

# Ok Birim Tailings Storage Facility Project

Environmental and Social Impact Assessment

## Appendix B

Hydrology, sediment transport and riverine particulate geochemistry report



*TECHNICAL REPORT ON THE IMPACT OF A TAILINGS  
STORAGE FACILITY AT THE LOWER OK TEDI (OK BIRIM)  
SITE*

*GEOMORPHOLOGY, SEDIMENT TRANSPORT AND  
RIVERINE GEOCHEMISTRY*

*PREPARED BY DR GEOFFREY PICKUP, CONSULTING  
GEOMORPHOLOGIST FOR TETRATECH COFFEY LTD*

*12 DECEMBER 2025*

## Disclaimer

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## GLOSSARY OF TERMS

|                  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Aggradation      | The deposition of sediment (in the Ok Tedi context applied mainly to mine-derived sediment) which results in a build-up of bed load sediment on the floor of the main channel (or in tie-channels) which results in a raising of the level of the riverbed (several metres in the main channel), the vertical extension of levees (metres) or the surface of the floodplain (several millimetres). Where fluvial processes result in a lessening of deposited sediment, scouring is said to occur.                                   |
| ANC              | Acid Neutralising Capacity (ANC) is a measure of a sample's capacity to neutralise acid. It is determined by the addition of a known amount of hydrochloric acid (HCl) to an accurately weighed sample, allowing the sample time to react (with heating), then back titrating the mixture with sodium hydroxide (NaOH) to determine the amount of unreacted HCl. The amount of acid consumed by reaction with the sample is then calculated and expressed in the same unit as the MPA, that is kg H <sub>2</sub> SO <sub>4</sub> /t. |
| ARD              | Acid Rock Drainage (ARD) describes drainage that has been affected by the products of sulfide mineral oxidation. It is produced by the exposure of sulfide minerals such as pyrite to atmospheric oxygen and water.                                                                                                                                                                                                                                                                                                                  |
| ANC/MPA Ratio    | The ANC/MPA ratio is frequently used as a means of assessing the risk of acid generation from mine waste materials. The ANC/MPA ratio is another way of looking at the acid base account. A positive NAPP is equivalent to an ANC/MPA ratio less than 1 and a negative NAPP is equivalent to an ANC/MPA ratio greater than 1. A NAPP of zero is equivalent to an ANC/MPA ratio of 1.                                                                                                                                                 |
| DEM              | Digital Elevation Model: in essence, this is a digital topographic model of the floodplain                                                                                                                                                                                                                                                                                                                                                                                                                                           |
| Dissolved copper | Copper may be present in water in or attached to particles (particulate copper) bound to organic materials (bound or complexed copper) or as free ions in solution. Dissolved copper (dCu) is defined as the copper which can pass through a 0.45µm filter – which is fine enough to filter out bacteria and most particles, so dissolved copper includes free copper ions and complexed copper. Dissolved copper is usually a better indicator of toxicity than total copper.                                                       |
| EWRD             | Engineered Waste Rock Dump. A dump built to remain stable with minimal losses                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| HEC-6            | A model developed in 1992 by the Hydrologic Engineering Centre (US Army Corps of Engineers) which has been used to model sediment transport, storage and water level changes on the Lower Ok Tedi and Middle Fly. This model is well suited to floodplain reaches and is probably the world's most widely used sediment model.                                                                                                                                                                                                       |

|         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|---------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| MPA     | <p>The Maximum Potential Acidity (MPA) that can be generated by a sample is determined from the sample sulfur content. The total sulfur content of a sample is commonly determined by the LECO high temperature combustion method. The calculation assumes that the measured sulfur content occurs as pyrite (FeS<sub>2</sub>) and that pyrite reacts under oxidising conditions to generate acid according to the reaction:</p> $\text{FeS}_2 + 15/4 \text{ O}_2 + 7/2 \text{ H}_2\text{O} \Rightarrow \text{Fe(OH)}_3 + 2 \text{ H}_2\text{SO}_4$ <p>According to this reaction, the MPA of a sample containing 1 %S as pyrite is 30.6 kilograms of H<sub>2</sub>SO<sub>4</sub> per tonne of material (<i>i.e.</i> kg H<sub>2</sub>SO<sub>4</sub>/t). Hence the MPA of a sample is calculated from the total sulfur content using the following formula: <math>\text{MPA (kg H}_2\text{SO}_4\text{/t)} = (\text{Total \%S}) * 30.6</math></p> |
| NAF     | <p>Non-acid Forming: a sample classified as NAF may, or may not, have a significant sulfur content but the availability of ANC within the sample is more than adequate to neutralise all the acid that theoretically could be produced by any contained sulphide minerals. As such, material classified as NAF is considered unlikely to be a source of acidic drainage. A sample is usually defined as NAF when it has a negative NAPP and the final NAG pH ≥ 4.5</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| NAPP    | <p>The Net Acid Producing Potential (NAPP) of a material is expressed in units of kg H<sub>2</sub>SO<sub>4</sub>/t and is calculated as follows: <math>\text{NAPP} = \text{MPA} - \text{ANC}</math>. If the MPA is less than the ANC then the NAPP is negative, which indicates that the sample may have sufficient ANC to prevent acid generation. Conversely, if the MPA exceeds the ANC then the NAPP is positive, which indicates that the material may be acid generating.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| OkARD   | <p>A model developed by EGi for OTML, used to predict future acid loads within the river system, taking into account the current mine plan and expected changes in mine waste geochemistry through time to predict the acidity / alkalinity balance at various locations.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| OkGrav6 | <p>Version 6 of the gravel transport model specifically developed to examine the storage and transport of gravel material in the mine area creeks and through the upper Ok Tedi.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| OkTUGS  | <p>Ok Tedi Unified Gravel-Sand Model: The <i>OkGrav6</i> sediment model, used to model the Upper Ok Tedi and tributaries, is not suitable for detailed prediction of sand supply to the Lower Ok Tedi. Also, <i>OkGrav6</i> is a depositional model and not well-suited to predict erosion. The <i>OkTUGS</i> model successfully handles the gravel-sand mixtures delivered to the river system by disposal of waste rock and tailings from the Ok Tedi Mine. The <i>OkTUGS</i> model uses a gravel and sand transfer functions that are linked to the grain size distributions in the surface layer, subsurface and bedload.</p>                                                                                                                                                                                                                                                                                                               |
| OTEMA   | <p>The Ok Tedi Environment Management Act 2019 – this legislation was fully gazetted in September 2024</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| ORWB    | <p>Off River Water Body (ORWB): refers to oxbow lakes, cut-off meanders and blocked valley lakes located along the floodplain.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| PAF     | <p>Potentially Acid Forming: a sample classified as PAF always has a significant sulfur content, the acid generating potential of which exceeds the inherent acid neutralising capacity of the material. This means there is a high risk that such a material could oxidise and generate acidic drainage if exposed to atmospheric conditions. A sample is usually defined as PAF when it has a positive NAPP and a final NAG pH &lt; 4.5</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| PCon    | <p>Pyrite concentrate (PCon) generated in, and extracted from, the tailings in the Tailings Pyrite Plant (TPP). The TPP is part of the Mine Waste Tailings Program which aims to remove up to 90% of the pyrite</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |

|                              |                                                                                                                                                                                                                                                                                                                                   |
|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                              | from the tails, producing a concentrate grade of up to 45%S reducing the sulfur content in the final tails to less than 1%S.                                                                                                                                                                                                      |
| <i>SRTM</i>                  | The Shuttle Radar Topographic Mapping Mission ( <i>SRTM</i> ) topographic data acquired by the US Space Agency NASA in February 2000 provides a basic DEM of the floodplain with a spatial resolution of about 90 metres and a vertical accuracy of a few metres.                                                                 |
| <i>SRTM</i> DEM              | The DEM constructed using <i>SRTM</i> data. However, this DEM requires modification to include tie channels and to allow for infill of flooded areas for which the <i>SRTM</i> did not supply elevation data given its acquisition during a la Nina phase.                                                                        |
| Total Suspended Solids (TSS) | The amount of particulate material in water, measured by filtering out the particles, usually on a glass fibre filter paper, drying the filter paper and weighing the material retained. TSS gives a measure of how “muddy” (or turbid) the water is.                                                                             |
| TPP                          | Tailings Pyrite Plant which consists of plant modifications at the Mill to remove 90% of the pyrite from mill tails. The pyrite concentrate (see PCon) is pipelined to PCon pits located in the Ok Tedi floodplain at Bige.                                                                                                       |
| Washload                     | Washload describes the fine material that travels more or less continuously suspended in the flow. Its size varies with the energy of the flow. Thus, coarse sand may travel as wash load in fast-flowing turbulent upstream reaches while washload in lowland sections of river will be made up of silt or clay-sized particles. |

