

# Acid Rock Drainage Management at the Ok Tedi Mine, Papua New Guinea

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## ABSTRACT

This paper describes measures taken by Ok Tedi Mining Limited (OTML) to minimise the risk of acid rock drainage (ARD) resulting from mining operations at its Mt Fubilan porphyry copper-gold mine in the remote Star Mountains of Papua New Guinea. The risk of acid generation and metal leaching as a result of oxidation of these sulfidic deposits has long been recognised by OTML. In 1998, OTML instigated the ARD Management Program to fully evaluate these risks and to formulate, if necessary, trial and implement appropriate management strategies.

In implementing the ARD Management Program, OTML has adopted a risk management approach consisting of five stages:

1. risk identification,
2. risk analysis,
3. risk assessment,
4. risk treatment, and
5. review and monitor.

Significant progress has been made in relation to risk identification, analysis and assessment. The work currently underway to put in place a comprehensive risk treatment and review process will ultimately determine the success or otherwise of this approach.

## INTRODUCTION

The Ok Tedi copper-gold mine is located in the remote Star Mountains of western Papua New Guinea (Figure 1). The mine commenced operations in 1984 with a 24 000 tpd gold plant that has since been expanded to a 90 000 tpd copper plant. Waste materials (both sulfidic and carbonate materials) from mining operations, at present comprising approximately 55 Mt of overburden and 31 Mt of tailings, are discharged each year directly into the headwaters of mine area creeks where erosion and sediment transport carries significant proportions of the total waste produced into the Ok Tedi and Fly River systems. Additional sulfidic sediment is sourced from the surrounding valley walls due to undercutting and erosion caused by movement of mine waste rock from the edge of the mine and mine area creeks (~7.5 Mt/yr).

The risk of acid generation and metal leaching as a result of oxidation of these sulfidic deposits was recognised before mining began in 1984. As a result several studies were conducted to characterise this risk particularly from mine waste rock and tailings. While these studies confirmed the acid generating potential of waste material, it was widely assumed that the relative abundance of limestone, as a proportion of waste rock, together with and the high natural background alkalinity concentrations in the catchment drainage, would largely ensure that little or no ARD impacts occurred.

In 1998, a risk assessment of the environmental impact of the mine concluded that further investigations into the potential for ARD at Ok Tedi were necessary. In response, Ok Tedi Mining Limited (OTML) instigated the ARD Management Program to fully evaluate these risks and to formulate and, if necessary, trial and implement appropriate management strategies. Specifically, the objectives of this program are to:

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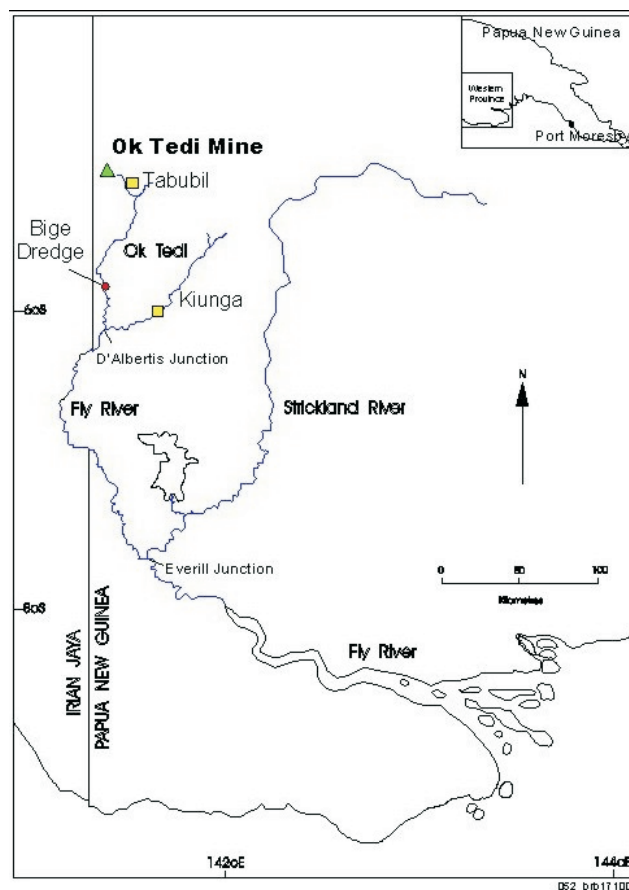


FIG 1 - Map showing location of Western Province, Ok Tedi mine and the Ok Tedi/Fly River catchment.

- evaluate the acid-base characteristics and acid-forming potential of waste rock and tailings to be discharged from the mine to the end of mine life;
- evaluate the acid-base characteristics and acid forming potential of materials deposited in the Ok Mani, Ok Gilor, Ok Tedi and Fly River catchments;
- predict the risk of developing acid drainage from the mine and river deposited materials stockpiled as a result of dredging at Bige;
- determine potential acid and metal loads from exposed mine-derived materials; and
- identify and evaluate management options for controlling or mitigating the risk of adverse environmental impacts from sulfide oxidation in mine waste materials.

This paper provides a description of the various components of the OTML ARD Management Program, the methods and strategies employed, and progress to date in its implementation.

The main results of work conducted to date, as part of the ARD Management Program, can be found in Rumble *et al* (2003, this volume), Pile *et al* (2003, this volume) and Miller *et al* (2003, this volume).

## PROJECT DESCRIPTION

Ok Tedi Mining Limited (OTML) owns the mine. OTML's shareholders comprise PNG Sustainable Development Program Limited (52 per cent), the State of PNG (30 per cent) and Inmet Mining Corporation (18 per cent).

Mining is conducted in a single open pit using conventional drill and blast, load and haul techniques. Processing of the ore takes place in the mill facility adjacent to the open pit. The copper concentrate, which also contains gold and silver, is pumped along a 156 km pipeline to the upper Fly River port of Kiunga (Figure 1). Barges then transport the concentrate from Kiunga down the Fly River about 820 river kilometres to a floating silo ship usually moored at the mouth of the delta. Ocean going vessels are loaded from this vessel for worldwide copper smelter destinations. OTML is currently the largest copper and third largest gold mine in PNG. Revenues from the mine account for about nine per cent of GDP and 18 per cent of total PNG export revenue.

