–55 Mt/yr TSS from natural sources). A preliminary sediment budget has been prepared for the Strickland river system.

The review team recommends the PJV develop a comprehensive sediment budget for the river system, and initiate a dump monitoring program including the analysis of particle size distributions in the river bed, and more rigorous monitoring of suspended sediment. A sediment routing model is required to understand the behaviour of the whole river system.

We endorse the PJV's plan to reduce the amounts of material placed in the erodible dumps, and recommend the PJV Environment Dept review its predictions of downstream impacts based on these modified dumping programs.

* the instantaneous maximum rate (nominally 17,700 t/d) equates to an overall average of 16,500 t/d allowing for plant availability.

Aquatic life

Fish populations appear low in these high rivers, with fish rarely found above an altitude of 1800 m. A preliminary analysis of the PJV's data suggests that fish populations in the upland river system have been in decline simce 1993. Further investigations are suggested, to show if this observation represents a mine-derived impact or is an artefact of altered sampling practices.

No monitoring addresses the possible long-term effects on aquatic life in this part of the river associated with tailings discharge, and there is no ecosystem information to explain variation in fish numbers. *The review team recommends data be collected on benthic invertebrates, the composition of key aquatic-based food chains leading to humans, the importance of side channels, and locally-derived inputs.*

Data are needed from a clean 'control' river to compare with the Strickland river system. It would be prudent for the PJV to consider a broader monitoring effort (with statistical power, proper controls and consistent methods) in the Lagaip River to ensure that any long-term ecological effects can be detected and explained.

Compliance monitoring

At SG3, the compliance monitoring point, the PJV's data show the operation has been consistently in compliance with the DEC's required regulatory criteria. However, SG3 is approximately 160 km downstream of the mine. Therefore, the review team encourages the PJV as it deliberates over adopting SG2 as the compliance point, some 40 km downstream from the mine. The change would enable the PJV to minimise the environmental risk posed in that part of the river. *SG2 should also be given priority as a hydrology master station for compliance purposes.*

Strickland River from the gorge to SG4

The risk of exposure and of human health effects is judged to be low in the Strickland River between the gorge and SG4 on the lowlands. The river is rarely used for food and the people are essentially hunter-gatherers, relying mostly on crops (bananas and roots) and game from the forest.

There is little deposition of fines and the river bed is largely cobbles. The river is confined to its channel and there is little opportunity for overbank flow. The risks in this part of the river system are therefore similar to those in the region above the gorge.

Community health in this region is poor, but there are no apparent mine-derived effects. There are hyperendemic malaria, a high incidence of filariasis, lower dental caries than at Lake Murray and lower blood pressure. The people, like those of the upper river, tend to be shorter and lighter than those at Lake Murray. Skin infections and childhood malnutrition (<5 yrs) are rife. Family size is small and infant mortality appears to be high.

Lower river, Herbert River, Lake Murray

Much of the lower river is a depositional environment where exposure pathways potentially occur. The PJV has already identified the possibility of long-term low-level effects of metal uptake on the human population, and continues to monitor the situation.

It is the opinion of the review team that the present EMMP does not fully address a number of risk factors here. Data from the flood plain are inadequate to indicate whether the mine is having an effect; more field work and risk assessment are required to define the potential effects on the population and environment. *The review team recommends the PJV undertake a program of integrative investigations in this region, using a risk assessment approach.*

A hydrological budget has been largely determined for Lake Murray. However, the present hydrologic network does not provide the necessary information about inflows to the Lake because of the extensive connections between the river and the flood plain in this region. *The review team recommends the PJV review the location of its hydrological stations in the Strickland/*

Herbert River region, to improve its knowledge of inflows/outflows to the Lake.

Sediments will be deposited both in- and off-river in this environment. We calculate that 20% of the fines in the river are mine-derived. There is therefore an increasing risk of long-term low-level metal effects from mine-derived sediment in this region. If a tailings 'signature' (a unique geochemical characteristic associated with the tailings) could be identified, then it would be simpler to assess whether mine-derived sediment deposition occurs on the flood plain. *The review team recommends the PJV use a program of core-sampling to estimate such inputs to the lower Strickland flood plain and their fate in that region.*

Various estimates suggest that about 150 kt/yr of mine-derived sediments are transported to Lake Murray and that much of this material is retained there. This could represent as much as 20% of the total sediment transported to the Lake from the Strickland River. However, the existing sediment and mercury budget for Lake Murray reveals that the system is poorly understood.

The pathway of mercury from the environment to the people of the Lake Murray region needs further research, but clearly a natural pathway must exist. (Lake Murray villagers have had elevated scalp-hair mercury levels since long before the inception of the mine.) People of the flood plain make extensive use of aquatic food supplies, and also grow sago, both of which can be potentially affected by deposition of mine-derived materials. *The review team recommends the PJV reconsider the Environmental Plan's assumptions about the structure of the biological food chains leading to humans in this region.*

Nevertheless, this review's health survey finds that Lake Murray people show no sign of ill-effects from the mercury or other metals. The villagers here are better educated than people in the upper river. They have a high incidence of skin infections and high dental caries. Malaria is hypoendemic. These villagers have higher blood pressure than people up-river, and also tend to be taller and heavier.

E.4 Conclusions

The PJV has made a good start in developing a 'world best practice' environmental program, and has undertaken or organised extensive and generally high-quality scientific work in an effort to understand the environmental effects of the mining operation. As well, there has been a genuine attempt in recent years to better characterise changes, through the use of more sophisticated statistical analyses.

According to PJV reports and data, mine-derived impacts generally meet the PNG Government compliance requirements at gauging station SG3.

This review team's assessments suggest that aspects of the EMMP, monitoring, data quality and reporting would stand rigorous scientific scrutiny, while others fall short of reasonable scientific requirements. By 'reasonable' we mean the expectation that (i) significant processes linking the mine and the receiving ecosystem have been identified and monitored, (ii) all or a large proportion of the planned measurements have been made, (iii) statistical analyses are defensible, and (iv) any values that exceed compliance requirements are always reported and acted upon.

The original predictions that most fine material would be routed through the entire river system appear generally valid. On the other hand, the Environmental Plan gave insufficient consideration to overbank deposition and the fate and effect of mine-derived sediment on the Lower Strickland flood plain. The EMMP did not include monitoring of off-river sedimentation (over-bank deposition) downstream of SG4.

The data available from the present monitoring program appear to reveal no evidence of bioaccumulation of metals in the fauna or people of the Lake Murray area, although this region has most exposure to mine-derived sediment. On the other hand, the PJV does not yet have all the necessary data from which to predict the effects of an accumulation of sediment in this region. The PJV needs to study and understand the system to minimise the opportunity for significant risk to humans and the ecosystem of the lower Strickland/Herbert flood plain and Lake Murray.

Overall we conclude that the design of the original EMMP reflects practice prevailing at the time when the mine was established; the focus was on compliance with those limits that could be specified, and on responsible monitoring of other factors. There is now a need for a broader approach* to fully define the riverine impact of the mine's activities.

In addition to compliance, the new approach should involve risk assessment, information generation, decision support, policy adjustment and communication. Risk analyses for mine operations need to be coupled to the environmental risk assessment. Further resources are required to collect the necessary additional environmental effect information, but the review team considers that, in short, *the PJV should now monitor (and manage) for impacts.*

Restatement of Executive Summary recommendations

To reiterate the report's recommendations as gathered in this Executive Summary, the review team wants to see the PJV:

1. aim for a more detailed understanding of the riverine system and how it functions, so as to better identify potential risks and strategies needed to reduce them;
2. provide the PJV Environment Dept with additional staff to carry out the more rigorous and refocused EMMP we are advocating;
3. employ a better-designed sampling program and select other 'control' catchments nearby, unaffected by upstream land uses, for comparison with the Strickland river system;
4. carefully assess: (i) the effect of increased production on residence times in the neutralisation circuit; (ii) the probability of accidental discharges of incompletely-treated materials; and (iii) the response mechanisms required to manage such eventualities;
5. develop a comprehensive sediment budget for the river system, and initiate a dump monitoring program including the analysis of particle size distributions in the river bed, and more rigorous monitoring of suspended sediment;
6. collect data on benthic invertebrates, the composition of key aquatic-based food chains leading to humans, the importance of side channels, and locally-derived inputs;
7. give priority to SG2 as a hydrology master station for compliance purposes;
8. undertake a program of integrative investigations in the flood plain and Lake Murray region, using a risk assessment approach;
9. review the location of hydrological stations in the Strickland/Herbert River region, to improve knowledge of inflows and outflows to the Lake;
10. use a program of core-sampling to estimate inputs of mine-derived sediment to the lower Strickland flood plain and their fate in that region;
11. reconsider the assumptions in the Environmental Plan about the structure of the biological food chain in the Lake Murray region;
12. monitor (and manage) for impacts.

*The review team is pleased to note that, since the completion of this study, the PJV has demonstrated a willingness to implement our recommendations to improve its environmental performance and assessment of risks.

1

Introduction

The Porgera Joint Venture (PJV) commissioned CSIRO to manage an independent review of the Porgera gold mine at Porgera in the highlands of Papua New Guinea.

As five years had passed since operations commenced, the PJV felt it was appropriate to conduct an independent review in accord with its environmental policy. The policy requires an active program of environmental auditing and independent reviews to identify and evaluate potential risks and to ensure environmental performance meets company policies and regulatory requirements. During the past five years community awareness of environmental protection has also increased world-wide, and this was an added incentive for the review. In addition, the PJV sought specific recommendations on how it could improve environmental performance at Porgera.

The report presented here combines the considerations, suggestions and recommendations made by the eight members of the review team after their visit to the mine site and riverine environment in January 1996 and their review of relevant existing data and documentation.

The following terms of reference for the review were developed by the PJV and CSIRO:

- ▲ identify and review the riverine impacts associated with the operation of the Porgera mine;
- ▲ assess the accuracy of riverine impact predictions;
- ▲ assess the quality and scientific rigour of the data generated from the present monitoring and research programs;
- ▲ determine whether the monitoring and research programs are adequate for quantifying riverine impacts and are able to withstand scientific scrutiny;
- ▲ identify any deficiencies in the present monitoring and research program and recommend any changes necessary to improve the assessment of existing and future impacts;
- ▲ review the operation's compliance with environmental regulations;
- ▲ provide an overview report integrating the findings of the independent review team.

The PJV first contacted Professor Graham Harris, aquatic biologist/ecologist and Manager of the CSIRO Environmental Projects Office (then called INRE Project Office), in August 1995. Professor Harris selected seven other scientists appropriate to the terms of reference. No member of the resulting international team had any direct connection with the PJV or any of the partner companies at the time of this review.

The review team comprised the following members:

- ▲ Professor Tom McMahon, hydrologist, Dept of Civil & Environmental Engineering, University of Melbourne. Professor McMahon is a program leader in the Co-operative Research Centre for Catchment Hydrology. He is a very experienced hydrologist with an extensive international reputation in his field of expertise.
- ▲ Professor Barry Hart, environmental biogeochemist, Water Studies Centre, Monash University, Melbourne, Victoria. Professor Hart is a leading expert in water

quality criteria and has specialist expertise in trace metal biogeochemistry. As a subconsultant to NSR Environmental Consultants in the 1980s the Water Studies Centre undertook water quality and sediment analyses for the Porgera project before the mine commenced. However, Professor Hart has had no recent connections with PJV or any of its partner companies.

- Professor Peter Campbell, geochemist and toxicologist, INRS-EAU, Université du Québec, Canada. Professor Campbell is an internationally-known expert in the field of metal speciation and sediment metal cycling. He co-authored papers that pioneered research in geochemical processes at the sediment–water interface, and the use of 'peepers' to study pore-water geochemical processes.
- Dr Tukutau Taufa, senior lecturer in medicine, Dept of Community Medicine, University of Papua New Guinea, Boroko, PNG. Dr Taufa carried out the baseline health survey for Lihir Island, and has also been involved in long-term studies of health in the Ok Tedi and Mt Obree areas of PNG. Dr Taufa has 23 years of experience in PNG, NZ, USA (Harvard University) and Australia, in public health, obstetrics & gynaecology, and clinical epidemiology.
- Dr David Fox, statistician, CSIRO Biometrics Unit, Wembley, Western Australia. Dr Fox is one of CSIRO's foremost experts in the areas of biostatistics and environmental monitoring. He has extensive experience in the design of monitoring programs and in data interpretation for complex systems such as the riverine system downstream of Porgera.
- Dr Rick Cardwell, risk assessor, Parametrix Inc., Washington DC, USA. Dr Cardwell manages the Environmental Toxicology and Chemistry division of Parametrix Inc. His 25 years of experience includes a number of human health risk assessments; for example, he has assessed the risks to humans and aquatic life from metals, pesticides and microbes in primary-, secondary- or tertiary-treated sewage discharged at the coast of the Sydney metropolitan area, for Sydney Water.

Plate 3. Bed material at SG2 on the Lagaip R.

- Mr John Tilleard, river engineer, Ian Drummond & Associates Pty Ltd, River and Catchment Management Consultants, Sale, Victoria (now ID&A Pty Ltd). In addition to his extensive experience within Australia and other tropical environments, Mr Tilleard has undertaken numerous assignments in PNG, including sediment investigations for the Ok Tedi, Misima and Mt Victor mines.

  Mr Tilleard was assisted by his associate, Dr Andrew Markham, a fluvial geomorphologist. Dr Markham has specialised experience in sediment monitoring in tropical turbid rivers, and has worked in PNG as senior hydrologist at Ok Tedi Mining Ltd.
- Team co-ordinator, Professor Harris, is an aquatic biologist with a long-standing international reputation. He has a proven record of assembling, leading and managing multidisciplinary teams in projects such as the Port Phillip Bay Study, a similar exercise which investigated the environmental health of Melbourne's principal marine embayment.

In late 1995, members of the team were sent copies of all previous reports relevant to the project (see box). In mid-January 1996 the team assembled in Cairns and was flown to

Examples of the documents reviewed during this project

Porgera Gold Mine Environmental Investigations Report for 1981

Porgera Project EP: Aquatic Resource Use Investigation; Fieldwork Report and Preliminary Findings (1984)

Porgera Environmental Plan: 1984 Investigation. Report on Data Analysis Techniques, Porgera water quality data (1985)

Porgera Project EP: Settlement and Aquatic Resources Investigation: Porgera, Lagaip and Strickland Rivers (1985)

Porgera Project EP: Lake Murray Investigations Fieldwork and Installation Report (1986)

Draft Porgera EP: Environmental Management and Monitoring Program (1987)

Porgera Gold Project, Draft Environmental Plan Vol. A (1987)

Porgera Gold Project Volume B: Environmental Plan (1988)

Inter-laboratory Comparison of Hair and Urine Mercury Analysis (1988)

Baseline Monitoring Program: Field Trip Information and Procedures (1989)

Review of Compliance Monitoring Proposals, Porgera Gold Mine (1990)

Environmental Management and Monitoring Program, Porgera Gold Mine (quarterly reports: 1990; 1993)

Porgera Gold Project Addendum to Environmental Plan: Rescheduling of Ore Production and Processing (1990)

Environmental Baseline, Porgera Gold Mine, Vol.1 Main Report (1990)

Determination of the Hg and As Budget in the Herbert River and Lake Murray (1991)

Quality Control Procedures for Environmental Sampling and Analysis (1991)

Environmental Monitoring Porgera Gold Mine. Annual Report (1991; 1992)

Review of the PJV 1991 Biological Monitoring Report, Catch Data Analyses (1992)

Report on Anjolek Engineered Erodible Dump Approved 300,000 cubic metres Trial Period 3 Aug–24 Nov 1992 (1992)

PJV Environmental Report Jan–Dec 1993 (1994)

PJV Environmental Report 1994 (1995)

the mine. During a ten-day visit, the team members inspected the mine and its operations and waste disposal activities. They observed the river system from the air and on the ground, familiarising themselves with the ecology of the entire catchment down to the junction with the Fly River. They visited the streamflow gauging stations and made limited measurements of the rivers' sediment loads and water quality. The team assessed the measurement, sampling, analytical activities, data storage and reporting practices and procedures used by staff of the PJV Environment Dept and the Environmental Laboratory, and re-analysed some of the previously collected chemical and biological data.

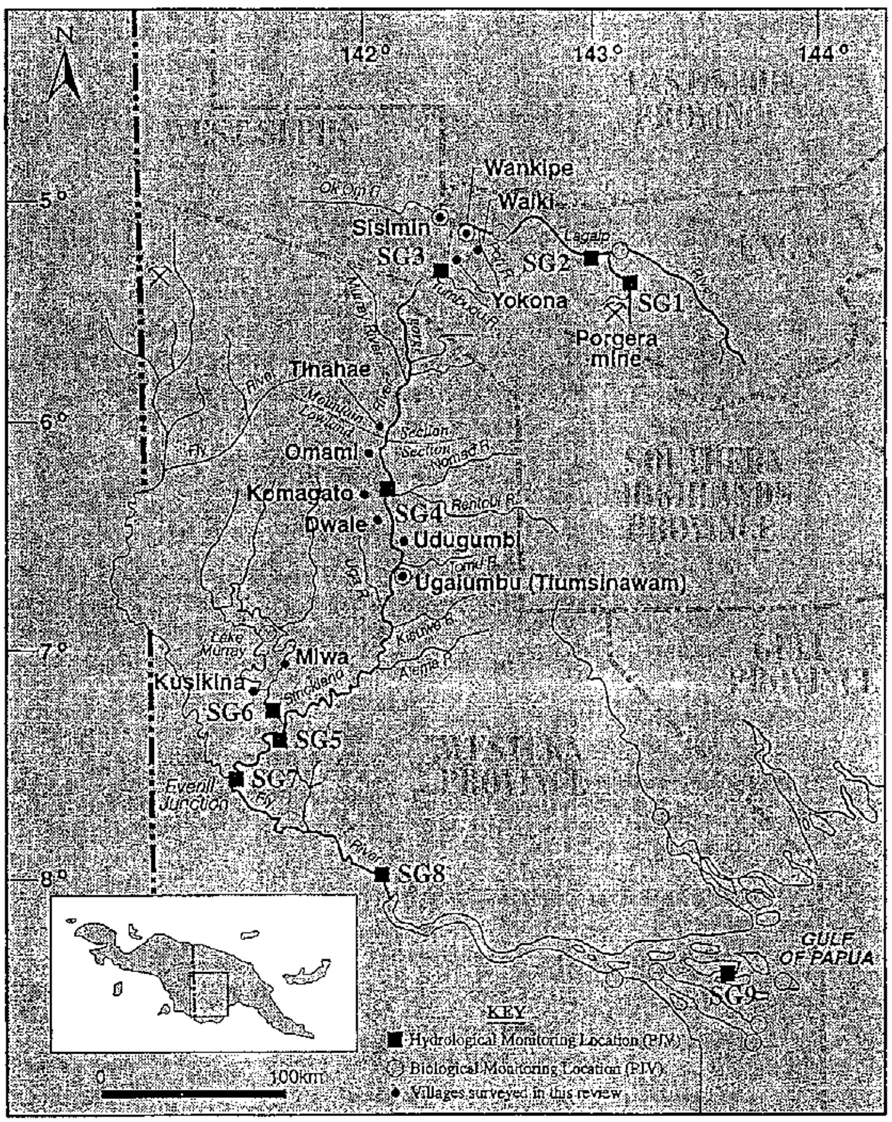
Concurrently, Dr Tukutau Taufa with nine assistants visited 12 villages along the river system and near Lake Murray (map 2) to conduct a survey of human health conditions.

Collating the results of their desk research, their own observations and sampling carried out during the visit, along with their discussions together, each team member drafted a report specific to his area of expertise. Professor Harris, assisted by Ann Milligan, then integrated their reports into this comprehensive overall review document.

The review report first describes the geographical context of the Porgera gold mine operations and reviews the aspects of processing which are relevant to the mine's riverine impacts (Chapter 2). Human health is discussed in Chapter 3 which comprises both the survey of existing health conditions and the potential risks to human health associated with the mine's riverine impact. The riverine environment in the upper catchment of the Strickland River, and effects of the mine on it, are reviewed in Chapter 4. In Chapter 5, effects of the mine on the riverine flood plain and Lake Murray environments are reviewed. Chapter 6 considers the Environmental Management and Monitoring Program (EMMP) in some detail. Chapter 7 summarises the team's overall recommendations (italicised within each chapter), and the essence of the whole is presented in the Executive Summary.

Acknowledgments

The team acknowledges with thanks the help of a number of people who made significant contributions to the progress of the review. Charlie Ross, previous employee and environmental consultant to the PJV, organised the PNG leg of the trip and the site visit with consummate skill, providing good humoured leadership, logistical talent and an essential source of local knowledge. The management of the Porgera mine (Peter Harris, Evert van den Brand, Dale Smith) co-operated with the team and ensured complete access to all requests. The staff of the Porgera Environmental Laboratory led by Jim McNamara were always enthusiastic, willing and helpful and the team's many discussions with them proved to be an invaluable source of information. The staff of the Porgera Community Services and Medical departments were also of great assistance both at the mine and in the field. Finally, Denise Peggs from Placer Pacific Limited showed great patience, and provided data and information (from the EQWIN database), usually at very short notice and late in the day. The team also thanks Jan Smith (CSIRO) for the review's overall logistics, and Ann Milligan for her work in taking a set of independent submissions and turning them into a co-ordinated document. They both provided immeasurable assistance.



Map 2. The Strickland/Fly river system, gauging stations (SGs) and surveyed villages

2

Mining and processing: discharges and monitoring

The Porgera Joint Venture (PJV) gold mine is owned by five companies: Placer (PNG) Pty Ltd (25%) which manages the mine, Highlands Gold Properties Pty Ltd (25%), Goldfields Ltd (25%), Mineral Resources Porgera Pty Ltd (10%), and Orogen Minerals Ltd (15%) which is 51% owned by the PNG Government. At December 1996 Mineral Resources Porgera Pty Ltd is wholly owned by the State of PNG; Highland Gold Properties Pty Ltd is a wholly owned subsidiary of Highlands Gold Ltd; and Goldfields Ltd is a wholly owned subsidiary of the Renison Goldfields Consolidated Ltd group of companies.

2.1 Physical geography

The Porgera valley is in the Enga Province of the Western Highlands of Papua New Guinea. Porgera gold mine itself is situated about 130 km WNW of Mount Hagen and about 600 km north west of Port Moresby. The terrain is rugged and mountainous (2000–3000 m above sea level) and covered in rain forest. Daily temperatures range from 10°C to 22°C.

The mine's runoff enters the Porgera River via several of its tributaries. The Porgera River is a tributary of the Lagaip River which then joins the Ok Om to become the Strickland River, the major tributary of the Fly River. South of Lake Murray in the lowlands, the Strickland River is joined by the Herbert River which drains Lake Murray. Therefore, downstream of the mine site, mine-derived materials may affect the Porgera, Lagaip, Strickland, Herbert and Fly rivers, and Lake Murray (see map opposite), generically referred to as the Strickland River system.

The regional geology is dominated by easily-weathered marine sediments including limestone, and metamorphic intrusions. Flow responds rapidly to rainfall events. This setting, combined with the high rainfall (3600 mm/yr at Porgera) distributed evenly throughout the year, and occasional seismic activity, causes large amounts of natural sediment, much derived from landslides, rock avalanches, slope failures and debris flows, to be delivered to the river system. Most natural sediment is generated in the steep upper catchment.

2.2 Development of the mine

Gold was discovered in Porgera by John Black in about 1939 (Macilwain 1947; Burton 1983). Jim Taylor and Mr J. Searson pegged claims in the area and small scale gold panning was carried out during the 1960s and 1970s.

In 1964, Bulolo Gold Dredging Ltd, which merged with Placer Development in 1966, carried out extensive trenching, mapping and channel sampling over two years. Later, Anaconda Australia Inc. and Mount Isa Mines Ltd did similar work, including some drilling. However, at the prevailing gold prices, the tonnage and grades were inadequate to support a mining operation.

The Porgera Joint Venture was formed in 1980 and acquired Searson's claim. In 1981 a preliminary technical and economic evaluation still showed the deposit to be uneconomic. It was not until 1984 that high grade ore was discovered, improving the project's feasibility. From 1984 to early 1989, exploration and feasibility studies continued, culminating in the granting in May 1989 of the PJV's Special Mining Lease. Construction work commenced immediately, and the PNG Government took

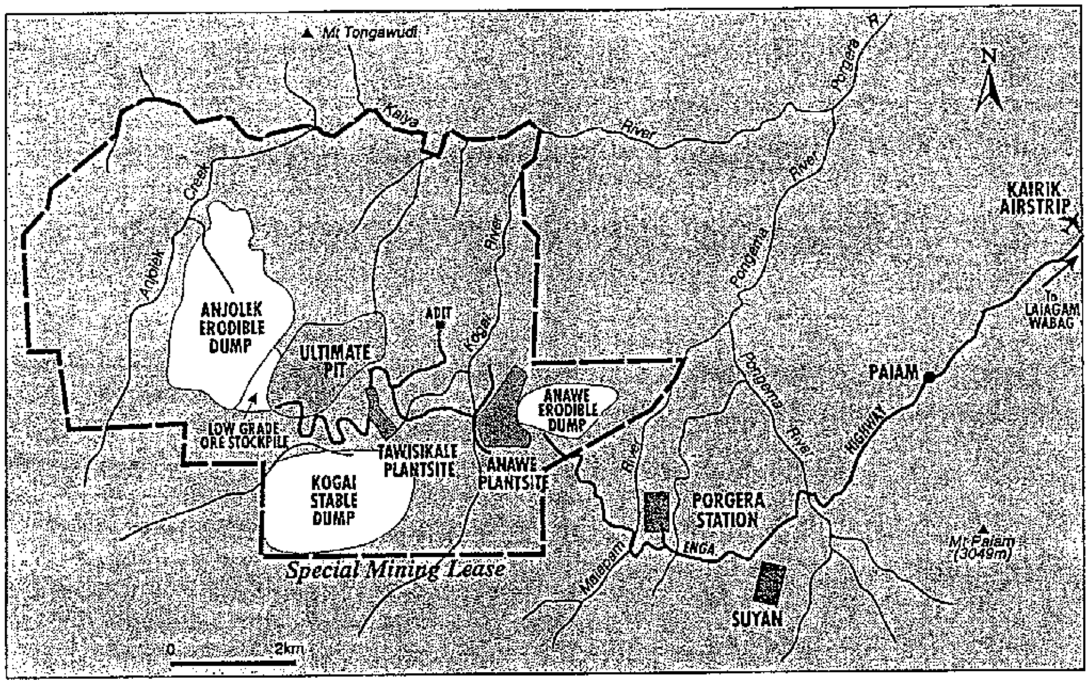


Figure 2.1 **General layout, Porgera Valley**

up its 10% entitlement. Gold production began in September 1990 from the underground operation, mining and processing 1500 tonnes per day (t/d), treating free and non-refractory gold only.

Stage 2 was completed a year later when the oxidation circuit was commissioned to extract refractory gold. Also in 1991, initial work began on the open pit. Stage 3, completed in September 1992, expanded production to 3500 t/d from underground and to 1000 t/d from the open pit .

Stage 4A was completed in October 1993 when, with additional oxidation circuit capacity, the plant was expanded to handle 8500 t/d, consisting of 4500 t/d from underground and 4000 t/d from the open pit.

Stage 4B was completed early in 1996. The plant was expanded to an instantaneous maximum* capacity of 17,700 t/d with additions to the mill and oxygen plant, increased flotation, leaching, lime production, power generation and water storage.

The proved and probable ore reserves at 30 June 1996 contained 11.5 million ounces of gold from 78.7 million tonnes (Mt) of ore, grading 4.5 g Au/t. These reserves are sufficient to support mining/processing activities until 2010. Underground mining is expected to cease in 1998 following exhaustion of the underground reserves.

For the open pit, which is being mined by conventional shovel and truck methods, a range of engineered waste dumps have been designed for storage of waste rock and ore stockpiles. An erodible dump is used for low strength (geotechnically incompetent) waste rock; stream action removes this material gradually. Stable engineered dumps are used for higher strength (geotechnically competent) waste materials and ore stockpiles (Figure 2.1).

Processing consists of crushing and grinding the ore, flotation of the gold-rich sulfide particles, pressure oxidation of the sulfides, complexation of the gold by cyanide, and recovery of the gold using the carbon-in-pulp

* the instantaneous maximum rate (nominally 17,700 t/d) equates to an overall average of 16,500 t/d allowing for plant availability.

(CIP) process. Overall gold recovery in the CIP circuit is approximately 80%.

More than 99% of the gold in solution is recovered in the CIP circuit. The carbon is then eluted to wash the metals into solution. The gold and silver metals are precipitated out onto steel wool electrodes, and later washed off, filtered out and treated to remove entrained mercury. The gold is smelted into 700 ounce bars of dore bullion which averages 88% gold.

The excess acidic thickener wash water and CIP tailings are combined to chemically neutralise the residual cyanide, and then combined with flotation tailings and treated to stabilise the residual dissolved metals and discharged to the Maiapam River, and ultimately the Porgera River and Strickland River system*.

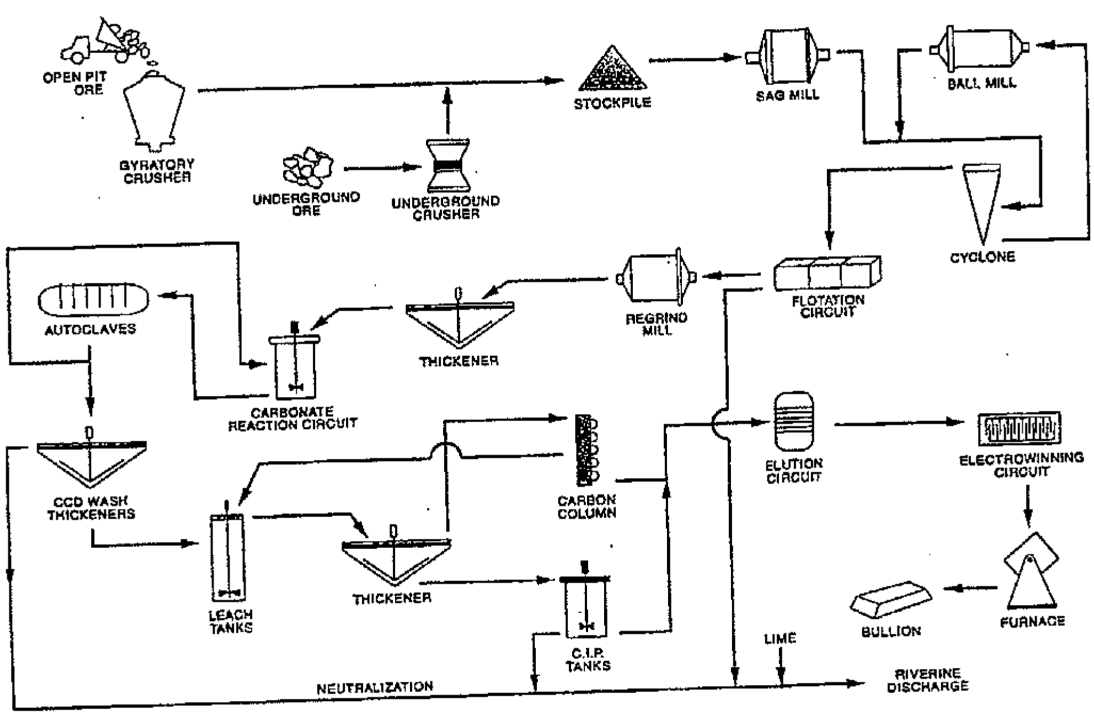
2.3 Riverine inputs from mining and processing: review

The mining process produces three streams of material: competent waste rock, incompetent waste rock, and ore which is processed to extract gold (and silver).