## EXECUTIVE SUMMARY

### PROJECT CONTEXT

The Ok Tedi Mine in Western Province, Papua New Guinea, has operated since 1985 with riverine disposal of tailings and waste rock. This practice has substantially altered the Mine Area Creeks, the Ok Tedi and the Middle Fly River systems, resulting in extensive sediment deposition, rising river levels, prolonged floodplain inundation, and ecosystem disruption. There has also been geochemical pollution, mostly in the form of deposited particulate copper and in some locations, deposition of particulate sulphur, creating a risk of acid and metalliferous drainage.

Ok Tedi Mining Ltd (OTML) now proposes constructing a Tailings Storage Facility (TSF) near the Ok Birim confluence with the Middle Ok Tedi, which would eliminate most tailings discharge into the river system. This Environmental and Social Impact Assessment (ESIA) supporting study evaluates hydrology, sediment transport, and particulate geochemistry, focusing on impacts with and without a TSF.

While a TSF will substantially reduce the input of sand and silt-sized material to the river system, it is not the only process operating. Downstream transport of sediment already in the system and losses from existing failing waste rock dumps will continue, whether or not a TSF is built.

When assessing the impact of TSF, we need to allow for the existing processes and trends in river behaviour and differentiate them from total system change so the sediment transport and riverine geochemistry model predictions in this report reflect **net impact** as well as total change when possible. This means that impact modelling must deal with the full gamut of background processes as well as the effect of removing most tailings from the sediment input stream.

## KEY FINDINGS

### Inputs and Outputs of Sediment

There are several inputs and outputs of sediment to or from the river system. The mine-derived or potentially mine-related inputs are listed below.

Waste Rock inputs have involved peaks of up to 80 Mt/year with recent averages of around 55 Mt/year. These have entered the system mostly via the Southern Dumps. Recent inputs via the Northern Dumps have averaged around 30 Mt/year. Future reductions of inputs to the river system are anticipated via engineered waste rock dumps (EWRDs) and a mine plan which sees total waste rock production reducing from around 2030 onwards.

Tailings production has declined historically from an average of about 26 Mt/year to 17 Mt/year since 2013; diversion to a TSF would cut tailings inputs to the river system by a further ~85–95%.

Landslides are common throughout the mountain areas of the Ok Tedi drainage basin and are a major, though intermittent, source of sediment delivery to the river system. Major natural and mine-triggered slides include the Vancouver Avalanche which delivered an estimated 115 Mt between 1989 and 1991 and the Harvey Creek landslides which added 19-28 Mt/year to the river system between 1991 and 1996.

The major outputs or sediment losses from the river system are dredge offtake, storage in very long-term depositional areas, notably on the floodplains, and discharge of sediment to the Lower Fly and the Fly Delta. The latter was not part of this study but is estimated at about 15 Mt/year when averaged over the whole of mine life so far. (Pickup, 2025).

Since 1998, dredging at Bige at the head of the Lower Ok Tedi has removed about 17 Mt/year of sand from the river. This has halted or reversed pre-dredging bed level rise on the Lower Ok Tedi and on the Upper and central Middle Fly but there continues to be very slow bed level rise further downstream as progression of material already in the river system downstream from the dredge site occurs.

Dredging does not capture the silt component of either tailings or waste rock inputs.

Diversion to a TSF will capture both the sand and silt component of tailings but not those of waste rock inputs. Waste rock has a large component of siltstone and limestone, both of which abrade to mostly silt. This means that the sand: silt ratio of the river sediment load will reduce by about 40% and change to reflect a finer sediment load.

Diversion of tailings to a TSF will further reduce bed level rise in the lower and central Middle Fly and eliminate it in the lower Ok Tedi and upper Middle Fly.

The Lower Ok Tedi and Middle Fly floodplains have developed over millennia as the river has meandered across its containing valley. As such, the floodplains are zones of long term sediment storage and loss of material from the sediment load of the river. Sediment is added to the floodplain both by channel migration and as overbank floods deposit material on the floodplain surface. As such, the floodplain becomes an area of long term sediment storage. Sediment is only released by floodplain destruction as the river channel migrates laterally which, on the Lower Ok Tedi and Middle Fly, is a very slow process occurring over many centuries. Pickup (2025) estimates a long-term average sediment loss rate of about 5 Mt/year.

### River and Floodplain Responses and Observed Trends<sup>1</sup>

In the Upper River system (Mine Area Creeks & Middle Ok Tedi) there has been ongoing deposition and rising water levels.

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<sup>1</sup> See Figs. 2-1, 2-2, 2-5 and 2-7 for locations.

On the Lower Ok Tedi & Middle Fly there has been increased floodplain inundation, continuing levee buildup, and some infilling of water bodies held in oxbow lakes on the floodplain. In the early years of mine operation, when tailings sulphur content was high, localised acid mine drainage breakout zones occurred in downstream reaches of the Middle Fly notably on levees and levee backslopes.

Floodplain inundation appears to be close to the maximum likely spatial extent which is limited by the higher ground that makes up valley edges. There may, however, still be some expansion into upper sections of tributaries.

## Future Predictions

Investigations are based on Mine Plan 240822 (AMC, 2024) with a TSF operating from 2030 and capturing 90% of tailings, plus dredging at Bige continuing throughout mine life, yields the following conclusions.

Without a TSF, there will be continued sedimentation, water level rise, and further floodplain impacts. However, at present, dredging is removing enough sand to limit bed level rise, especially in upper floodplain reaches.

With a TSF:

- there will be significant reductions in sand and silt delivered to Lower Ok Tedi and Middle Fly.
- A potential two-thirds reduction in sand delivery for dredging at Bige and a reduction in the sand: silt ratio of the sediment load which will become much finer than previously.
- Increased riverbed erosion on the lower Ok Tedi and at the upper end of the Middle Fly but little change further downstream, and possible continued deposition on the lower Middle Fly but at a very slow rate.
- Reductions in water levels on the lower Ok Tedi but at a decreasing rate further downstream with minimal change beyond Mabaduam and into the central and lower Middle Fly .
- Possible reduction in floodplain inundation frequency and delivery of mine derived sediment to floodplain surfaces and ORWBs.
- Levee growth is a slower process than changes on the riverbed and is likely to slowly continue but at a reduced rate, especially in the upper floodplain reaches.

Both with and without a TSF:

- Floodplain isolation from the main river is likely to continue.
- Most sediment delivered to the floodplain will remain in long term storage due to limited lateral channel migration and erosion.

A Recovery Baseline run (a model run with no further disposal of waste rock or tailings after 2025) provides insight into long-term natural reworking of stored sediments. It shows a reduction in sand and silt in the sediment load to a base level over a period of 5-10 years but little change beyond that over the next 25-30 years (the limits of modelling) suggesting further decades of elevated sediment transport. The base level is about twice the estimated pre-mine sediment transport rate.