In 2001 OTML produced 694 900 dry metric tonnes of Cu concentrate. This contained 203 702 tonnes of Cu, 455 222 troy ounces of Au and 1 150 031 troy ounces of Ag.

### Waste rock

With approval from the State of Papua New Guinea approximately 60 Mt of waste rock from the Mt Fubilan mine was discharged to the Ok Tedi river system in FY 2002. The waste rock comprises mainly limestone, siltstone and intrusives (monzonite, monzodiorite) that contain disseminated and vein-hosted sulfide mineralisation (typically <10 per cent) containing copper at concentrations below the cut-off grade for sulfide ores. The particle size of the waste rock is variable and ranges from less than 0.01 mm to over 200 mm; the  $D_{50}$  is estimated at approximately 45 mm. Waste is discharged at the Taranaki (Northern) and Harvey Creek (Southern) dumps. These are designed as failing dumps where the residence time is quite short, ranging from several hours to two to three days before entering into the river system. It has been estimated that approximately 40 per cent of the total waste material released to the river is retained in the creeks immediately surrounding the mine including Harvey Creek, Ok Mani and Ok Gilor.

The available data indicate that siltstone, monzonite, monzodiorite, endoskarn and skarn all contain reactive sulfides and some units are significantly deficient in acid neutralising capacity (ANC) and are potentially acid forming (PAF). Limestone is the main source of ANC in the bulk waste rock.

### Tailings

OTML currently discharges approximately 30 Mt of tailings each year into the Ok Tedi catchment, again with the approval of the State of Papua New Guinea. Tailings exiting the mill comprise an alkaline slurry of fine particulate material with a typical copper concentration of 1500 mg/kg, although this varies according to the type of ore being processed. The alkaline pH of the tailings is rapidly neutralised by the riverine receiving waters (within 10 km downstream of the mine) resulting in a pH of around 7.8. Minor amounts of tailings deposit in the upper reaches of the river system; however, the majority is transported as suspended load through the river system. The size range of the tailings is relatively narrow and the  $D_{80}$  averages 180  $\mu\text{m}$ . Mineralogically the tailings are mainly comprised of varying amounts of silicates, calcite, magnetite and the sulfides, pyrite, chalcocite and

chalcocite. Pyrite, the mineral of greatest interest from an ARD perspective, because of its abundance and potential to generate acid, typically accounts for approximately 5 wt per cent of the tailings.

## Lower Ok Tedi Dredging Project

The Lower Ok Tedi Dredge Project, located near the village of Bige, was initiated in March 1998 (Figure 1). The principal objective of the project is to accelerate floodplain dieback recovery by reducing riverbed levels and, therefore, reducing the frequency of overbank flooding. Mine derived sand is trapped within a dredged slot located in the main channel of the Ok Tedi and is delivered to an on-land stockpile, via a cutter suction dredge capable of in excess of 10 million  $\text{m}^3$  sand production per annum.

The existing dredge sand stockpile is located on the eastern bank of the Ok Tedi floodplain offset 500 m from the main Ok Tedi channel. The existing east bank sand stockpile is being developed in a series of cells, which are progressively raised to an RL of 42 m in 4 m high lifts. A total of 37 million  $\text{m}^3$  of dredged sand material has been placed within the east bank stockpile as of 21 February 2002.

Sediments dredged from the Bige river slot are a mixture of mine waste materials and natural sediments eroded from the Ok Tedi catchment. Dredged sands during the first half of 2002 have an average  $D_{50}$  of 0.13 mm and 15 per cent passing the 0.075 mm sieve (Klohn Crippen, 2002). Dredge sands are mainly composed of quartz and feldspar (~50 per cent), limestone rock fragments (~12 per cent), opaque grains (mainly magnetite (~10 per cent) and pyrite (~3 per cent)), and lesser amounts of clay, volcanic and igneous rock fragments and ferromagnesian minerals such as hornblende (~25 per cent). Pyrite the dominant sulfide mineral present, occurs mainly in the 38 to 212  $\mu\text{m}$  fraction where it can range up to ~15 wt per cent of the sample.

## PHYSICAL SETTING

### Geology

At Mt Fubilan, porphyry (granitic) intrusions 1.1 - 2.9 million years old intrude mainly Cretaceous to Tertiary marine sediments including a thick sequence of limestone, mudstone, siltstone and sandstone. Cu-Au-Ag mineralisation is associated with emplacement of the porphyry intrusions.

Pyrite and chalcocopyrite are the dominant sulfide minerals present in the ores and associated waste rocks and occur either as fine disseminations or as vein or fracture fills in intrusives and adjacent sediments. Significantly about 25 per cent of ore reserves occur as calc-silicate, sulfide and magnetite skarns that have formed at the contact between intrusives and adjacent sediments.

While host strata are shallow dipping, the regional structure, together with the high rainfall and level of seismic activity in the area result in frequent, and sometimes spectacular landslides.

### Hydrology

The mine is located in the headwaters of the Ok Tedi ('ok' means river in the local language) on the southern slopes of the Star Mountains, about 1000 km from the Gulf of Papua (Figure 1). The Ok Tedi, along with the Strickland River are the major tributaries of the Fly River. The Fly River catchment covers approximately 76 000  $\text{km}^2$  and has a mean annual run-off per unit catchment area of about 2500 mm; the highest in the world (Maunsell and Partners, 1982).

As the catchment is relatively small, stream flow is characterised by short-term water level fluctuations with rapid changes between flood peaks and drought periods. Both rainfall and river flow show only limited seasonality.

Long-term mean discharge rate of the Ok Tedi at the junction with the Fly River (flow of 1178 m<sup>3</sup>/sec at Kiunga) is 923 m<sup>3</sup>/sec. The combined flow is 2161 m<sup>3</sup>/sec in the upper Middle Fly. At Obo, in the lower Middle Fly, the long-term mean discharge is 2244 m<sup>3</sup>/sec. The Strickland discharges 3110 m<sup>3</sup>/sec into the Fly at Everill Junction, just downstream of Obo. The combined flow is about 5300 m<sup>3</sup>/sec in the lower reaches of the river before entering the tidally influenced delta on the south coast.

November (530 mm) and the wettest is March (756 mm). El Nino events are a characteristic of the catchment and result in dry conditions and low water levels periodically in the Ok Tedi and Fly Rivers. They occur on average every five years. Recent events occurred in 1972, 1982, 1991 - 1993, 1997, 2002.