Competent waste rock, accounting for 70% of the total, is currently placed in the stable Kogai dump.

The incompetent waste rock (30% of total) is distributed between the Anawe and Anjolek erodible dumps. These dumps consist of about 50% black sediments and about 50% mudstone (M. Thompson, pers. comm.). The Anawe dump was commenced in July 1989, and is situated between the Anawe plant site and the Maiapam River, a distance of approximately 2.5 km. The mainly mudstone and colluvium material placed in this dump is eroded into the Pongema River and then into the Porgera River. The Anjolek dump is west of the open pit. Material from this dump enters the Kaiya River which subsequently becomes the Porgera River. Totals of 38 Mt and 26 Mt have been placed in Anjolek and Anawe respectively to the end of 1995. However, work is currently underway in an attempt to maximise the storage of waste rock within the engineered waste dumps, hence reducing the amount disposed of to the erodible dumps.

The gold extraction process itself produces



* Placer Pacific Ltd supplied most of the information above and in Section 2.4.

three waste streams:

- ▲ flotation tailings (pH 9.4; relatively innocuous but contain low levels of residual process chemicals) used to partially neutralise acidic streams;
- ▲ CIP tailings (pH 10.7; contains residual cyanide and some dissolved metals);
- ▲ acid wash effluent (pH 1.2; contains high concentrations of dissolved metals).

The waste streams are mixed (with Na_2S to assist in precipitating Hg) in the tailings neutralisation circuit. This effluent treatment circuit contains five tanks in series with an overall residence time of around 10 hours (NSR 1988). It seeks firstly to detoxify the residual free cyanide left in the CIP tails by precipitation as an iron complex, and secondly to neutralise the acid wash effluent and precipitate the high concentrations of metals liberated by the oxidation process, using both the neutralising capacity of the flotation tailings and added lime.

The tailings solids (approximately 15% by weight) and liquid effluents contain elevated concentrations of some metals — particularly As, Cd, Cu, Pb and Zn — and cyanide. In the tailings liquid the dissolved cyanides occur both in the free form and complexed with metals. The colour of the tailings can change from red to brown depending upon the extent of oxidation of iron in the autoclaves; red sediments result from compete oxidation of the iron sulfides to the iron oxide mineral haematite while the brown sediments result from the formation of goethite rather than haematite.

The concentrations of metals and cyanides in the tailings have changed over the life of the mine, due to changes in the ore grade being processed (underground versus open pit) and the use of higher cyanide concentrations to improve gold recovery (PJV 1995 Sect. 4.0). Initially, the tailings neutralisation circuit achieved a pH of 10.5 (NSR 1988 p.19). However, the target pH has been reduced over the life of the project, averaging 8.6 during Stage 2 (1991/92), and 7.7 during Stage 3 (1992/93) and the early part of Stage 4A (to March 1994). Tests conducted in early 1994 suggested that the pH could be lowered to 7.0 with little change in the efficiency of the treatment process, hence the target pH was lowered to an average of 7.2, but considerable variation occurs in the actual pH in the circuit (range 6.8 to 10.3).

It is unlikely that precipitation of metal hydroxides can explain the efficient metal removals observed in the treatment process. Given the high (oxidized) iron content of the tailings stream, it seems likely that most metals are removed not by precipitation *per se* but rather by association with iron oxyhydroxides (adsorption/co-precipitation). According to the PJV's internal documentation, the nominal decrease in pH from 7.8 to 7.0 in the final neutralisation tank, as carried out in April 1994, did not greatly affect the dissolved metal levels in the tailings effluent. This apparent insensitivity to H^+-ion activities in the pH range 7–8 is consistent with the strong adsorption behaviour exhibited by many metals in this pH range (Tessier 1992).

The average rate of discharge of tailings during 1995 was 10,500 t/d. However, with the full implementation of Stage 4B, the tailings discharge reaches a nominal rate of 17,700 t/d, though this is yet to be achieved.
A total of 10.6 Mt of tailings was discharged between 1990 and 1995 (C. Ross, pers. comm.). Projected discharge rates following the completion of the Stage 4B expansion are up to 6.5 Mt/yr (M. Thompson, pers. comm.).

The quality of the tailings effluent can vary quite markedly on a daily basis due to variations in the plant operation. Furthermore, the metal sorption in the neutralisation tanks, discussed above, is not an instantaneous process. This review assumes that with the progressive increase in mill production, residence times in the effluent treatment tanks have decreased.

Considerably fewer potential contaminants would be added to the river system if even part of the tailings solids could be safely stored on-site. The PJV's major geotechnical consultant (Klohn Krippen) has reported that it may be possible to safely dispose of the tailings by integrating tailings impoundment with the waste rock dump or co-disposal of wastes. The review team considers the PJV should continue to assess this option with some urgency.

This review recommends that the PJV vigorously pursue the possibility of containing all or part of the tailings solids on-site. A similar recommendation is appropriate for waste rock.

2.3.1 Monitoring: current and proposed

The operation of the tailings neutralisation circuit is monitored continuously by means of pH sensors located in each of the five tanks. Additionally, plant operators take grab samples, hourly for pH and free-CN, while environmental staff collect samples three times per day (bulked) for pH, TSS, total-CN, WAD-CN and free-CN, dissolved metals and total metals.

The review team recommends that the PJV carefully monitor the effects (trends) of the reduced neutralisation circuit residence time on the tailings effluent quality associated with increased mill throughput from an average of 10,500 to 16,500 t/d.

The review team also recommends that the program for monitoring treated tailings be:

- ▲ *continued for pH, TSS, cyanides and conductivity on a daily basis,*
- ▲ *modified to analyse the composite heavy metal samples weekly rather than at the present fortnightly frequency, and*
- ▲ *modified to monitor such ancillary parameters as Fe, Ca and SO_4, Cl, thiocyanate and process chemicals in the tailings, to improve understanding of the sorption/precipitation processes involved in metal removal, and to help refine the equilibrium speciation calculations performed on the effluent.*

2.4 Environmental monitoring

The Porgera gold mine was constructed following approval, by the PNG Government, of a Proposal for Development. The Proposal included an Environmental Plan (EP) for the project. The Proposal was approved in May 1989 on condition that an Environmental Management and Monitoring Program (EMMP) be prepared. An initial baseline sampling program was carried out in May and June 1989, and reported in *Environmental Baseline Porgera Gold Mine* (1990).

The PNG Dept of Conservation & Environment (DEC) proposed criteria against which the results of the PJV's environmental monitoring were to be compared. After analysis of the baseline data and some discussion with DEC, the EMMP was revised and expanded to cover the monitoring of all the impacts and issues agreed by all parties.

As the PJV states in the introduction to the EMMP (April 1990),

> A sound program of environmental management and monitoring will enable the Porgera Joint Venture (PJV) to minimise the impacts of the Porgera Gold Project on the environment, to continually assess the significance of impacts and take remedial action where unacceptable impacts are indicated. The program is designed to provide the PJV with pertinent information regarding the effects of its mining operations on the environment, as well as satisfying environmental quality objectives set by the PNG Government.

The EMMP discusses issues related to land and rivers:

- ▲ vegetation clearing, waste rock dumps, revegetation, industrial waste disposal, domestic refuse disposal, conservation of flora and fauna,
- ▲ sediment runoff, residual cyanides, trace metals, sewage, compensation for damage, as well as dust and noise and transport of hazardous substances. It outlines the PJV's validation and ambient monitoring, quality control and timing.

The following is summarised from the EMMP (April 1990).

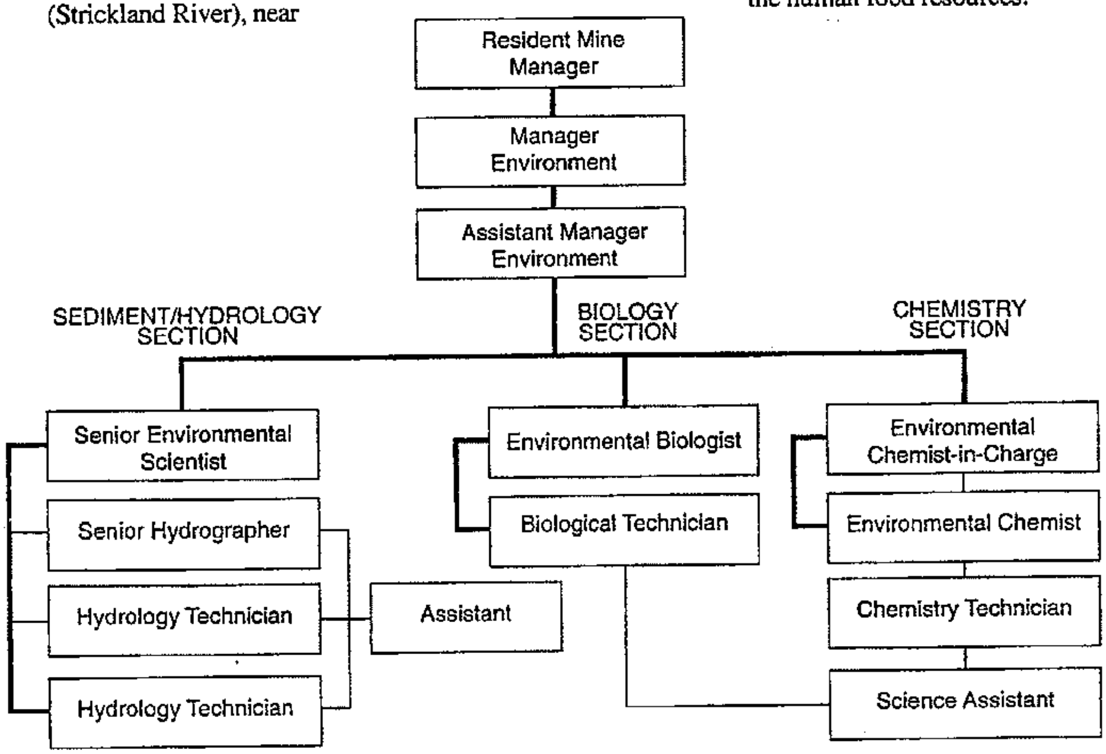
- ▲ Hydrological monitoring is carried out at gauging stations (SG) as follows: Porgera River at SG1; Lagaip River at SG2; Strickland River at SG3, and at SG5 in cooperation with Ok Tedi Mining Ltd (OTML); Herbert River–Lake Murray at SG6; June River at LM2; lower Fly River and delta at SG7, SG8 and SG9, with OTML. Knowledge of local meteorology and hydrological conditions in streams at the mine site, in the river system and at Lake Murray are used to define sediment transport capacity and to predict the fate of mine-derived sediments.

- ▲ Water quality at SG3, the end of the mixing zone for mine-derived materials, must comply with criteria set by DEC. For each variable, the monthly mean* of the monitoring results is compared with its DEC criterion. As well, physico-chemical sampling is carried out at SG5, SG6, SG7, SG8 and SG9 and in Lake Murray, for total suspended solids (TSS), pH, dissolved oxygen, conductivity, filterable trace metals and major cations and anions, and hardness. Bed sediments are analysed for trace metals and redox potential.
- ▲ Sediment build-up in the rivers is monitored at the gauging stations. Riverbed profiles are measured at SG1, SG2, SG3, SG5 and SG6, and sediment samples are collected for particle size analysis. TSS is measured in water samples.
- ▲ Biological parameters are monitored in aquatic reed (Lake Murray) and in key aquatic animal species appropriate to each sampling site: populations; size, weight and condition of animals; analysis of trace metal residues. Monitoring sites are at Wankipe village (Lagaip River), at Tiumsinawam (Ugaiumbu) village (Strickland River), near Miwa village (Lake Murray), and in Purutu Channel (Fly River delta).
- ▲ Villagers' use of aquatic resources is monitored at the same four sites used for biological monitoring. Dietary preferences are surveyed once every three years, and trace metals (Hg, As) are analysed in samples of human scalp-hair.

The work required by the EMMP is carried out by staff of the PJV Environment Dept (see diagram). Its key responsibilities are to assess the environmental effects of the mining operation; to provide advice to management on performance improvement; to monitor for environmental compliance; to report to the PNG Government and other stakeholders; to develop and co-ordinate environmental research and to obtain and maintain environmental licences and approvals.

This review notes that, in general, the monitoring program has been maintained, with some changes over the years. Chapter 6 reviews the EMMP in more detail. Chapters 3, 4 and 5 include comments on the variables being monitored in rivers, on the flood plain and in the human food resources.

Organisational Structure



* The review team notes that, in this remote location, these data are collected at regular intervals over three to four consecutive days.

3

Human health

This chapter discusses human health in the villages downstream of the Porgera operation and potentially affected by the riverine discharges. As described in Chapters 4 and 5, mine-derived materials are carried along the river system until they reach the flood plain. There they begin to settle out of the water column, particularly in the vicinity of Lake Murray, and, as always recognised by the PJV, have greater potential to affect humans in this region.

Section 3.1 reports the results of a health and socio-economic survey carried out, as part of this independent review, by Dr Tukutau Taufa and a team of nine assistants provided by the PJV. Previous studies commissioned by the PJV have investigated the villagers' dietary preferences and activities that would expose them to the waters of the Strickland River system (NSR Environmental Consultants 1985; Yok & Blomely 1989; Yok 1990a,b). Before mining operations started, the PJV Environmental Plan (NSR 1988 p.53) reported: 'High levels of mercury in fish of the Fly-Strickland Rivers generally, and in the villagers of Lake Murray particularly, have been known for some time. ... Mercury levels in Lake water and sediments are low.' Since mining began, the PJV's Environment Dept has monitored various environmental parameters, including scalp-hair mercury concentrations, to comply with the government's environmental requirements.

Section 3.2 discusses the pathways by which humans might be at risk from mine-derived sediments and the metals they contain, and highlights information required to fully to assess that risk. Risk assessments offer objective, scientific means for accurately defining the magnitudes of risks, if any, to human health (Finkel 1990).

3.1 Survey of human living conditions and health

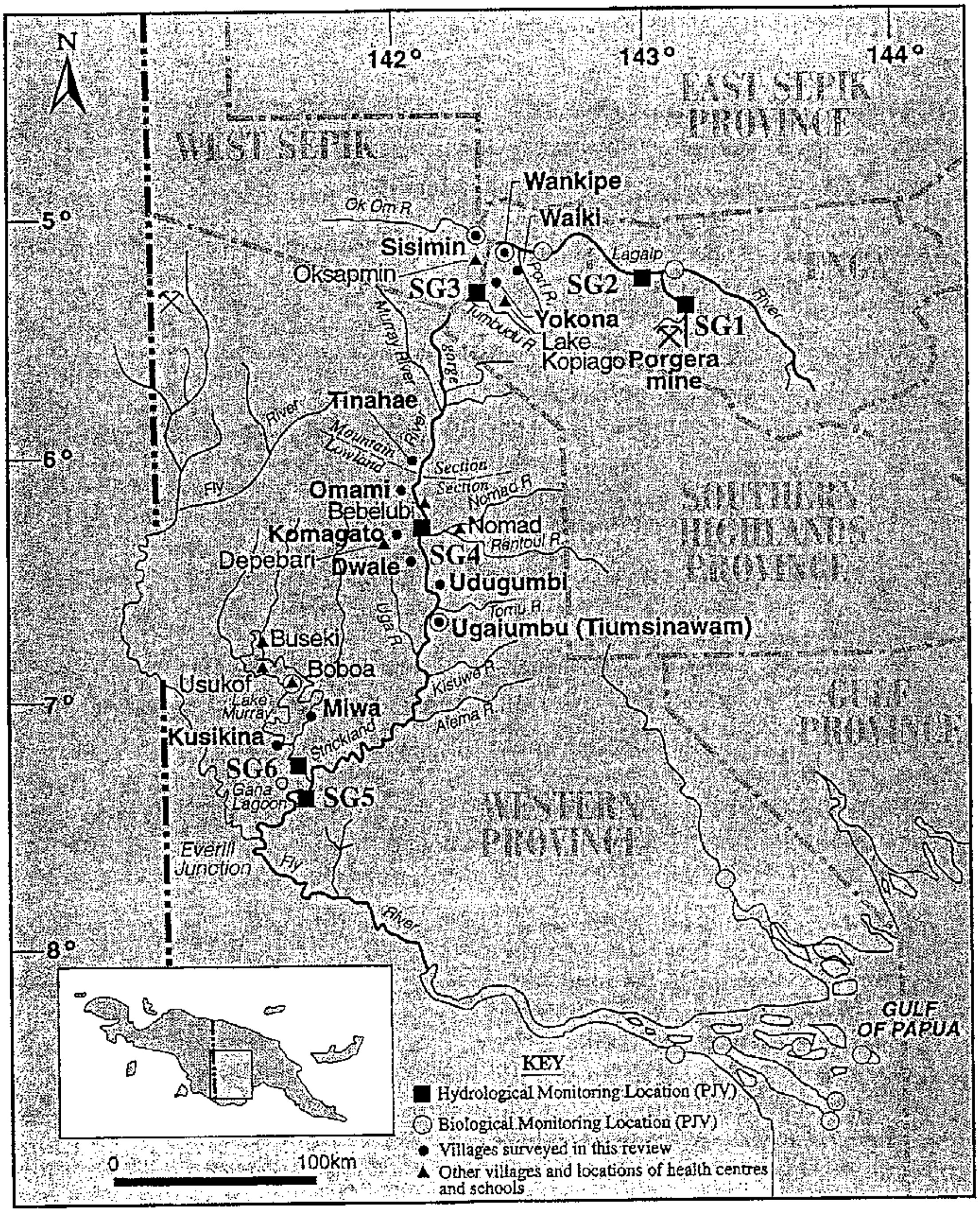
The area surveyed ranged from the villages of Southern Highlands Province and the open grassland areas of Upper Strickland and Lagaip which is part of the highlands-fringe, to the jungle-covered lowlands of the Lower and Middle Strickland, and finally to the lowland lakes of Lake Murray (see map 3). The contrasting geography and vast distances give rise to variations in people, languages, lifestyles and disease patterns, as described below.

3.1.1 Description of surveyed villages

Lagaip and Upper Strickland villages

Wankipe

Wankipe consists of multiple hamlets by the Lagaip River. The airstrip was built with the help of the Lutheran Church in 1989. There is a non-functioning Aid Post and a school that was closed due to lack of teachers. The nearest health centre and school are at Lake Kopiago Patrol Post about a day's walk away. The people's diet resembles that in Yokona (see p.3-3). The village has one water tank for drinking water plus numerous small creeks from the surrounding mountains. The Lutheran guest house has a solar battery-operated refrigerator for use by guests. Most adults speak Pidgin, but not Police Motu, and the few who have been to school understand English.



Map 3. Villages surveyed during this review, and locations of health centres and schools

Sisimin

Sisimin is located on level land on the west bank where the Lagaip joins the Ok Om to form the Strickland River. Sisimin is at the head of the Strickland gorge and was settled about 10–12 years ago judging by the height of the coconut trees. It is in West Sepik Province, one day's walk from Oksapmin Patrol Post where the health centre for the area is located. There is a functioning Aid Post in the village. The community school has been closed since 1993 due to lack of teachers, but it is hoped that it will re-open this year. The villagers' diet is similar to that in Tinahae (see p.3-3). Drinking water is obtained from a small stream, and the people occasionally wash in the Ok Om River which is sometimes, but not always, cleaner than the Lagaip and the Strickland rivers. The old airstrip further up the Lagaip River is rarely used and the people are planning to build another one nearer the village. There is a steel suspension bridge across the Ok Om River for walking to Oksapmin Patrol Post. Their language differs from those in Tinahae and Yokona. Most speak Pidgin, and children who have been to school understand English. No Police Motu is spoken in the area.

Waiki

Waiki is situated in the mountains above the Lagaip River. An Aid Post is under constr-uction and in the meantime the people go to the Lake Kopiago Health Centre for medical care, about one and a half day's walk away. The nearest community school is also at Lake Kopiago. The people's diet resembles that in Yokona. Water for drinking and washing comes from nearby streams. Most adults understand Pidgin, but not Police Motu, and the few who have been to school understand English.

Yokona

Yokona is a Southern Highland village located in the mountains above the Strickland gorge. The people go down to the lower grassland of the Strickland gorge to hunt for wild game; otherwise they live and garden in their jungle-covered mountainous area. They have a non-functioning Aid Post, and the health centre plus community school are at Lake Kopiago Patrol Post, about a day's walk away. Their staple diet consists of sweet potatoes supplemented by bananas and taro with no sago. Protein comes from occasional wild game or domestic pig and, rarely, fish. Drinking water is obtained from nearby streams, and now a new water tank has been installed with a few sheets of corrugated iron roofing for water collection. A new airstrip is slowly being built with picks and shovels. Most people speak Pidgin, few understand English and no Motu is spoken.

Middle Strickland villages

Tinahae

Tinahae is a new village, built in 1994, and is perched on a mountain slope above the west bank of the Strickland River. The village is below Devil's Rapid and the Strickland gorge. Administratively it seems to be in 'no-man's-land'. It had one visit from a govern-ment official from Olsobip Patrol Post, Western Province but it is closer to Oksapmin Patrol Post in the West Sepik Province. Instead of visiting either of those, the people walk for eight days to Koroba Patrol Post in the Southern Highlands Province. They have no Aid Post and for medical care they walk for three days to Dahamo ECP Mission station where the nearest school to their village is located. Their diet is similar to that of the villages above, but they consume the least amount of sago and river fish. Their drinking water is obtained from a local stream. They speak the same dialect as the Omami people and most adults speak Pidgin. No English or Motu are spoken in the village.

Omami

Omami is a new village built 2–3 years ago, on the west bank of the Strickland. The area is undulating, increasing to mountainous towards the Highlands. There are neither coconut trees nor Aid Post in the village. The villagers walk for two days to Dahamo ECP Mission Station for medical care and schooling. Administratively the people come under Nomad, but no one goes there because of the long distance; instead they walk for eight days to Koroba Government Station in the Southern Highlands Province. In their physical appearance and language the people are more like Southern Highlanders than the Western Province people of Lower Strickland. Their diet, though, is similar to that of Komagato villagers. They get their drinking water from a nearby stream, in which they also wash. The villagers are currently clearing an area for an airstrip; their helipad is spectacularly sited at the edge of the village just above the Strickland river. A few people speak Pidgin but no Motu or English are spoken.

Komagato

Komagato is on the western bank of the Strickland. They have no Aid Post in the village and it is one day's walk to Dahamo ECP Mission Station where the only health centre and school for the area are located. Administratively the people come under Nomad, but because of the long distance they do not go there and are not visited by Nomad Government Officials. The current village site is about 8–10 years old, based on heights of coconut trees. The people's diet is similar to those of the Lower Strickland villages. Their drinking water comes from a small stream by the village where they also wash. An Australian conducting research has a house in the village with solar-powered electric light and refrigerator — examples of the use of appropriate technology. The people have their own language, and two of the children who have been to school speak English. No Police Motu is spoken; however most adults can speak Pidgin.

Lower Strickland villages

Dwale (Igibera)

Dwale (Igibera) is located on the west bank of the Strickland River. It is one day's walk away from Depebari ECP Mission station where the people go for medical care and schooling, as Nomad Government Station is far away. Like the two previous villages, the people formerly lived in small hamlets inland and were urged by government officials to move to their current site. Going by the heights of the coconut trees the village must be 8–10 years old. There is no Aid Post in the village. The diet is similar to that of the two previous villages and drinking water is obtained from a nearby small stream where the people also wash. No English or Police Motu is spoken. Half the adults speak Pidgin apart from their own language which is different from that of the Udugumbi people.

Udugumbi

Udugumbi is located on the steep eastern bank of the Strickland River. Like the Ugaiumbu people, these villagers formerly lived in small hamlets inland and were urged by government officials to move to their current location near the river for ease of administration and communication. The village is about 8–10 years old judging by the height of coconut trees. There is no Aid Post in the village and it is one day's walk to Nomad where the only health centre and school are located. The villagers' diet is similar to that of the Ugaiumbu people. Drinking water is obtained from a small stream nearby, where they also wash. The language differs from that at Ugaiumbu and half the people also speak Pidgin. No Police Motu or English are spoken in the village.

Ugaiumbu (Tiumsinawam)

There is some confusion as to the name of this village. The PJV maps and reports refer to it as Tiumsinawam. The 1990 National Census report refers to two villages under Tomu river as Goiyobom and Asalabi. The villagers we saw insist that the village is called Ugaiumbu, and according to them they were in small hamlets inland and were urged by government officials to move to their current location near the river for communication and administrative convenience, thus the new village and name. The village is situated where the Tomu River joins the Strickland, on the east bank. The surrounding area is fairly flat. Judging by the heights of the coconut trees the village could be 5–8 years old. The people are currently building a new airstrip. It is two day's walk to Nomad Government Station where the only health centre and school are located. The village has a new Staffed Aid Post. The staple diet consists of bananas, taros and tapioka, supplemented with sago at times. Their main source of protein is wild game such as wild pigs, possum, tree kangaroo and python. This is occasionally supplemented by fish from the Tomu and the Strickland rivers. Drinking water is obtained from a small stream that flows to the Tomu River, and the people also wash there or in the Tomu River. Their language differs from that spoken in the Lake Murray area; a few people speak Police Motu, more speak Pidgin and only two people have some understanding of English.

Lake Murray villages

Kusikina

Kusikina is on an island near the mouth of the Herbert river, which joins Lake Murray to the Strickland River. The current village site was settled in the early 1950s according to the villagers and judging by the height of coconut trees. It is about one hour by outboard motor to Boboa Government Station where the health centre is situated. There is a non-functioning Aid Post in the village. The community school is at Miwa village on another island about 25 minutes away by outboard motor. The people's staple diet is sago supplemented by varieties of bananas, taro and sweet potoatoes and occasionally rice and flour. Barramundi and other varieties of fish from the Lake are their main sources of protein with occasional pork, both domestic and wild, chicken, wild duck and fowls, tinned fish and meat. Currently they get their drinking water from a large water tank installed by the PJV, and another village has a 200 litre tank. During the dry season, the drinking water comes from the Herbert River or Gana Lagoon. They wash in the Lake. Apart from their own language which is also spoken in Miwa, the people speak Police Motu, Pidgin and English.

Miwa

Miwa is on an island that was also settled in the early 1950s. Boboa Government Station is about 30 minutes away by outboard motor. The village Aid Post which was reported as having no medicine in 1994 (Purewa 1994) is unstaffed and closed. There is a community school in the village for the surrounding villages. Diet is similar to that of Kusikina village. Drinking water comes from three water tanks in the village and, during dry seasons, from Herbert River and village wells. The people wash in the Lake. They speak Police Motu, Pidgin and English apart from their own language.

3.1.2 Methods

At each village, the purpose of the field work was explained and questions were answered before each survey commenced. The field work was done in Aid Posts, village halls, houses or open shady areas, depending on the village. Villagers voluntarily came forward to be interviewed, examined and have specimens collected.

Heights were measured in millimetres with subjects standing against a vertical pole that had a pointer which rested on their scalps. Babies had their height taken lying flat on a calibrated board: crown to heel height was measured. Weight to the nearest kilogram was taken with subjects standing on a calibrated set of scales. Babies were weighed with an adult and their weight obtained by appropriate subtraction.

A malaria blood slide was taken from all subjects. The distal medial aspect of the left finger was swabbed, then pricked with a lancet. The first drop of blood was wiped off, then the second drop placed at the end of a labelled glass slide for a thick smear. Another blood drop was placed in the middle of the glass slide, then spread out thinly to the opposite end with a different glass slide for a thin smear. These were allowed to dry, then wrapped with soft tissue paper for transport to the laboratory for microscopic examination. Numbered plastic containers were given to all adults (≥15 yrs) for urine collection. They were collected at a designated spot outside the clinic area and were tested with impregnated multi-coloured litmus paper after the clinic or before departure. The subsequent colour change of the litmus strip was compared to a colour chart representing the different levels of glucose and protein; these were recorded.

No leading questions were asked and all medical complaints and conditions observed were recorded. During the medical examination, special attention was paid to the

Table 3.1 Number of people examined as a percentage of the total

Villages	Estimated 1996 Pop.	Pop. seen	Pop.seen as %	Areas	Area pop. seen as %
Kusikina	442	219	49.5		
Miwa	542	289	53.3	Lake Murray	51.6
Ugaiumbu*	135	78	57.8		
Udugumbi	64	43	67.2	Lower Strickland	63.8
Dwale	80	57	71.3		
Komagato*	33	31	94.0		
Omami *	30	26	86.7	Middle Strickland	78.6
Tinahae	79	9	11.4		
Sisimin *	190	142	74.7		
Yokona	159	52	32.7	Upper Strickland	47.2
Wankipe	137	118	86.1		
Waiki	169	35	20.7	Lagaip	50.0
Total	2060	1099	54.3		53.3

oral cavity, respiratory and cardiovascular systems, skin diseases, malaria, diarrhoea and any evidence of heavy metal poisoning. The spleen was palpated with the subject lying supine, and classified according to Hackett (WHO 1963). Lastly, blood pressure was measured in people 15 years and older, while they were still lying supine.

During the medical examinations, a team member inspected the village and counted the total number of: sleeping houses with traditional or with iron roofs; water tanks and other sources of village water supply; number of toilets; operating trade stores, fishing nets, outboard motors, large canoes, dinghies and any business activities. As well, the locations of the school, Aid Post and the nearest health centre and Government Patrol Post were recorded.

3.1.3 Results

Demography

On average, 53% of village residents were surveyed in 12 villages, during the period 17 to 23 January 1996. Village populations at that time ranged from 30 people in Omami in Middle Strickland, to 542 people in Miwa on Lake Murray. (Table 3.1).

The populations of villages marked with an asterisk in Table 3.1 are based on a family census taken during the survey. Populations of those villages without asterisks are based on 1990 census figures, extrapolated by their respective provincial annual growth rates (PNG National Census 1990). Dwale was listed under its old name of Igibera. Neither Tiumsinawam nor Ugaiumbu were listed in 1990; instead two villages of Asalabi and Goiyombu were listed under Tomu River and the two combined are listed under Ugaiumbu.

The crude birth rate ranges from 20.1/1000 in the Lagaip to 47.6/1000 in the Middle

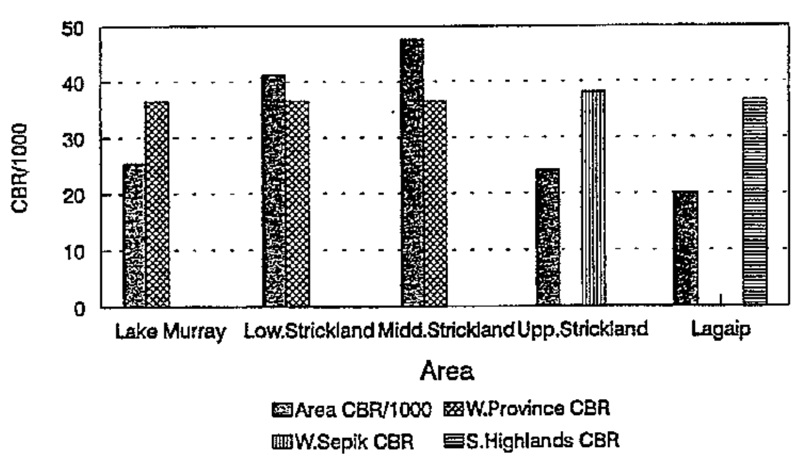


Figure 3.1 Crude birth rate/1000 by area visited

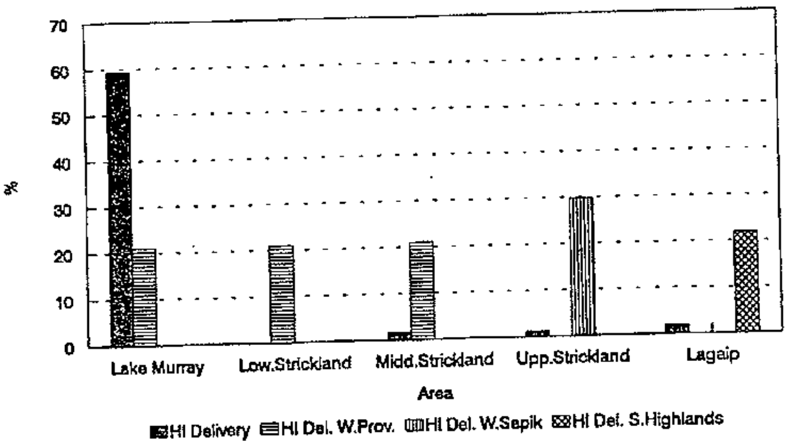


Figure 3.2 Health institution delivery rate and provincial figures

Strickland area (Fig. 3.1). Neither area uses family planning methods, basically because there are no health services available near the villages. The Middle Strickland figure is well above PNG's crude birth rate (34 per 1000).