Uncertainty of estimates. All the model projections are subject to a degree of uncertainty imposed by accuracy of inputs and limitations of the technology in use. Other sources of uncertainty come from future changes to the mine plan, especially in the mine closure date. Investigation of increases in rainfall due to climate change yields ambiguous results with no apparent change since 1984 in most upper Ok Tedi station records but some increases further downstream in lowland areas starting around the year 2000. No apparent further changes were found since then in either upland or lowland records. No changes in the number of extreme events over time were detected in the water level records of the Ok Tedi and the Fly River. If they exist, they are masked by changes in river morphology due to deposition of mine waste and the small number of events.

## Geochemistry

-Particulate metals dominate the geochemical pollution of the Fly River system with over 99% of copper released into the river in particulate form, while less than 1% is present in dissolved form. This means that sediment storage,

remobilisation, and floodplain deposition are key pathways through which geochemistry shapes downstream ecosystems.

Sulphide-bearing mine waste tailings and some components of waste rock may be rich in sulphur and heavy metals. Some studies indicate that sulphide tailings with sulphur concentrations above 1 % have the potential to generate acid rock drainage and this level of concentration was the norm up to 2010 at Ok Tedi. Sulphur concentrations in tailings now sit slightly below 1% and are projected to remain there for the remainder of mine life since the tailings pyrite processing plant provides an engineered control of tailings sulphur concentration. Addition of ground limestone to tailings further reduces the likelihood of acid rock drainage.

Acid neutralising capacity (ANC) (largely derived from limestone) reduces the possibility of acid generation with ANC:MPA ratios<sup>2</sup> of 2 or more being regarded as indicating minimal acid generation risk. Ratios of 1-2 are regarded as showing some level of risk. Geochemistry model predictions for future sediment outflows from the Middle to the Lower Ok Tedi indicate that without a TSF the ratios will lie between 2 and 3. With a TSF, the ratios lie between 5 and 6. ANC:MPA ratios from depositional bars in the Middle Ok Tedi which contain only limited amounts of deposited tailings can be much higher, indicating minimal ARD risk.

Copper content of tailings is now about one third to one quarter of values in the early 2000s. This reduction is due to decreased head grades in ore combined with increased copper recoveries in the processing plant. Sulphur values have decreased by more than 60% due to the operation of the tailings pyrite processing plant.

The highest concentrations of deposited particulate copper in the floodplain reaches of the river system occur on main channel and tie channel levees close it. Monitoring of levees in the Lower Ok Tedi and Middle Fly shows progressive reduction of copper and sulphur concentrations over time and increasing ANC. ANC declines downstream due to dilution by Upper Fly inputs but downstream ANC:MPA ratios measured from levee sediment samples would be classified as Non-Acid Forming and unlikely to be a source of acidic drainage for the remainder of mine life.

The persistence of mine-derived sediment, especially sulphur-bearing tailings in oxbows and floodplain waterbodies may extend these risks by creating long-term repositories of once reactive material. Little is known of this material as there has been only limited floodplain surface sampling and coring since the early 2000s (Bolton and Pickup, 2021). However, most this material is either submerged or buried suggesting that it is low risk.

With a TSF, particulate copper discharge to the Lower Ok Tedi will decrease by about 50% compared with no TSF with values decreasing from an average of 371 mg/kg for the 2030-2050 period to 196 mg/kg. These differences will persist on the levees downstream throughout Lower Ok Tedi and Middle Fly with only limited dilution by input from the Upper Fly.

With a TSF, the decrease in % sulphur in sediment discharge (as measured in Bige dredge material) is about 28% for the 2030-2050 period, from 1.29% to 0.93%. Concentrations on the Lower Ok Tedi levees are about 60% of these values with the differences initially persisting downstream on the levees but becoming more diluted by Upper Fly inputs and in the lower Middle Fly.

With a TSF, ANC (as measured in Bige dredge material) increases from 101 kg H<sub>2</sub>SO<sub>4</sub>/tonne to 140 kg H<sub>2</sub>SO<sub>4</sub>/tonne or a 39% increase. There is minimal dilution on the Lower Ok Tedi levees, slightly more below the junction with the Upper Fly with a further decrease in the central Middle Fly and beyond.

With a TSF the ANC:MPA ratio (as measured in Bige dredge material) almost doubles from 2.58 to 5.11 with the differences also persisting downstream on the levees suggesting little ARD risk compared with the early 2000s.

The TSF therefore provides a significant improvement to lower river system particulate geochemistry.

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<sup>2</sup> The MPA is the maximum amount of acid that could be generated by the sulphur contained within a sample assuming that all the sulphur occurs as reactive pyrite.

## Tailings Storage Facility – Local Impact

The local impact of the TSF on the geomorphology of the river system is mostly confined to the eastern branch of the Ok Yep, a small lowland area on the western side of the Ok Tedi. There is no outflow into the relatively pristine Ok Birim. Within the Ok Yep catchment, there may be elevated sediment yield and deposition along the watercourse during the construction period. Post construction, some of the deposits may be eroded but sediment yield from the catchment is likely to remain higher than under pre-construction forested conditions.

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## CHAPTER ONE - INTRODUCTION

### PROJECT BACKGROUND

Current operations at the Ok Tedi Mine involve riverine disposal of tailings and waste rock. Tailings are discharged into the Ok Kumiup, a small tributary of the Ok Mani on the south side of the mine. Waste rock is placed into on-site eroding waste rock dumps, with eroded material transported downstream via the Ok Tedi to Bige and beyond into the Middle Fly River.

River dredging has been undertaken at Bige since 1998 to recover the sand component of the tailings and waste rock for land deposition. However, the silt component of both the tailings and eroded waste rock and an estimated 15% of the sand passes downstream into the Lower Ok Tedi and the Middle Fly River.

Recent modelling (Pickup and Ridd; 2024) suggests that about 900 Mt of sediment is stored in the Mine Area Creeks and the upper and Middle Ok Tedi. Also, 200-300 Mt of pre-dredging era material is stored on the riverbed, in levees and on the floodplains of the Lower Ok Tedi and the Middle Fly, raising water levels and increasing the extent, frequency and duration of floodplain inundation. Clearly, the forty years of riverine tails and waste rock disposal has had significant environmental and social impacts downstream.

In a significant shift, OTML now proposes to construct a tailings storage facility (TSF) downstream from the south bank of the Ok Birim near its confluence with the Ok Tedi, approximately 60 km south (by direct distance) from the existing Ok Tedi Mine (Figure 2.1). Establishing the proposed TSF would largely eliminate current riverine tailings disposal by the mine and potentially reduce the amount of dredging required to prevent further water level rise in downstream reaches of the Lower Ok Tedi and the Middle Fly Rivers

Tetra Tech Coffey Pty Ltd (Tetra Tech Coffey) has been engaged by Ok Tedi Mining Ltd (OTML) to prepare the Environmental and Social Impact Assessment (ESIA) for the proposed Ok Birim Tailings Storage Facility Project (the project) in the Western Province of Papua New Guinea (PNG). This report presents a hydrology, sediment transport and particulate geochemistry assessment as a supporting study for the ESIA.

The report covers the Mine Area Creeks, the Ok Tedi, the Middle Fly and the lower reaches of the Upper Fly which joins the Ok Tedi at D'Albertis Junction to become the Middle Fly. It does not extend into the South Fly downstream from the junction of the Middle Fly and the Strickland at Everill Junction. Studies of benthic geochemistry & total suspended sediment in the South Fly (Bolton and Pickup, 2021; Pickup, 2025; Bolton, *in prep.*) indicate that about 85% of delivered sediment comes from the Strickland. Thus, it is unlikely that the impact of a TSF would be

discernible in the South Fly and even less in the Fly Delta where marine sourced sediment inputs may exceed those of the South Fly tenfold (Wolanski, *et al*, 1998).