Average temperatures range from a minimum 20°C to daily maximum of 27°C at Mt Fubilan. The mean annual humidity in the lowlands is about 85 per cent.

**Climate**

The climate at Ok Tedi is wet tropical. Rainfall is highest in the upper Ok Tedi region and decreases towards the south coast. Annual rainfall averages about 2 m on the coast, 4.5 m at Kiunga, 4 - 7 m in the lower Ok Tedi, 8 m at Tabubil (the town servicing the mine), and 10 - 12 m at Mt Fubilan. Although October to March is generally considered to be the monsoon period, the mean monthly rainfall tends to be relatively uniform throughout the year (Figure 2). The driest month at Tabubil is

**ARD MANGEMENT PROGRAM**

The ARD Management Program, as noted above, was initiated following a two-year Human Health and Environmental risk Assessment (HERA) study to identify environmental and human health risks associated with the operations of the Ok Tedi mine (Parametrix, 1999). Specifically, the HERA identified the risk of metal-rich acid drainage developing from sulfide-bearing materials exposed to the atmosphere as a result of OTML mining operations.

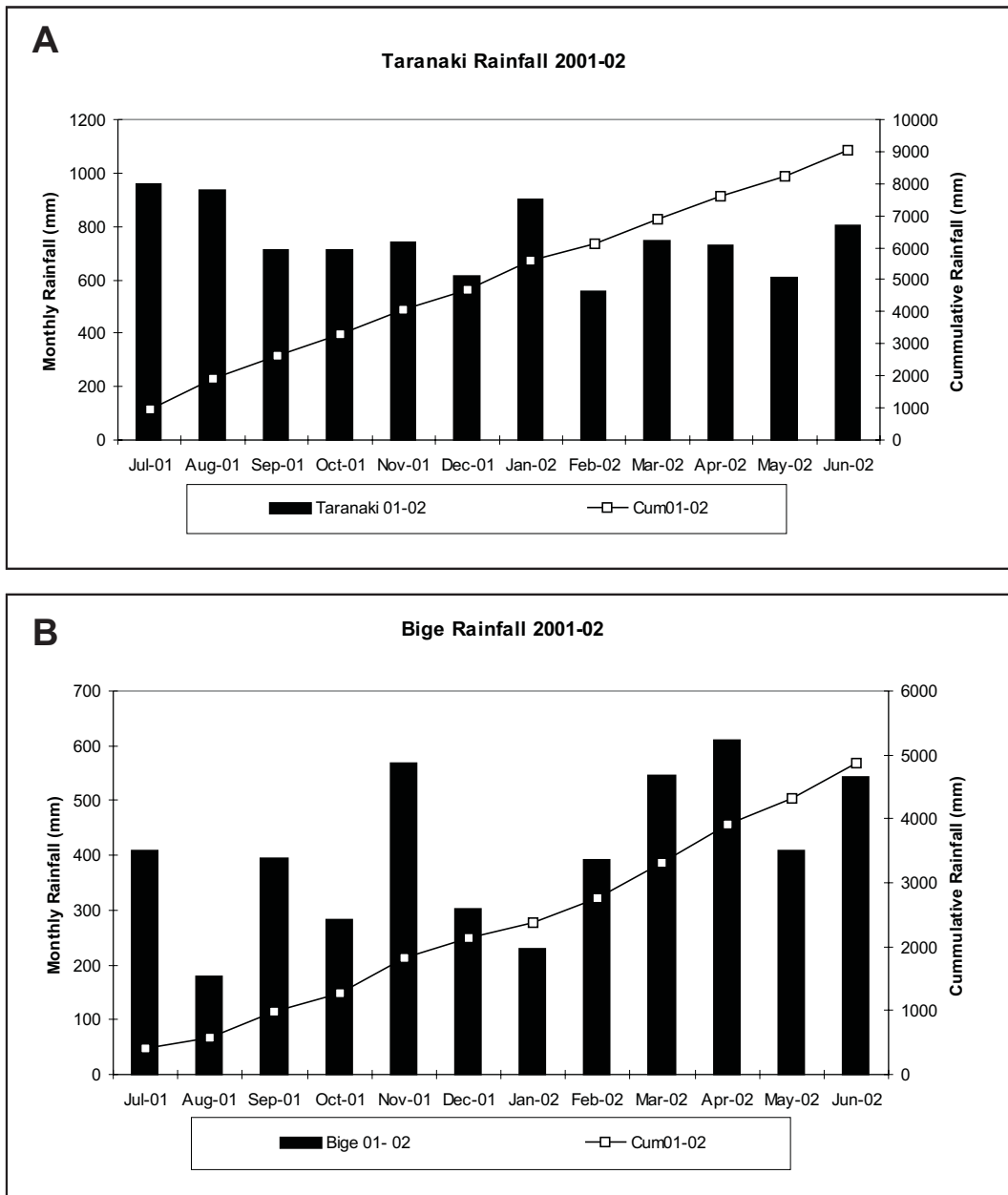


FIG 2 - (a) Monthly rainfall data for Taranaki gauge at mine, (b) Monthly rainfall data for Bige dredge site.

In managing these risks, OTML has adopted a five-stage approach, encapsulated in the OTML Environmental Risk Management System (ERMS) (Figure 3). The stages are:

- risk identification,
- risk analysis,
- risk assessment,
- risk treatment, and
- review and monitoring these treatments.

These risks, once identified have been added to the OTML EMS Risk Register (EMSRR). This register has enabled all information related to assessing and managing environmental risks, including those related to ARD, to be located in a single computer-based database. It is also capable of calculating performance indicators to track performance of treatment options.

Presented below is an account of the overall context in which environmental risk assessment is conducted and details of the findings and procedures adopted in fulfilling the five-stage approach described above.

The OTML Environmental Regime, accepted into law by the State of PNG in December 2001, was developed with the aim of maintaining the following environmental values:

- water quality is to a drinkable standard downstream of the mining operation following settlement of the total suspended solids;
- the water-based resources of the Ok Tedi and Fly Rivers downstream of the mining operation are available to meet normal community requirements;
- fish and other aquatic resources of the Ok Tedi and Fly Rivers and Gulf of Papua receiving environment are safe to eat;

- land and land-based resources of the Ok Tedi and Fly River floodplains downstream of the mining operation are available to meet normal community requirements;
- crops and natural forest resources included in the normal dietary intake of the local community are safe to eat; and
- the main channels of the Lower Ok Tedi and Fly River are navigable for village craft and commercial shipping.