Health institution delivery is taken as a rough indication of health services use by the villagers. The 59.3% health institution baby delivery among the Lake Murray villages exceeds both the provincial and national average of 39.1% (Fig. 3.2). The other areas hardly use any health institutions for childbirth as there are none nearby. At the time of this survey only one village, Ugaiumbu (Tiumsinawam), had an Aid Post, though one was being built at Waiki near the Lagaip River. The Lake Murray villagers surveyed can reach government medical services by a half- to one-hour boat trip (outboard motor). Other villagers have to walk for one to three days to reach mission stations or government stations which offer medical care.

Unfortunately, due to the unfamiliarity of the team members with the medical records form, mortality rates in the area, especially of infants, could not be reliably evaluated.

Socio-economic parameters

Water tanks supply drinking water to the villages of Kusikina and Miwa in the Lake Murray area, Yokona above the Strickland gorge, and Wankipe by the Lagaip River. All the other villages (plus Yokona and Wankipe) have access to clean nearby creeks or streams for drinking and washing, and Kusikina people also drink water from the Herbert River or Gana Lagoon in the dry season, and wash in Lake Murray. No village surveyed used the Lagaip–Strickland River for drinking or washing.

Only the Lake Murray villagers have some form of economic activity (Fig. 3.3). They sell Barramundi to the local Co-operative, crocodile skin to traders and own a few trade stores with out-board motors, fishing nets and iron roofed houses for collecting clean rain water. This in turn attracts some services to their area. The remaining areas up the Strickland and the Lagaip have no means of earning any income locally, and hence attract no services to their areas.

In the mountain villages of Wankipe, Waiki and Yokona, the houses are small, allowing about 5 m^3 per person, and have no windows. The Middle Strickland villages experience the least overcrowding, with about 32 m^3 per person. Their houses are about 180 m^3 in area, like those in the Lake Murray villages though the latter offer only about 24 m^3 per person. We assessed house occupancy and space, and toilet use on the basis of estimated population knowing that not everyone was seen during the survey. Toilet use is very poor; our survey

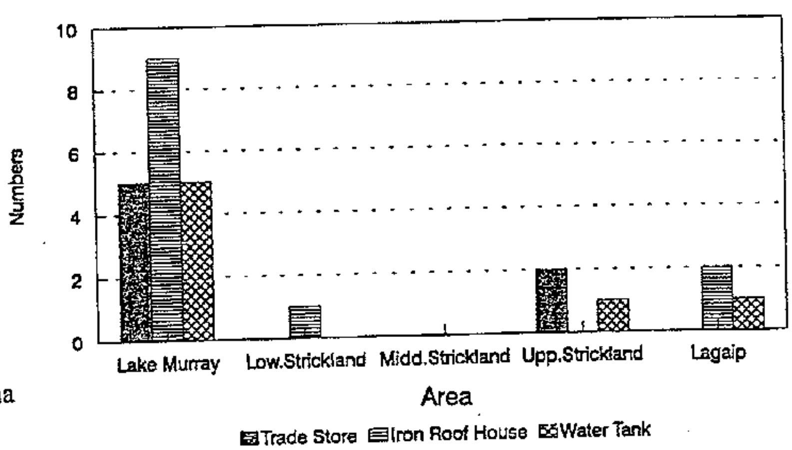


Figure 3.3 Some economic indicators and water tanks, Jan. 1996

suggests that each pit latrine serves between 10 people (Middle Strickland) and 22 people (Lower Strickland).

There is better primary school attendance (seven years or older) in the Lake Murray area — about 70.8% compared to the average national primary school attendance of 69.8% (PNG Commission for Higher Education 1994). From the other villages, between 1 and 13 children go to school; in the Upper Strickland and Lagaip areas this is 8% to 11% of children, compared to those provinces' average attendances of 20.2% and 15.8%. As with health services, schooling is offered by Mission or government stations. Schools are up to three days walk away for most villagers, except in the Lake Murray area where the school is at Miwa and accessible from other villages by outboard motor boat.

Some alcohol consumption was recorded in the Lake Murray area and none at all in the other areas. Smoking and betel nut chewing increase as one moves up the river. The various Churches operating in the area have some moderating effect on the people's drinking, smoking and betel nut chewing habits.

Maternal and child health

Malnutrition in the area, for children under five years old, is very high; it ranges from 39% and 44% in the Upper Strickland and Lake Murray areas to 74% and 75% in the Lagaip and Middle Strickland areas. The highest recorded previously in the country was 58% in Milne Bay Province in 1983 (National Nutrition Survey 1983). Children whose weight for age is less than 80% are regarded as malnourished. The Lake Murray and Upper Strickland villages have significantly less malnutrition than the remaining areas. The high malnutrition rate of the Lower Strickland area (67%) is reflected in the low adult weight and height. The malnutrition rate for the Lagaip villages is higher than the 40.5% reported by Kramer in 1992 but comparable to that of Upper Strickland villages (Kramer 1992). The provincial figures presented for comparison in Fig. 3.4 are taken from the 1986–90 National Health Plan (NHP).

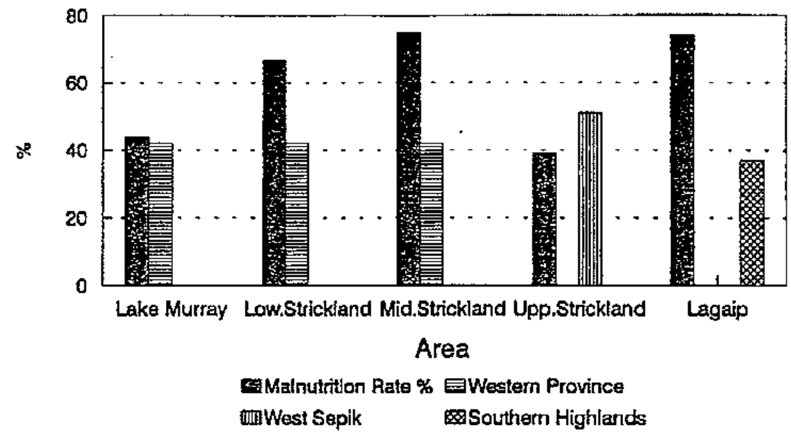


Figure 3.4 Under fives' malnutrition rate

The vaccination coverage rate is indeed very poor except for areas covered by the Church health services and Oksapmin Health Centre.

Family planning is used predominantly in the Lake Murray area because of accessibility. The polygamous marriage rate (20%) is significantly higher in the Lake Murray area than in the other areas (3.3% to 5.4%). Very

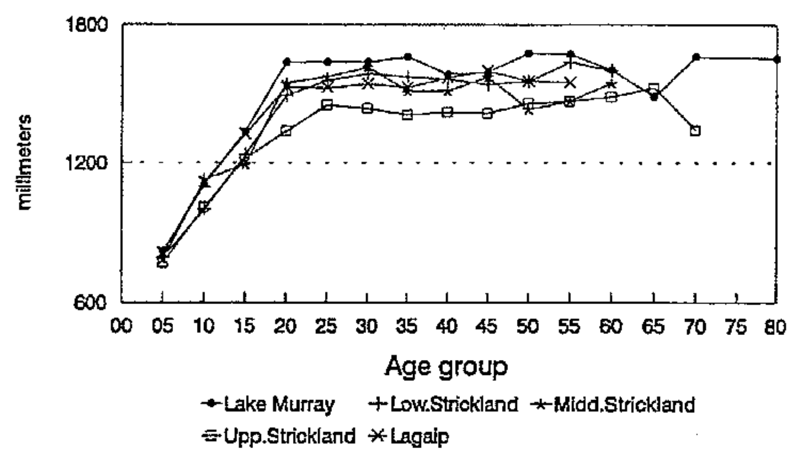


Figure 3.5 Mean height of males, Jan. 1996

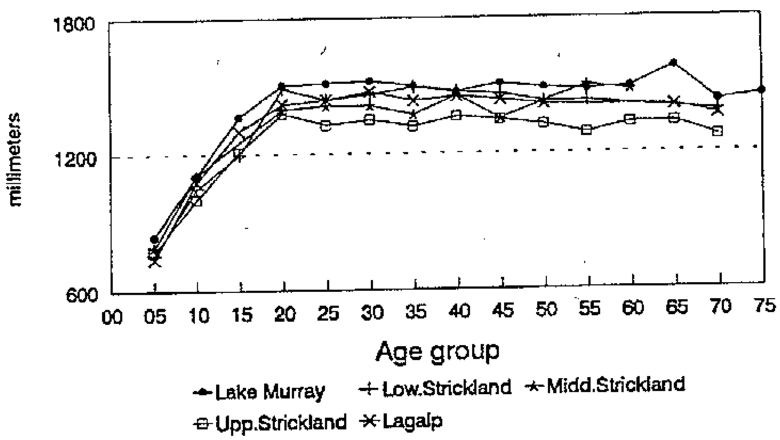


Figure 3.6 Mean female height (mm) Jan. 1996

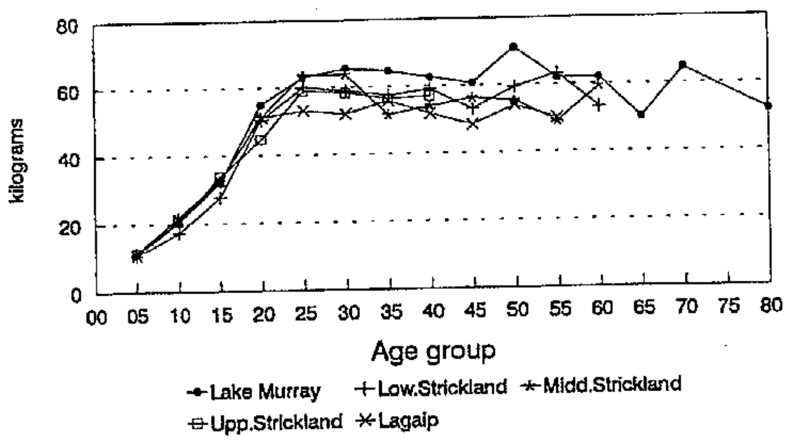


Figure 3.7 Mean male weight (kg), Jan. 1996

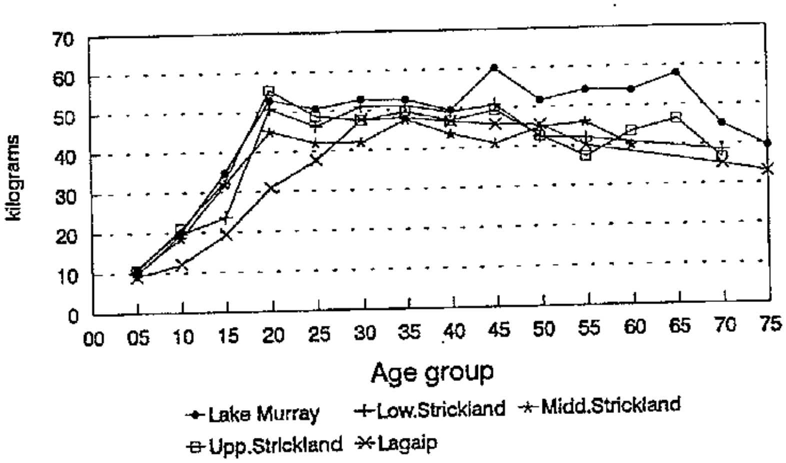


Figure 3.8 Mean female weight (kg), Jan. 1996

few single or divorced mothers were recorded as most would be absorbed into polygamous unions as a means of social security.

Physical measurements

The height and weight measurements clearly show that the people along the river system are not physically uniform. Their environment has considerable influence. The Lake Murray people with a high fish-protein diet are significantly taller and heavier than people from other areas, particularly the Upper Strickland or Lagaip villages (Figs 3.5, 3.6). Peak weight for people from the Lake Murray region occurs at 45–50 years of age, a trend found in urban dwellers. Males' and females' weights from the other areas peak at 20–35 years of age as is typical of people engaged in hunting and shifting cultivation practices (Figs 3.7, 3.8).

The significantly higher blood pressure of Lake Murray villagers compared to the others ($p < 0.0001$), could be due to their prolonged exposure to Western influence or to the cuff effect of the sphygmomanometer on different arm circumferences. The mean adult male and female systolic blood pressure decreases as one moves up the Strickland river from the Lake Murray area (Figs 3.9, 3.10). All the blood pressure readings decrease with age except in the Lake Murray villages where the readings are not only the highest but increase with age, which is very unusual for PNG blood pressure trends but similar to Western trends (Miall & Lovell 1967).

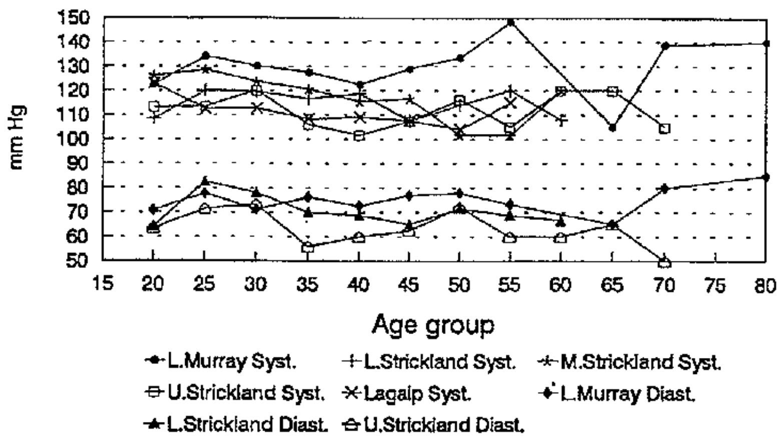


Figure 3.9 Mean male systolic and diastolic blood pressure

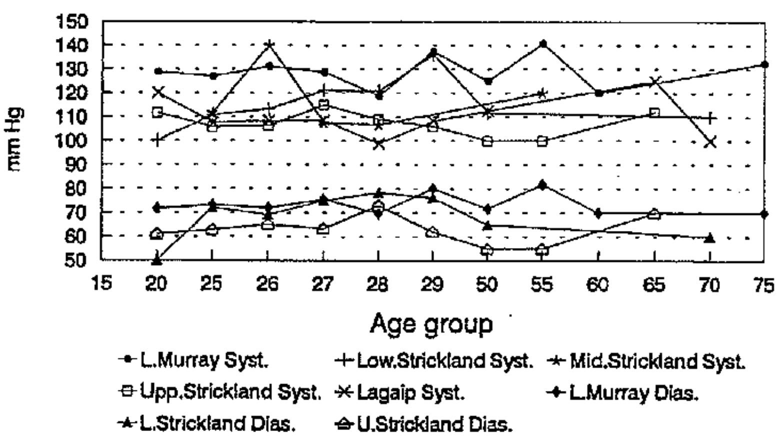


Figure 3.10 Mean female systolic and diastolic blood pressure

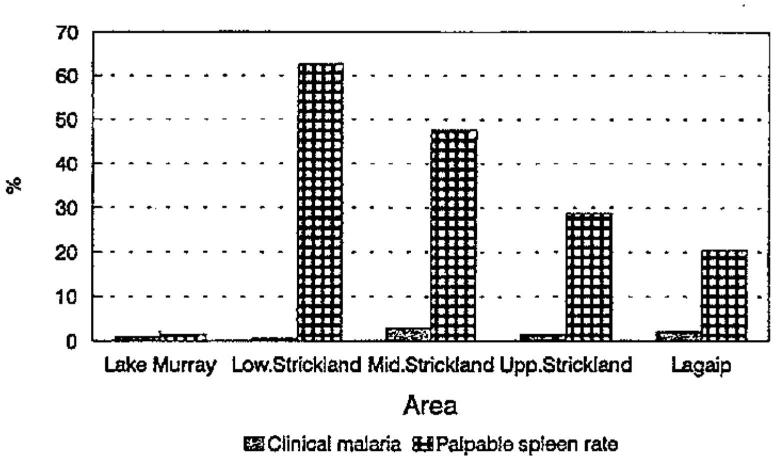


Figure 3.11 Clinical malaria and palpable spleen rate, Jan. 1996

Diseases

According to spleen measurement and clinical observation, malaria and filariasis are more endemic in the Lower and Middle Strickland areas and decrease as one moves up the Strickland and Lagaip rivers (Fig. 3.11). The blood malaria parasite results confirm the apparent low malaria infection levels in the Lake Murray area, which is possibly explained by the villagers' use of mosquito nets; they have been found to be an effective means of reducing mosquito-borne infections (Graves *et al.* 1987). The proteinuria results (protein in urine samples) also correlate with malaria and filariasis infections.

A person with clinical malaria is defined as someone with intermittent fever, generalised body aches and shivers, after clinically excluding other causes of fever. The clinical malaria rate is highest in the Middle Strickland area and this corresponds with their hyperendemicity of malaria, by spleen rate. The hypo-endemicity of malaria in Waiki is consistent with the endemicity of high altitude villages. The 57% palpable spleen reported by Bannick (Bannick 1995) at Ugaiumbu (Tiumsinawam) in December 1995 is consistent with our finding. The reported 70% to 79% palpable spleen in the Lagaip and Upper Strickland areas (Kramer 1992) is more than twice our findings. The palpable spleen rate is highest in the Lower Strickland area and decreases as one moves

Table 3.2 Malaria parasite blood results

Village	no. of slides	Total no. of parasites %	Total no. of P.f. %	Total no. of P.v. %	Total no. of P.m. %	Total no. of P.f.v. %	Total no. of P.f.m. %	Total no. of P.f.v.m.%
Miwa	280	8	52	38	5	5	0	0
Ugaiumbu	78	60	64	9	9	9	11	0
Udugumbi	42	52	64	32	0	5	0	0
Dwale	57	46	73	8	11	4	4	0
Komagato	30	67	50	20	10	20	0	0
Omami	25	64	75	19	6	0	0	0
Tinahae	8	25	100	0	0	0	0	0
Sisimin	142	74	75	9	1	6	7	2
Wankipe	114	74	73	6	6	8	7	0
Yokona	55	45	76	20	4	0	0	0
Waiki	35	51	66	10	6	6	6	6

P.f. = *Plasmodium falciparum*; P.v. = *P. vivax*; P.m. = *P. malariae*; P.f.v. = *P. falciparum vivax*; P.f.m. = *P. falciparum malariae*; P.f.v.m. = *P. falciparum vivax malariae*

up the Strickland River to the higher altitude area in Lagaip.

The results in Table 3.2 confirm the hypoendemic spleen rate found in the Lake Murray area. The predominant parasite is *Plasmodium falciparum*, which is characteristic of malarious areas in PNG (Parkinson 1973) and responsible for the higher spleen rates (Schuurkamp 1992). With a malaria control program, *P. falciparum* decreases more than *P. vivax* (Schuurkamp 1992). There is no difference in malaria parasite rate between the sexes, and the high infant parasite rate indicates active malaria transmission in all the villages except in the Lake Murray area. The highest parasite positive rates (74%) are from the Lagaip villages of Sisimin and Wankipe.

Two men, one from Sisimin and the other from Ugaiumbu, were negative for malaria parasite, but were found to have microfilariae, an indication of the high filarial infection in the area. The rate of filariasis (Fig. 3.12) is calculated for adults over 15 years old as no filariasis has been recorded for anyone below the age of 15. Clinical filariasis is significantly more prevalent ($\chi^2 = 12.9$; d.f. = 4, $p < 0.02$) in the Strickland villages and Lagaip compared to the Lake Murray villages.

Clinical filariasis in the Middle Strickland villages is also higher than the 5% incidence recorded in filariasis endemic areas in PNG (P. Sapak, pers. comm. 1996). The trend of clinical filariasis is similar to that of palpable spleen, being highest in the Lower Strickland area and decreasing as one moves upstream to the Lagaip area. This confirms the enlarged spleen as tropical splenomegaly syndrome, and any program that is going to reduce malaria is going to reduce filariasis and splenomegaly also. Anti-microfilarial treatment with diethylcarbamazine in the Ok Tedi area caused reductions not only in microfilaria but in malaria and splenomegaly as well (Schuurkamp 1992).

Very little in the way of respiratory tract infection and diarrhoea were seen, as cross-sectional surveys are not good ways to measure

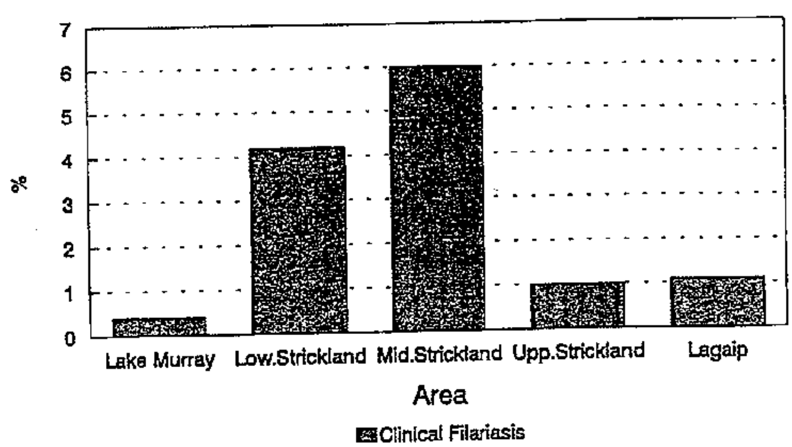


Figure 3.12 Clinical filariasis in >15 year olds

acute conditions. Dental caries is higher in the Lake Murray area as those people have more trade stores and chew very little betel nut (Fig. 3.13). Areas with higher betel nut prevalence have less dental caries, due to its cariostatic effects.

Skin infections and sores are predominant throughout. Fungal skin infection reflects personal hygiene, availability of adequate water for washing, and the humidity of the area. *Tinea vesicolor* and *Tinea circinata* are fairly common in the Lake Murray villages and decrease significantly ($\chi^2 = 132.6$; d.f. = 4, $p < 0.001$) as one moves up the Strickland River. *Tinea imbricata* on the other hand is low in the Lake Murray area and increases significantly ($\chi^2 = 89.1$; d.f. = 4, $p < 0.001$) up the Strickland River (Fig. 3.14), contrary to expectation (it should decrease as one moves up to the higher, less humid areas). Yokona, which is a high altitude village, reflects the effect of low humidity on fungal skin infections. Incidentally, *T. vesicolor* is so common that it is often regarded as normal skin and no treatment sought. In the past, *T. imbricata* was associated with poorer prospects of education, employment and marriage (Schofield *et al.* 1963).

Sores (not boils or tropical ulcers) and scabies were monitored as an indicator of personal cleanliness, hygiene and adequate water supply (Fig. 3.15). As expected, incidence of sores and scabies is lowest in the Lake Murray villages, where water is

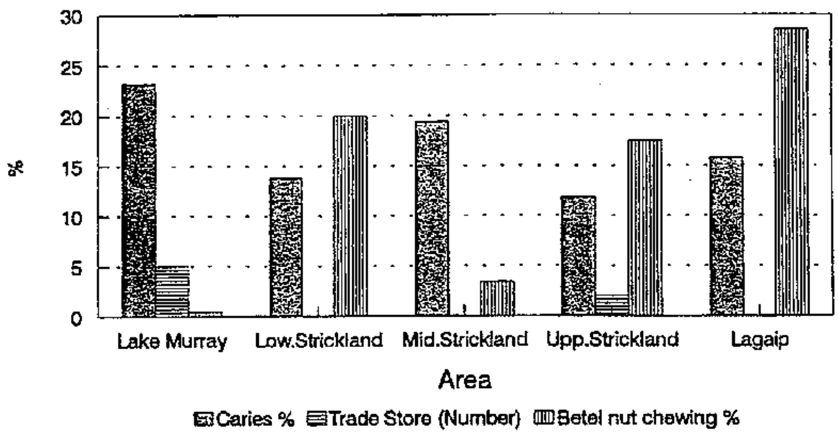


Figure 3.13 Dental caries, trade stores and betel chewing

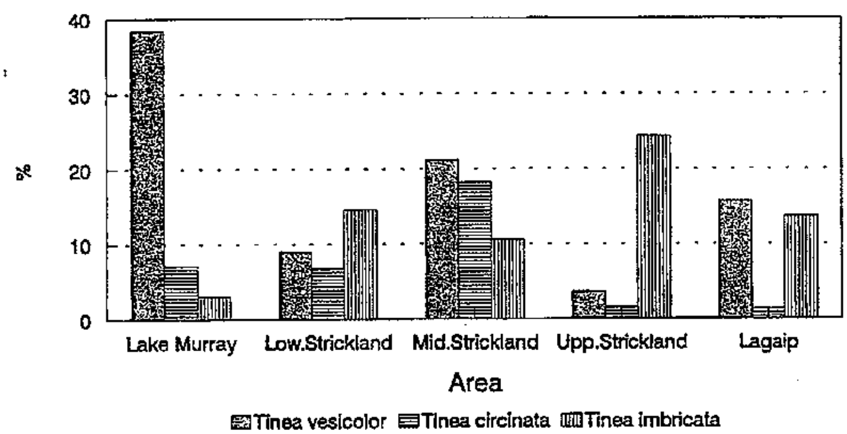


Figure 3.14 Fungal skin infections, Jan .1996

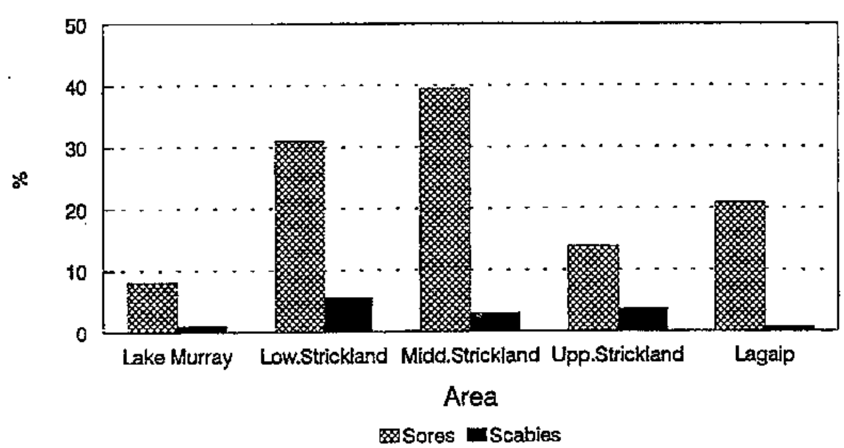


Figure 3.15 Sores and scabies, Jan. 1996

available in abundance, and increases as one moves up the Strickland River. However, it is difficult to explain the lower incidence of scabies in the Lagaip area, as Vines reported higher prevalence of scabies in the Highlands in his epidemiological survey (Vines 1970).

No cardiovascular disease or sexually transmitted diseases were seen.

Heavy metals

Infants and foetuses are more sensitive to heavy metal poisoning than adults, and the organ most affected is the nervous system (Clarkson *et al.* 1988). Therefore, this survey recorded motor nerve development of children below 24 months old.

For each surveyed village, Table 3.3 shows the number of months taken by the child who took longest to attain each stage of physical development. They are all within the normal range and are comparable to 13 years of physical development results from the Mt. Obree area of the Central Province, PNG, where there is no mining or any economic activity at all (Taufa, unpublished data). However, as there has been no previous assessment within these villages, one cannot be absolutely certain of their actual normal range of physical development.

No clinical or epidemiological evidence of heavy metal poisoning was observed. People were simply asked if they had any medical complaints (Table 3.4), and no signs or symptoms of heavy metal poisoning as described by GESAMP (1986) were presented. In fact, three previous medical visits to the area by three different medical people (Kramer in the Lagaip and Upper Strickland areas, November 1992; Purewa, Lake Murray, August 1994; Bannick, Lower Strickland, December 1995) all failed to find any clinical or epidemiological evidence of heavy metal poisoning.

3.1.4 Recommendations

As a result of this health and socio-economic survey, the review team recommends the following, not all of which relate directly to our terms of reference.

The PJV should supply basic drugs and equipment such as chloroquine, antibiotics, dressings material and aspirins to people living along the Strickland and Lagaip rivers. It is most unlikely that the National or Provincial Governments will provide health services to these people. Malaria, skin infections and sores, and respiratory infections can be effectively and cheaply treated at their villages with basic drugs administered by a person from each village who has been trained for some weeks as a Village Aid worker. The subsequent

Table 3.3 Physical development (motor nerve development) in months in children less than 2 years old

Village	No.	Hold head *(2–6 mths)	Sit (5–12 mths)	Crawl (9–15 mths)	Stand (8–24 mths)	Walk (8–48 mths)
Kusikina	24	2	4	10	13	13
Miwa	21	4	6	13	13	20
Ugaiumbu	7		6			
Udugumbi	5	4	5			
Dwale	8	4	8			19
Komagato	2			10	10	
Omami	3					
Tinahae	0					
Sisimin	16	3		8	15	18
Yokona	2		5			
Wankipe	9				9	13
Waiki	1		9	10		0

*The normal ranges of physical development (motor nerve) are from Illingworth (1986)

Table 3.4 Medical conditions seen in the field, in their order of frequency

Condition	Frequency	Condition	Frequency
Arthritis, upper and lower limbs	19	Sago caused eye injury	2
Backache	19	Pig bite	1
Malaria	18	Burn wrist	1
Asthma	17	Cellulitis of foot	1
Headache	16	Post meningeal spasiticity (TB)	1
Toothache	14	Shoulder pain	1
Fever or PUO	9	Chronic obstructive airway disease	1
Upper respiratory infections	8	Dysentery	1
Filariasis of limbs	7	Pyomyocitis of left thigh	1
Cataract	6	Gingivitis	1
Pneumonia	5	Anaemia	1
Tropical ulcer	5	Knife wound by husband	1
Cough	5	Snake bite	1
Stomach ache	5	Strabismus	1
Menorrhagia	4	Albino	1
Molluscum contageosum	4	Carbuncle	1
Lepromatous leprosy	3	Right knee arthrodesis	1
Epilepsy	3	Perforated ear drum	1
Abdominal lipoma	3	Lipoma of left arm	1
Filariasis of scrotum	3	Facial injury caused by husband	1
Otitis media	2	Deaf and dumb	1
Dog bite	2	Uterine fibroid	1
Facial burn	2	Generalised body ache	1
Burn to the chest	2	Peri-menopausal night sweats	1
Conjunctivitis	2	Schizophrenia	1
Urinary tract infection	2	Scratches to limbs — fell from tree	1

reduction of morbidity and mortality, plus the lives saved and improved relations established with the PJV would far outweigh the cost of those basic drugs.