Based on the 2025 C5 TSF Concept Design by Klohn Crippen Berger (2025). The project will include:

- **TSF.** The proposed TSF will feature a ring-dyke (paddock) impoundment design with two cells to store tailings. An on-site cyclone house will separate piped tailings into fines and coarse sands prior to TSF disposal, with coarse sands used for embankment construction. The TSF will be constructed in stages, covering an area of approximately 1,431 hectares. The design provides storage for up to 173 Mt of tailings material. A sediment pond below the ultimate embankment toe will collect decanted slurry water and incidental rainfall and settle suspended sediments prior to ultimately discharging into the Ok Tedi.
- **Access road and bridge / river crossings.** An existing road runs along the east side of the Ok Tedi and links the Ok Tedi Mine site with Ningerum, which is the nearest township to the proposed TSF site, approximately 6 km east. The TSF site is located on the west side of the Ok Tedi so bridge and river crossings are required to access the site depending on the final selected pipeline and general access route.

## APPROACH

While a TSF will substantially reduce the input of sand and silt-sized material to the river system, it is not the only process operating. Downstream transport of sediment already in the system will continue, whether or not a TSF is built. Most gravel-sized material will remain in the Ok Tedi upstream from the dredge site at Bige at the upstream end of the Lower Ok Tedi. However, the finer fraction of sediment eroded from waste rock dumps, currently held in riverine deposits and created by abrasion during downstream transport of gravels will continue to move into the Lower Ok Tedi and the Middle Fly. Material still held in failing dumps at the mine site will also continue to enter the river system.

When assessing the impact of TSF, we need to allow for the existing processes and trends in river behaviour and subtract them from total system change so the sediment transport and riverine geochemistry model predictions reflect **net impact** as well as total change. This means that impact modelling must deal with the full gamut of background processes as well as the effect of removing most tailings from the sediment input stream. This requires a description of the river system, its current state and the ongoing range of river system change processes. These are addressed in Chapter Two which deals with the individual reaches of river, the floodplains, the off-river water-bodies (ORWBs) and interchanges between the river and the floodplain, including the transfer and deposition of mine-derived sediment. The ORWBs are of particular biological importance as they may be the only surface water-retaining bodies outside the main river channel during the periodic droughts that affect the region.

Chapter Three addresses the main sediment inputs and outputs affecting the river system. It examines the mass of tailings and waste rock delivered to the river from the mine from the start of operations in 1985 to the present day and up to the planned mine closure date in 2050. It covers waste rock inputs from the failing dumps on the north and south side of the mine, tailings inputs and known inputs from large landslides and capture of material by river dredging.

Information on past and projected mine waste inputs to the end of mine life based on the current mine plan (240822 (AMC, 2024) is presented. This includes projected reductions in waste rock inputs if an engineered waste rock dump (EWRD) on the north side of the mine can be successfully constructed and operated. If successful, it will substantially reduce waste rock inputs to the river. We currently estimate that waste rock delivered to that dump input may reduce coarse material inputs to the river system to an annual loss of 5% existing EWRD contents plus 5% of inputs for the year in question.

A second EWRD on the south side of the mine is also under consideration. As with the constructed dump on the north side of the mine, we expect it to lose 5% of annual inputs plus existing EWRD contents to the Ok Mani system after losing 10%/year during the first two years while construction is in progress. It is also likely that the Ok Mani, which is a less steep system than the northern dump on Sulphide Creek in the north, will release material to Ok Tedi much more slowly.

Landslides are a mostly natural phenomenon and occur throughout the Upper Ok Tedi catchment (Blong, 1991) but can be triggered by mine-related activities and have been known in extreme cases to increase total sediment inputs very substantially (Hearn, 1995). Since mining began, four or five large landslides have occurred in the project area which had the ability to impact mine operations to some degree including damage to the mine access road and water and concentrate pipelines (e.g. Marshall, 2018). While landslides cannot be predicted, sediment inputs from previous landslides are examined and will be used to construct an example case to be used in sediment input and transport modelling if a TSF is constructed.

Riverbed dredging at Bige about 100 km downstream from the mine has been used since 1998 to extract sediment from the river and reduce water level rise and flooding due to sediment deposition. On average, 17 Mt/year is dredged and stored in tailings sand stockpiles on the east and west side of the river at the dredging location whereas PCon is transported by pipeline from the mine to the PCon storage on the west side of the river. Mostly sand is captured, but the fine component of tailings and waste rock passes downstream. If a TSF is constructed, the rate of dredging and the length of time it is planned to continue for is expected to change as the supply of sand could be reduced by up to two-thirds meaning that there will be less sand available to be dredged, irrespective of dredge capacity.

Chapter Four examines the response of the upper river system to waste rock and tailings disposal. It describes patterns of aggradation in each of the Mine Creeks that receive inputs of mine waste and landslides. In some reaches, up to 100m of aggradation has occurred, leaving a set of deposits that continue to erode and transmit material downstream. The Mine Area creeks flow into the Middle Ok Tedi, a largely gravel bed river occupying a gorge for some of its length then becoming braided. Aggradation of 1-4m here is common and water levels have risen by at least 2m. The Ok Mani currently receives tailings but transmits most of them downstream so diversion to a TSF is only likely to have a very limited impact in this reach of the river system.

Chapter Five deals with the floodplain systems of the Lower Ok Tedi, the Upper Fly and the Middle Fly River. These are much lower gradient, largely sand bed systems and besides experiencing main channel deposition, also export sediment into ORWBs as well onto the floodplain surface itself. This section describes bed level rise, levee build up and floodplain inundation. It also examines how connectivity between channel and ORWBs occurs and how some linkages have become blocked in response to the increase in sediment load in the river. The extent of floodplain penetration by mine sediment is also explored using the copper content of mine sediment as a tracer.

Chapters Six and Seven deal with predicting the future both with and without a TSF. The main approach to assessing future impact is to use a set of predictive sediment transport and particulate geochemistry models that OTML has developed over the last 20-25 years. The models have been extensively tested and reviewed, and, if necessary and where possible, calibrated and validated by comparing model predictions with observed data. Detailed descriptions of each model, including their initial development and validation are provided in a series of Appendices to this report. The Appendices also describe the regional hydrology models used to generate flow data at various locations down the river system.

Several waste disposal options, both with and without a TSF and with either one or two engineered waste rock dumps have been run through the models for comparative purposes and these are described in Chapter Six. An additional model run, the "Recovery Baseline" has also been carried out. This assumes no further waste rock or tailings disposal after 2025. This is used to provide information on how the river system will evolve when the only processes involved are future losses from existing failing dumps and downstream movement of sediment already present in the rivers system. As such it gives an indication of how the river system may evolve over the long term after mine closure.

Where modelling is not feasible due to technology limitations or lack of data, qualitative predictions of changes and future trends have been made based on observations and understanding of the river system by OTML's consultants who have many years' experience in monitoring the Fly River and similar systems elsewhere in the world. These trends are described in detail in Chapters Four and Five while Chapter Eight applies what is known of observed trends and provides qualitative predictions of changes in the channel blocking, levee deposition and floodplain inundation extent.

Chapter Nine deals with upper river system particulate geochemistry. Two models are used and both are described in Appendix Three and below in the section on models. The first deals with sulphur and acid neutralising capacity and focuses on outputs from the upper river system comprising the Mine Area Creeks and the Middle Ok Tedi. Data on ANC:MPA ratios are also presented as these provide a measure of acid generation risk. The second deals with particulate copper concentration. Input data come from the various mine plans and historical sampling data going back to 2001 when the current sampling regime began.