The ARD Management Program is relevant to all of the above values except that related to navigation. As such it is a key component of OTML’s Environmental Regime with clear links to the current ecology-based programs – the Riverine Aquatic Ecology and Terrestrial Ecology Management Programs (OTML, 2001).

**Stage 1 – Risk identification**

The principal risks identified in relation to this program include:

- oxidation of sulfide minerals in mine-derived waste products;
- discharge of acid drainage;
- mobilisation and release of dissolved metals to receiving environment;
- adverse effects on downstream water quality; and
- adverse effects on downstream aquatic and terrestrial fauna and flora.

It is the risk of adverse changes to drinking water quality and the aquatic and terrestrial fauna and flora, following the onset of ARD and metal mobilisation from mine-derived materials, that provides both the rationale and assessment endpoints for the ARD Management Program.

As such the overall objectives of the program are to ensure that there are no adverse changes that are unacceptable to the State, relating to river chemistry as a result of OTML mining operations.

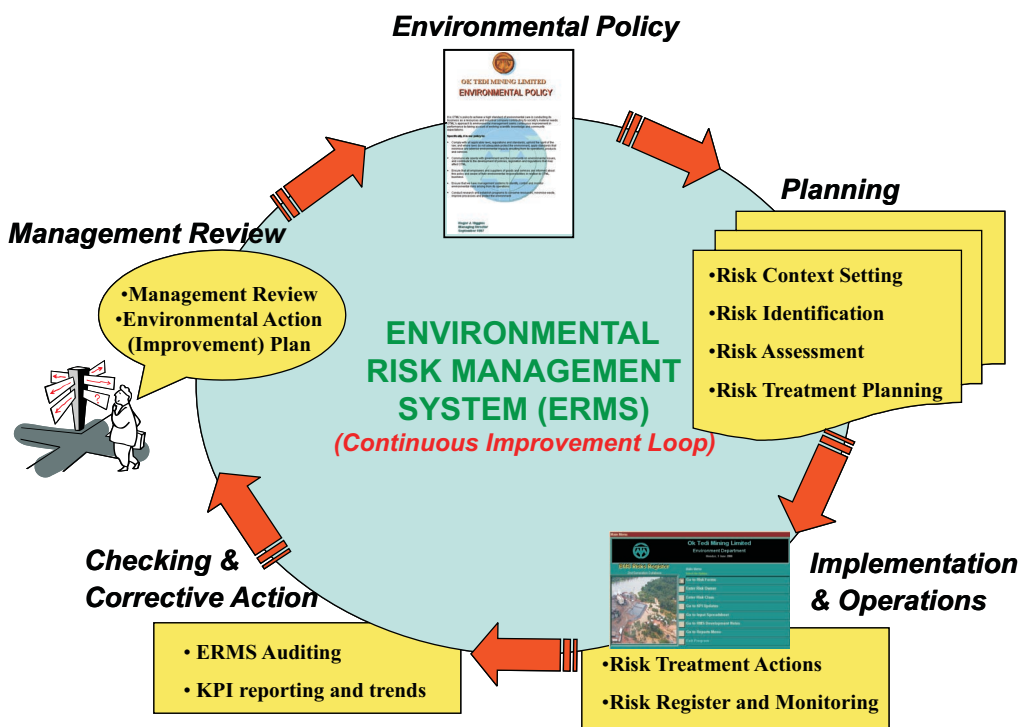


FIG 3 - The OTML Environmental Risk Management System.

**Stage 2 – Risk analysis**

The main purpose of this stage is to characterise the potential sources of ARD, their distribution in the system, and the nature of their interaction (contact) with the river and its ecology. This stage also involves evaluation of allied Regime programs being conducted by OTML to better understand the relationship between ARD effects and the response in the river ecology (ie causality) and to define the potential impact on assessment endpoints. Much of the work conducted during this stage is directed towards the reduction in uncertainty in regard to the

likelihood and consequences of ARD effects.

Investigations conducted as part of the ARD Management Program are being undertaken in all areas impacted by mining operations (Figure 1). This includes the mine pit and immediately surrounding area, the mine area creeks into which mine waste is currently discharged, the Ok Tedi and Fly Rivers and their levee banks and floodplains, and the sand stockpiles at the Bige dredge site on the lower Ok Tedi. Figure 4 is a schematic diagram showing the potential ARD sources and impact areas.