Through these Village Aids, the PJV could obtain vital information on births and deaths in the villages, and monitor the causes of deaths, etc. At present there is a complete lack of information. An epidemiological monitoring or surveillance system could be established which would detect any abnormal human events along the river system. Full epidemiological and laboratory investigations could then be mounted if required.

The PJV should combine clinical examination with human hair or blood collection for heavy metal analyses. It is more meaningful to correlate and interpret hair results with clinical findings. Some villagers, especially in the Lake Murray area, complain that their hair has been collected over the years but they have had no information about the results; therefore *the PJV should include 'feedback' as part of its monitoring program.* Surveys which also provide treatment to the sick generally improve relations with a community more than those surveys which only collect samples.

The PJV should consider giving some economic projects to areas other than Lake Murray. Currently the PJV buys Barramundi from the Lake Murray people and this helps them economically while the other areas miss out completely. The villagers are good at growing taro, pineapples, pawpaws and peanuts and the PJV could consider buying them in bulk from Ugaiumbu (Tiumsinawam), Omami, Sisimin and Wankipe air strips for consumption at the PJV site. This would help keep the villagers in their area instead of moving to mines or urban centres. The money would go straight to the villagers and not just to the young men who work in the mine. *The PJV should also consider selling them treated mosquito nets at a subsidised price.* Experience has shown that free things are not appreciated as much as bought things. The use of mosquito nets would be very effective in the prevention of malaria and filariasis.

The PJV should consider providing solar-operated refrigerators for medical purposes. The reason given at Lake Murray for the poor vaccination coverage is that there is no continuous electricity power to the refrigerator for vaccine storage. At the same time there is a 24 hour power supply to the refrigerator for Barramundi storage 200 metres from the health centre. A bit of common sense, dedication and goodwill can overcome this obstacle. If the Lutheran Church can maintain a good solar-operated refrigerator for their vaccines at Wankipe then the other villages could also use this sort of facility.

The PJV should introduce communication campaigns on maintaining drinking water quality. Some villages have been given water tanks for clean drinking water. It should be appreciated that most villagers are away during the daytime — gardening, fishing, hunting — or even away for months collecting sago, and they therefore do not always drink from the water tank. They should be encouraged to boil their outside water before drinking. Traditionally, people drink from small streams that flow to the larger rivers.

The PJV should advise local villagers about proper housing and ventilation to reduce respiratory infections, and about the building and proper use of pit toilets.

The PJV should investigate the heavy metal level of sago that grows in the swamps along the Strickland and the Lagaip rivers, and compare the results with 'control' measurements from another river system that is not affected by upstream land uses.

3.2 Assessment of risks to human health

On the basis of this review's activities (see Chapters 4 and 5), we conclude that potential risks to human health from the PJV mine wastes and wastewaters discharged to headwaters of the Strickland River catchment appear largely restricted to certain villages located in (i) the Lower Strickland River region below approximately Bebelubi–Ugaiumbu (Tiumsinawam) (SG 4) and (ii) the lower middle half of the Lake Murray region. Of particular concern are villagers who frequently eat aquatic organisms*, although other pathways of exposure exist as well.

The above conclusion, which agrees with the evaluation made by NSR Environmental Consultants in 1985, requires further data collection and use of formal risk assessment procedures. Upstream of Lake Murray, it is necessary to find out whether the lack of human exploitation of the aquatic food resources reflects a limited potential for aquatic food production in various reaches of the Lagaip–Strickland rivers, or whether there are cultural or other barriers. The question is based on dietary studies of village inhabitants living along the upper and lower Strickland River catchment (NSR 1985; Yok & Blomeley 1989; Yok 1990a,b; health survey above), and on assessment of the aquatic resources of the Strickland catchment from Porgera to Lake Murray.

Apart from diet, other potential exposure pathways could include drinking, washing, gardening, swimming, or wading in the waters of the Strickland river system downstream of the mine. As discussed below, villagers obtain most of their food from gardens, supplemented by hunting. With respect to drinking water, as mentioned above, residents in the upper river catchment rely on much clearer springs and tributaries of the Lagaip/Strickland for drinking water and bathing, though villagers at Kusikina and Miwa sometimes drink from the Herbert River. Wading in the rivers, as when panning

* Aquatic life food organisms are defined here to include fish, aquatic invertebrates such as prawns (*Macrobrachium*), turtles and crocodiles.

for gold near the mine, probably poses negligible risk as the potential for uptake of metals and chemicals will be practically nil.

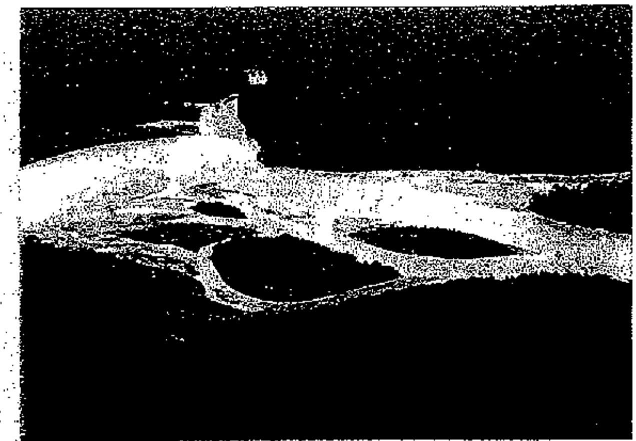


Plate 4. The Strickland River near SG4

3.2.1 Diet

During the health survey reported above, villagers were asked about their diet. In the Upper Strickland (above the Strickland gorge) and along the Lagaip River, the staple food consists of sweet potatoes supplemen-ted by bananas and taro with no sago. Protein comes from occasional wild game or domestic pig, and, infrequently, fish. Villagers in Lower and Middle Strickland eat a staple diet consisting of bananas, taros, and tapioka that is supplemented with sago at times. Their main source of protein is wild game such as pig, possum, tree kangaroo or python, with occasional fish from the Strickland River and tributaries. The health survey found that of this group, villagers at Tinahae in Middle Strickland eat the least amount of sago and river fish. Lake Murray people, at least in Kusikina and Miwa, eat sago, supplemented by bananas, taro and sweet potatoes and occasionally rice and flour. Their protein comes mainly from Barramundi and other Lake fish, with occasional domestic or wild pig, chicken, wild fowl, tinned fish and meat.

Yok & Blomeley (1989) calculated villagers' dietary intakes and reported a very similar dietary pattern. From their figures, fish and other meat make up 30% of the diet at Ugaiumbu (Tiumsinawam), while bananas are the main food. On the other hand, sago and fish make up 90% of the food intake in three of the four Lake Murray villages they surveyed: Kusikina, Miwa and Usukof. In the fourth village, Buseki, sago and fish made up only 40% of the diet, while over 50% of the people's intake was bananas and tubers.

As discussed elsewhere (p.4-4), it appears that indigenous fish do not inhabit the Strickland river system above 1800 m elevation (Allen 1991), because the natural habitat is so turbid and torrential. For a quantitative risk assessment, however, the PJV should establish the reason why these aquatic resources contribute so little to dietary protein intake, as mentioned above.

In the Lower Strickland and Lake Murray areas, by contrast, people may come into contact with mine-derived contaminants via their food: fish, crocodiles and turtles; sago and pond weed; wild game and livestock that may drink from the river or Lake.

3.2.2 Lower Strickland River and Lake Murray

The PJV has always recognised that potential risks to human health are possible in the Strickland River downstream of SG4 (Bebelubi village) and in lower Lake Murray villages. As just discussed, people have the opportunity to be exposed to mine-derived metals both via swimming and via their current intake of food that may be mine-affected*. In these regions the aquatic resource is large, and may be more intensively exploited in the future if it is not adversely affected by loss of habitat through sedimentation. However, while there must be a natural mechanism linking villagers near Lake Murray to mercury in the environment, it is not known whether an actual exposure pathway exists for mine-derived metals to enter the food chain in that region, as discussed on p.5-6.

Risk can be understood and quantified using standardised methods (e.g. USEPA 1988, 1989). The cumulative risks need to be

* For example, the metal contents of processed sago are unknown.

examined, for all exposures. Risk assessments are needed for all people living downstream from the mine including the people living immediately adjacent to the erodible dump along the Kogai River, and extending to villagers living along the Porgera, Lagaip and Strickland Rivers, Lake Murray, and the Fly River delta. In order to conduct these risk assessments, the existing data need to be refined and expanded through a focused sampling program.

This review recommends that the PJV initiate a detailed risk assessment program:

▲ *measuring metal residues in villagers' food items that (a) have not been previously defined, (b) are common food items, or (c) may contain significant metal concentrations.* Metals should be analysed in all edible parts* of the villagers' foods; for example, residents of Lake Murray station told us they eat virtually the whole of a fish[a]. The measurement of metal content in composite samples of all food items, collected under all sorts of river flow conditions, is an absolute necessity for accurate quantification of risks. (Also see p.5-6 for recommendations regarding the measurement of metal bioavailability.)

▲ *determining why residents of Lower Strickland villages (e.g. Bebelubi and Ugaiumbu) do not have greater dependence on fish.* For example, does this reflect cultural biases, overestimated fish abundance/availability, or lack of gear. Some data (NSR 1985) indicate fish are abundant in the Strickland River and can be caught readily with gill nets.

Plate 5. Lake Murray Station, Boboa.

▲ *conducting new surveys of dietary preferences of villagers from Eyaka, Wankipe, Bebelubi, Ugaiumbu, and lower Lake Murray (i.e. Kusikina, Miwa and Lake Murray Station at Boboa). At least one objective of these surveys should be to support the risk assessments.* Thus, interviewers should obtain data on total daily food and water intakes, in grams and litres, including specifically what aquatic species are consumed, exactly what water sources are used for drinking and bathing, and the extent of swimming. In addition, the accuracy of previous exposure assumptions, based on NSR (1985), Yok & Blomeley (1989), Yok (1990a,b), should be confirmed through surveys during the wet and dry seasons when food preferences may vary.

After completing these surveys, *the review team recommends the PJV conduct formal quantitative probabilistic human health risk assessments for residents of each village along each reach of the river system* (e.g. mine to SG2; SG2 to SG3; etc.). The PJV should assess all potential exposure pathways: drinking water♦; food (fish, turtles, crocodiles, terrestrial game, garden produce, sago making, etc.); incidental water

* A composite sample of a homogenate of each specimen, reflecting all the parts consumed, is preferable to measuring the individual parts (i.e. liver, spleen, intestine, gills) and attempting to reconstruct the dose. A few samples of important non-aquatic food items should also be analysed if their metal content is unknown, and their contributions included.

[a] For example, in catfish, they eat the entire fish except for large bones, bony fin rays, and the gall bladder. They explicitly stated they consumed the gills, stomach, liver, spleen, pyloric caeca, intestine and gonads. There appears to be slight variation in what parts of each species are consumed, and this needs to be confirmed through thorough interviews and observation. For example, villagers said they did not consume the lower part of the large intestine in Barramundi, in addition to avoiding the large bones, bony fin rays and gall bladder.

♦ In addition, consider water sources for fishermen and people camping out making sago, who may not necessarily have access to springs, etc.

ingestion (swimming); gold panning (Porgera River waste dumps only); etc.

The concept is to address all risks that are raised as significant public issues, regardless of their merit. For minor issues, the assessments should be simple and inexpensive because little effort is required to demonstrate negligible risk. Usually risks that are perceived to be great or important receive the most comprehensive assessment.

If there is evidence of potentially significant exposure, a risk assessment offers a good, objective and formal means for characterising the actual magnitude of exposure and attendant risks. A conservative risk assessment method to follow is that used by the USEPA (1988, 1989). Means of reducing such risks can also then be explored.

3.2.3 Risks via wildlife and livestock

For wildlife and livestock, drinking water and not food is believed to be the most important exposure route, particularly near the Porgera and Lagaip rivers. However, negligible risks to livestock (i.e. pigs) and wildlife are predicted because there are so many alternate sources of water.

This review considers that, near the mine, risks to game and livestock, and ultimately to humans, may exist only if the animals drink extensively from water on and immediately downstream of the erodible dumps. The Anawe dump receives treated wastewater/ tailings effluent from the mill containing residual cyanide and metals that may pose a risk to wildlife and livestock, if ingested.

The review team suggests PJV survey livestock and wildlife use of the dump area, from the mill to the Pongema River's confluence with the Porgera, once monthly at random times on randomly chosen days.

If large enough use is detected, the PJV should restrict animal access to the dumps, by fencing them off, for example.

4

Riverine effects: upland river system

This chapter addresses in detail the potential risks from mine-derived impacts to the riverine environment above SG4 on the Strickland River — that is, the Pongema, Porgera, Lagaip and upper Strickland rivers to where the lowland floodplain section of the river system begins. Chapter 5 examines the riverine effects on the flood plain and Lake Murray.

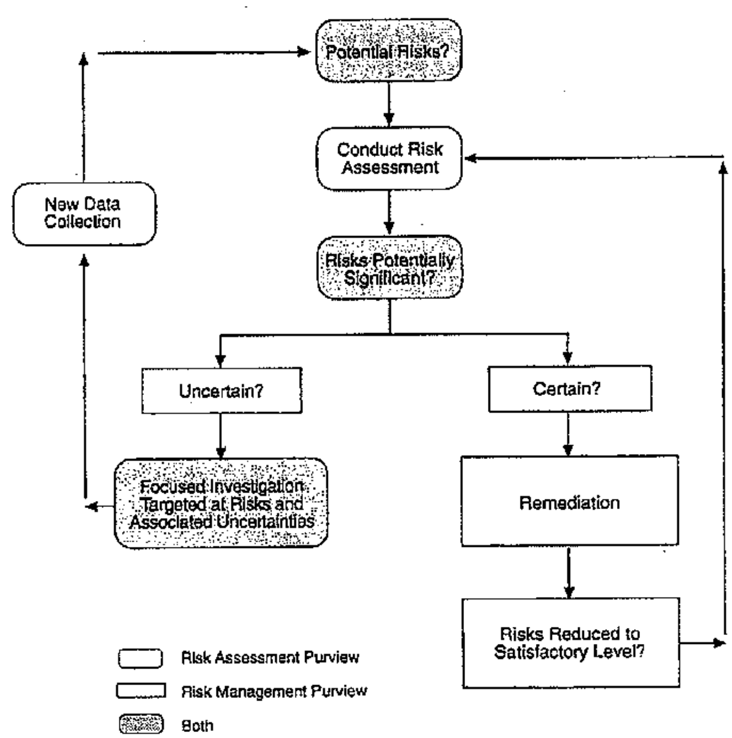
The PJV has already undertaken considerable investigation to define possible adverse environmental effects along the river system, with the major areas of investigation being the aquatic ecosystem and humans (mainly through the aquatic food chain). The results to date suggest little physical or chemical impact on these receptors.

Nevertheless, the review team proposes that the PJV adopt a quantitative risk-assessment approach to its future environmental investigations of mine-derived impacts, to obtain reliable estimates of risks and their associated uncertainties*. Then the PJV management can use that information to focus its monitoring program and decide whether the risks, if any, warrant remedial action or special investigations. Figure 4.1 shows that this should be an iterative process conducted over the course of mine operation.

Risk assessment involves a knowledge both of the target organism (or group of organisms), and its exposure to the contaminant(s) in question (see also Hansen & Winton 1995; Beer & Ziolkowski 1995). Use of this technique should help management to both identify and prioritise the risks, and assist in identifying any critical gaps in knowledge, particularly in a variable system such as the Strickland River.

* These uncertainties are extremely important to risk managers, as they index the reliability of the risk estimates. For example, a highly uncertain estimate of risk, with very large uncertainty bounds (e.g. confidence limits) around the true value, could compel the risk manager to defer a remediation decision until additional data are collected to define the real risk and reduce the uncertainties to an acceptable level.

Figure 4.1 Relationships and steps in the iterative risk assessment/management process



4.1 Description of sediment inputs

The mine's riverine impacts are primarily associated with the tailings and waste rock disposal described in Chapter 2. Treated tailings effluent is discharged into the Maiapam River and ultimately into the Porgera River. Incompetent waste rock is eroded from the Anawe dump into the Pongema river, and from the Anjolek dump into the Kaiya River. Both these rivers flow into the Porgera River and thence the Lagaip/Strickland River.

Annual loads (1989–2007) of sediment at SG1, just downstream of the mine and the Anjolek, Kogai and Anawe dumps, have been estimated by consultants and personnel of the PJV. The resulting estimated 'life-of-mine' totals, with the loads of fines given in parentheses, are 230 Mt (140 Mt) from the mine and dumps, and 2.8 Mt (1.7 Mt) from natural sources, giving an estimated total 'life-of-mine' load at SG1 of 233 Mt (141 Mt). The review team notes that estimated total-mine-life loads from mine sources are now substantially larger than the original estimate of 74 Mt for 21 years (NSR 1988).

These mine-derived sediment inputs, with a range of particle sizes, potentially have both physical and chemical effects on aquatic life, humans, livestock and wildlife exposed to the river system downstream, although no unequivocal effects were apparent at the time of this review (but see p. 4-6). Sediments are the medium by which metals and other compounds are transported as particulates through the river system. Also sediments may alter the nature of the river bed and the cross-sectional areas of the rivers.

Relatively little information is available about the rivers' natural background loads. Historical data supplied by the PJV suggest a background total suspended solid (TSS) load of less than 1 Mt/yr at SG1 on the Porgera River and approximately 34 Mt/yr at SG3. High natural sediment loads are generated by slope and valley wall failures in catchments of the mainstream and tributaries throughout the system, with failures in steep tributaries for example delivering debris torrents to the main stream, so that its natural load increases markedly as it travels.

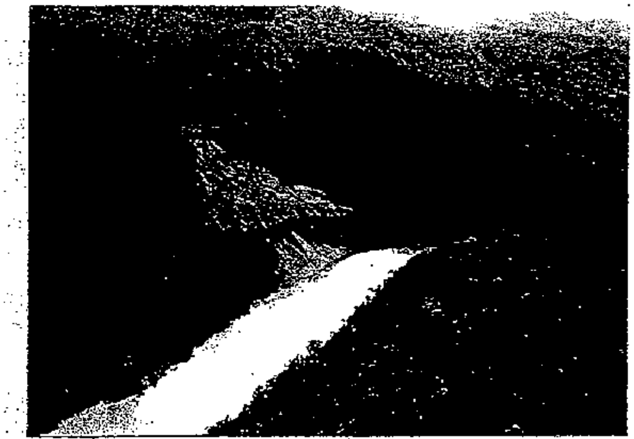


Plate 6. Natural landslip, Lagaip River

The fate of sediment in the river systems will be very sensitive to its particle size distribution. More than 80% of the tailings are in the silt/clay range and will be transported in suspension at least as far as the estuary of the Fly River. The design grind indicates that 80% of tailings particles are finer than 108 µm (PJV mill personnel, pers. comm.). Assumed particle size distribution of waste rock from the erodible dumps is shown in Table 4.1 and is based on an average of several colluvium gradation curves computed by PJV consultants Klohn Leonoff (project PB 3437 16) and Klohn Crippen (project PB 6082 09).

4.2 Physical impacts

4.2.1 Effects on the river beds

The review team examined the PJV's data and reports concerning sediments in the river system. To assess our understanding of the processes of sediment delivery, transport and deposition, we used helicopter survey, generated a conceptual model of the system, collected some data to check the proposed sediment balance, and reviewed key literature. As map 4 shows, we distinguished seven zones of the river system: zones 1–5 before the flood plain and zones 6 and 7 on the flood plain.

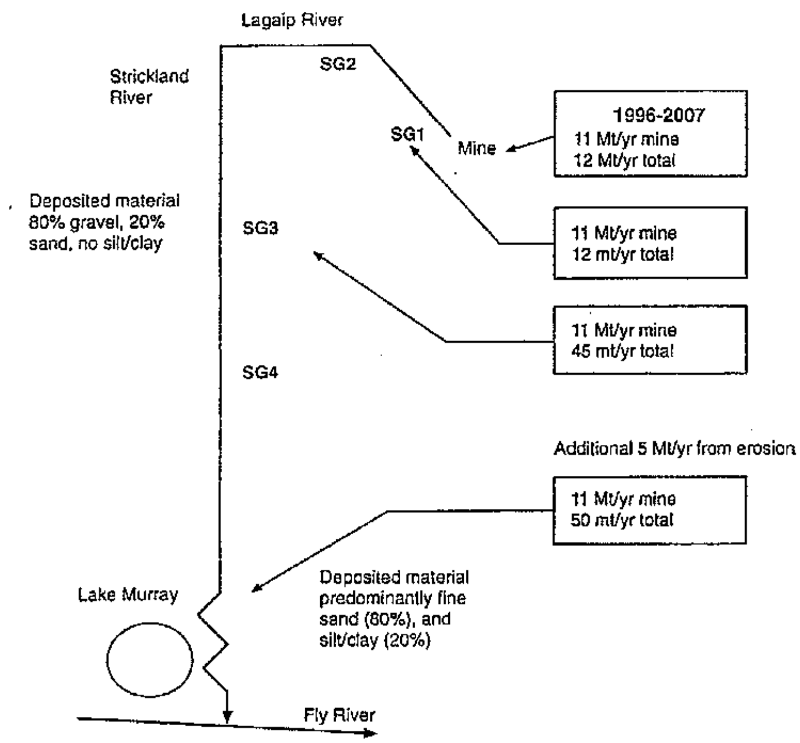


Figure 4.2 Generalised sediment balance for fine (silt/clay) material

From benthic sampling of five of the seven river zones the review team found that in the Lagaip River there were large clasts up to 0.5 m diameter (e.g. see plate 3, p.1-2); sediments consisted of about 65% gravel and 35% sand. Downstream of the Strickland gorge, in zones 5 and 6, samples were about 80% gravel and cobbles and 20% sand. In the lower meander zone (7), sediments were 80% sand and 20% silt, suggesting the potential for some deposition there. A small percentage of the silts and clays may be stored overbank and in the interstices of the benthic sand and gravel.

The review team drew up a generalised sediment balance for silts and clays (Fig. 4.2), based on the following assumptions and data:

Table 4.1 Assumed size (mm) distribution of dump export material

Size fraction	% in size class	Classification
<0.075	58%	silts and clays
0.4	10%	fine sand
2.0	10%	medium sand
4.8	7%	coarse sand
>4.8	15%	gravel

- mean annual pre-mine suspended load at SG1 was less than 1 Mt/yr (limited data supplied by David Yok and Denise Peggs);
- mean annual mine-derived suspended load leaving waste streams (1989–1995) is 3.0 Mt/yr and (1996–2007) 11 Mt/yr (maximum 13 Mt/yr, from above model);
- mean annual suspended load 1991–1995 at SG3, derived from the TSS and flow data, is approximately 40 Mt/yr, representing both natural and mine-induced loads. This figure was independently verified by Dr David Fox of the review team;
- assumed additional natural loading between SG3 and SG5 is 5 Mt/yr;
- mine-derived silts and clays are of the order of 20% of the total load in zone 7.

This scheme does not take into account processes of abrasion in the river, but assumes that 60% of mine-derived sediment is abraded to silts and clays on entering the river system. This load is likely to be transported through the system at least as far as SG4. Some sand deposition will occur in the Lagaip River, but the fine sediments will fill interstices in the larger deposited

Plate 7. Medial bar at Porgera/Lagaip rivers

material, contributing to 'embeddedness' (the degree to which the gravel and cobbles are joined together or cemented with small particles), and will be unlikely to have a significant impact on channel bed topography. The heavy (in-channel) deposition down-stream of the Strickland gorge is mostly of gravel and sand.

According to the team's sediment balance for sands and gravels, approximately 20 to 30 Mt of mine-derived coarse sand and gravel will be delivered to the river system from the erodible dumps over the life of the mine. 10% of the mine-derived load is gravel. Most will be deposited in zones 2 and 3, and will be abraded to finer particles.

The review team noted that 30% of mine-derived sediment is sand. Most of this will be deposited (temporarily) in river zone 6, where the river's longitudinal slope changes abruptly. The review team's aerial inspections supported this conclusion. Any accelerated aggradation in this area might cause an increased frequency of overbank flow and associated transport of mine-derived fine sediment, but there appear to be few data from this area with which to assess this issue.

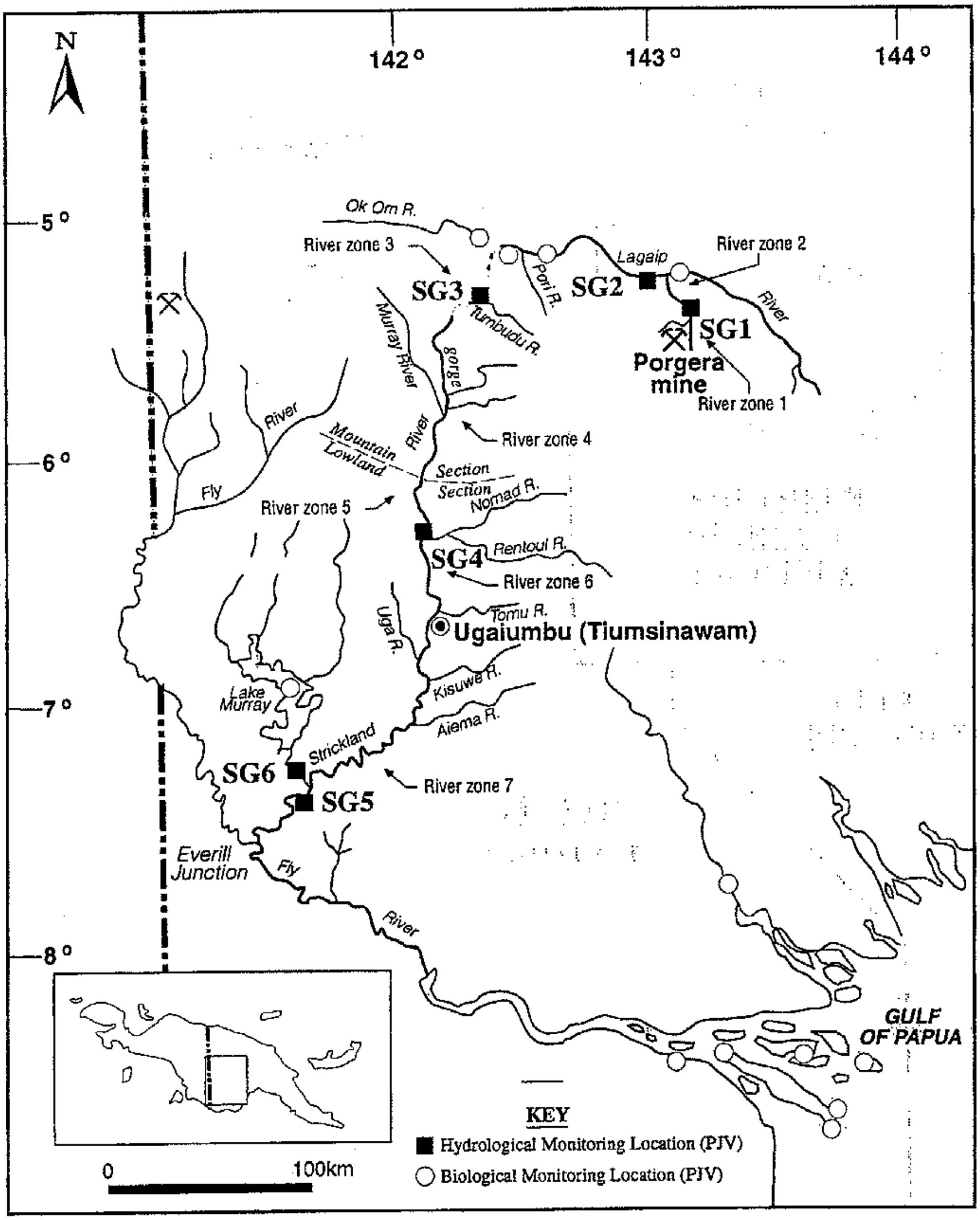
Graphs of the rivers' cross-sections (PJV 1995) show little evidence of ongoing aggradation, at least since 1989. Upstream of the Porgera–Lagaip confluence there appear to be alternating scour-and-fill episodes, so the deposits on the river beds (benthic deposits) will be transient through this reach.

Overall, the team expects the high physical impact to be restricted to upstream of SG2 and to increase as the mine's production grows. Most sediment would be transported through the Porgera River, down-stream of SG1, but with transient deposition and later scouring. Valley wall erosion and widening of the channel are expected, particularly as sediment load increases. The Lagaip River carries large natural loads from landslips in the catchment. There will probably be transient deposit of mine-derived coarse sediment here too (the review team observed medial and lateral bars along the length of the Lagaip), and fines may settle into interstices in the river bed during low flows. There also may be isolated deposition over-bank. It is difficult to assess aggradation of the bed because of lack of data.

4.2.2 Physical effects on aquatic life

Clearly, the mine can affect aquatic life (fish, invertebrates, plants) living in these upper rivers. It seems the Tandan (eel-tailed catfish) *Neosilurus equinus* and its invertebrate food items occur in the Strickland River from at least SG2 downstream (NSR 1985). Examination of stomach contents of Tandan from the Lagaip River indicates a predominance of terrestrial food sources, but it is not clear whether this is by choice or because benthic invertebrates are limited. However, upstream of SG3 the waters are highly turbid and rapidly flowing, with a bedload that is moving downstream and hence is unstable. Such habitats do not typically support much aquatic life (Waters 1995). Allen (1991) reports the absence of native fishes in the Strickland above 1800 m, and this certainly must reflect the inhospitable conditions.

Mine-derived risks to aquatic life in the Porgera, Lagaip and Strickland Rivers are likely to be due to the effects of suspended and settleable solids, development of embeddedness in the sediment, and the scouring action of the sediment bedload, where these can be distinguished from the



Map 4. The Strickland/Fly catchment, showing seven 'zones' of the Strickland river system

effects due to natural loads. This hypothesis should be tested by risk assessment. The risks probably are most important during low streamflows, which may embrace critical periods for reproduction of aquatic species. Embeddedness prevents fish eggs and invertebrates from reaching the interstices in the deeper hyporheic zone below the streambed, which provide a refuge to both fish and invertebrates in times of floods (Merritt & Cummins 1996 p.44; Waters 1995 p.68).

This review recommends the PJV research the aquatic creatures' ecology so as to understand how their occurrence, reproduction, and feeding are affected by river conditions, turbidity, sedimentation and embeddedness, as well as by variables associated with the mine wastes.

It is important that the PJV re-examine its statistical treatment and reporting of the sampling for aquatic life, in these upper rivers at least (see Chapter 6). The review team's preliminary analysis of the PJV's data suggests that fish populations in the upland river system have been in decline since 1993. Further investigations are suggested, to show if this observation represents a mine-derived impact or is an artefact of altered sampling practices.

4.2.3 Monitoring: current & recommended

The PJV's monitoring activities, between the sediment sources and the Lagaip/Ok Om junction, currently assess the behaviour of the mine-derived sediments and survey the river cross-section. The review team considers that reliable figures of the monthly loads of suspended material and metals added to the river system from the erodible dumps may be obtained from an intensive period of water quality and sediment sampling and analysis (possibly over a six month period), in addition to regular surveys of the dumps.

In situ sampling of bed material and survey of the cross-sections of the Porgera and Lagaip rivers, as required by the EMMP, should be more intensive. The review team suggests the routing of fines and aggradation of the river be considered/modelled, with coordinated benthic sampling and periodic water sampling for TSS. The loading with natural sediment also needs to be determined. Aerial photography would assist calculations of dump storages and sediment balances.