Chapter Ten describes predictions for levee particulate geochemistry in the Lower Ok Tedi and Upper, Central and Lower Middle Fly. Annual levee sampling allows comparison with the results from the geochemistry mass balance models. In most cases, multiplying these results by simple dilution coefficients gives reasonable predictions of the levee data and allows for the largest dilution effects due to inputs from the Upper Fly.

Chapter Eleven examines the local geomorphic changes resulting from the construction of a TSF. These mostly involve drainage diversions.

## MODELS

In situations where modelling is feasible, five models are used in this study:

*OKTUGS* - This is a theoretically-based sediment transport model built around the *TUGS Unified Gravel-Sand* sediment transport equation (Cui, 2007) and a structure initially developed by Parker (1987). The model was built for OTML by Cui and Pickup (2009) and brought to its final calibrated form by Pickup and Cui (2014). It was designed to be suitable for steep, rapidly flowing mountain streams carrying very high sediment loads and with very high suspended sediment loads, a condition which defeats many of the currently available sediment transport equations which were developed and tested in much less challenging conditions. It runs by taking a set of waste rock, tailings and, in some cases, landslide inputs and calculates erosion, sediment transfer, deposition and output in each of the Mine Area Creeks, the Ok Mani and the Middle Ok Tedi. The model runs on a daily time step from 1985 to 2060, covering the whole of mine life and reports annual data. Outputs include deposition in each reach of river and annual discharges at the downstream end of the model of both sand and silt. Daily TSS<sup>3</sup> values at Ningerum on the Middle Ok Tedi are also produced. The model runs both with and without a TSF and the sand component of the downstream outputs may be directly captured by the dredge at Bige. A detailed description and levels of accuracy achieved when compared with observed data are provided in the development reports in Appendix One, Parts One and Two.

*HEC-6* - As with the previous model, *HEC-6* is a theoretically-based sediment transport model. It is a one-dimensional, movable boundary, open channel flow and sediment movement model originally developed by the US Army Corps of Engineers Hydrologic Engineering Centre (1992). It simulates changes in river profiles caused by scour and deposition over extended periods, typically years, by analysing the interaction between flow hydraulics and sediment transport rates. *HEC-6* is designed for long-term river and reservoir behaviour analysis and offers a wide range of sediment transport equations. It is best suited to sand bed rivers flowing at gradients similar to those on the Lower Ok Tedi and Middle Fly. Outputs include sediment loads, in-channel erosion and deposition and water surface profiles. The water surface data are better for model validation than the erosion and deposition data as they smooth out irregularities in erosion and deposition resulting from variable river channel morphology and/or measured cross sections which are spaced at insufficiently close intervals on the river long profile. Although it is one of the older models now available, *HEC-6* is still one of the most widely used and has probably had more testing than any other model. It offers a very wide range of sediment transport functions, all of which were tested during application to the Ok Tedi and Middle Fly. Despite this, *HEC-6* in its off-the-shelf form substantially underestimated sediment transport in the system but could be calibrated to produce realistic values by running in a speeded-up mode. Appendix Two describes model application plus describes the regional hydrology relationships to provide the water discharges needed for a model run.

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<sup>3</sup> TSS – Total Suspended Solids

Both sediment transport models have been reviewed by external expert panels previously, the lower river sediment transport model (*HEC-6*) in 2004 and 2013, and the newer upper river model (*OKTUGS*) in 2013. Both were accepted subject to the limitations imposed by available technology and input data availability and quality.

#### *MASS BALANCE-ARD and MASS BALANCE-COPPER*

The two particulate geochemistry mass balance models (EGI and Pickup, 2012; Pickup, 2014; Pickup *et al*, 2018) are an update of the *OKARD* model (Miller *et al*, 2003). The models use quarterly inputs of the mass, sulphur content, copper and ANC values of waste rock and tailings derived from observed values and the current or future mine plan (for future inputs). Both models are empirical but attempt to mimic observed processes in the river. Waste rock from the southern side of the mine and tailings pass through a series of storages or nodes consisting of Harvey Creek, the Ok Mani, the Upper Middle Ok Tedi and the Lower Middle Ok Tedi.

Tailings are added at the upper end of the Ok Mani. Waste rock from the northern side of the mine passes through Sulphide Creek and the Upper Ok Tedi without any significant deposition in these reaches. Deposition then begins in the Middle Ok Tedi. There is also a fast path whereby some of the waste rock either consists of sand and silt or breaks down very quickly to finer material and passes straight through the gravel reaches of the system as washload before potentially being deposited on the bed of the Lower Middle Ok Tedi.

Each set of deposits is treated as having an upper storage and a lower storage. The upper storage contains sediment which is largely in transit. The lower storage holds buried material which is only re-excavated if the river begins to erode long term sediment deposits. Deposition rates and changes in storage are obtained from the *OKTUGS* sediment model. Additions from the natural load of the river are added and allowed to dilute the load from the mine. Other calculations allow for storage of finer material within gravel deposits, conversion of gravel to sand or silt by abrasion, and, in the Lower Ok Tedi, enrichment of the sulphur component due to selective deposition of heavier material.

Model parameters are derived empirically, calibrated and verified by comparison with observed deposition in each river reach and with observed copper, sulphur and ANC. Model output is verified by comparing results at each node if observed data are available and with the geochemistry of Bige Dredge sediments so while the model processes are largely physical it is also likely that some chemical reactions are captured by the empirical model equations. An earlier version of the model did have intrinsic oxidation rates explicitly built in (Miller *et al*, 2003) but it proved difficult to obtain parameter values representative of such a complex system. Models are described in Appendices 3 Parts One and Two.

The geochemistry modelling concentrates on the particulate material rather than that transported in solution. Previously there has been concern about the extent to which soluble forms of copper would be released into the system. A thorough review of this work is presented by Apte (2009) who notes that perhaps less than 1% of copper released from the Ok Tedi Mine is in dissolved form and the rest is particulate. A dissolved copper prediction method was originally developed as a supplement to the Copper Mass Balance Model (Pickup *et al*, 2018) but has not been tested sufficiently for operational use so has not been used in this project. Water quality conditions in the river system and the potential impacts of a TSF are examined in a separate report (EGI, 2025).

#### *LOWER RIVER GEOCHEMISTRY*

Levee surface particulate geochemistry values correspond with the Mass Balance Model predictions for particulate copper, sulphur and ANC at Bige reasonably well when averaged over a reach. Much of the future change on the levees in the future including the effect of building a TSF can therefore be modelled by applying simple dilution coefficients to the Bige results (Bolton and Pickup, 2021). These are compared with observed levee surface geochemistry as part of the sections on predicting TSF impact in Chapters Nine and Ten.

## CHAPTER TWO - GEOMORPHIC CHARACTERISTICS OF THE MINE AREA CREEKS, THE OK TEDI AND THE MIDDLE FLY RIVER SYSTEM

This section of the report describes the geomorphology of the river system, the main sediment input types and locations and summarises the response of the river system to the increase in sediment load due to mine waste disposal. As such, it provides a guide as to where the changes arising from diversion of tailings to a TSF may occur but also where they may not.

The Fly River system drains an area of about 75,000 km<sup>2</sup> in western Papua New Guinea (Fig. F2-1). There are three major rivers in the system: the Ok Tedi which drains the Hindenburg Ranges; the Upper Fly which drains the southern part of the Victor Emanuel Range; and the Strickland which drains the Victor Emanuel and Central Ranges. The Upper Fly and the Ok Tedi meet at D'Albertis Junction to form the Middle Fly which meanders down a 400 km long floodplain with extensive scroll bar complexes, meander cutoffs (oxbows) and blocked valley lakes. The Middle Fly and the Strickland meet at Everill Junction before entering the increasingly tidal Lower Fly and the Fly Delta. The delta covers about 10,000 km<sup>2</sup> and extends downstream for another 400 km before entering the ocean in the Gulf of Papua (Fig. 2-1).