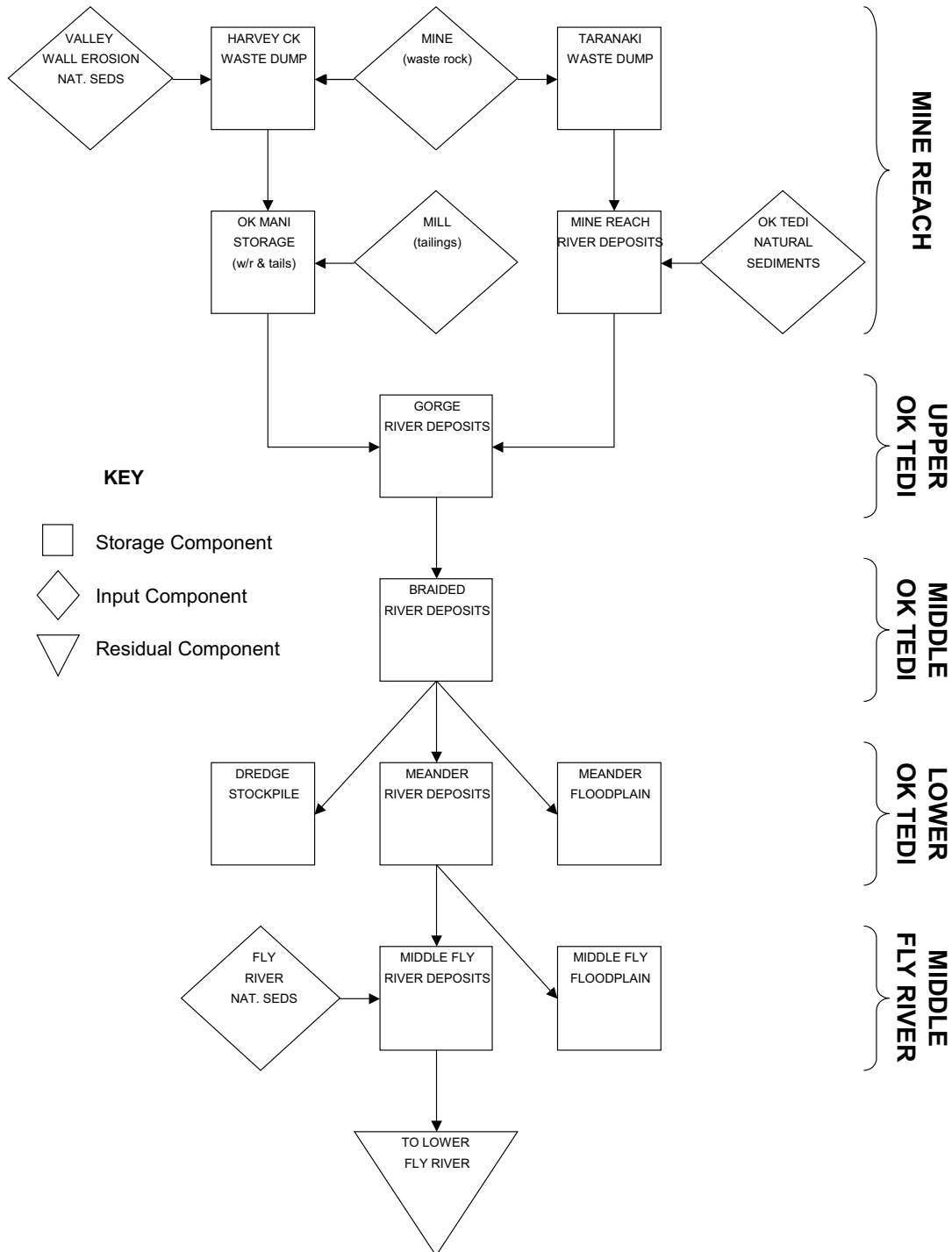


FIG 4 - Schematic diagram showing potential ARD sources and impact areas.

All of these areas contain reactive sulfides and therefore create a risk of developing ARD. To fully evaluate these risks the ARD Management Program includes a series of projects to:

- geochemically characterise the nature and risk of solid input and stored materials;
- characterise water chemistry of drainage from the mine pit and stored waste materials;
- characterise and model surface and groundwater flows in storage sites to determine hydrological conditions and their impact on ARD risk;
- model the likely water quality (alkalinity/acidity ratio, acid load, etc) (stressor species) downstream of storage sites;
- determine the potential impact on environmental values (assessment endpoints);
- determine the areas where risk can be reduced; and
- conduct a sensitivity analysis for varying conditions.

In addition, the following projects being undertaken by the environment department at Ok Tedi, as part of OTML's Environmental Regime, also provide essential information necessary for analysing the ARD risk. These include projects to:

- Characterise and model sediment/waste transport in the receiving environment.
- Characterise and model, at various points in the receiving environment, the water quality effects on a range of aquatic animals and plants under relevant conditions. This includes analysis of stressors, their source, and pathways to receptors, exposure mechanisms and chronic and acute toxicities.

The following sections provide a brief description of the progress to-date with ARD risk analysis at Ok Tedi.

### Geochemical characterisation – solids

Geochemical characterisation of all major rock and sediment types produced or exposed as a result of operations was undertaken to:

- assess the potential for mine waste materials to generate acid and release metals;
- provide input data for calibration and validation of predictive ARD models; and
- provide baseline data for monitoring of geochemical trends.

Material types characterised included the waste rock, tailings, pit wall rocks, waste materials deposited in the creeks immediately surrounding the mine (mine area creeks), the river deposited sediments of the upper Ok Tedi, floodplain sediments and river sediments dredged from the river at Bige on the lower Ok Tedi.

The specific objectives of the geochemistry program are to:

- geochemically characterise the tailings and waste rock generated during mining;
- determine the geochemistry of river deposited sediments and evaluate the risk of environmentally significant acid (lowering pH) or metal release to the river system;
- evaluate and provide strategies to minimise the risk of acid formation and metal leaching from the dredged sand stockpiles at Bige; and
- evaluate the risk of developing acidic or low pH conditions on the floodplains.

This work usually encompasses two stages:

- defining the acid-base and acid generating characteristics of materials (total sulfur, ANC, NAPP); and

- classification of materials as either potentially acid forming (PAF), non acid-forming (NAF) or uncertain (UC).

Geochemical characterisation, using this approach, has been completed for all major potential sources of ARD at Ok Tedi. A detailed description of the methods used can be found in Miller (1996) while results, as noted above, are given in Miller *et al* (2003, this volume), Rumble *et al* (2003, this volume) and Pile *et al* (2003, this volume).

### Geochemical characterisation – liquids

Analysis of liquids at Ok Tedi involves two main lines of investigation:

- kinetic tests, including the use of field test pads and bench-top leach columns to assess the future water quality of run-off and leachate from waste materials; and
- the collection and analysis of contact waters from all major potential sources of ARD including the pit, waste rock dumps (mine area creeks), sediments deposited in the river system (channel and floodplain) and the dredge stockpiles at Bige.

#### *Leach columns and field test pads*

A testing program is currently being conducted at Ok Tedi to investigate the leaching behaviour of various mine waste materials including waste rock, tailings, river deposited and dredge stockpile sediments. The program currently includes 34 free-draining aerobic leach columns that are designed to provide information on a range of issues including oxidation kinetics, sulfide reactivity, and metal solubility (Figure 5). A better understanding of the kinetics of sulfide oxidation and metal leaching characteristics will improve our ability to predict the risk of ARD and environmentally significant metal release from the different mine impacted domains.

At Bige, the location of the lower Ok Tedi dredging project, four field lysimeters have been recently established to investigate the geochemical behaviour of dredge sediments stockpiled on the adjacent floodplain.

The field lysimeters consist of a lined base measuring approximately 10 m × 10 m and side bunds to contain the dredge sediment in a flat-topped pile that is approximately 3 m high (Figure 6). The dredge sediment is leached by rainfall and the pad design incorporates a drainage collection system for monitoring of leachate flow and quality. The leachate results are used to estimate rates of sulfate release, acidification, and metal leaching. It is anticipated that test pads will operate for a number of years to provide sufficient information for field evaluation.