Sediment transport is calculated from suspended solid and flow data. Calculations would be improved if more data were being collected at SGs 1, 2, 4 and 5. The PJV's original predictions concerning sediment transport were probably reasonable. Likewise the predictions that most fine material would be routed through the entire system are generally valid, but the higher the tailings and waste rock discharge, the higher the suspended solid concentrations.

It is essential that the PJV has the ability to forecast impacts on the river system. A critical step is to determine a sediment balance for the system. Such a balance would route sediment by size fraction through the river system, possibly on a yearly basis, identifying areas where sediment is likely to deposit and in what quantities. *The PJV should develop a better understanding of the sediment balance by combining field data and geomorphic interpretation of flow and sediment processes into a sediment transport model.*

With respect to aquatic life, the review team recommends that the PJV define the size (and hence importance) of the populations of fish and invertebrates in the Lagaip River upstream and downstream of the Porgera River confluence (~SG2) and at Wankipe (Logatyu River confluence). Importance can be judged in at least two ways: abundance relative to that in tributaries, and fish catch-per-unit-of-effort (CPUE). There should be a minimum CPUE below which villagers will never seriously attempt to harvest the resource because the energy return is less than the energy expended.

The PJV should also define the relative importance to aquatic life of tributaries to the mainstream Lagaip and Strickland rivers. Maybe the limited fish populations observed in the Lagaip River depend on certain tributaries for food production and perhaps spawning. The relative abundance of aquatic life could be examined by seasonal sampling

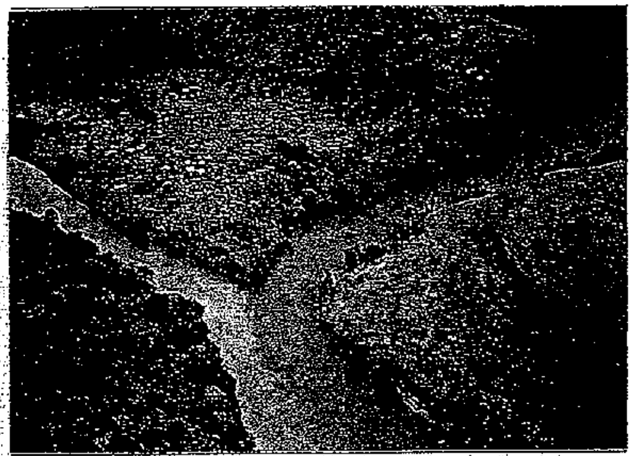


Plate 8. The Ok Om River (left) sometimes carries more sediment than the Lagaip River

of the lower tributaries and their confluences in such a way that the data may be compared with results from the mainstream rivers.

4.3 Chemical impacts

We distinguish between the potential chemical effects of *dissolved* inputs (primarily in the tailings stream with metals, ammonia, cyanide) and those of *particulate* material (both the tailings stream and inputs from the waste dumps). From an immediate toxicological point of view, dissolved constituents will be of most concern (to satisfy the compliance criteria, for example); in the longer term, particulate inputs may also be important.

The silt and clay particles (less than 63 µm in size) not only travel further than do larger particles, possibly reaching the flood plain as discussed above, but also have a higher ratio of surface area to volume, carry disproportionate amounts of adsorbed metals, and thus generally represent more of a risk than larger particles. Smaller particles will be ingested by suspension feeders which may assimilate metals from them, depending on the digestion chemistry of these organisms (pH, pE, gut residence time) and the metal–particle bonding strength.

4.3.1 Effects between mine and SG2

There are important geochemical differences between tailings and waste rock. Much of the tailings input will have been oxidized and the overall composition of the tailings will be reasonably consistent for extended time periods; the particle size will be very fine, the amounts of tailings known, and the metal content high. In contrast, inputs from waste rock will contain some reduced, sulfur-bearing material; inputs will tend to be sporadic, influenced by dumping operations, rainfall and dump instability. The particle size of inputs from the waste rock dumps will tend to be variable, the amounts difficult to measure, and the metal content generally lower than tailings (except perhaps for the 'black sediments' sent to the erodible dumps).

The review team has considered the potential for the black sediments (that are increasingly being added to the erodible waste rock dumps) to create acidic conditions in the Lagaip and Strickland rivers, and subsequently liberate heavy metals. There is now sufficient evidence available on the slow rate of oxidation of the black sediment material and the relatively high 'neutralising capacity' in the receiving waters, to confidently predict that acidic conditions are most unlikely to occur within the Lagaip and Strickland rivers.

Dissolved inputs

Dissolved heavy metals appear to be released from the existing erodible dumps, because the limited water quality monitoring conducted downstream of the Anjolek dump shows elevated concentrations of lead and zinc. In addition, there are potential risks if 'upset' episodes occur in mill operation, posing risks to aquatic life inhabiting the river above SG2, i.e. upstream of the dilution afforded by the Lagaip. 'Upsets' refer to periods when the tailings treatment process is not operating normally, and increased concentrations of dissolved constituents or treatment chemicals are inadvertently discharged.

At SG1, chemical toxicity may be a stressor because the PJV monitoring data there show that concentrations of HCN and several dissolved metals (Ag, Cu, Hg) exceed the relevant ANZECC water quality criteria that apply in Australia and/or the USEPA water quality criteria for aquatic life continually exposed to these substances. However, dissolved metals are unlikely to be of concern in the receiving waters below SG2, though risk assessment should be used to show whether or not they pose negligible risks.

Particulate inputs

These rivers have large loads of suspended solids and approximately neutral pH, so dissolved cations in the tailings stream for example would be expected to adsorb strongly and fairly rapidly to the suspended solids in the rivers. As discussed earlier, particulates the size of sand and silt/clay are likely to be transported through these upper river reaches with little deposition.

The review team recommends that the PJV undertake research with the aim of determining a tailings 'signature': that is, a set of elements in the tailings that can be used to trace their downstream movement and to quantify mine-derived inputs. Possible signature elements might include Ag, As or Pb, some combination of these, or some other minor constituent of the ore which, however, is not difficult to detect analytically; an unequivocal signal is needed.

To test the usefulness of a given element or combination of elements as a signature, the PJV would need to collect and analyse samples of the fine suspended solids from representative (turbid) tributaries in the upper catchment, e.g. the Lagaip upstream from the Porgera River, and other turbid tributaries upstream from SG3 (e.g. see plate 8), and demonstrate that these 'natural' inputs can be distinguished from those derived from mine-related activities.

4.3.2 Monitoring: current and recommended

To fully evaluate the riverine impacts of the waste rock inputs, the PJV should monitor dissolved inputs derived from the weathering and leaching of the erodible waste dumps. This review recommends that the PJV also measure the size distribution of particulate material in tailings effluent and eroding from the erodible waste dumps and reaching the river, and the mineralogy/chemical composition of the fine fraction and its reactivity in the receiving waters.

Monitoring results from 1994 in the Anjolek/Mungarenk Creek area, downstream from the Anjolek erodible dump, show that concentrations of suspended solids (TSS) and dissolved metals are very variable, as would be expected in such an unstable, upland environment. Therefore, the current monthly sampling frequency is unlikely to be sufficient to detect the natural variability in this system.

4.3.3 Impacts between SG2 and SG4

Dissolved inputs

Between SG2 and SG4, near Ugaiumbu (Tiumsinawam), the concentrations of all dissolved metals and cyanide (CN) appear to be within internationally recognised water quality criteria, except for Ag and Hg. At SG3, the compliance point, the PJV's data for dissolved constituents shows the operation has always been in compliance with regulatory limits.

Concentration–discharge relationships are often useful for distinguishing between point discharges and diffuse (non-point) sources. To examine the behaviour of dissolved metal concentrations with changes in flow, the review team graphed dissolved metal concentrations against river discharge for SG3 for the period 1990–1995 (Figs 4.3–4.4). Visual inspection of the plots for As, Cu, Ni and Zn shows a clear dilution effect with increasing discharge, whereas dissolved Cd exhibits no apparent relationship with discharge. For most of the sampling dates the values for the remaining metals (Ag, Hg, Pb) were below the limit of analytical detection.

The absence of a concentration–discharge relationship prior to 1990 is not surprising. In the 1990–95 period, the decrease in concentration of dissolved metals with higher discharge, or increase at low discharge, can be interpreted as indicating that *dissolved mine inputs are detectable at SG3,* even though the actual concentrations remain well below the compliance criteria. The existence of a concentration–discharge

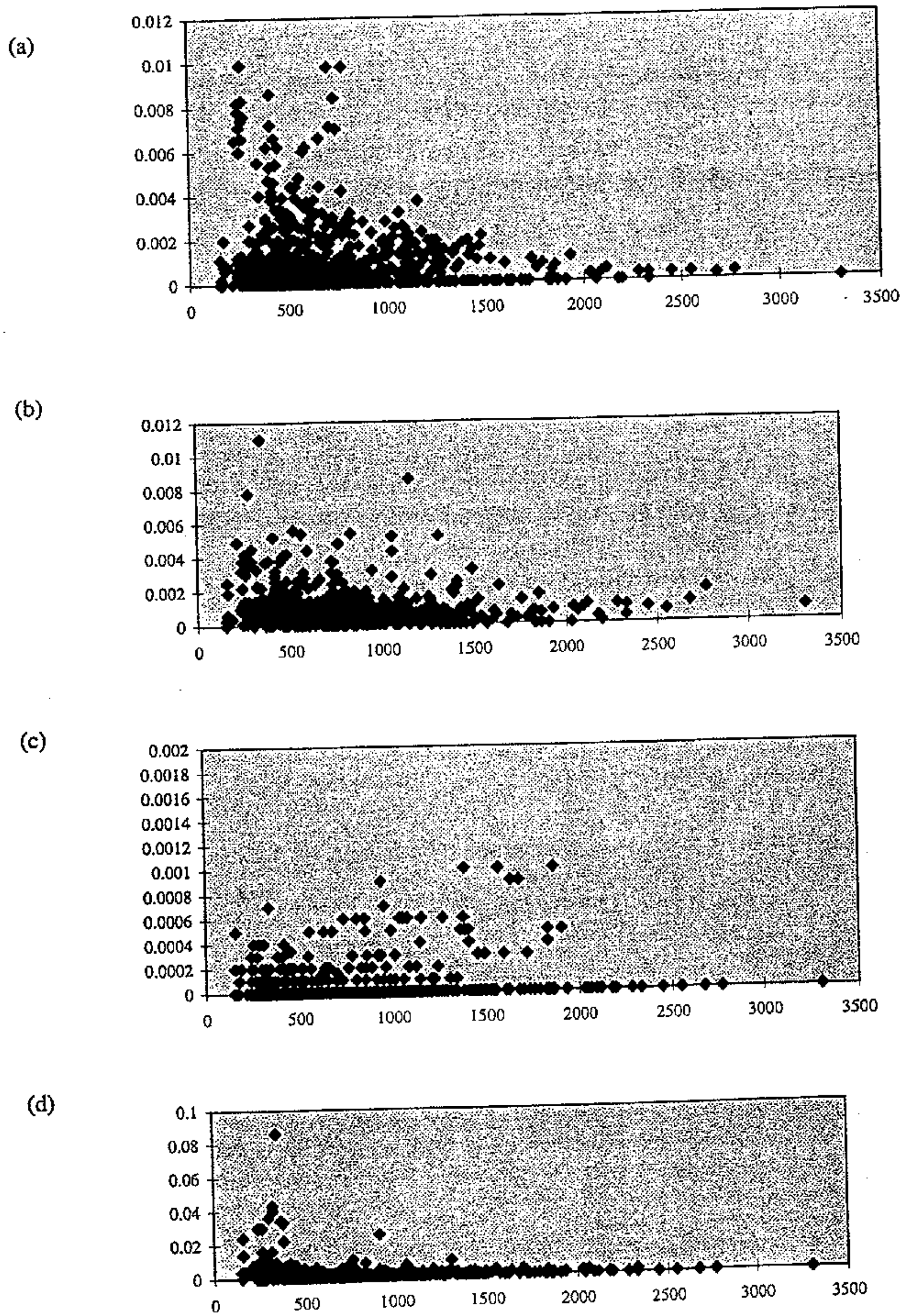


Figure 4.3 Variations in concentrations (mg/L) of dissolved metals (y axes) at SG3 as a function of river discharge (m^3/s) (x axes) 1990–1995: (a) As; (b) Cu; (c) Cd; (d) Zn

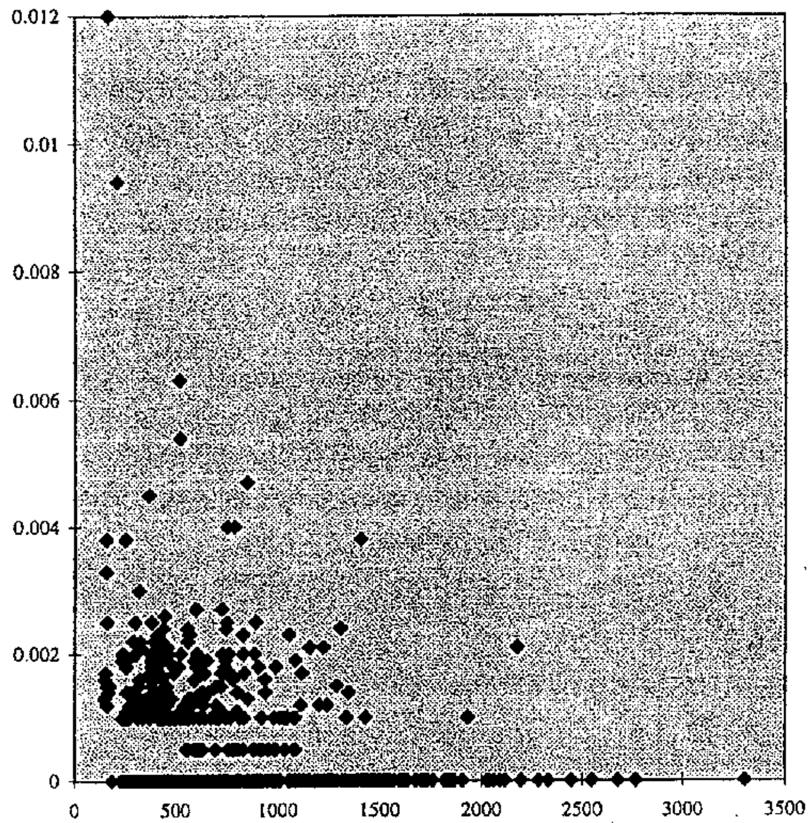


Figure 4.4 Variation in concentration (mg/L) of dissolved Ni at SG3 (y axis) as a function of river discharge (m^3/s) (x axis) 1990–1995

relationship also suggests that the variations of dissolved metal concentrations over time at SG3 are real, not just due to analytical variability.

Particulate inputs

There are three ways to distinguish the effects of mine-derived riverine metals and sediment loads from those of the rivers' natural background contents.

(a) Data gathered since the mine began could be compared with baseline data. For example annual mean concentrations of metals in suspended solids at SG3 have clearly increased since 1990 (e.g. see PJV 1994 Vol. A Table 5.3). Mean values of As and Pb show the greatest increases over the 'baseline' values, ~7- and ~10-fold increases respectively. However, as discussed in Chapter 6, baseline and preliminary data were scant, in some cases determined on the basis of a single sampling campaign in August–September 1984 and the review team considers them inadequate, especially for such a variable river system.

(b) 'Control' data can be gathered from rivers or tributaries in catchments unaffected by upstream land uses. The control data are then compared with data collected on the same sampling trip from the rivers downstream of the PJV mine. Some such data exist for the Lagaip upstream from the Porgera River and other turbid tributaries upstream from SG3 (Table 4.2, S.C. Apte, CSIRO CAAC, pers. comm., Jan. 96). It is interesting that TSS from the Pori and Kaiya rivers appear to be (naturally) enriched in Ni and especially Cr.

(c) Data can be presented as time-series plots to detect trends. Such a plot for As concentrations in suspended solids for the 1990–95 period shows marked variations as a function of stream flow, but the review team found that a positive trend can be extracted from the data. With this approach, when looking for the tailings 'signature' in the suspended solids load, it might be helpful to concentrate on *low-flow periods*, where TSS inputs from the catchment proper will be minimal.

Table 4.2 Particulate metal concentrations (µg/g) in suspended solids collected at various sampling points in the Strickland River catchment

Sample	Metal										
	As	Cd	Cr	Cu	Hg	Ni	Pb	Ag	Zn	Mn	Fe(%)
Lagaip R	6	<0.1	46	30	<0.1	42	13	0.08	100	578	4.42
Pori R	23	0.3	239	30	0.3	128	17	0.14	182	724	5.56
Kaiya R	31	0.4	332	31	<0.1	264	17	0.48	112	544	4.24
Ok Om R	15	<0.1	37	31	0.2	34	29	0.08	111	785	4.48
SG1	789	3.3	39	83	9.0	29	326	17	741	1726	5.72
SG2	194	1.3	37	41	4.2	34	127	6.2	301	1050	4.77
SG3	64	0.4	42	39	1.5	85	59	2.3	162	857	4.80
SG4	104	0.6	75	38	1.7	64	45	1.4	167	740	4.10
Herbert R	23	0.5	75	23	0.5	55	33	0.5	118	1093	5.51

It is also instructive to identify how the concentrations of metals in suspended solids vary along the river system. Existing data from the PJV's monitoring can be compiled in this way (Tables 4.2, 4.3), but comparisons are difficult because the analyses have not been normalised for variations in grain size or mineralogy.

For interest, the review team inspected the PJV data for metals in suspended solids, and compared them with sets of toxicity criteria recognised in Canada and USA. Environment Canada (1995) defines a threshold effect level (TEL) that represents the concentration below which adverse effects are expected to occur rarely, and a PEL (probable effect level) that defines the level above which adverse effects are predicted to occur frequently, based on statistical analysis of an extensive laboratory and field database. The values refer to the *total* metal concentrations in surficial sediments (i.e. the upper few centimetres of bed sediment) expressed on a dry weight basis.

In the USA, other sediment criteria (Long *et al.* 1995) have been developed using data on the toxicity of sediment-bound chemicals to *estuarine* and *marine* organisms. There has been relatively widespread support in the United States for using these criteria for screening freshwater sediments, because they are based on such a wide array of sediment toxicity data, both laboratory and field. In these, the ER-L (effect range low) is the sediment concentration of the constituent which has a 10% effect on test organisms, according to the literature.

None of these criteria applies to all field situations — total metal concentrations in sediments are an imperfect guide to metal bioavailability. However, *the review team recommends the PJV use sediment toxicity criteria when making a preliminary judgement concerning the potential for risks. If potential risks are found to exist, then it is recommended that the PJV measure metal concentrations in sediment pore water (see also p.5-6) and also conduct site-specific sediment bioassays to further assess such risks.*

Based on the above approach, it was noted that some of the 1995 suspended solid metal concentrations at SG3 were already approaching levels reported to cause effects on benthic communities (Environment Canada 1995). For example, As and Pb exceed the PEL, and concentrations of Cd, Cr, Hg and Zn all lie between the TEL and PEL values. In the PJV's data from Tiumsinawam (Ugaiumbu) (PJV 1995 Table 6-8), As, Ni and perhaps Hg in bulk sediments exceed the ER-L, whereas Cd, Cu, Cr, Pb and Zn do not. Arsenic in sediment has exceeded the ER-L by ~2 or more since commencement of mine operation.

4.3.4 Monitoring: current and recommended

The review team recommends that detection limits for dissolved Ag and Pb should be lowered in the PJV's analyses, because

Table 4.3 Average particulate metal concentrations (µg/g) in suspended solids collected at various sampling points on and close to the mine site, and downstream as far as SG3

Sample	Metal								
	As	Cd	Cr	Cu	Pb	Hg	Ni	Ag	Zn
Tailings' 95	660	9.9	18	93	530	3.2	40	13	1550
Anjolek Ck	6	0.5	20–30	13–16	44–50	0.7–5	14–21		72–136
Mungar. Ck	9	0.5–6	2–88	2–26	9–196	0.5–0.9	2–33		8–485
Kaiya R.	35–110	4.4–7	35–37	38–57	51–61	1.6–5.4	18–22		56–94
SG1 '94	83	5	34	52	53	4.2	33	0.2	1210
SG2 '94	99	2.5	57	52	33	2.1	45	4.8	660
SG3 '94	39	1.3	42	29	124	0.4	35	2.3	233
SG3 '95	72	1.4	43	32	121	0.3	39	2.5	230
Baseline (SG3 '84)	6.2	0.5		22	17		23		88
*River TSS	5	18		100	150		90		350

dissolved concentrations of Ag, Hg and Pb are frequently undetectable. We presume the dissolved forms are monitored for compliance purposes. At present, 'detectable' values could be real or a result of random sample contamination (see also pp.5-6, 6-5). Any risk assessment based on over-estimates of dissolved metals would be very conservative. *This review also recommends that only total Hg be monitored at SG3 as the true dissolved values are likely to be in the pico-molar region.*

Although the compliance criteria at SG3 are expressed in terms of dissolved metals, nevertheless *it is recommended that metals associated with suspended solids at SG3 continue to be monitored to:*

(i) test whether or not the 'signature' of mine-derived solids can be detected, notably for tailings inputs, and to follow this signal over time;

(ii) serve as an estimate of particulate metals loadings delivered to the lower Strickland flood plain; and

(iii) allow a comparison of the metal concentrations in this material with internationally accepted sediment quality criteria.

The review team also recommends that:

(1) particulate metal data (µg/g) be adjusted to take account of particle size, so they can be reliably compared throughout the river system; and

(2) the bioavailability of particulate metals (in particular As and Pb) at SG2 and SG3 be evaluated. This evaluation should involve measurement of their pore water concentrations, and other laboratory studies (e.g. sediment bioassays) and field investigations (e.g. bioaccumulation of metals in indigenous biota).

Depth-integrated water samples are normally collected for measuring and characterising suspended solids in rivers. *This review recommends that the PJV determine whether its current grab sampling approach is appropriate at the key sampling stations on the Lagaip and Strickland rivers, through a comparative depth-integrated sampling program* (see also p.6-7).

* River TSS values refer to the 'average' metal concentrations in the suspended sediments of the world's rivers. Cited concentrations come from Table 4.35 in NSR (1990).

5

Effects on the flood plain and Lake Murray

This chapter examines the potential risks from mine-derived sediments to the flood plain of the Strickland River, including Lake Murray. Risk may exist when animals and/or humans are exposed to a potential contaminant, and when their physiology is such that an adverse effect can be detected.

The PJV has always recognised that mine-derived sediments may affect the flood plain of the Strickland River. The flood plain is the deposition zone for the river-borne fine sediments which are most important from a toxicological viewpoint (see p.4-7), as mine-derived metals may accumulate in this region. The major exposure pathways for people are food and drinking water. Other exposure pathways include wading, swimming and washing in the Lake or rivers, and gardening in flood-deposited sediments.

To limit the potential risk to drinking water supplies, from mine-derived sediments, the PJV has installed drinking water tanks in villages along the Strickland River. The PJV has also monitored Hg in scalp-hair in villagers in the Lake Murray area since before the mine began operating (see p.3-1), and the people's health has been inspected by visiting doctors. As reported in Chapter 3, no effects of heavy metal toxicity have been detected by the health surveys.

Nevertheless, this review proposes the PJV use risk assessment to quantify the risks that mining operations might pose to human health on the flood plain now and in the future. Risk assessment techniques (USEPA 1988, 1989) use scientific and site-specific data to determine the probability and severity of any adverse effects resulting from exposure. The risk-based approach to data-gathering will help the PJV improve its data-gathering and reduce uncertainties in the estimates of risk.

In this chapter the review team assesses the mine's potential physical and chemical effects on the flood plain and its aquatic life.

5.1 Physical impacts

5.1.1 Sediment load

The review team considers that virtually all the mine-derived and natural fine-grained materials (silts and clays) will rapidly make their way through the upper catchment, taking only a few days, and begin to settle out of the water column in the lower reaches of the Strickland and Fly rivers, starting in the Lake Murray region. The mean annual loading from all sources is estimated to be about 50 Mt of silt/clay.

The review team assessed the possibility of over-bank flow of water from the Strickland River, followed by deposition of its suspended solids load on the flood plain. The team's consensus was (i) that such deposition is feasible in the case of the Strickland River, but that it probably does not occur much before the meander zone, and (ii) that this deposition would be very difficult to model (predict) quantitatively.

In more detail, in-channel deposition of mine-derived sand is possible downstream of SG4 on the Strickland flood plain. There is little likelihood of severe channel aggradation, but over-bank depositions of mine-derived silt and clay are possible, dependent on flood frequency. No impact can be measured at present, and the review team considers there is only moderate to low probability that an impact will occur in future.

In the meander zone of the Strickland River, adjacent to Lake Murray (map 5), the estimated annual load of mine-derived fines amounts to approximately 10 Mt. This material is not likely to cause aggradation in the river channel, but may have an adverse effect if deposited over-bank on the grassed and forested flood plain and in other water bodies off-river, such as oxbow lakes. The deposition could amount to 0.5 Mt/a, based on historical estimates of similar deposition from the Fly River.

Lake Murray normally drains into the Strickland River via the Herbert River, but periodically the flow of the Herbert reverses and water flows from the Strickland River into Lake Murray.

On behalf of the PJV, NSR Environmental Consultants have calculated an approximate fine sediment balance for Lake Murray. However, the review team considers the balance needs to be reassessed. After inspecting the previous studies, and consultation with other experts, and a visit to Lake Murray, the review team notes some characteristics of water and sediment flow that do not appear to have been taken into account before.

For example, Strickland River water and sediment appear to flow into Lake Murray via the Herbert River channel, and through relict and other channels (e.g. Mamboi River). However, canoe passages across the flood plain, and over-bank flow from the Strickland and Herbert rivers into the wetlands and grassed flood plain to the east of the Lake, may also be significant pathways. These wetlands are contiguous with the southern end of Lake Murray and presumably are connected directly with it. As well, water that enters the Herbert River can spread laterally over its low levees before entering Lake Murray proper. Severe inflow events will occur during sharp river rises after prolonged low flow (for example, around January).

Likely areas for deposition of mine-derived sediment around Lake Murray and the Strickland flood plain are:

- ▲ southern part of Lake Murray;

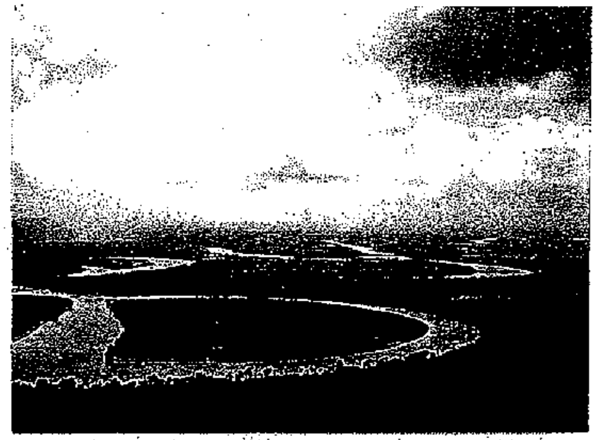


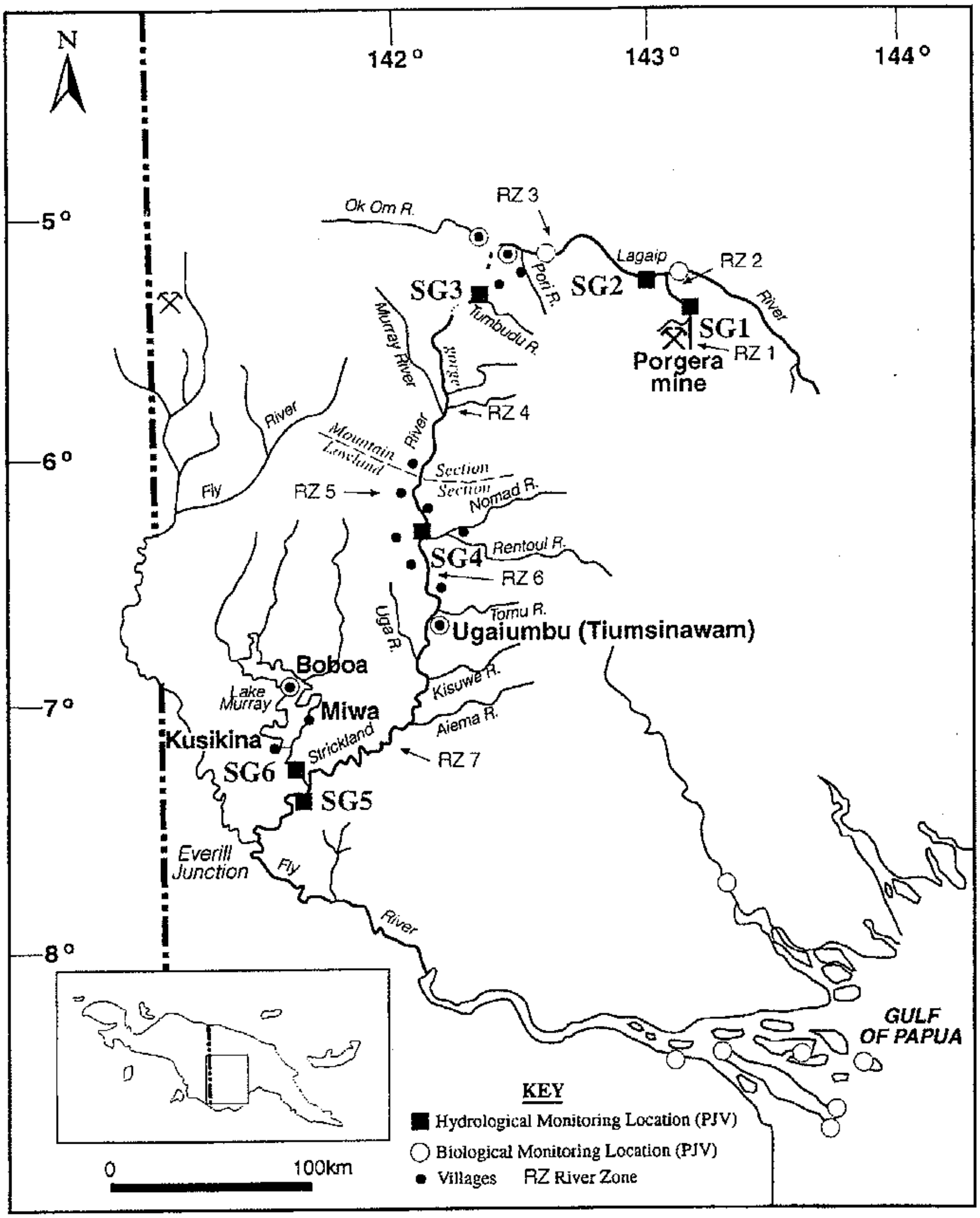
Plate 9. Flood plain of the Strickland River

- ▲ water bodies adjacent to the Herbert River (concentration will decline with distance from river);
- ▲ channels and levee areas between the Strickland and Lake Murray;
- ▲ the flood plain between the Strickland and Lake Murray; and
- ▲ the Strickland flood plain upstream and downstream of Lake Murray.

However, since the river water that escapes the Herbert channel and enters the wetlands will rapidly lose its suspended sediment load, the only water flows of importance to the sediment inputs to Lake Murray itself will be those which enter via the main Herbert River, and perhaps from the Strickland via the relic channels across the flood plain when the water levels are high. Since the waters of the Herbert River are usually colder than Lake water (NSR 1990, Appendix 2), they may well tend to sink on entering the Lake.