In its upper reaches, the Fly River and its tributaries drain a heavily dissected mountain landscape. Ridges rise to over 2,000 m ASL in the north but most of the catchment lies between 200 m and 800 m ASL. The eastern part of the basin is karst country and includes the massive Hindenburg Wall escarpment and contains large areas of landslide debris and old debris flow deposits. In the west, igneous rocks are exposed on high mountains but much of the area consists of shales, limestones and sandstones. Slopes are unstable and landslides and debris flows are common in spite of a dense rainforest cover (Hearn, 1995; Pickup and Marshall 2009). The mine area is shown in Fig. 2-2.

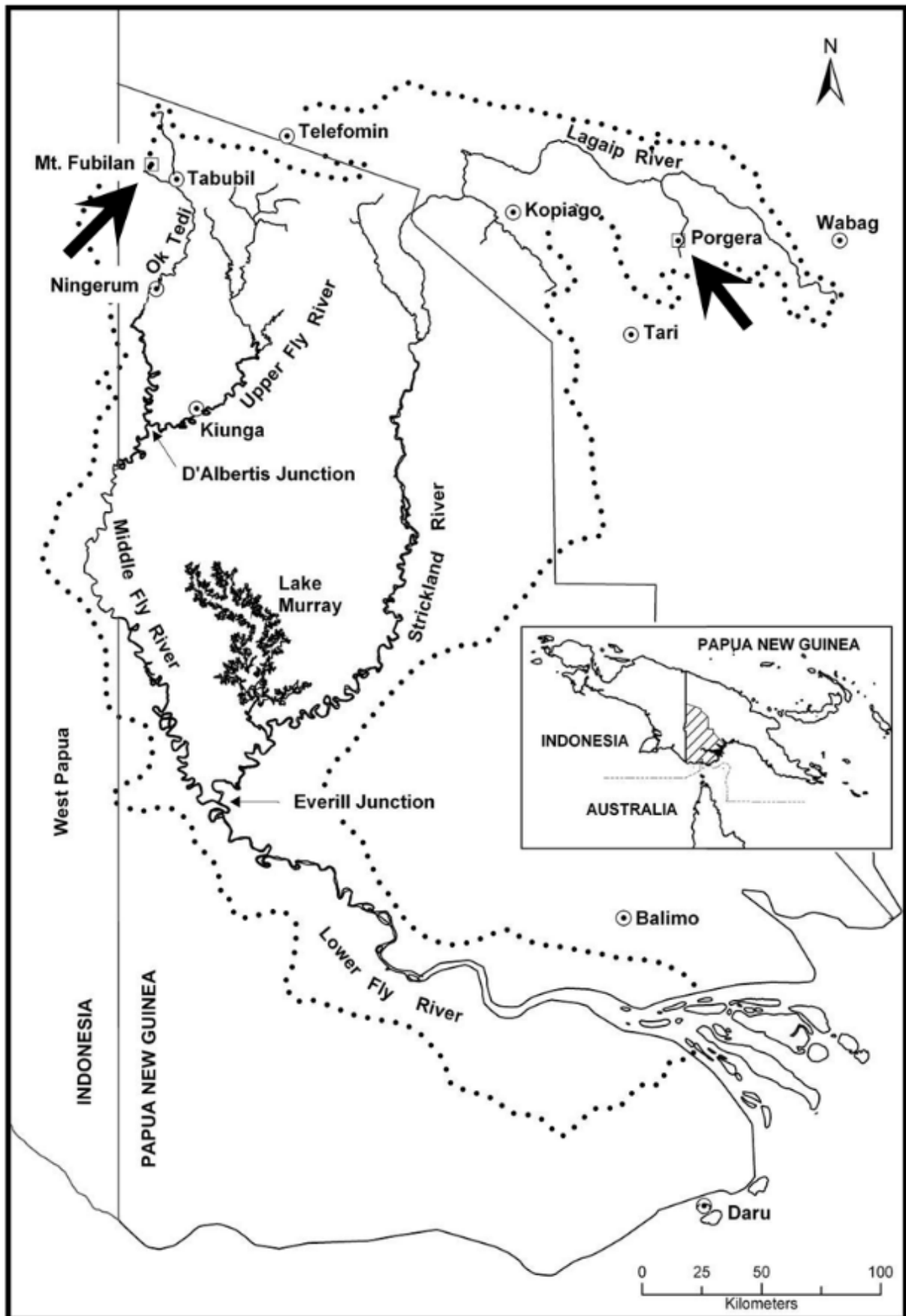


Figure 2-1. Location map. Mining operations at Mt Fubilan and Porgera are shown by arrows.

## THE MINE AREA CREEKS

The Ok Tedi receives waste rock and tailings from the Mount Fubilan (Ok Tedi) Mine while the Strickland receives sediment load from mining operations at Porgera. Since 1985, when mining commenced on Mount Fubilan, the waste inputs have increased the sediment load of the Ok Tedi by a factor of 8-10. Inputs from the Porgera mine, while still significant, are substantially less.

The impact of mine waste disposal is at its most visible in the upper reaches of the Ok Tedi and its mine area tributaries. Further downstream, mine-derived material spread across the floodplains fairly quickly (Day *et al*, 2009) and it is here that the greatest potential for ecosystem impact lies. The floodplain is also the location of maximum human impact since it supports a large population mostly reliant on traditional gardening, harvesting of food plants such as sago, and a traditional fishery, with fish being the main source of protein in the diet.

In its upper reaches, the Fly River and its tributaries drain a heavily dissected mountain landscape. Ridges rise to over 2,000 m ASL in the north but most of the catchment lies between 200 m and 800 m ASL. The eastern part of the basin is karst country and includes the massive Hindenburg Wall escarpment and contains large areas of landslide debris and old debris flow deposits. In the west, igneous rocks are exposed on high mountains but much of the area consists of shales, limestones and sandstones. Slopes are unstable and landslides and debris flows are common in spite of a dense rainforest cover (Hearn, 1995; Pickup and Marshall, 2009). The mine area is shown in Fig. 2-2.



*Figure 2-2. Landsat TM satellite image of the Ok Tedi mine and the Mine Area Creeks.*

## THE OK TEDI

The Upper Ok Tedi (Ok Tedi upstream of Ok Mani confluence) is a fast-flowing river capable of transporting large quantities of coarse sediment, including boulders. For much of its length it occupies a narrow bedrock gorge which opens out in the 3 km immediately upstream of the Ok Mani junction and allows channel braiding. Debris flow deposits flank parts of the Upper Ok Tedi (Fig. 2-3) and riverbed levels have fluctuated over time in response to massive landslides from its upper catchment. These include a 7 km<sup>3</sup> landslide (which has been dated to about 8,800 BP) from the 500 m high cliff face of the Hindenburg Wall on the upper Ok Kam (Fig. 2-2), a tributary of the Ok Tedi (e.g. Pickup *et al.* 1979; Blong 1991). However, unlike the Mine Area Creeks, the bed had a veneer of boulders and coarse sediment in transit, much of which probably came from a more recent 1977 Hindenburg Wall landslide (Pickup and Marshall, 2009).



**Figure 2-3. Former debris flow deposits on top of exposed bedrock in the upper reaches of the Middle Ok Tedi. Note the size of gravels in the riverbed which illustrate the transport capacity of the river. 1979 (pre-mine) photo.**



***Figure 2-4. Debris flow deposits probably from the 8,800 BP Hindenburg Wall landslide exposed at the edge of the Ok Tedi. Note the small figure at base of the rock face for scale. 1979 (pre-mine) photo.***

The Middle Ok Tedi is the reach between the Ok Mani confluence and Konkonda, approximately 53 km downstream of Ningerum (Fig. 2-5). In this reach, the river has a concave-upwards long profile (Fig. 2-6) and for much of its length occupies a narrow gorge with a single channel. There are occasional wider sections where the single channel becomes braided and may branch into several arms. The pre-mining Middle Ok Tedi had a gravel-bedded channel with largest particles as coarse as 1000 mm in diameter near the Ok Mani confluence but becoming finer downstream.