The test pads at Bige have also been fitted with a system for the collection and measurement of oxygen concentration along two profiles through the test pad sediment; one at the centre, the other mid-way to the perimeter (Figure 6).

It is also planned to trial two surface treatments as potential cover systems over dredge stockpiles, should these be required. They are summarised below:

- Sand-bentonite cover – this cover would be constructed by mixing the dredge sand with bentonite at a ratio of about five per cent.
- Geosynthetic clay liner (GCL) – this GCL will be placed directly on the surface of the sand. The GCL is a manufactured product that consists of two nonwoven fabrics that contain a thin layer of bentonite. A layer of dredge sand up to 600 mm thick will subsequently be placed over the GCL.

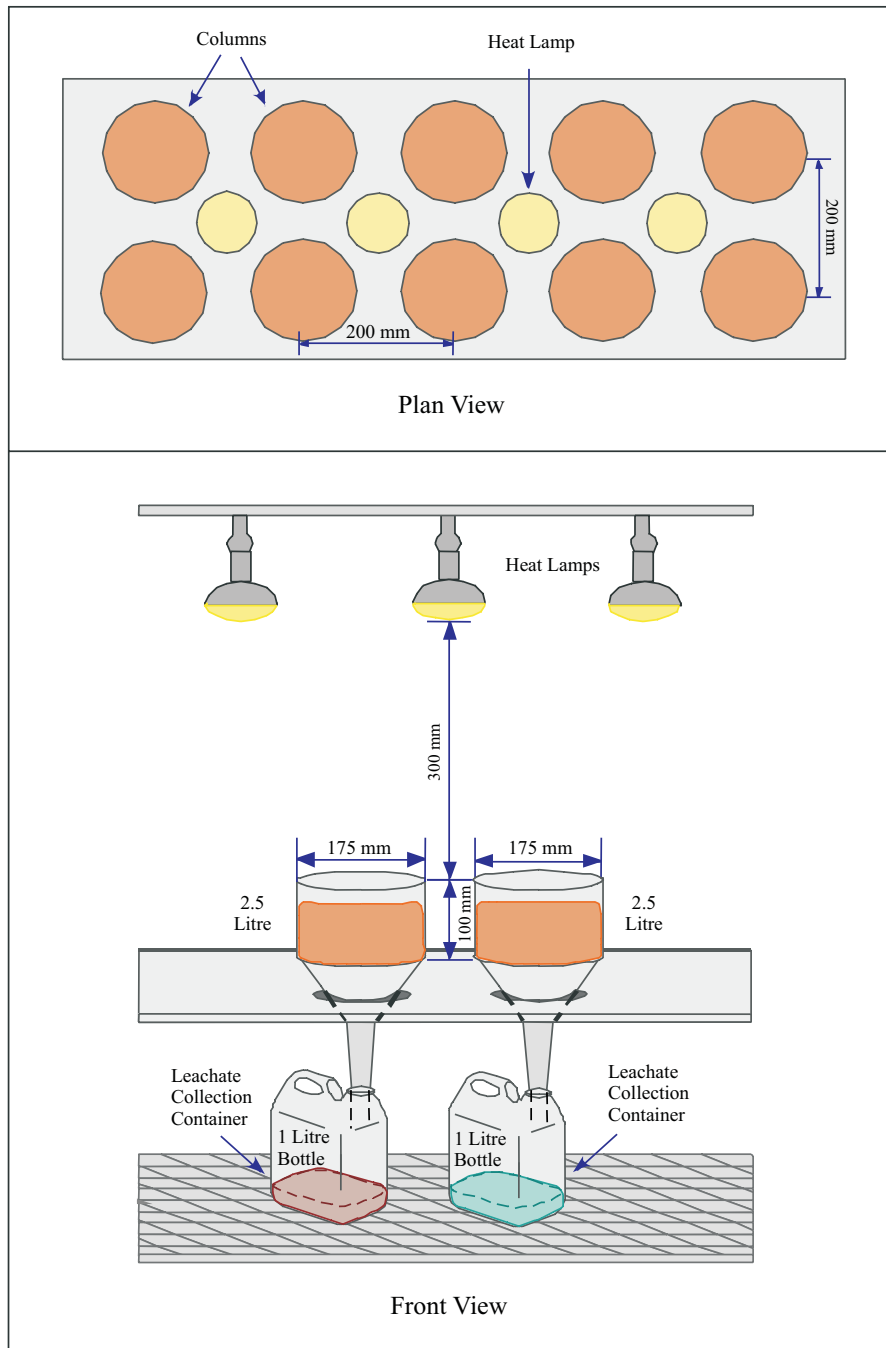


FIG 5 - Free-standing leach columns.

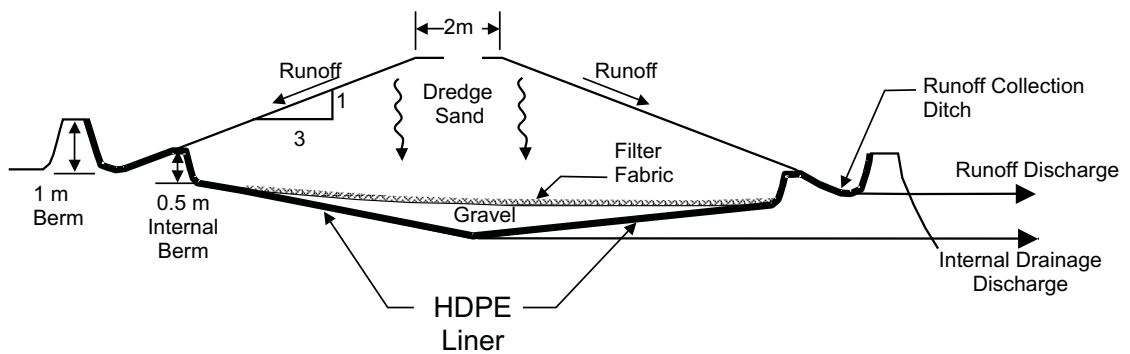


FIG 6 - Bige test pad design.

### Characterisation of contact waters

Water samples from surface run-off and underground sources in contact with potentially acid-forming materials are currently being collected to enable characterisation of water chemistry.