When the flow reverts to the normal 'downstream' direction, it is not known from what depth the water will be drawn. If there is even a slight sill at the outlet from the Lake, the return to normal flow may tend to draw water from the Lake surface rather than the Lake bottom. In such a case, water that enters via the Herbert River channel would stay longer in the Lake, and the time for settling of its particulate load would be extended.

Thus, there is uncertainty over the accuracy and assumptions of the existing fine sediment balance. The review team estimates that about



Map 5. The Strickland river system showing the seven 'zones'

Water balance for Lake Murray can be estimated based on these assumptions:

catchment area of Lake Murray	6850 km^2
average Lake surface area	550 km^2
average Lake depth	5 m
catchment mean annual rainfall	3700 mm
catchment mean annual actual evapotranspiration	1500 mm
Lake mean annual rainfall	3000 mm
Lake mean annual evaporation	2000 mm

The resulting annual catchment runoff is 2200 mm (3700 – 1500) or 15.0 million ML, and net annual Lake rainfall minus evaporation is 1000 mm (3000 – 2000) or 0.5 million ML

150 kt/a of mine-derived sediment are transported to the Lake. This could represent as much as 20% of the total sediment transported to the Lake from the Strickland River. The processes of water and sediment transfer between the Lake, the Strickland River and the Strickland flood plain are not understood. Therefore we have assumed that most of the mine-derived sediment transported to the Lake would remain there. *However, we recommend the PJV reassess the sediment balance for the Lake.*

5.1.2 Lake Murray water balance

The Environmental Plan discusses the nature of water flows between the Herbert River and Lake Murray. During an 18-month period of data collection, flows from the Strickland River into Lake Murray via the Herbert River were equivalent to 9% of the volume of outflow from the Lake. The Environmental Baseline report (NSR 1990 Section 5.2.2) discusses the flow in the Herbert River, based on analysis of normal and reverse flows for 1110 days at SG6. From the analysis it was concluded that reverse flow occurred approximately 15% of time with the annual normal flow from the Lake to the Strickland River estimated as 16.7 million ML and the annual reverse flow being 1.7 million ML (consistent with the Environmental Plan). During another monitoring period, reverse flow was recorded 25% of the time.

Using the data on normal and reverse flows available at SG6 for the two experimental periods December 1985 to May 1987 and November 1992 to October 1993, and assuming no bank over-flows between SG6 and the mouth of Lake Murray and no flow from the Strickland direct to Lake Murray, the following outflows and inflows can be estimated along the Herbert River:

Outflow from Lake Murray	17.1 million ML/yr
Inflows to Lake Murray	2.6 million ML/yr
Net outflow from Lake Murray	14.5 million ML/yr

An alternative method to estimate the net outflows from the Lake is to carry out a water balance for the Lake and its catchment. Using that approach, and the estimates in the box above, Lake Murray outflow can be estimated as 15.5 million ML per year or 490 m^3/s. This is similar to the outflow computed above using SG6 discharges.

From this analysis and noting that the average volume of the Lake is approximately 3.2 million ML, it is estimated that the storage retention time within the Lake is approximately two months.

The review team recommends that the PJV calculate a water balance for Lake Murray either by estimating inflows as (direct rainfall + catchment runoff – Lake evaporation) in conjunction with Lake levels, or by monitoring net outflows in conjunction with Lake rainfall and evaporation and Lake levels.

5.1.3 Below Lake Murray

There appears to have been very little consideration of the fate of the PJV mine-derived sediment downstream of Everill Junction (the confluence of the Strickland and Fly rivers), through the Fly Estuary and Gulf of Papua. This PJV sediment, which could be up to 10 Mt/a, is probably less than 10% of the total load of the Fly, and massive dilution can be expected from the estuarine muds and other Gulf rivers.

There is likely to be deposition on the flood plain downstream of Everill Junction, but there are no data available with which to assess the impact. In terms of sedimentation and turbidity, the impact downstream of Everill Junction is considered negligible.

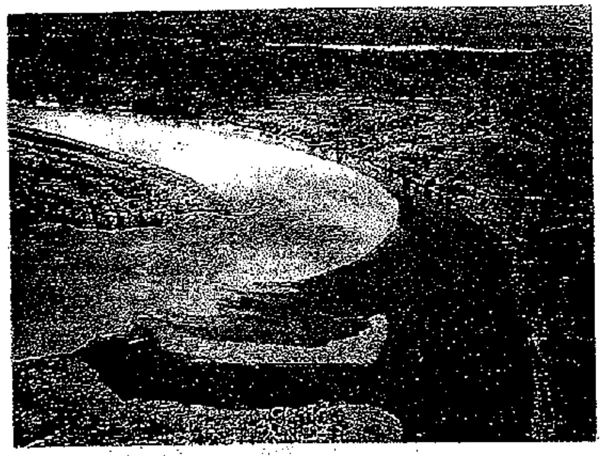


Plate 10. Strickland/Herbert river confluence, looking south

5.1.4 Monitoring: current and recommended

Downstream of SG4 (zone 6), and in the meander zone of the Strickland adjacent to Lake Murray, the PJV does not currently undertake any monitoring.

On p.4-6, the review team has recommended that the PJV develop a computer model of the sediment balance for the river system. *To calibrate such a model below SG4, the PJV should measure aggradation in the river channel, using cross-sections or GPS survey or remote sensing of sediment plumes. The Herbert and Mamboi rivers should be sampled during reverse flow to identify whether this is an important pathway for mine-derived sediment. Also, the team considers it important that the PJV identify a geochemical signature (or pattern of elements) with which to trace mine-derived sediment* (see also p.4-8), *and then search for it via a program of systematic coring on transects extending at least 2 km either side of the river at key positions.*

To calculate ingress of mine-derived sediment to Lake Murray at present the PJV measures flow by directional current meters in the Herbert River and operates gauging stations at SG5 and on a northern tributary. *The review team recommends that the PJV re-assess the current hydrological monitoring program* (see pp.6-2, 6-3). *It is also recommended that the PJV evaluate the usefulness of remote sensing for tracking the fate of sediment and the frequency and extent of Lake level fluctuations.*

With respect to the proposed coring program, *this review recommends the PJV core the surface sediments in off-channel water bodies in the lower Strickland (notably ox-bow lakes in the deposition zone) to establish if mine-derived sediment can be detected. Similar cores should also be collected in transects away from the Strickland and Herbert river channels, towards the wetlands adjacent to Lake Murray.*

Water bodies appropriate for coring would be within the area likely to be affected by over-bank deposition, within 200 m of the present channel, and no longer in permanent flow. A number of sites should be cored, some close to the river and others further away, to establish a gradient away from the main river channel (several candidate lakes were observed during the aerial survey of the Lower Strickland). Several cores — at least three each about 0.25 m in length — would be needed in each lake or tie-channel, to be dated and analysed with high resolution to determine whether mine-derived sediments have been deposited in the 1990–1995 period.

The review team recommends that the PJV estimate the annual export of sediment from the Strickland River to the Fly River, based on data from SG3 and SG5.

During flow reversal events when water from the Strickland River enters Lake Murray, it is recommended that research be undertaken to determine whether the water entering the Lake is colder or not and whether it mixes with the Lake water or sinks to the bottom of the Lake. Vertical temperature profiles at several points in the southern end of the

Lake, in the area influenced by the Herbert River inflow, would be an appropriate means of quantifying this behaviour.

5.2 Geochemistry

As stated in the original EMMP, in the lower Strickland River and in Lake Murray the concentrations of dissolved metal ions are so low they can only be measured reliably with 'trace-metal-clean' techniques (Nriagu *et al.* 1993). The values reported from previous monitoring should be treated with caution. They are so close to the detection limit that they may simply reflect contamination during sampling instead of true differences in dissolved metal concentrations.

The metal loadings transported by the Strickland and Herbert rivers are almost entirely particulate. Therefore, chemical impacts on the flood plain around Lake Murray may occur if there is long-term remobilisation of metals after the mine-derived sediment is deposited on the flood plain where conditions may be more conducive to metal release than in the Strickland River itself (e.g. lower pH, possibly low oxygenation, high concentrations of dissolved organic carbon).

Compared with the overlying water column, aquatic sediments tend to have narrower ranges of temperature and pH, higher concentrations of dissolved organic carbon, more surface area, more intense microbial activity, and much steeper concentration gradients for dissolved ions. In oxygen-rich surface sediments, Fe and Mn oxyhydroxides and sedimentary organic matter play key roles in determining the concentrations of dissolved metal ions. In oxygen-poor sediments, sulfides tend to control the solubility of metal ions.

Following settling and deposition, mine-derived metals associated with sediments will be subjected to diagenetic processes. Aquatic sediments normally react with and adsorb metals, and only rarely is there significant remobilisation. A possible exception to this general statement might occur if mine-derived sediments were deposited in an oxygenated environment and subjected to a cycle of alternate wetting and drying which would oxidise any sulfides they contained. Thus, metal profiles in sediment cores must be interpreted with caution — vertical gradients may be caused by chemical reactions of some elements after deposition (notably Fe, Mn and As) rather than by changes in metal deposition rates.

The transfer of ions between water and sediment is the subject of research worldwide, but at present it seems that total metal concentrations in sediments are a poor guide to metal bioavailability. However, the concentrations of metal ions in sediment pore water are thought to indicate the ions' potential to be reactive at the sediment–water boundary. In this context, that also indicates the metal's bioavailability (Campbell & Tessier 1996), i.e. high pore-water concentration represents high bioavailability.

The basic reason for this is that metals must normally dissociate from sediment particles, either in the external environment or within an organisms's digestive system, before they can affect the organism, just as they must dissociate from sediment particles to enter the sediment pore water. These processes are thought to be controlled by the strength of the metal–particle association in any particular micro-environment (Luoma & Jenne 1976, 1977).

5.2.1 Monitoring: current and recommended

The review team recommends that the PJV consider measuring the concentrations of metal ions in the pore water of sediment cores to help in its risk assessment. To make these measurements, the team recommends the PJV collect and analyse the pore water, using pore-water peepers.

It is recommended that, following appropriate risk assessment, the PJV discontinue monitoring dissolved metals in the lower Strickland River because the true concentrations are likely to be in the nano- to pico-molar range, and ultraclean sampling and handling techniques would be required to minimise sample contamination.

The monitoring of particulate metals should be continued.

5.3 Effects on aquatic life

In broad terms, to assess the risks that mine-derived sediment pose to aquatic and other life downstream of SG4, the PJV needs to define the effects of TSS, sedimentation, dissolved metals, and surficial sediment metals on (1) habitat quality, reproduction and rearing of riverine species, and (2) species inhabiting the lowermost Herbert River and adjacent Lakes/side channels subject to periodic flooding from the Strickland River. The main focus should be on organisms used for food by villagers at Ugaiumbu (Tiumsinawam), Kusikina, Miwa, and Boboa.

The impact of mine-derived suspended sediments on Lake Murray will depend on its limnological characteristics. The Lake has a very convoluted high water shoreline, and is relatively shallow with a mean depth at high water of about 8 m, and unstratified. Water renewal time is short (nominally about two months, assuming complete interchange between the pelagic and littoral zones) and water levels fluctuate markedly with the seasonal changes in rainfall (e.g. a drop of 4 m from April to November 1982, cited in Osborne *et al.* 1987; drop of 8 m from March to November 1994, cited in PJV 1994). The waters in Lake Murray are soft, of low salinity, and of approximately neutral pH (though a slight pH gradient exists in the north–south direction, the waters in the northern part of the Lake being slightly more acid than those in the south; S.C. Apte, CSIRO CAAC, pers. comm., Jan. 96).

Based on the very high water levels prevailing during the review team's visit to Lake Murray (January 1996), one might legitimately speculate that most of the microbial heterotrophic activity occurs in the littoral regions of the Lake, close to the extensive beds of floating grasses. To confirm this, *the benthic oxygen demand should be measured at various points in the Lake, along defined transects*; if the littoral zones dominate Lake metabolism, oxygen demand would be greater in the littoral sediments than in the pelagic sediments.

Plate 11. Floating reed beds, upper Lake Murray

5.3.1 Effects of sediments

Apart from any chemical effects, suspended sediments can affect fishes' food supply, spawning habitat, and breathing/feeding. The 'no observed effect concentration' (NOEC) for TSS for aquatic life is about 200 ppm, based on studies concerning juvenile salmonoids, oyster larvae, and echinoderm larvae. For example, Sigler *et al.* (1984) reported effects (thickening of gill epithelium) at concentrations greater than 270 mg/L (as diatomaceous earth) and reported reductions in salmonoid growth at turbidities exceeding 25 nephelometric turbidity units.

Any effects of sediment on fish spawning would primarily affect lithophilic species, i.e. those dependent on a clean stony substrate for spawning, that do not guard and clean their nest sites (Waters 1995). An understanding of the basic habitat requirements of the fish species in the various reaches of the Strickland would improve impact assessment.

Sediment could also be clogging the gill filaments and similar fine feeding structures of zooplankton and bivalves (mussels). This effect should be limited to planktivorous species in the lower Strickland, and the species most obviously at potential risk are zooplankton, the planktivorous herrings

(*Nematolosa flyensis* and *N. papuensis*) and perhaps anchovy (*Thryssa spp.*). These species filter phytoplankton, zooplankton and other suspended microorganisms from the water and would be vulnerable to suspended particles of a size similar to that of their food organisms.

In general, when suspended solids settle in off-channel/oxbow/lake habitats, the particulates have the potential to smother benthic plants and animals and may exert sediment toxicity. Sedimentation, and particularly its effect on embeddedness, can cause major reductions in the abundance of invertebrates (Waters 1995).

This review recommends that these potential risks be investigated; the investigations should be phased, and only extended if there is increasing evidence that such risks exist and require further definition.

The review team disagrees with the food chain proposed in the Environmental Plan; it appears to be much simpler. Based on field observations, the team initially hypothesised a food chain comprising littoral weedbeds + phytoplankton – zooplankton – planktivorous fish (Lake Herring) – carnivorous fish (Barramundi) – humans. However, the Lake Murray villagers also eat catfish (and other species), which feed on benthic invertebrate populations (a very short food chain), much more frequently than Barramundi. The chain clearly must be identified, to define any pathways that link humans to heavy metals in sediments.

The review team concludes that, at present, the PJV cannot determine if there are impacts on food supply due to suspended sediment, because the food chains in the lower river are poorly understood (e.g. invertebrate populations and their relationships to sediment particle size).

5.3.2 Mercury

It is clear that mercury levels have been high in fish and human scalp-hair near Lake Murray since before the development of the Porgera mine (NSR 1988 p.53), though the actual concentrations of Hg in the Lake sediments are not abnormally high. The reasons for these Hg concentrations are less obvious. The key question is whether the deposition of mine-derived particulate material in the Lake will aggravate an already potentially hazardous situation. *The review team recommends the PJV accurately define the Hg pathway to humans and quantify its contribution to Hg levels and additional risk.*

Mercury that has been methylated by aquatic bacteria has greatly increased bioavailability. Since mercury methylation is facilitated by the presence of fresh, labile organic matter, it follows that the methylation rate might be enhanced in the littoral region. Some recent studies of temperate wetland ecosystems indicate a substantial contribution of 'pre-formed' methyl-Hg coming from the terrestrial margins of the ecosystem (e.g. Bishop *et al.* 1995).

If mercury methylation takes place in the littoral zone of Lake Murray, not in the deeper offshore Lake sediments, and if the Herbert River water sinks to the deepder bottom of Lake Murray as speculated, then those newly arrived particles may not have much influence on the overall Lake Hg cycle. However, the review team has suggested above that river water which escapes the Strickland or Herbert river channels may lose its suspended sediment load in the wetlands. Therefore the area at risk from increased loading of mine-derived sediment may not be the Lake itself, but rather the downstream wetlands that lie in the area bounded by the Strickland and Herbert rivers.

The methylation and bioaccumulation of mercury are stimulated by several factors, including the presence of an active microbial community (e.g. as observed in newly flooded reservoirs in northern Quebec and Manitoba). There is a possible analogy here with the Lake Murray system, with its pronounced wet–dry cycle which could lead to periodic pulses in microbial activity. But very little is known about the Hg cycle in Lake Murray, especially with regard to the transfer of mercury to humans via the food chain.

In some of the existing data on the relative methylmercury (MeHg) concentrations in different fish species, the percentages of MeHg relative to total Hg are far lower than

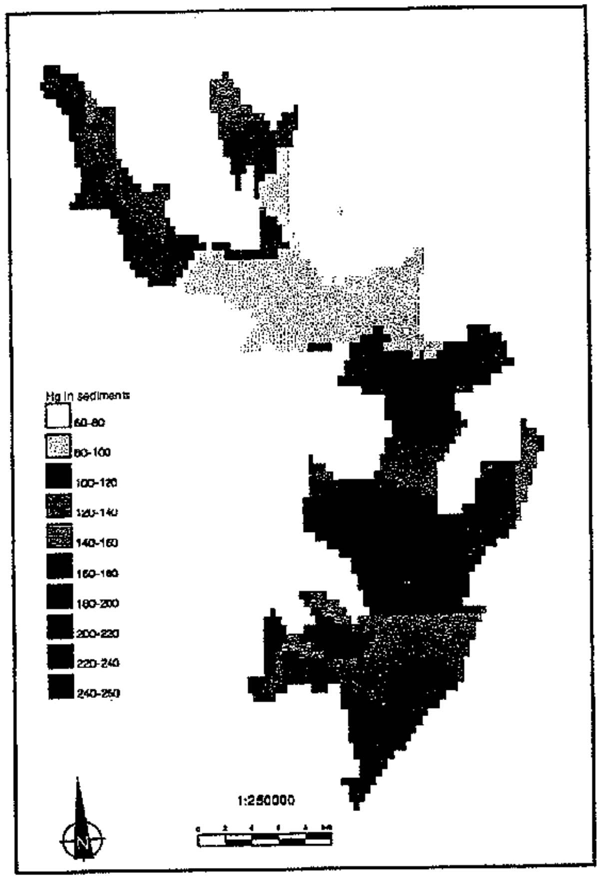


Figure 5.1 **Hg concentrations in Lake Murray sediments, interpolated from sampling points**

would have been expected (9–50%; see *Environmental Baseline Porgera Gold Mine, Vol. 1 Main Report*, p. 5-68). Concentrations of MeHg in fish muscle tissue are normally 90–100% of the total Hg content (Watras & Bloom 1992). *The review team recommends that the PJV clarify this difference, since allowable dietary intake of Hg is usually calculated assuming that all the mercury in fish tissue is present as MeHg.*

5.3.3 Monitoring: current and recommended

The current biological monitoring lacks a spatio-temporal element. *The review team recommends that the PJV identify appropriate spatial scales and allocate sites and determine an appropriate frequency of sampling.* The review team advises the use of a GIS coupled with appropriate statistical tools to help the PJV monitor and understand key ecological processes that are taking place over both time and space. For example, a spatially-interpolated map of Lake Murray sediment Hg levels (*log* scale) derived from the baseline report (NSR 1990b) (Fig. 5.1) shows the north–south stratification of mercury in sediments of Lake Murray.

Multiple capture techniques should be used to estimate the abundance and composition of aquatic biota. The results of this exercise could also be incorporated into a GIS to provide spatially-referenced descriptions of change in populations over time.

It might be possible to use stable-isotope studies to trace the flow of carbon, in other words the predator–prey relationships, in the Lake Murray ecosystem, and from that to deduce the pathways for Hg transfer.

It is recommended that the PJV consider the use of filter-feeding molluscs as biomonitors for Hg (if possible, at least two sites should be chosen, one close to the Lake outlet into the Herbert River and the other upstream, far removed from the possible influence of mine-derived sediment).

The review team recommends that the PJV define, for the key species comprising food consumed by villagers, whether there are 'critical periods' in their life cycles that *could be affected by dissolved metals, TSS, sedimentation, flow, etc. If there is a critical period(s), then the PJV should adjust its sampling program to focus on the critical period(s).* Critical periods are key points in the life cycles where survival is very dependent on environmental factors. For example, the timing of plankton blooms is a critical period for species of fish larvae dependent upon a supply of plankton of certain size, abundance, etc.

It is important that the PJV carefully monitor the diet of the villagers living near the Lake and on the flood plain, and the MeHg content of the various food items.

6

Environmental Management and Monitoring Program: Review

The current Environmental Management and Monitoring Program (EMMP) approved for Porgera collects information related to the effects of the mining operations on the environment, and also satisfies the environmental quality objectives set by the PNG Government.

The EMMP's objective is to evaluate the accuracy of impact predictions made in the Environmental Plan, to identify any unforeseen effects and to monitor operations for compliance with permit conditions.

The review team was asked to assess the adequacy of the EMMP in assessing riverine impacts, and to recommend specific improvements to the EMMP. In the previous chapters we have discussed the variables the PJV has been monitoring in relation to effects on the riverine system as well as the flood plain, and recommended certain changes. The present chapter addresses the practicalities of monitoring: the equipment and techniques being used, the PJV's analytical and reporting capacities, and the changes the review team recommends.

6.1 Monitoring equipment, timing and techniques

6.1.1 Hydrometeorological program

In regard to the meteorology and hydrology program, the review team concludes that the PJV is collecting on a regular basis the information needed to meet the objectives set out in the EMMP. An Australian hydrological consulting group, ECOWISE, has recently reviewed the hydrometric network operated by the PJV, and its field data collection and hydrologic data processing and storage system using HYDSYS (Skinner 1995). Subject to the implementation of ECOWISE's recommendations, the PJV will have a hydrologic data collection program that will withstand rigorous scientific scrutiny.

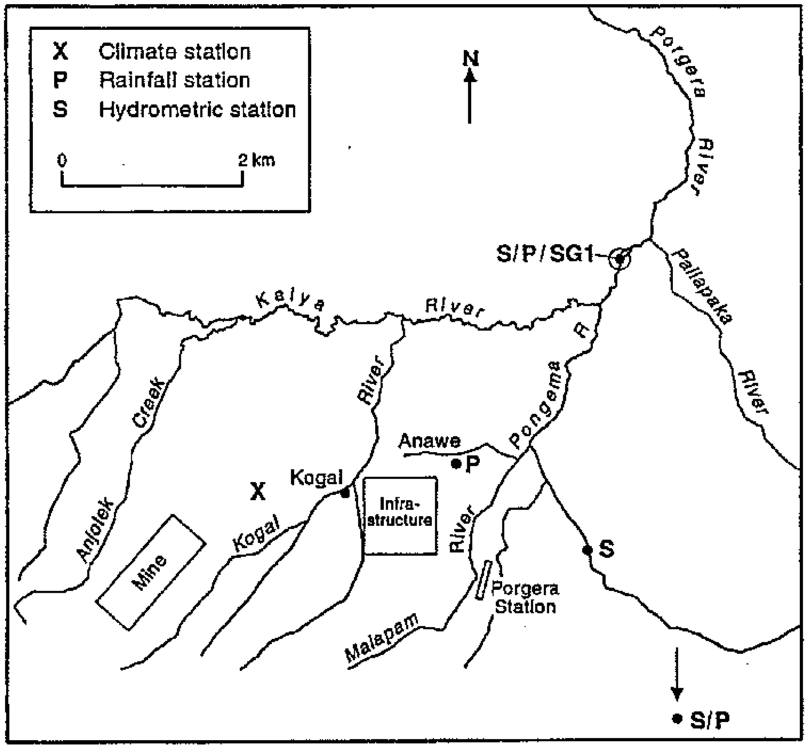
Rainfall and climate

The present review team has examined some of the automatic meteorological stations (mainly pluviometers or pluviographs for rainfall) in the vicinity of, and downstream from, the mine site. ECOWISE has reported on the others. The near-mine instruments have been adequately installed and maintained and have recorded a high level of useful data. Overall rainfall data recovery at SG2 and SG3, of 80% and 90% respectively, is considered satisfactory, given the difficulties at SG2. There is a reasonable coverage of rainfall stations for the SG2 and SG3 catchments, and the quality of data appears satisfactory.

Two meteorological stations operated by the PJV, one at Pandadaka, the minesite station (map 6) and the other at Lake Murray at Boboa (map 7) record daily rainfall, maximum, minimum, wet bulb and dry bulb temperatures, wind run, sunshine hours and Class A pan evaporation. During the past few years nearly 100% recovery has been achieved at both sites; however it is planned to relocate the instruments at Pandadaka to minimise vandalism. For even greater reliability, both stations could usefully be replaced by automatic weather stations.

Streamflow

This review acknowledges that the nature of the terrain, either in steep country or in the



Map 6. Near-mine hydrometeorological stations

very flat lowland area, imposes difficulties in setting up accurate streamflow measurement stations; vandalism is another major problem, and landholder issues can sometimes restrict access to sites for several months.

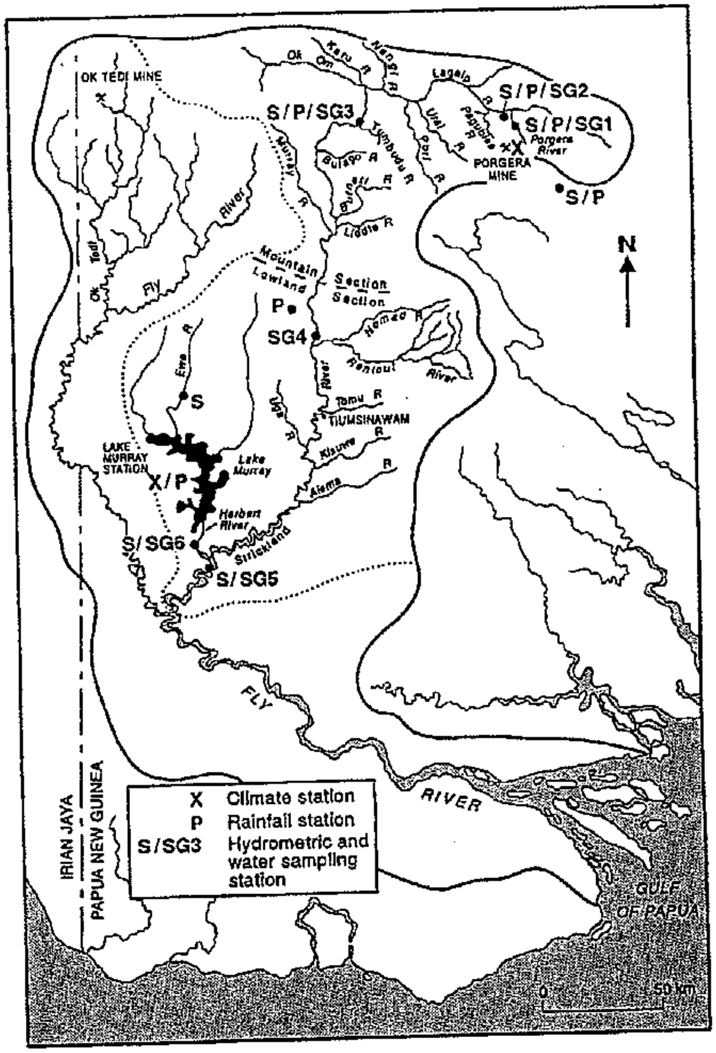
Three stream-gauging stations are located near the mine site (map 6), and gauging stations SG2–SG6 are on the Lagaip, Strickland and Herbert rivers (map 7, Table 6.1). Although SG3 is the compliance point, gauging station SG2 is considered to be a key site in assessing the environmetal impact of the mine operation on the riverine system. *This review recommends SG2 be given higher priority to ensure high quality discharge data are obtained in the future.*

A key part of operating a stream-gauging station is developing a relationship (known as the 'rating' curve) between 'stage' (river height) and discharge, from measurements with current meters and continuous water-level recorders. Reliable stage–discharge (rating)

Table 6.1 Streamflow measuring stations in the Strickland and Lake Murray catchments

Station Ref No.	Station Name	Catchment Area (km²)	Data Period	Days Missing Per Year
804839	Lagaip R. @SG2 (Tamako)	3 423[a]	Jan 85–May 95	106
804800	Strickland R. @SG3 (d/s Tumbudu)	11 700	Dec 88–Dec 95	88
804880	Strickland R. @SG5	35 500[b]	May 88–Apr 94	Operated by OTML
805603	Ewe R. @ Utopovia	not known	Dec 91–Mar 94	240
805605	Herbert R. @SG6	not known	Jan 86–Oct 94	116

Data extracted from HYDSYS data storage system held by PJV.
a: Catchment area is not available in HYDSYS nor in original station file. Area provided by G. Mules (Jan 96)
b: Catchment area given in NSR (1988)



Map 7. All hydrometeorological stations

curves are as fundamental to the accurate measurement of discharge as are continuous records of river height. Without both, stream discharges cannot be predicted adequately.

The review team examined the relevant rating curves for each station. Generally, considerable extrapolation beyond current meter measurements was necessary to estimate higher discharges. The extrapolations were performed using HYDSYS algorithms. In view of the importance of accurate estimates of discharges, *the team recommends that specialist advice be sought on how best to extend the rating curves.*

Whenever feasible, streamflow measurement stations should be gauged on every visit. Since 1992 and especially during 1995 the number of current meter gaugings at the near-mine stations and at SG2 and SG3 have declined (Table 6.2). The near-mine stations are also generating noticeably less stream water-level data (Table 6.3). However, at both SG2 and SG3 a satisfactory stage–discharge relationship is being developed. The percentage recovery of data at SG3 is excellent and at SG2 the recovery is reasonable except for 1994. Discharge data for SG3 are important for understanding the hydrology at this site.

If the SG1 station is decommissioned due to maintenance difficulties, *it is important that the new station proposed for the Kogai River be established as soon as possible and that SG1 remain in service until an appropriate level of correlation is established between SG1 and Kogai and with Pongema @ Road Crossing. This review also recommends that the Waile Creek station (downstream of Dam) be closed.* No data from this station are expected to be used in the PJV's environmental studies and it is of little use in relation to Waile Dam operation. *It is also recommended that the streamflow measuring station established in 1991 on the Ewe River, at Utopovia Village, be closed.* Site conditions there are not very suitable for flow measurement, and the data appear inadequate to estimate flows into Lake Murray from its catchment. Similarly, stations on the June River and the Kaim River are providing little relevant data and should be discontinued.

SG5 is located downstream of the junction of the Strickland and Herbert rivers and may be affected by backwater from the Fly River. It is an important flood plain site, operated by the Ok Tedi Mining Ltd (OTML) hydrographic group. This review recommends that the PJV take joint responsibility for station SG5 with OTML.

At SG6, a stage-height recorder and recording current meter (RMC4) have provided

Table 6.2 Numbers of current meter gaugings at sites operated by the PJV

Station Ref No.	Station Name	1992	1993	1994	1995
804609	Waile Ck	26	11	2	0
804633	SG1	55	25	11	3
804633	Pongema	58	6	1	0
804634	Kaiya#	31	12	6	0
804839	SG2	12	7	2	0
804800	SG3	19	11	6	0

Data extracted from Skinner (1995).
Kaiya station has been de-commissioned as a result of a landslide

Table 6.3 Percentage recovery of data per streamflow station operated by the PJV

Station Ref No.	Station Name	1992	1993	1994	1995
804609	Waile Ck	78	94	98	88
804633	SG1	98	94	66	70
804633	Pongema	96	86	60	61
804634	Kaiya#			56	52
804839	SG2	91	89	56	98
804800	SG3	85	86	99	100

Data extracted from Skinner (1995).

satisfactory data to assess the flows from the Strickland via the Herbert into Lake Murray. If this site continues to be operated, an alternative anchoring arrangement to minimise fouling should be considered.