The pre-mining Middle Ok Tedi had a gravel-bedded channel with largest particles as coarse as 1000 mm in diameter near Ok Mani confluence but becoming finer downstream. The upper part of the river had a mobile veneer of gravel and boulders but, as the gradient decreased downstream, the bed became heavily armoured by large cobbles. This was succeeded by a braided reach marking a gravel-sand transition zone between Ningerum and of Bige. The gravel-sand transition zone extended about 8 km downstream of Konkonda (Lower Ok Tedi) beyond which the river developed a sand bed.



**Figure 2-5. Landsat TM satellite image of the Middle Ok Tedi. The upper gorge section is on the left with the downstream braided section on the right. The transition to a single channel set in a floodplain occurs just after the Bige dredge site.**

The Ok Tedi and the Mine Area Creeks have concave upwards long profiles (Fig. 2-6). At the very downstream end of the system, the gradient is low enough to allow meandering whereas in the upper reaches the river is steep enough to have processes dominated by mass movement of sediment and debris flows. Added to this are the very large sediment inflows to the river system from mine tailings and waste rock. All have proved a challenge to sediment transport modelling and required several models, one of which is tailor-made for the system, to produce realistic results.

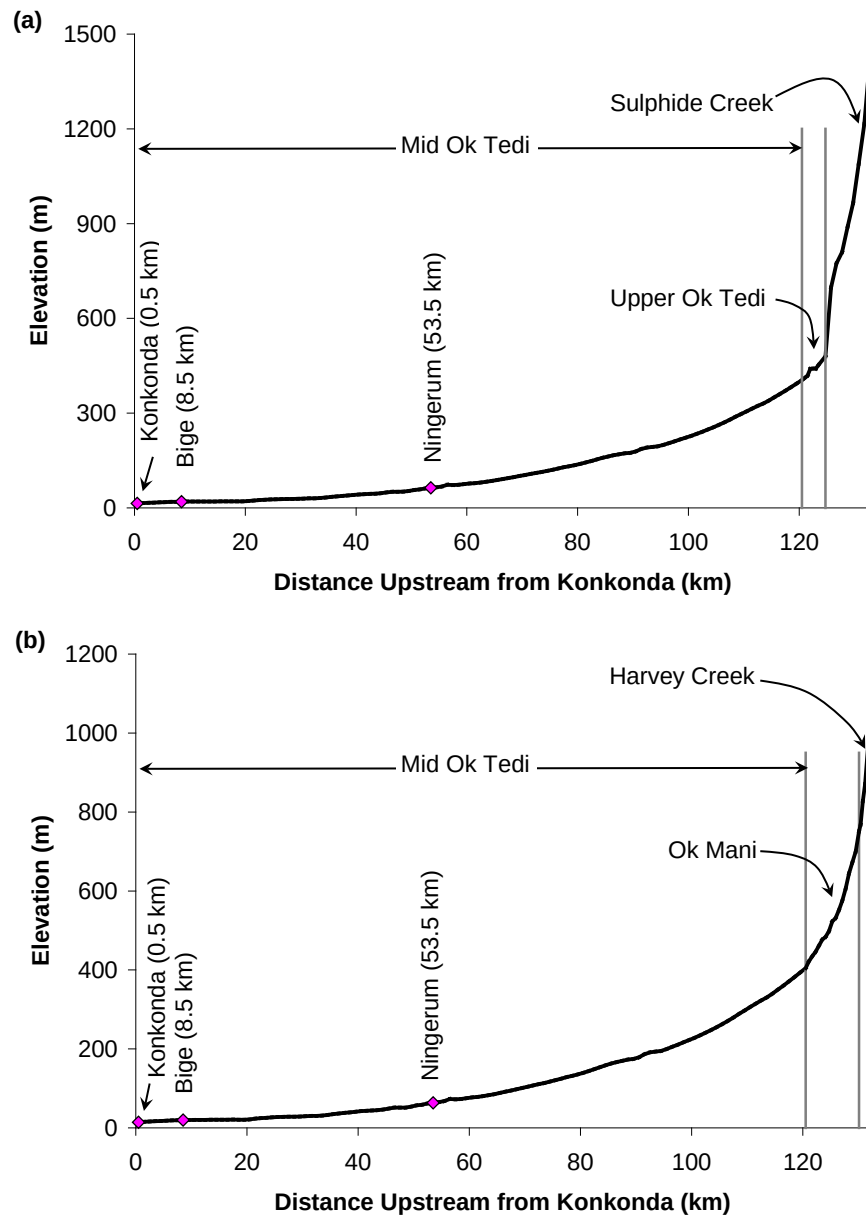


**Figure 2-6. Longitudinal profiles of the study area. (a) Sulphide Creek, the Upper and Middle Ok Tedi; and (b) Harvey Creek, Ok Mani, and Middle Ok Tedi.**

## THE MIDDLE FLY

The floodplain reaches of the Fly River are of particular significance because they support a large human population. Inputs from the mine have had a substantial direct effect by causing main river deposition and a greater in- river sediment load, increasing water turbidity and raising river water levels. Floodplain water levels are closely linked to river water levels (Pickup and Marshall, 2023). Indirect effects include increasing deposition on channel levees, changes in the fishery resource, extensive forest dieback, expansion of aquatic vegetation cover, increased extent of flooded areas and longer periods of floodplain inundation. Removing tailings and reducing waste rock inputs from the sediment input stream to the floodplain reaches of the Fly River has potential to slow down or reduce some of these impacts but the process of change will be complex and the results variable, both in location and extent. This section aims to provide an understanding of what processes are involved and the known impact on the river at the present time as a guide to potential future changes.

The main features of the Middle Fly are shown in Figs. 2-7 and 2-8. The river valley sits within a gently sloping dissected piedmont of considerable age with highly weathered sediments, some of which outcrop next to the river and form highly resistant banks which block lateral migration of the channel (Fig. 2-9). There are many small tributary valleys which feed in lowland runoff and a small amount of eroded sediment into the Fly. However, the more elevated tributary valleys have a dense forest cover and gentle slopes which inhibit erosion.