Specific objectives of the hydrogeochemistry sampling program are to:

- characterise the chemistry of contact and ground waters associated with rocks exposed in the Ok Tedi mine pit;
- provide information on the acid forming nature, oxidation kinetics and metal leaching characteristics of waste rock, tailings, mine derived river deposited sediments and stockpiled dredge sediments;
- investigate mechanisms controlling copper solubility in the waste rock and tailings; and
- investigate the effect of limestone blending on maintaining pH and metal solubility control within the waste rock.

Regular sampling of contact waters (both run-off and seepage) provides essential information on the nature of chemical reactions taking place in the major mine waste repositories, as well as monitoring the quality of water released into the Ok Tedi and Fly River system.

Current hydrogeochemical sampling is usually conducted on a monthly basis and includes analysis of a range of parameters including, pH, EC, acidity/alkalinity, SO<sub>4</sub>, Cu, Al, Ca, Cd, Fe, K, Mg, Mn, Na, Zn.

### Hydrological characterisation and ARD modelling

#### Hydrology

The main purpose of the hydrology component of the ARD Management Program is to provide essential information on the flow characteristics of those water masses likely to be a source of ARD. Water balance and seepage analysis studies also provide information on the depth of oxidation likely to be observed in sulfide-bearing materials; a key factor in evaluating the risk of ARD developing under a range of climatic scenarios.

Specifically, the objectives of this component of the Program are to:

- develop a hydrological model to predict the rate of filling of the final void;
- determine the quantities and flow paths for the principal water types entering and leaving the mine pit during the remainder of the operation and after mine closure;
- develop a hydrologic model of the dredge stockpiles to enable a prediction of their future behaviour; and
- establish a monitoring program on the dredged stockpiles to enable comparison of predicted performance with actual behaviour, followed by optimisation and refinement of the hydrologic (seepage) model for use in future stockpile design and ARD minimisation.

The establishment of a comprehensive hydrologic monitoring network at Bige over the dredge stockpiles and subsequent water balance and seepage analysis has provided a better understanding of factors controlling water table fluctuations in the stockpile and the estimation of the volume of unsaturated sediments. This information has in turn allowed estimates of metal and other chemical loadings from the stockpiles to be made.

At the mine, work has been initiated on the establishment of a hydrologic network designed to provide essential input data to models, which, together with water quality information, will be used to predict water quality in the final void after mine closure.

Further work is planned on both networks to improve the confidence of results of modelling. In addition work is underway to install instrumentation on several sand bars and levee banks along the Ok Tedi and Fly Rivers to provide hydrologic input to efforts to estimate current and future chemical loadings entering the river system.

#### ARD modelling

The aims of the current modelling work are to:

- develop a pit water quality model to predict pit water quality in the final void following mine closure; and
- develop a model for prediction of the acid-base balance (NAPP) for all Program Domains and provide an ARD risk rating for these domains under a range of operational scenarios.

The OTML predictive ARD model (OkARD) has been developed and simulations are routinely run to predict the ARD risk throughout the various components of the catchment system under a range of different mine operation scenarios (Figure 7). Field measurements collected to verify and calibrate the model suggest the model is relatively accurate and provides a reliable prediction of the acid-base balance and resulting ARD risk. The model uses a number of assumptions and ongoing work is being carried out to confirm and refine these assumptions in order to improve the predictive capabilities of the model.

The results of OkARD simulations will in turn be used to identify gaps in the present geochemical database and to evaluate mitigation options under a range of environmental conditions (eg extremely wet or dry climatic conditions). A more detailed account of OkARD is given in Miller *et al* (2003, this volume).

### Stage 3 – Risk assessment

This stage involves the assessment of risk throughout the receiving environment on the basis of probability and consequence. The approach taken is essentially semi-qualitative with numerical scores being assigned to each risk following comparison to both likelihood and uncertainty risk criteria.

Once identified and analysed risks are then ranked on the basis of exposure or consequences. Events with the highest environmental or health risk can then be given priority for action. At OTML this process is accomplished by use of a risk register that lists all possible risks, risk owners, risk management plans and the means to assess performance.

This process has also enabled the identification of gaps in the information base. As a result decisions can then be made as to where additional work is required to reduce uncertainties in both probability and consequence to acceptable levels of confidence.

### Stage 4 – Risk treatment

As with most risk management projects, OTML recognises that there exists a range of treatment or mitigation options (see also Lee, 1999). These include:

- risk elimination – by removal of the source of the risk, eg sulfide removal from ex-mill tailings entering river system;
- risk reduction – by reducing the sources of risk or their likelihood of occurrence, eg design changes;
- impact mitigation – minimising the consequences of risk by implementing strategies such as contingency planning, regular audits and technical compliance;
- risk transfer or sharing; and
- risk acceptance.