To estimate the Strickland–Lake Murray flood plain flows, an extra stream gauge (directional current meter, temperature probe and stage recorder) should be installed on the Herbert River at the mouth of Lake Murray. Here it will be important to establish the relationship between velocity as measured by current meter and the average cross-sectional velocity. Another new stream gauge could be installed on the Strickland River upstream of the flood plain. The differences in flows between this new station, SG5 and SG6 will provide a measure of potential flood plain storage. All stations gauging the Strickland flood plain and Lake Murray should be linked to a common datum as there are only small differences in elevation.

This review agrees with ECOWISE that several stations are ready for upgrading and a more vigorous overall maintenance program is needed. We concur with the PJV's decision to appoint ECOWISE to oversee the hydrographic operations.

We recommend that all historical data (rainfall, streamflow and climate) for all the PJV stations be obtained from the relevant PNG authorities and included in the HYDSYS data base. Also, historical and current data for SG5 should be requested from OTML. The HYDSYS database must also contain basic information such as catchment area, station elevation, latitude and longitude, for each gauging station.

6.1.2 Water quality

At present DEC requires the PJV to undertake compliance water quality monitoring monthly at SG3, where flow has been measured continuously since 1983. Compliance is based on the mean concentrations of pH, ammonia, free-CN, sulfide, and dissolved (less than 0.45 μm) heavy metals (Ag, As, Cd, Cr, Cu, Pb, Ni, Zn). There is no compliance level specified for mercury, although the PJV monitors for both total and dissolved mercury as well as total heavy metals at SG3.

The review team considers that an adequate set of water quality parameters is being measured at SG3, but that there is no reason for continuing the measurement of sulfide.

The review team recommends that water hardness should be reported explicitly because of its close tie to the toxicity of certain dissolved metals, namely Cd, Cu, Pb, Ni and Zn (Hamelink *et al.* 1994; Pagenkopf 1983). Preferably, hardness should be measured directly using the wet chemical titrimetric technique and reported as total hardness.

Comparison of the instantaneous flows at the time of sampling with the continuous flow record over the month shows that for the period 1990 to 1995 a reasonable range of flows was sampled. Sampling of low to median flows is important because there is less dilution of mine-derived metals and suspended solids at these times. Low streamflows may also embrace the critical periods for reproduction of aquatic species. It is at these times that dissolved heavy metal and free-CN concentrations will be at their highest, possibly large enough to initiate long-term effects on aquatic organisms' physiologies. On the other hand, at times of very high flows, the loads of total suspended particulate matter may be highest and the potential for river transported particulate matter to be deposited on the flood plain and in Lake Murray will be greatest.

The PJV's Environment Dept samples other sites (e.g. see maps 3, 4, 5) downstream of the mine '... to gain a better understanding of the riverine environment and changes in water quality that may be attributable to the mine operation' (PJV 1995 p.6-1). These include: three sites designed to monitor runoff from the original Anjolek dump site and from the existing Anjolek erodible dump (sampled monthly); the Kaiya River at Yuyane, which collects drainage from the upper catchment and mine site drainage via the Kogai River (sampled monthly); the Porgera River at SG1 located 8 km downstream of the mine (sampled monthly until prevented a couple of years ago by local unrest); the Lagaip River at SG2 located 40 km downstream of the mine site and below the confluence of the Porgera and Lagaip rivers (sampled monthly). Water samples are also taken during an annual five-day biological sampling trip to the Lagaip River at Wankipe, the Strickland River at Ugaiumbu (Tiumsinawam), and the Fly delta.

The review team recommends a detailed review by the PJV of its objectives in sampling these sites, as the application of these data is limited by the relatively low sampling frequency.

The PJV is reviewing the possibility of using SG2 instead of SG3 as a compliance point and hence reducing the mixing zone from 160 km to 40 km of river. The review team strongly endorses such a change, and furthermore suggests that the PJV consider increasing the frequency of the water quality sampling at SG2 to weekly to provide a sufficient database for use in future impact assessment.

This review recommends that the present water quality sampling regimes at the compliance point SG3 and at potential compliance point SG2 be maintained and expanded to be sure of sampling a representative range of river conditions, including very low and very high flows.

6.1.3 Geochemistry

While the high suspended solids concentration and slightly alkaline pH of the Lagaip River are expected to maintain dissolved metals at low levels, the corollary is that it will be a challenge to obtain reliable analytical results for dissolved metals (see also pp.4-12, 5-6). Indeed, some of the early results for dissolved metals appear unreliable, notably those quoted for the baseline study for SG3 (NSR 1990 p.4-57; PJV 1994 Vol.A Table 5.1).

Even the 'current' values for dissolved metals may be too high, since some colloidal material may pass through the 0.45 µm filter; metals associated with any such colloidal material would be expected to have elevated metal concentrations on a µg/g basis (Perret *et al.* 1993). One way of checking this might be to measure dissolved Fe routinely, since in well aerated waters, the true dissolved iron should be extremely low; hence if it is measured in appreciable quantities in the 'filtrate', this would indicate that colloidal iron oxyhydroxides passed the filter (metal to Fe ratios in the 'filtrate' could be compared to those reported for natural iron oxyhydroxides at pH 7–8).

A better approach to determining dissolved metal concentrations might be to use in situ dialysis (cf. Apte *et al.* 1989; Benes 1980). This technique involves filling a pre-cleaned dialysis bag with deionized water and then leaving the bag to equilibrate in the lake or river for 10–14 days. The bags are recovered, returned to the laboratory and opened carefully in a clean-room environ-ment. The sample within the bag is transfer-red to a pre-cleaned (Teflon) bottle, acidified with 'ultra pure' grade nitric acid, and analysed.

The advantages of this approach are its passive nature (colloids are not forced through a filtration membrane under vacuum) and the fact that it minimises sample handling and thus the dangers of accidental sample contamination. By its nature, in situ dialysis provides a time-integrated sample; this characteristic may be seen as an advantage (if the aim of the monitoring program is to evaluate 'average' conditions over time in the receiving waters), or a disadvantage (if the monitoring program is designed to detect extreme events of short duration).

Limitations of the in situ dialysis approach include the need to ensure that the dialysis bag remains submerged and intact for the entire sampling period, and the small volume that can be retained within the bag (though several bags could be used at once).

This review recommends the PJV compare the current technique for measuring dissolved metals (filtration under a laminar flow hood) with in situ dialysis, following the procedure used by Benes (1980), with the intention of adopting the latter approach if it proves feasible.

For suspended sediments, as noted above (p.4-8) the fine fraction (silts and clays <63 μm) is most important from both a geo-chemical and a biological perspective. It follows that the suspended solids collected at SG3 should be separated into standard particle size ranges before being subjected to metal analysis. The PJV will then be able to compare analyses of each size fraction between sampling times and locations. (Samples which differ in particle size are not truly comparable.) This should also improve the potential for detecting the tailings 'signature' (pp.4-8, 5-5).

In geochemical studies, the concentrations of metals in sediments are often compared to 'normal' concentrations of such 'crustal' elements as Al, Fe and Mn, to identify 'anomalous' or 'enriched' samples (Horowitz 1991). Similarly, metals such as As and Hg can be 'normalised' with respect to organic matter.

This review recommends that PJV analyse the TSS samples collected in the Lagaip and Strickland Rivers not only for the concentrations of various mine-derived metals but also for Fe, Al, Mn and organic matter, after the samples have been separated into ranges of particle sizes. Indeed, the determination of these complementary parameters probably should apply to *all* sediment samples, both suspended and settled.

6.1.4 Sediment transport

Based on various reports and discussions, this review concludes that the PJV has followed standard procedures when collecting sediment-related data and making cross-section surveys of the rivers. However, all sampling procedures should be docu-mented. Cross-section surveys should use permanent benchmarks or real-time GPS.

As mentioned previously (p.4-6), *this review recommends that a sediment balance model be prepared.* A sediment balance would act as a focus for the sediment monitoring data, helping to ensure that data are processed and stored in a consistent and accessible fashion. In the longer term, the model would refine the data collection effort to target the parameters to which the impacts are shown to be most sensitive.

Initial emphasis on interpreting sediment impacts should therefore be on modelling volumes and sizes of sediment delivered to the various high impact areas. Later, detailed analysis can target specific areas.

This review recommends the PJV add the following to its monitoring program on a regular basis to obtain information for a sediment balance model:

- ▲ *aerial photography or remote sensing. The initial imaging should embrace the* *whole river system, providing a background or baseline. Later runs can focus on particular aspects once or more per year, revealing changes in the river channels and identifying problem areas, especially downstream of SG4 where over-bank deposition of fines has now been identified as a potential issue (see p.5-2).*

- *particle size analysis of the river beds about every six months should enable the PJV to determine trends in sedimentation from data on the changing composition of the beds over time. Apart from the PJV's normal sampling sites, this review suggests the confluences of the Strickland with the Tomu and Nomad rivers should be sampled, and the gravel/sand transition in river zone 6 (see map 5), as well as sites near Lake Murray.*
- *suspended sediment sampling every week at SG3 and SG5, with a campaign effort downstream of SG1, using the depth-integrated method at SG3 and SG5 in a representative range of river heights to calibrate the current gulp sampling method. This should yield a reliable estimate of annual sediment load.*

This review recommends the PJV mount a monitoring campaign to

- *examine the behaviour of the erodible waste dumps, particularly their capacity, inputs from the mine and losses to the river (assessed by automatic water sampler and rainfall/ runoff model). Apart from contributing information to the sediment balance, this should help better define material inputs and transport in the river system.*
- *determine how much mine-derived sediment is deposited downstream of SG1 and upstream of the Lagaip confluence, using river bed particle size analysis, cross-section surveys and imaging from fixed reference points. This could later be extended to include other potential depositional areas as indicated by the sediment balance model.*
- *determine the fate of mine-derived sediment on the Strickland River flood plain and its ingress to Lake Murray, via shallow cores along transects extending across and up to 5 km each side of the Herbert River and Lake Murray, especially at its southern end (see also p.5-5).*

6.1.5 Aquatic life

The review team recommends the PJV should gather data about the populations of vertebrate or invertebrate aquatic organisms in the river system, in 'control' or reference catchments as well as at various points downstream of the mine (see p.4-6). The objective is to determine whether the mine is affecting the aquatic life or not, and the relative importance of the populations in the various parts of the river system. To be useful the data must characterise the key organisms' life cycles, and the data must be comparable between locations and times. Reference streams need to have elevation, flow regime, substrate composition and temperature comparable to the reaches downstream of Porgera, and not be significantly affected by upstream land uses.

In the Porgera, Lagaip and Strickland rivers above the gorge, invertebrates should be sampled with a 500 micrometer Hess sampler (ASTM 1985) for a standard duration (e.g. 2 minutes) and depth (e.g. 15 cm). Hess samplers should be used only in the fast-flowing sections with gravel–cobble substrates; other equipment (e.g. dredges, see Merritt & Cummins 1996) would be necessary in the lower parts of the Strickland, and in the off-channel habitats. It is important to define the number and types of species in these different environments.

For fish, the review team recommends the PJV estimate the 'standing stock', that is the abundance and biomass of the species per unit area and volume of water sampled. Catch per unit effort (CPUE) can substitute for density data only if the CPUE and density are shown to be highly correlated using that particular fishing or sampling gear.

Gear and fishing methods are highly biased for certain species and sizes of fish. Although the gear types used (currently beach seines and gill nets* in the rivers and purse seines and gill nets in Lake Murray) are reasonable choices, they need to be used appropriately. Other gear types and fishing techniques should be evaluated as well for different situations, such as small seines, purse seines, and electroshocking equipment used in conjunction with block seines. Seines are difficult to use and inefficient in streams with boulders and other snags.

The chosen sampling technique should be validated by comparing the selected method with a standard approach, to ensure it is obtaining a representative sample. This may be done by sampling adjacent reaches of a stream with an electroshocker and beach seine and gill net, at a time when the electroshocker (with block seines) is expected to provide an accurate estimate of abundance.

To make the data comparable, the PJV should employ the same technique at each site every time and achieve an optimum level of experience using each sampling method to minimise variability due to different crews. If either gear or sampling techniques are modified, the modified and unmodified practices should be calibrated against each other. The catches need to be independent rather than correlated, so sampling sessions at a given location should be well separated in time.

When sampling for metal analysis, fish species (and other aquatic life, whether plant or animal) and body parts that are being consumed by local villagers each season should be selected, based on the villagers' representative diet. It is critically important to have a good estimate of each item's contribution to the total daily food consumption (e.g. 600 g sago, 30 g red catfish, etc.), which would have to be obtained by survey. Metal residues

* cast nets are not considered suitable because they fail to subsample the species available or their abundance.

Plate 12. One net catch in Lake Murray

accumulate more in some parts of a fish than in others, so all the parts that are normally eaten should be analysed. The villagers' intake of metal residues can then be calculated to give a true picture of the risk to villagers who eat that fish.

In the region between the Strickland River and Lake Murray, and in Lake Murray itself, it is critical to identify any food chain(s) linking metals bound to Strickland River particulates (and other carbon sources) and the fish, sago and other organisms that people are consuming. This recommendation should only be addressed if the human health risk assessment indicates villagers are currently exposed to a real risk from mine-derived metals, from consuming fish and other aquatic species.

6.2 Environmental laboratory

The PJV's environmental laboratory staff are mainly concerned with assessing and reporting the operation's compliance with the PNG Government's environmental requirements. The major environmental issues identified at Porgera relate to: mill tailings, waste rock management, transportation of hazardous chemicals, waste oil and garbage disposal, sewage treatment, spill containment, drinking water supply, permits for water use and discharge, and rehabilitation. Monitoring the impacts of tailings and waste rock disposal account for a large proportion of the PJV's environmental effort, and accordingly most of the laboratory's resources are devoted to assessing the impacts of these aspects of the mining operation.

The review team considers that monitoring should be adaptive in response to potential impacts. Monitoring comprises three components: (a) compliance monitoring; (b) broad scale monitoring for issue detection and for record; (c) campaign monitoring to gather intensive data to address a specific potential issue. The current effort concentrates on (a) at the expense of (b) and (c).

6.2.1 Staffing

The level of staffing (see p.2-6) observed by the review team is considered a minimum for the amount of data collection and processing required for environmental compliance at present, and too low for the proposed expanded program. For example, to increase the emphasis on biological monitoring in the Lake Murray region, at least one extra biologist position is recommended.

The review team considers there is an urgent need to improve the statistical skill-base of the laboratory, until most of its staff are capable of effectively analysing data (beyond reporting simple descriptive statistics), planning monitoring efforts, assessing the adequacy of existing data, identifying suitable forms of analysis, and investigating complex space–time related issues. Ideally, they would be capable of studying the processes controlling possible environmental impacts close to the mine and within the Lagaip/Strickland river system

The review team recommends the PJV enhance the statistical capability of the environmental laboratory by providing new and existing staff with (i) leadership in the form of a specialist statistician (this person would be trained to Honours or Master's degree level in mathematics and/or statistics) and (ii) training, as necessary, in contemporary statistical methodology; this should include an element of spatial statistics, time series analysis, statistical design, non-parametric statistics, probability theory and risk assessment.

6.2.2 Computing equipment

The review team recommends an immediate upgrade of computing processing and storage facilities in general, and peripheral hardware. In particular, we recommend adequate appropriately resourced computers, provision of software tools (statistics, graphics, spreadsheets and word processors), printers and plotters, so that the reports required by the EMMP are more easily understood and digested by managers and government agencies alike.

The review team suggests that at least a minimal networking system be provided which will also allow the sharing of resources such as hard disk, printers etc. A dedicated 'server' is required as the hub of the local area network, and also to serve as the central repository of all data collected for the EMMP. Data security, archiving and subsequent retrieval would be greatly enhanced by a tape back-up unit to the server, with back-ups performed automatically at predetermined intervals. An internal back-up unit (with tapes stored off-site) would allow for the automated and unattended back-up of important data and files.

When upgrading staff skills in statistics and computing, the PJV should initiate a comprehensive assessment of the laboratory's computer software requirements, paying particular attention to the adoption of common standards for database management, document preparation, and statistical information systems.

Although not crucial to the operation of the laboratory, the establishment of internet and modem access might ease communication between laboratory personnel and consultants or advisers in government, academia, and industry. Some data that are otherwise typed into computer databases could be transmitted electronically, from gauging stations and analytical laboratories for example, avoiding duplication of effort and transcription errors. Given the present high cost of sampling and difficult access to some sites, the feasibility of this option should be explored.

6.2.3 Water quality laboratory

The PJV Environment Section has a small chemistry laboratory, consisting of a separate 'clean room' where samples for heavy metal analysis are processed, and a general area where other non-analytical activities also take place.

This review recommends that the environmental chemistry laboratory area be urgently upgraded.

The chemistry laboratory staff analyse water samples for pH, conductivity, TSS, major cations, anions, total-CN, WAD-CN and free-CN. The staff also process water samples and sediment samples for heavy metal analysis, the actual analyses being done in external laboratories. Biological samples for heavy metal and mercury analysis are handled by the biology section.

The chemistry staff are competent and capable of undertaking the analyses for which they are responsible. The senior chemist (Mr John Okai) displayed a clear understanding of good laboratory practice and in particular the potential problems associated with low level heavy metal analyses. Equipment is adequate for the analyses presently being undertaken, and well maintained.

The laboratory is well organised and well run. Samples and determinands are recorded and uniquely identified. All analytical methods are well documented and rigorously followed. Records of all analyses are kept and can be quickly recovered. Analytical results are checked by the senior chemist. The procedures used in the 'clean room' to filter and preserve water samples for heavy metal analysis appear to be of high quality.

A check of one particularly high TSS concentration revealed that this high value had been recognised at the time of analysis, but a repeat analysis was not undertaken. This is not desirable, and all suspect results should be identified and a repeat analysis undertaken.

The environmental chemistry laboratory has declared its intention of achieving NATA accreditation, and much of the documentation is already prepared.

This review recommends that the PJV seek accreditation for the environmental laboratory as soon as possible.

The review team is aware of the considerable amount of biological work that has been undertaken by Ok Tedi Mining Ltd over a period of almost 10 years. The extent of the interaction between the two companies at present seems to be limited to combined sampling at the Fly estuary. We urge the PJV to develop closer links with OTML environmental personnel, and identify issues and monitoring procedures in common and cooperate wherever possible.

6.3 Quality assurance and control

Quality assurance has at least five components: the quality of the data collected or analysed; the quality of the sampling and sample handling; data entry and checking; outlier detection; and process capability.

As mentioned above, the quality of the hydrometeorological data appears good, but the network needs upgrading and more current meter measurements are needed so that reliable rating curves can be defined. The PJV has appointed ECOWISE to oversee and lead the hydrographic operations.

In regard to water quality and biological samples, the team reviewed both external and in-house laboratory QA/QC practice.

The performance of the external analysts appears to be generally satisfactory. Adequate procedures have been adopted at NAL, University of Technology, for the heavy metal analyses in water samples. They use a filter blank, a standard reference material, and an in-house secondary standard, with each batch of samples. Sediment and biological samples are analysed by the Queensland Department of Primary Industries (QDPI) who use appropriate standard reference materials for each batch of samples analysed.

For 'in-house' analyses, appropriate standard reference materials are available and should be used. *This review considers the environmental laboratory should formulate and adopt a consistent approach to (i) units of measurement for all data collected by the* *laboratory; and (ii) the recording and treatment of data whose values are below the achievable detection limits.*

It is also recommended that all recorded data use as many significant figures as the accuracy of the experimental procedure will permit. For example, many of the data presently stored in EQWIN are recorded in mg/L when in fact μg/L is more appropriate (for example an actual value of 0.2345 μg/L is subsequently recorded as 0.0002 mg/L).

Similarly, many values for water chemistry data are below the detection limit of the analytical procedure used and there does not appear to be any uniform method of dealing with these observations. EQWIN provides the following four options: use the '<' sign to denote under detection limit (e.g. < 0.002)*; or assign a value equal to the detection limit; or assign a value that is half way between zero and the detection limit; or assign a zero value.

Clearly, these extremely small values present no difficulty from a compliance point of view, although inconsistency in their labelling will tend to distort derived statistical measures. It is therefore suggested that the '<' convention be adopted for recording purposes but that these be converted to the detection limit for statistical computations. This will cause a small upward bias in reported means and a possible slight lowering of measures of variability, although it is expected that these effects will be minimal.

During field sampling excursions, it is possible that the dissolved heavy metals, ammonia and free-CN concentrations in samples may change, even over these relatively short time periods, in spite of the samples being kept on ice. The nature and scale of such changes should be investigated to assess their significance.

This review recommends that appropriate QA/QC procedures be used for all in-house analyses. If external laboratories report unacceptable values for QA/QC samples, the matter should be investigated promptly in a well-defined sequence of actions. Outcomes of this investigation should be fully documented. A special investigation should research whether significant changes occur in the concentrations of dissolved metals, free-CN and ammonia due to the storage of samples with a range of suspended solids concentrations.

* It is not clear how EQWIN treats these observations in the subsequent computation of sample statistics.

6.3.1 Data entry and data validation

It is essential that staff check the accuracy of data entered into the databases. To avoid transcription errors, external laboratories could provide results electronically in a format that is acceptable to the environmental laboratory, and send them in by e-mail or dial-in facility or on computer disks.

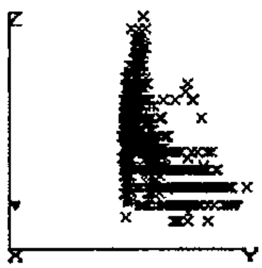
It is therefore recommended that the use of electronic media for data acquisition be investigated.

6.3.2 Outlier detection

The environmental laboratory should establish criteria against which monitoring data, such as the results of analyses, are compared. Aberrant observations should be identified and investigated, and any changes to the originally recorded data values arising from these investigations should be recorded in a log-book. This log should note information such as: name of investigator; date; reading(s) altered; original value(s); new value(s); reason(s) for change; and database(s) affected.

Staff in the environmental laboratory carefully scrutinise all recorded data; the process is greatly facilitated by automated routines programmed into software packages such as EQWIN and Microsoft ACCESS. Typically, a 'flag' is raised if a recorded observation violates a criterion that has been established by the *user*. There are some potential problems with that approach: i) specification of the criterion is often subjective; ii) it is difficult to trap all types of 'aberrant' observations with this approach; and iii) the procedure only ever considers single variables and is thus insensitive to outliers that arise in a multivariate context.

As already recognised by the environmental laboratory staff, the identification of a potential outlier should *not* lead to its



Axis	Variables
X	total Hg
Y	pH
Z	Temp

Fig. 6.1 Scatterplot of tailings data

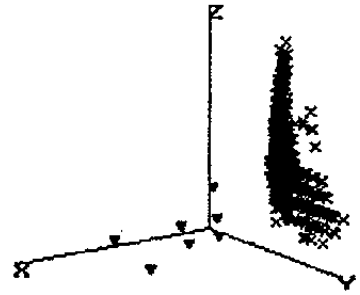


Fig. 6.2 Rotated scatterplot of tailings data

automatic removal from the database. However, if a source of contamination or interference can be found, the observation can be discarded, provided that appropriate records of such changes are maintained.

A dilemma is presented when no explanation exists for the cause of the 'outlier'. The effects of even a single, but extreme observation in subsequent statistical analyses can be profound, to the extent of altering (and perhaps invalidating) subsequent conclusions. Alternatively, if no explanation can be found, the observation may be legitimate and represent one of those rare events where extremes occur by chance.

How these outliers are handled depends to some extent on subsequent statistical analyses and the ultimate objective of the data collection exercise. We suggest that in matters of environmental monitoring and compliance, the PJV should make conservative judgements that clearly avoid bias and/or manipulation. This includes the situation where an unexplained outlier's effect will narrow the gap between current operational levels and compliance. On the other hand if the outlier tends to widen this gap, then a less contentious approach would be to replace the offending observation with a 'missing value' code. It is thus immediately apparent to any observer that a recording *was* made, but that it is not being used in the computation of summary statistics.

The power of graphical presentations to both identify trends and variability in datasets and as a management tool cannot be overstated. Lists and summary statistics are, of course, necessary and useful for any statistical analysis, but they suffer at least two drawbacks: i) patterns, trends and outliers are not easily depicted; ii) they discourage careful inspection and comprehension, both by management personnel and by external agencies.

For illustrative purposes only, we present part of the tailings data using simple scatter plots in Figs 6.1 and 6.2. In Fig. 6.1, a very low pH (1.0) is visible in the lower left corner of the plot (the computer display actually highlights previously identified outliers in red). It is also clear that there is no obvious relationship between the plotted variables. Fig. 6.1 is in fact a 3D plot in which the viewing angle is coincident with the *x*-axis. By rotating the plot a different perspective is obtained (Fig. 6.2) and the discordance with other observations is apparent.

The graphical approach is useful when assessing the degree of normality (or log-normality) in some population for which we have sample data. Simple graphical devices such as histograms and box-plots should be routinely used in the presentation of environmental data. The degree of normality exhibited by the *log*-transformed concentrations of some parameter can be readily assessed by a visual inspection of a *normal probability plot*. Such a plot is shown in Fig. 6.3.

The departure from linearity exhibited by the plot in Figure 6.3 is evidence that the *log*-transformation has *not* successfully restored normality. This observation is supported by the test statistic appearing in the bottom right corner of Fig. 6.3. The *p*-value of 0.000 of the formal test of the hypothesis of normally-distributed data is highly significant, leading us to reject the assumption of an underlying *log-normal* population. Again, this finding, while fairly innocuous, may have important ramifications for the way in which these data are both reported and analysed.

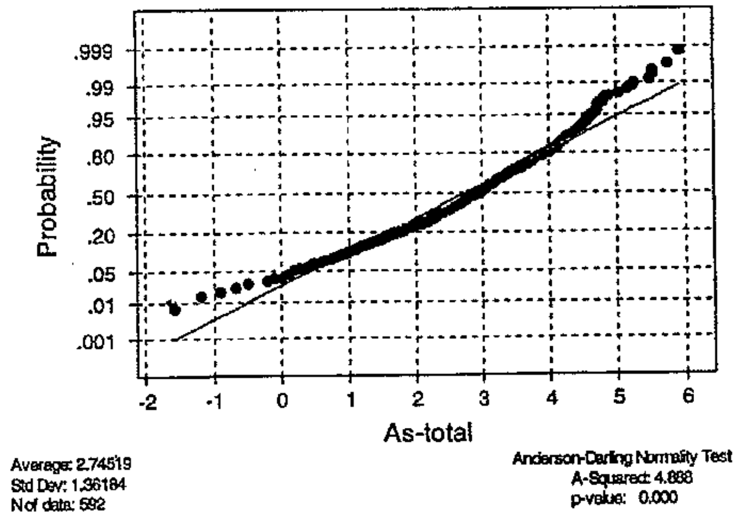


Fig. 6.3 Normal probability plot for log-transformed total As data (SG3, 1991–94)

Graphical tools are often greatly enhanced when combined with powerful statistical methods for exploratory data analysis (EDA). A number of robust procedures are available for signal analysis, filtering, and smoothing and some of these have remarkable abilities to extract an underlying signal from very noisy data. By way of example, we have applied a Super-smoother (Friedman 1984) to As concentration data obtained at SG3 between March 1990 and October 1995. The raw data together with the extracted signal are shown in Fig. 6.4. Although difficult to detect from the original data, the smoothed plot (solid curve in Fig. 6.4) clearly shows a very periodic signal with a linear upward trend. The periodicity observed in Fig. 6.4 is related to flow and the extracted flow signal is shown in Fig. 6.5. Comparison of both plots shows a strong association between the peaks in Fig. 6.4 and the troughs in Fig. 6.5. This of course is to be expected.

This review recommends the use of appropriate statistical tools and graphical methods whenever possible, for visualising and presenting compliance data. The PJV needs to use more sophisticated ways of detecting outliers in complex, multivariate data sets.

6.3.3 Process capability

There are strong parallels between environmental monitoring for compliance, and monitoring in industry using statistical process control (SPC). In SPC, we generally wish to (a) determine if a process is *capable* of conforming to certain tolerance specifications and (b) distinguish between 'in-control' and 'out-of-control' processes. It has been previously suggested to the PJV (NSR 1991 section 2.1.4) that some basic SPC charting facilities be incorporated into the environmental monitoring effort.

This review strongly encourages the PJV to adopt some basic SPC technologies, not only for environmental monitoring, but also for production-based reporting and monitoring. As the PJV gears up for increased production, it would be useful to conduct some process capability analyses to determine whether or not facilities such as the neutralisation circuit are capable of continuous 'in control' operation over sustained periods.

This review recommends that the PJV adopt a monitoring culture that embraces some basic principles and procedures of statistical process control (SPC) to help it better observe, understand, and control key components of its production facility.

6.4 Storage of data

This review recommends the environmental laboratory develop a unified database management strategy that addresses security, storage, maintenance, and back-up issues. Consideration needs to be given to the establishment of a single database for the

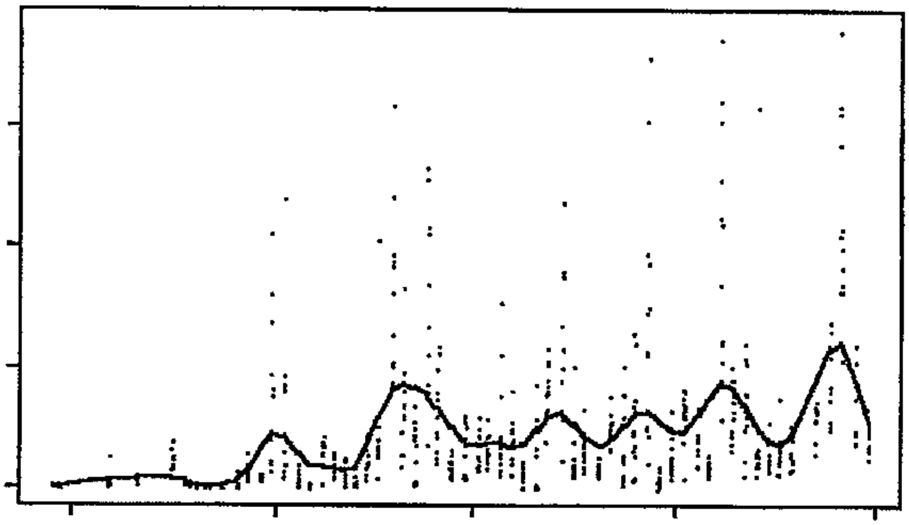


Fig. 6.4 Robust smoothing of As concentrations (in suspended solids) at SG3, Mar. 1990 to Oct. 1995

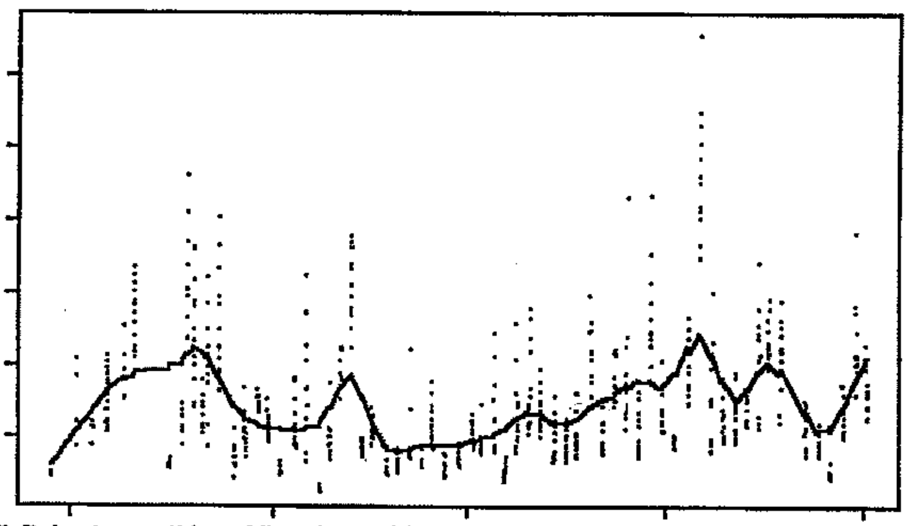


Fig. 6.5 Robust smoothing of flow data at SG3, March 1990 to October 1995

storage of all data collected by the laboratory.