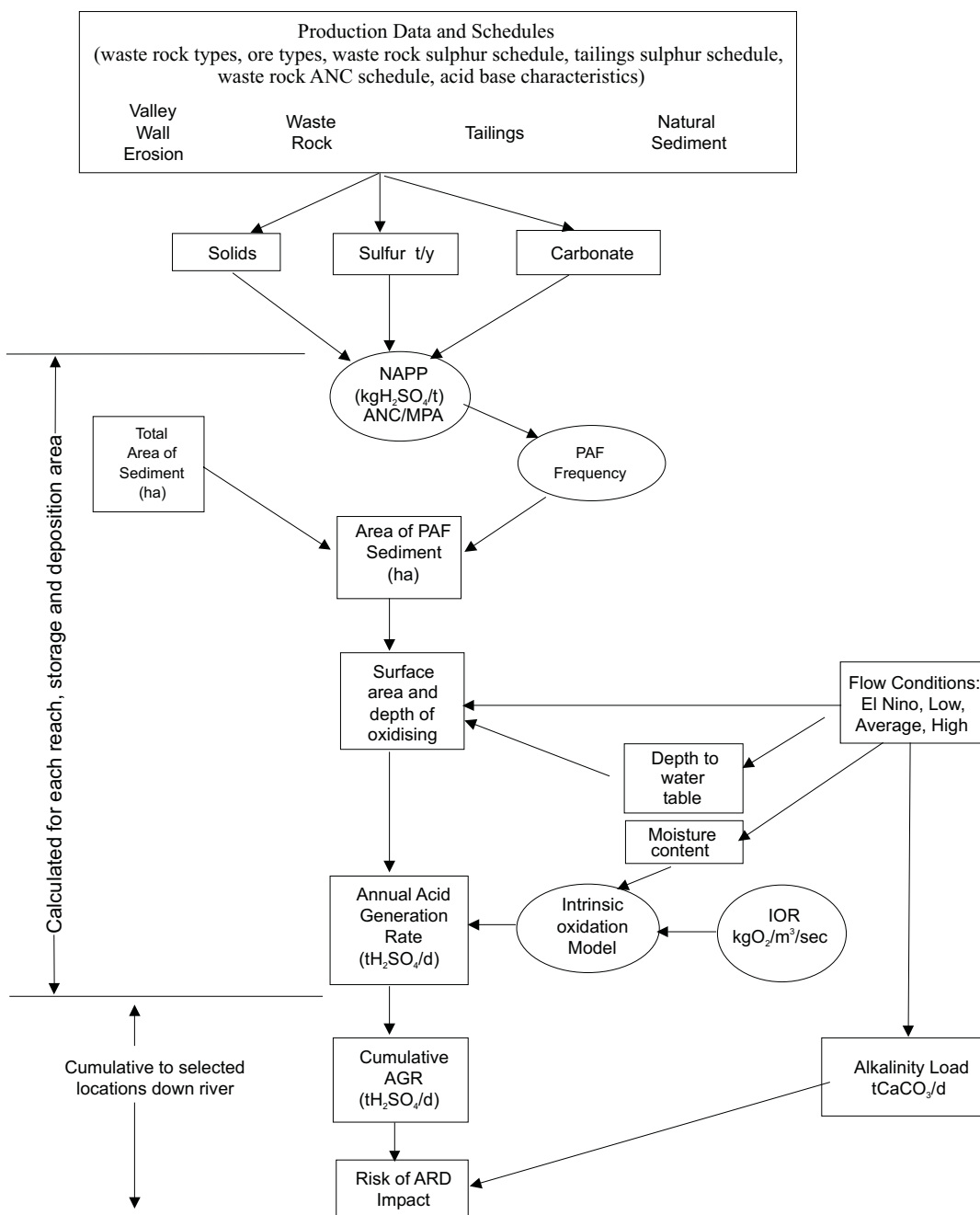


FIG 7 - Main components of the OkARD model.

The basic approach taken at OTML to risk treatment is one of prevention rather than remediation. The risk assessment procedures in place have and will enable the identification and implementation of a range of engineering or administrative controls such that the exposure to ARD effects is greatly reduced.

All these strategies are currently either under review or have been adopted in one form or another at Ok Tedi. For example it is now known with some degree of certainty that should a pit lake be allowed to form at mine closure that it would become acidic and therefore pose a risk to the surrounding and downstream environments. As a result studies are underway to examine whether flows into the pit lake can be engineered to ensure acceptable water quality (risk reduction) or, if this cannot be achieved, recommending that final pit configuration not include a pit lake (risk elimination).

Miller *et al* (2003, this volume) and Rumble *et al* (2003, this volume), describe other mitigation measures being implemented at Ok Tedi.

Another key element of this stage is that of community consultation. This is particular so where the risk of ARD impact has the potential to cause public outrage. To this end, OTML consults with all relevant stakeholders (government, local landowner, NGO's, church groups, media) on a regular basis. The main purpose of this engagement, in relation to the ARD Program, is to inform stakeholders of the results of risk assessment and what steps are planned to either prevent any potential adverse effects or mitigate their impact, should they occur. Consultation sessions are also an opportunity to understand the concerns of the people potentially impacted by OTML operations and to discuss ways in which these concerns might be addressed through follow-up investigations.

Effective communication with the senior management of the company is a further requirement for successful implementation of risk treatment options. At OTML this is being done through regular engagement with operations personnel to provide updates on the results of risk characterisation; by their direct involvement in the identification and implementation of mitigation measures, and feedback sessions to report on the performance of mitigation or risk reduction trials. Gaining the support of senior OTML management and the Board is also essential in terms of securing the resources required.

## Stage 5 – Review and monitor

### *Risk action plans*

With much of the ARD risk identification, analysis and assessment now complete, the focus of recent effort has been the establishment of risk action plans. These plans will provide detailed guidelines for risk management. They typically include:

- scheduling of any preventative or remediation actions;
- a detailed description of the risk and evidence in support of the likely exposure and consequences;
- a comprehensive list of risk treatment options together with cost-benefit analysis;
- recommendations for risk treatment including anticipated timing, as well as resource, responsibility, reporting and budgetary requirements; and
- monitoring requirements to assess performance.

Risk action plans are either already in hand or are under development at Ok Tedi to enable efficient management of all ARD risks identified to date.

### *On-going monitoring*

A key component of the ARD Management Program is system-wide monitoring. The main aims of this work is to provide:

- a measure of performance against targets;
- a means of early warning such that indications of approaching non-compliance successfully trigger, in the first instance, more detailed level of investigation and, should the cause of the trend be attributed to mining operations, implementation of risk reduction or elimination treatment options; and
- information needed for modelling on a probabilistic basis as opposed to the use of single values.

At the time of writing, OTML has instigated a comprehensive monitoring program involving collection of a range of sample types, from all major areas of risk, to evaluate geochemical trends and assess the performance of mitigation measures being implemented.

Recognising that the acid-base balance of mine waste materials to be released over the remaining years of mine life will change in accordance with the changing geology of the ores

and associated waste rock, it is imperative that the acid-base balance and acid forming potential of the major repositories throughout the receiving environment are monitored. To this end representative samples of ex-mill tailings, the waste rock dumps associated with the mine area creeks (eg Harvey and Sulphide Creeks), selected sand and gravel bars in the Upper Ok Tedi, the dredge sediment stockpiles at Bige and selected parts of the levee bank and floodplain of the Lower Ok Tedi and Middle Fly Rivers, are collected and characterised on a regular basis.

## CONCLUSIONS

OTML has long recognised the risk posed to the communities and ecology of the Ok Tedi/Fly River system from ARD. It has in recognition of these risks established the ARD Management Program based on best practice risk management strategies. Significant progress has been made in regard to risk identification, characterisation and assessment. The work currently underway to put in place a comprehensive risk treatment and review process will ultimately determine the success or otherwise of this approach.

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