The environmental laboratory operates at least three databases:

- ▲ hydrologic data are archived using HYDSYS, a powerful data processing and archiving system used by most water authorities and research institutions in Australia. HYDSYS is well understood by the PJV staff who were able to respond to all requests for data during this review. ECOWISE in their review noted several areas that need attention; nevertheless overall the arrangements were found to work very well.
- ▲ water quality data reside on another computer and are being entered into the database EQWIN;
- ▲ biological data are maintained on a third database using Microsoft ACCESS.

That arrangement may be satisfactory for compliance monitoring and reporting purposes, but it complicates the task of providing an integrated overview of the PJV's operations and their effects on the environment.

There appears to be no database for the storage of sediment data. This review suggests that cross-sections, and sediment data if possible, are stored in HYDSYS. Alternatively, a database or spreadsheet model could be set up to store particle size distribution data and the results of other sediment-related investigations, e.g. dump surveys. The key issue is that it is easy to transfer data between systems. It must be possible to combine data as required; for example, TSS, metal concentrations and flow data to produce annual loads.

Alternatively, formation of a common database, or combination of the current databases on a central server, would enable staff to link otherwise disparate pieces of information according to key variables such as date, site, time, or event. We do not underestimate the magnitude of this task and accordingly *recommend that the PJV outsource the task of establishing an integrated database facility*.

Central to the successful operation of this facility is the development of a database management strategy which clearly identifies lines of responsibility, functional roles, change control procedures, validation procedures, security procedures, and maintenance and backup plans. This strategy could be the responsibility of the specialised statistician recommended for the environmental laboratory.

Current database security arrangements could be enhanced if the database itself were subject to a form of encryption. There are some freely available software products that incorporate the latest encryption technologies and these could operate almost transparently in the background so that the database is decrypted (after entry of legitimate password) when it is first accessed and then re-encrypted when the user exits the system.

6.5 Baseline data

The Environmental Plan (NSR 1988) recommended an initial baseline study of a range of relevant natural environmental variables in those areas affected by the project, to provide information on the condition of the river system before any effects due to the mining operation occurred. Then, information derived from an on-going monitoring program could be compared with the baseline to determine the relative scale and nature of changes in key quality indicators.

However, the resulting baseline database is limited in extent, and its statistical analysis is seriously flawed. While its scope may have been considered acceptable when undertaken, it is inadequate by today's standards. In designing a water quality monitoring program it is now considered essential to specify both the magnitude of the change and the power of the analysis to detect this change (Underwood 1991, 1993).

No hydrologic results are given in the baseline report. Some discharge parameters are presented for SG4 based on a SMEC report (1985), but no low flow frequencies nor flow duration curves are given. Median discharge at SG5 was estimated from only seven months of daily flows collected over two years.

The baseline report describes, very briefly, prevailing winds, mean annual rainfall, relative humidity and monthly temperatures of Lake Murray, plus long-term monthly rainfall for several stations in Lake Murray region and its catchment. Flow in Herbert River is discussed, based on analysis of normal and reversed flows for 1110 days at SG6.

The baseline water quality data were gathered from relatively few locations and on relatively few occasions, reflecting the logistical difficulties of obtaining sufficient pre-mining data in such remote areas (NSR 1990a, b). Information is available for studies carried out in 1984, 1988 and in May and June 1989.

Some participants in the interlaboratory comparisons produced poor results. Sample sizes were too small to permit calculation of meaningful relative standard deviations (or coefficients of variation), but these were then subjected to analysis of variance (ANOVA). Not surprisingly, anomalies were noted in the ANOVA results and the confidence-interval-based analyses.

While much of the water quality baseline data, at least, will be useful for comparison purposes, it is too sparse to allow statistically valid 'before-and-after' mine operation comparisons to be made; hence the need to establish and use control sites for making statistical comparisons.

6.6 Data processing, interpretation and reporting to company and DEC

The effectiveness of monitoring depends on interpretation of data. The review team considers the Environment Dept must develop its abilities at interpreting data to:

- assess existing impacts;
- detect potential impacts;
- adapt monitoring programs; and
- determine long-term prognoses.

The Environment Dept should increase its use of peer review processes to ensure its operation has credibility.

6.6.1 Processing: reliance on means

The PJV and DEC need to identify appropriate and powerful statistical methods to analyse data gathered as part of the EMMP. Computational details and data processing requirements should be prescribed in sufficient detail to ensure (i) the results are reproducible, (ii) there is no ambiguity in methods to be adopted. This process needs to acknowledge the possible subtle difference between a statistically significant result and an environmentally significant result.

Much of the present compliance monitoring is focused on means or *average* values with little or no attention given to the important issue of *variability*. This review disagrees that means can be relied on as key indicators of environmental change. For example, a greater degree of safety is afforded by a dam that will withstand a one-in-one hundred year flood rather than one which is designed to withstand an 'average' flood. Similarly, one may argue that it is not the average concentration of a pollutant that is biologically or environmentally important — it is the frequency of exceedence of a threshold or 'critical' value with which we should be most concerned.

For example Fig. 6.6 shows two distributions that have different shapes but identical means of 45. Suppose a value of 100 corresponds to a lethal toxic concentration for some contaminant. If the *true* distribution of contaminant concentrations corresponds to the dashed curve, there is almost a zero probability of obtaining a value of 100 or larger, but there is about a 10% chance of this happening if the true distribution corresponds to the solid curve. However, the means of these two distributions are indistinguishable, even though the distribution represented by the solid line is far more environmentally 'damaging'.

6.6.2 Processing: statistical distributions of data

The setting of compliance criteria using conventional statistical tools invariably requires some strong assumptions to be made about the underlying distribution of values. Violation of any one of these assumptions can lead to seriously flawed conclusions being reached. For example, if the concentrations of a contaminant are assumed to follow the dashed curve in Fig. 6.6, we can readily deduce that there is only a 4% chance that the mean of a *sample* of 12 observations, say, will exceed 50. Thus 50 might be used as a compliance criterion against which the mean of 12 observations is compared. However, the solid curve in Fig. 6.6 exceeds that criterion approximately 30% of the time even though the average concentration is at an 'acceptable' level.

Thus, there would appear to be a fairly compelling argument for regulatory agencies to avoid the use of classical, parametric statistical inference in setting compliance criteria. A preferred alternative would be to adopt more robust, *non-parametric* approaches that are generic and do not make assumptions about distributions.

D. Fox (pers. comm.) has suggested the use of sample percentiles as a possible alternative to mean-based compliance monitoring. *The PJV should engage the services of a research-capable statistician to identify more robust alternatives to mean-based inference.*

6.6.3 Processing: statistical versus environmental significance

This review also warns against preoccupation with *statistical* significance. Hypothesis testing, though useful, invariably requires a number of key assumptions to be met for the correct application and interpretation of results.

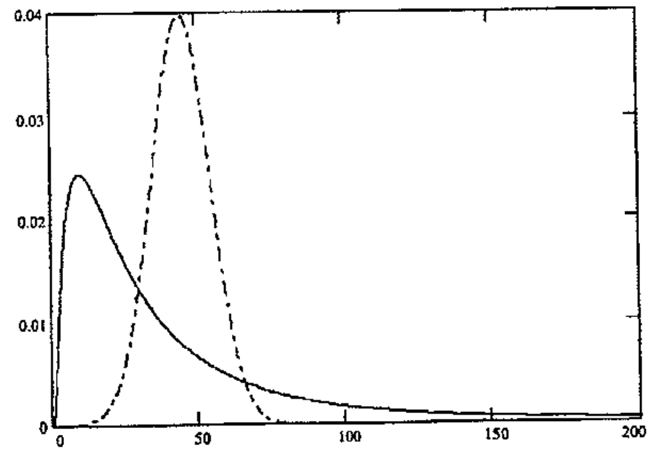


Fig. 6.6 Comparison of two distributions having the same mean

The difference between statistical significance and ecological significance is illustrated in Fig. 6.7. Samples that are too small have low *power* — that is they lack the ability to detect a change when one has taken place. Conversely, very large samples will frequently detect trivial effects which are of no ecological or environmental relevance.

Previously the PJV appears to have determined appropriate sample sizes on a fairly *ad hoc* basis. A detailed examination of the past five year's compliance data should satisfactorily resolve sample size issues although such a task is beyond the scope of this review.

This review acknowledges that the concepts of statistical power and sample size determination are difficult to apply to environmental data and that this process is not an exact science. Nevertheless we believe it is important that the PJV assess the power of the existing monitoring program, to decide at least if it is 'capable' or 'incapable' of detecting effects or change of some prescribed magnitude.

This review supports the PJV in its commitment to a comprehensive review of data collected over the past five years with a view to identifying appropriate strategies for data collection and analysis, suitable for on-going compliance monitoring.

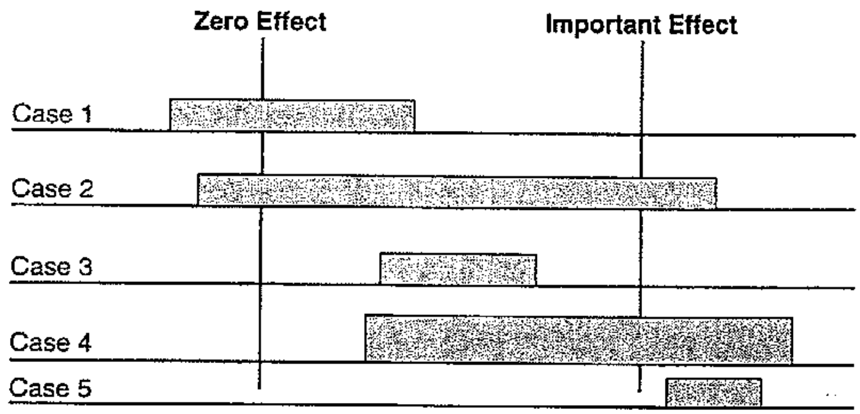
6.6.4 Processing: raw versus transformed data

Logarithmic transformations remain a vexing and persistent issue in the statistical treatment of data for compliance monitoring. the PJV staff routinely compute summary statistics (e.g. sample mean) on *log*-transformed water quality data and then 'back-transform' this quantity to the original scale. The rationale is that this process provides a more realistic measure of an 'average' value. We do not disagree with this justification, but it is misplaced.

It can readily be shown that this transformation process of log-normally distributed data* can lead to considerable underestimation of the true mean value. In practice, this is unlikely to alter the PJV's *current* position with respect to compliance, as many water quality values are presently below the limits of detection. As well, the review team has analysed water quality data for 1990–1994 (PJV 1995 Table 5.1) which show that the median dissolved metal concentrations at SG3 do not exceed the compliance levels (which are in the form of maximum concentrations not to be exceeded). However, this issue will attract greater attention if and when metal concentrations threaten to exceed compliance levels (e.g. if the compliance monitoring location is moved upstream to SG2 and/or *total* concentrations are adopted in place of dissolved concentrations).

The overriding consideration is that if compliance is couched in terms of a mean value (and we have previously argued that

* The log-normal distribution has been shown to provide a reasonable description of many water quality variables.



Case 1: The observed effect is not statistically significant, and the results imply it is not large enough to be acted upon.
Case 2: The observed effect is not statistically significant, although the results imply it is large enough to be acted upon.
Case 3: The observed effect is statistically significant but the results imply it is not large enough to be acted upon.
Case 4: The observed effect is statistically significant and it may or may not be large enough to be important.
Case 5: The observed effect is statistically significant and we can be confident that it is large enough to be important.

Fig. 6.7 Ecological significance versus statistical significance

this measure should be reviewed), then the *sample mean of the raw data* provides the best (unbiased, minimum variance) estimator of the *true* mean, irrespective of the properties (spread, skewness, etc.) of the underlying distribution.

This review recommends the PJV cease its current practice of logarithmically transforming compliance data prior to the computation of sample statistics. Sample means and standard deviations that are routinely reported to DEC should be based on raw (untransformed) data. Data transformations should only be undertaken where this is necessary to satisfy the requirements of statistical methods used to analyse the data. In such cases, both the statistical method and the form of the transformation should be agreed upon by the PJV and DEC and be specified in the EMMP. *This review recommends the PJV consider reporting the range of monitoring data for dissolved contaminant concentrations, as well as the mean and variance values.*

6.6.5 Processing: need for control sites

The review team considers the PJV should monitor at additional sampling locations which can act as 'controls', for instance at Lagaip River upstream of Porgera River confluence, Ok Om River upstream of its confluence with the Strickland River, Tumbudu River.

In the case of the Lagaip/Strickland River a direct comparison could be made of water quality both with and without mine-derived inputs. The natural variation in riverine water quality and flows could then be subtracted from the monitoring results, presumably making them less 'noisy'. Without such controls, there is a risk that both short-term (seasonal) and longer-term or larger-scale *natural* impacts will be erroneously ascribed to mining operations.

This review recommends the PJV reconsider the location of monitoring sites along the riverine system from Porgera to the Fly Delta, so as to (i) assess the suitability of each site to contribute to the resolution of spatial and temporal variability in monitored data, and ii) identify suitable locations for the placement of 'control' sites.

6.6.6 Interpretation

The current EMMP, approved by DEC in 1991, provides a fairly rigid framework for compliance monitoring. It appears that the focus of the PJV's data collection and analysis has been driven by the activities it is required to undertake for compliance, as distinct from those necessary to *interpret* and *understand* the information contained in those same data.

This review considers the objectives of environmental monitoring should be broadened, placing increased emphasis on interpretation of results, and on investigative studies within a unified framework aimed at identifying and understanding relationships between Porgera activities and downstream environmental effects. The individual monitoring components could be combined into a unified framework such as a computer model, complementing the routine reporting of compliance data to the DEC and assisting the PJV in fine-tuning its operations to minimise environmental impacts.

The PJV is routinely gathering data from a number of sources on a host of target variables. This review considers the PJV should use this information with a view to *modelling* the system (mine + environment). This would give the PJV a much needed prediction and forecasting capability which would lead to a more pro-active approach to environmental management rather than reactive monitoring.

6.6.7 Reporting

There is considerable scope to improve the Annual Environment Reports from the PJV to DEC. While they contain a summary of the environmental monitoring results for the relevant period, they give very limited interpretation, in either words or graphs and diagrams.

For example there could be more detailed discussion of trends in the water quality data, and synthesis of those results that add to the PJV's understanding of the river system. The current year's hydrologic data could be added to those of previous years, and the current data should be interpreted relative to the longer trends. The predictions in the Environment Plan should then be specifically addressed.

The reports could also contain better documentation of the sampling procedures and equipment used. For example, fish sampling information should list the specific mesh sizes and types and numbers of seines used at each location, how they were deployed (e.g. round haul), and how the unit effort was defined.

A hydrology and sediment monthly report to management could be produced, summarising the fieldwork completed, data analysis, trends and their implications and progress of special projects and ongoing monitoring.

As well, there is scope for a series of overview (synthesis) reports and reviews to be prepared, published and widely distributed. Several of the reviews prepared by Dr Simon Apte from CSIRO are of a very high standard and would stand up to detailed scientific scrutiny (e.g. Apte 1994a–c).

This review recommends that the PJV (i) upgrade the quality of the annual environment reports, including interpretation of current results in the light of those of previous years; (ii) consider the preparation and publication of a series of overview and review reports on the environmental work being undertaken; and (iii) report the results of health surveys and analyses to the villagers living along the river system.

At the time of this review, we specifically recommended that the environmental manager should report directly to the mine manager. We note that this matter is no longer an issue. Nevertheless, we consider that the PJV should continually assess the mechanisms by which information on the environmental performance of the operations is relayed internally to senior management and externally to DEC, DMP and other relevant parties

This review recommends that the PJV develop a coherent and comprehensive research plan for the operations, and that this plan address specifically how the results of this research will be transferred to management and stakeholders.

7

Summary of this report's recommendations

The following list summarises the review team's recommendations, made (in italics) in the various sections of the report. Several recommendations have been combined here, to avoid repetition, but the source of each is given in square brackets [chap-page]. The recommendations progress from human health issues to those for aquatic life, then mine processes, chemical effects, sediment and physical effects, and sampling/reporting techniques. Finally, we repeat the recommendations given in the Executive Summary.

With respect to humans

the review team considers it important for the PJV to:

1. supply basic drugs and equipment such as chloroquine, antibiotics, dressings material and aspirins to people living along the Strickland and Lagaip rivers. In addition the PJV could arrange for a person from each village to be trained as a Village Aid worker. [3-13]
2. consider providing solar-operated refrigerators for medical purposes. [3-15]
3. consider trading with villagers in areas other than Lake Murray, in order to give them some economic independence and improve malaria and filariasis control. The PJV might buy bulk fruit and vegetables from the villagers, for consumption at the mine site, and sell them treated mosquito nets at a subsidised price. [3-14, 3-15]
4. introduce communication campaigns, advising on the maintenance of drinking water quality, on housing and ventilation to reduce respiratory infections, and on the building and proper use of pit toilets. [3-15]
5. undertake clinical examination of the villagers during sampling of their hair and/or blood for heavy metal analysis, to permit more meaningful correlation between hair analyses with clinical findings, and ensure the results are communicated to the villagers to further improve relations with them. [3-14]
6. measure metal residues in villagers' food items that (a) have not been previously defined, (b) are common food items, or (c) may contain significant metal concentrations. Metals should be analysed in all edible parts of the villagers' foods, collected under all sorts of river flow conditions, and the results, particularly for sago, should be compared with those of similar analyses of items from a 'control' system. [3-15, 3-17]
7. determine why residents of Lower Strickland villages (e.g. Bebelubi and Tiumsinawam) do not have greater dependence on fish. [3-17]
8. conduct new surveys of habits and dietary preferences of villagers from Eyaka, Wankipe, Bebelubi, Tiumsinawam, and lower Lake Murray (i.e. Kusikina, Miwa and Lake Murray Station at Boboa), obtaining data on total daily food and water intakes in grams and litres during all seasons, specifying what aquatic species are consumed, and exactly what water sources are used for drinking and bathing, and the extent of swimming. [3-17]
9. (after tasks 6–8), conduct formal quantitative probabilistic human health risk assessments for residents of each village along each reach of the river system

(e.g. mine to SG2; SG2 to SG3, etc.), for major exposure pathways: drinking water; food (fish, turtles, crocodiles, terrestrial game, garden produce, sago making, etc.); incidental water ingestion (swimming); gold panning (Porgera River waste dumps only); etc. [3-17]

10. use internationally recognised sediment toxicity criteria when making a preliminary judgement concerning the potential for risks. If potential risks are found to exist, then it is recommended that the PJV measure metal concentrations in sediment pore water and also conduct site-specific sediment bioassays to further assess such risks. [4-11]
11. accurately define the Hg pathway to humans and quantify its contribution to Hg levels and additional risk. As part of that, (i) consider the use of filter-feeding molluscs as biomonitors for Hg (if possible, at least two sites should be chosen, one close to the Lake Murray outlet into the Herbert River and the other upstream, far removed from the possible influence of mine-derived sediment); (ii) find out why the percentages of methylated Hg (MeHg) relative to total Hg are so much lower than expected; (iii) measure benthic oxygen demand at various points in Lake Murray to determine if littoral areas are sites of greater heterotrophic microbial activity; and (iv) determine the feasibility of using stable isotopes to clarify the flow of carbon in the Lake. [5-7, 5-8, 5-9]

For aquatic life:

12. evaluate the bioavailability of particulate metals (in particular As and Pb) at SG2 and SG3. [4-12]
13. research the ecology and population sizes of aquatic creatures that are part of the human food chain in all parts of the Strickland river system including lakes/channels adjacent to the Herbert River, so as to understand how their occurrence, reproduction, and feeding are affected by river conditions, turbidity, sedimentation and embeddedness, as well as by variables associated with the mine wastes. Make a phased investigation of the potential risks from such effects. (This includes defining the relative importance to aquatic life of tributaries to the mainstream Lagaip and Strickland rivers, and comparing the results with those from 'control' or reference catchments.) For fish, the review team recommends PJV estimate the 'standing stock' of key species, that is the abundance and biomass per unit area and volume of water sampled. [4-6, 5-8, 6-7]
14. define whether there are 'critical periods' in the life cycles of the fish (targeted by villagers for food) with respect to dissolved metals, TSS, sedimentation, flow, etc., and adjust the sampling program to focus on any critical period(s) found. [5-9]
15. identify appropriate spatial scales and allocate sites and determine an appropriate frequency of sampling for biological monitoring; also employ multiple capture techniques to estimate the abundance and composition of aquatic biota, and incorporate the results of this exercise into a GIS to provide spatially-referenced descriptions of change in populations over time. [5-9]

With respect to mine processes:

16. monitor the effects (trends) of reduced neutralisation circuit residence time on the tailings effluent quality associated with increased mill throughput from 10,500 to 16,500 tonnes per day; at the same time (i) continue to monitor pH, TSS and cyanides and conductivity on a daily basis, and (ii) initiate monitoring of such parameters as Fe, Ca and SO_4, Cl, thiocyanate and process chemicals in the tailings, to improve understanding of the sorption/precipitation processes involved in metal removal, and to help refine the equilibrium speciation calculations performed on the effluent.

    The composite heavy metal samples should be analysed weekly rather than at the present fortnightly frequency. [2-5]
17. vigorously pursue the possibility of containing all or part of the tailings solids and waste rock on-site. [2-5]

With respect to chemical effects:

18. fully evaluate the riverine impacts of the [tailings and] waste rock inputs, by (i) measuring the size distribution of particulate material in tailings effluent and eroding from the erodible waste dumps and reaching the river, and the mineralogy/chemical composition of the fine fraction and its reactivity in the receiving waters; and (ii) monitoring dissolved inputs derived from the weathering and leaching of the erodible waste dumps.[4-8]

19. undertake research with the aim of determining a tailings 'signature': that is, a unique set of geochemical elements in the tailings that can be used to trace their downstream movement and to quantify mine-derived inputs. [4-8, 5-5]

20. continue to monitor metals associated with suspended solids at SG3 and at sampling locations below SG4, adjusting the data to take account of particle size, so they can be reliably compared throughout the river system; use the data to (i) test whether or not the 'signature' of mine-derived solids can be detected, notably for tailings inputs, and to follow this signature over time; (ii) serve as an estimate of particulate metals loadings delivered to the lower Strickland flood plain; and (iii) allow a comparison of the metal concentrations in this material with internationally accepted sediment quality criteria. [4-12, 5-7]

20. consider reporting the range of monitoring data for dissolved contaminant concentrations, as well as the mean and variance values. [6-18]

21. analyse the TSS samples collected in the Lagaip and Strickland Rivers not only for the concentrations of various mine-derived metals but also for Fe, Al, Mn and organic matter, after the samples have been separated into ranges of particle sizes. [6-6]

22. maintain and expand the present water quality and discharge sampling regimes at the compliance point SG3 and at potential compliance point SG2, to be sure of sampling a representative range of river conditions, including very low and very high flows. [6-2, 6-5]

23. lower detection limits for dissolved Ag and Pb, because dissolved concentrations of Ag, Hg and Pb are frequently undetectable; monitor only total Hg at SG3, as the true dissolved Hg values are likely to be in the pico-molar region. Report water hardness separately. [4-11, 4-12, 6-4]

24. following appropriate risk assessment, discontinue monitoring dissolved metals in the lower Strickland River (i.e. only monitor total metals) because the true concentrations are likely to be in the nano- to pico-molar range, and ultraclean sampling and handling techniques would be required to minimise sample contamination. [5-6, 5-7]

25. compare the current technique for measuring dissolved metals (filtration under a laminar flow hood), against in situ dialysis by the procedure used by Benes (1980), with the intention of adopting the latter approach if it proves feasible. [6-6]

26. reconsider the location of monitoring sites along the riverine system from Porgera to the Fly Delta, to (i) assess the suitability of each site to contribute to the resolution of spatial and temporal variability in monitored data, and (ii) identify suitable locations for the placement of 'control' sites. [6-5, 6-18]

27. consider measuring the concentrations of metal ions in the pore water of sediment cores to help in the risk assessment; for these measurements, collect and analyse the pore water using pore-water peepers. [5-6]

With respect to sediment and physical effects:

28. initiate a program of systematic coring of the surface sediments on transects extending at least 2 km either side of the Strickland and Herbert river channels at key positions, and in off-channel water

bodies, to establish if mine-derived sediment can be detected. [5-5, 6-7]

29. develop a better understanding of the sediment balance by combining field data and geomorphic interpretation of flow and sediment processes into a sediment transport model, and calibrate it by measuring aggradation in the river channel below SG4, using cross-sections or GPS survey or remote sensing of sediment plumes. [4-6, 5-5, 6-6, 6-7]
30. obtain information for a sediment balance model by (i) aerial photography or remote sensing, initially of the whole river system, providing a background or baseline, and later focussing on particular aspects once or more per year, revealing changes in the river channels and identifying problem areas; (ii) particle size analysis of the river beds about every six months to determine trends in sedimentation from data on the changing composition of the beds over time; (iii) suspended solids sampling every week at SG3 and SG5, with a campaign effort downstream of SG1, using the depth-integrated method in a representative range of river heights to calibrate the current gulp sampling method, to yield a reliable estimate of annual sediment load. [4-12, 6-7]
31. evaluate the usefulness of remote sensing for tracking the fate of sediment and the frequency and extent of Lake Murray level fluctuations. [5-5]
32. as part of a reassessment of the water and sediment balance for Lake Murray, and the current hydrological monitoring program near the Lake, during several flow-reversal events (i) check whether or not the waters of the Herbert River are colder than Lake Murray water and whether or not the two waters mix, and (ii) identify whether the Herbert and Mamboi rivers are important pathways for mine-derived sediment entering the Lake. [5-4, 5-5]
33. estimate the annual export of sediment from the Strickland River to the Fly River, based on data from SG3 and SG5. [5-5]
34. mount a monitoring campaign to (i) examine the behaviour of the erodible waste dumps, particularly their capacity, inputs from the mine and losses to the river (assessed by automatic water sampler and rainfall/runoff model), to better define material inputs and transport in the river system; (ii) determine how much mine-derived sediment is deposited downstream of SG1 and upstream of the Lagaip confluence, using river bed particle size analysis, cross-section surveys and imaging from fixed reference points. [6-7]

With respect to monitoring and reporting techniques:

35. reorganise the hydrometeorological station system, ensuring calibration of new stations (on Kogai River for example) against the old, some of which can be closed. Update the HYDSYS database with all historical data that can be obtained from other operators for all stations. The HYDSYS database must also contain basic information such as catchment area, station elevation, latitude and longitude, for each gauging station. Seek specialist advice on how best to extend the rating curves derived from these stations. [6-3, 6-4]
36. undertake a comprehensive review of data collected over the past five years with a view to choosing sample sizes suitable for on-going compliance monitoring. [6-16]
37. identify, in consultation with the regulatory authority, appropriate and powerful statistical methods to analyse data gathered as part of the EMMP.

    Computational details and data processing requirements should be prescribed in sufficient detail to ensure (i) the results are reproducible; and (ii) there is no ambiguity in methods to be adopted. [6-16]
38. enhance the statistical capability of the environmental laboratory by providing new and existing staff with (i) leadership in the form of a specialist statistician (this person would be trained to Honours or

Master's degree level in mathematics and/or statistics) and (ii) training, as necessary, in contemporary statistical methodology (this should include an element of spatial statistics, time series analysis, statistical design, non-parametric statistics, probability theory and risk assessment). [6-9, 6-16]

39. use appropriate statistical tools and graphical methods whenever possible, for visualising and presenting compliance data. For example (i) use more sophisticated ways of detecting outliers in complex, multivariate data sets, (ii) cease the current practice of logarithmically transforming compliance data prior to the computation of sample statistics (sample means and standard deviations that are routinely reported to the regulatory authority should be based on raw untransformed data). [6-13, 6-18]

40. upgrade computing processing and storage facilities in general, and peripheral hardware; investigate the use of electronic media for data acquisition. [6-9, 6-11]

41. develop a unified database management strategy for the environmental laboratory, that addresses security, storage, maintenance, and back-up issues; consider the establishment of a single database for the storage of all data collected by the laboratory, outsourcing the task of setting it up. [6-13, 6-15]

42. upgrade the environmental chemistry laboratory area and seek accreditation for the environmental laboratory as soon as possible. [6-10]

43. formulate and adopt a consistent approach to (i) units of measurement for all data collected by the environmental laboratory; and (ii) the recording and treatment of data whose values are below the achievable detection limits (all data should be recorded to as many significant figures as the accuracy of the experimental procedure will permit).

    The environmental laboratory should establish criteria against which monitoring data, such as the results of analyses, are compared. [6-10, 6-11]

44. use appropriate QA/QC procedures for all in-house analyses.

    If external laboratories report unacceptable values for QA/QC samples, the matter should be investigated promptly in a well-defined sequence of actions, and the outcomes fully documented.

    A special investigation should research whether significant changes occur in the concentrations of dissolved metals, free-CN and ammonia due to the storage of samples with a range of suspended solids concentrations. [6-11]

45. upgrade the quality of the annual environment reports, including interpretation of current results in the light of those of previous years; consider the preparation and publication of a series of overview and review reports on the environmental work being undertaken; and report the results of health surveys and analyses to villagers living along the river system. [6-19]

46. adopt a monitoring culture that embraces some basic principles and procedures of statistical process control (SPC) to enable management to better observe, understand, and control key components of its production facility. [6-13]

47. develop a coherent and comprehensive research plan for the operations, which addresses specifically how the results of this research will be transferred to management and stakeholders. [6-19]

48. broaden the objectives of environmental monitoring, placing increased emphasis on interpretation of results, and on investigative studies within a unified framework aimed at identifying and understanding relationships between Porgera activities and downstream environmental effects. [6-19]

In the Executive Summary

the report's 48 recommendations are gathered together into these 12:

ES1. Aim for a more detailed understanding of the riverine system and how it functions, so as to better identify potential risks and strategies needed to reduce them.

ES2. Provide the PJV Environment Dept additional staff to carry out the more rigorous and refocused EMMP advocated by the review team.

ES3. Employ a better-designed sampling program and select other 'control' catchments nearby, unaffected by upstream land uses, for comparison with the Strickland river system.

ES4. Carefully assess (i) the effect of increased production on residence times in the neutralisation circuit, (ii) the probability of accidental discharges of incompletely-treated materials, and (iii) the response mechanisms required to manage such eventualities.

ES5. Develop a comprehensive sediment budget for the river system, and initiate a dump monitoring program including the analysis of particle size distributions in the river bed, and more rigorous monitoring of suspended sediment.

ES6. Collect data on benthic invertebrates, the composition of key aquatic-based food chains leading to humans, the importance of side channels, and locally-derived inputs.

ES7. Give priority to SG2 as a hydrology master station for compliance purposes.

ES8. Undertake a program of integrative investigations in the flood plain and Lake Murray region, using a risk assessment approach.

ES9. Review the location of hydrological stations in the Strickland/Herbert River region, to improve knowledge of inflows and outflows to the Lake.

ES10. Use a program of core-sampling to estimate inputs of mine-derived sediment to the lower Strickland flood plain and their fate in that region.

ES11. Reconsider the assumptions in the Environmental Plan about the structure of the biological food chain in the Lake Murray region.

ES12. Monitor (and manage) for impacts.

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