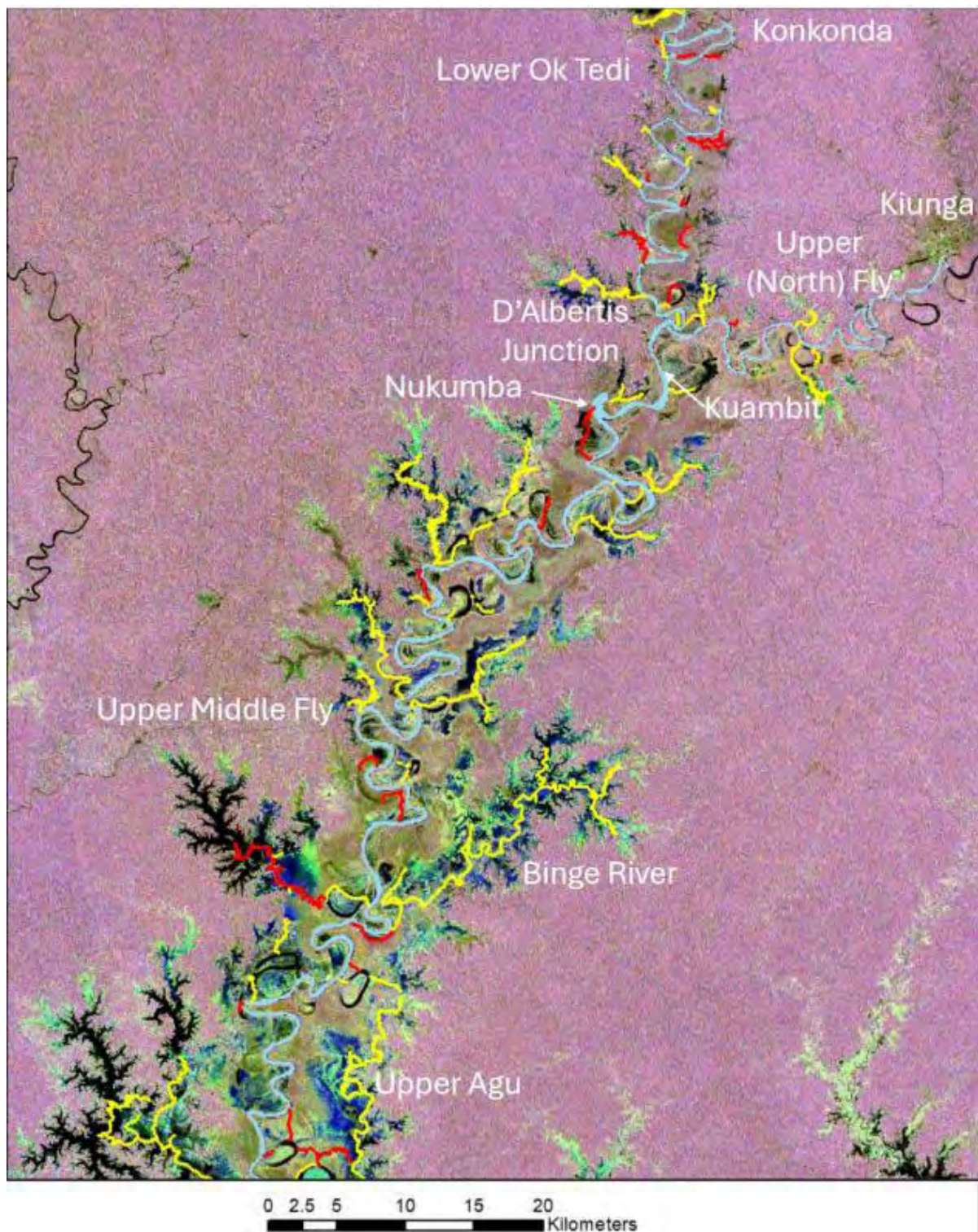


**Figure 2-7: Upper Middle Fly – geomorphology and flood regime. PALSAR DATA showing 2015/2016 change from dry floodplain to inundated. Note the difference between upstream and downstream sections. Brown areas indicate a difference between wet & dry. Green areas are flooded forest. Black/blue areas are flooded most of the time. Main river tie channels and tributary rivers are shown in yellow (open) and red (blocked or impeded). Tie channels were mapped from 2015 30m resolution LANDSAT data.**

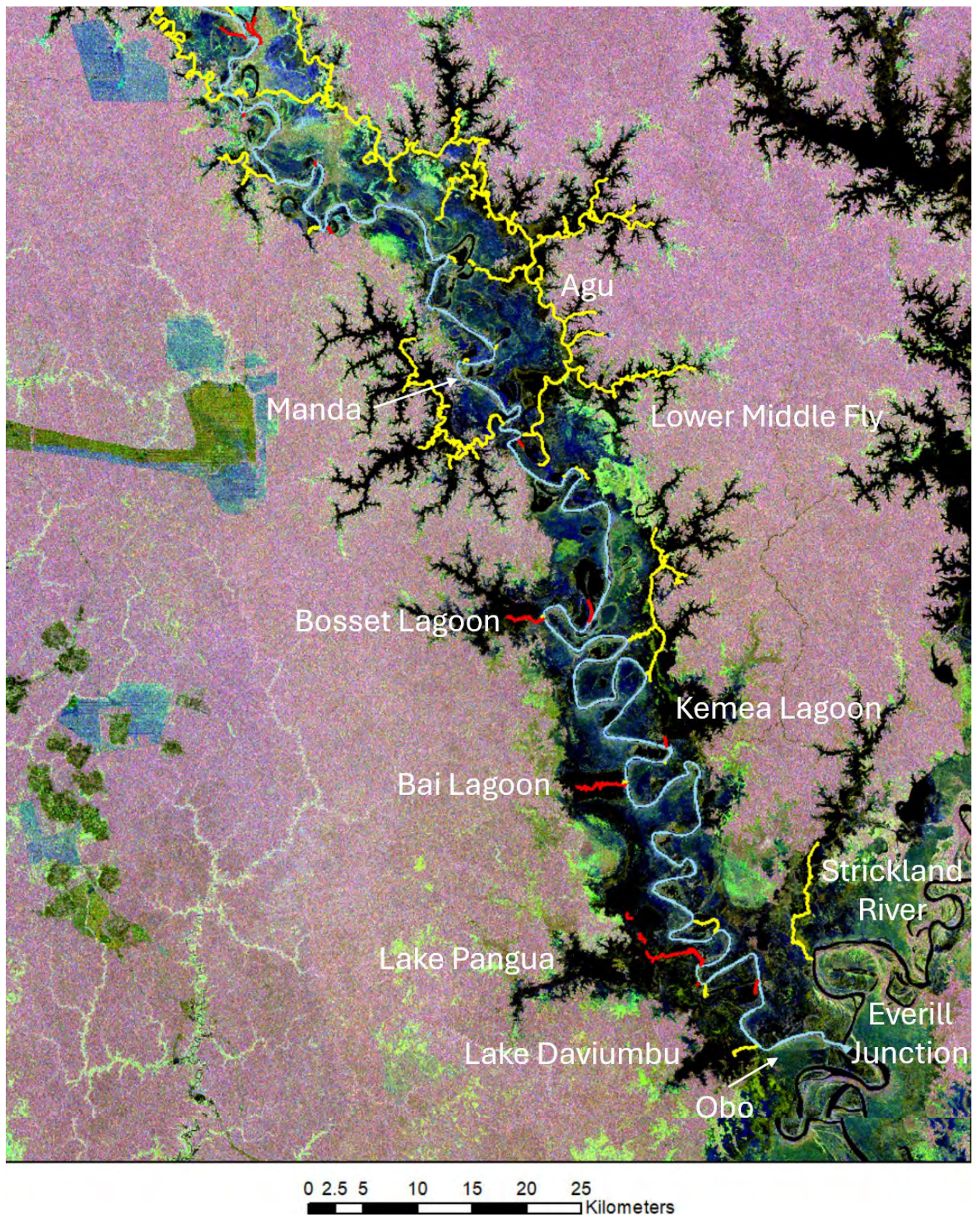


**Figure 2-8: Lower Middle Fly – geomorphology and flood regime. PALSAR DATA showing 2015/2016 change from dry floodplain to inundated. Note the difference between upstream and downstream sections. Brown areas indicate a difference between wet & dry. Green areas are flooded forest. Black/blue areas are flooded most of the time. Main river tie channels and tributary rivers are shown**

*in yellow (open) and red (blocked or impeded). Tie channels were mapped from 2015 30m resolution LANDSAT data.*



**Figure 2-9. Manda Village - erosion resistant remnant of the piedmont system that borders the Middle Fly floodplain and limits lateral channel migration.**

It is common in Papua New Guinea for large rivers to build up an inner floodplain which eventually becomes higher than the floodplain margins. The floodplain may then develop local drainage along the floodplain margin parallel to the inner floodplain. These may develop into small lowland rivers that capture tributary inflow and which may or may not be connected to the main river. The backplains may contain shallow margin lakes or they may develop into small rivers. The largest of these systems on the Middle Fly is the Agu (Figs. 2-7 and 2-8) which runs parallel to the eastern side of the main river channel, beginning on the Upper Middle Fly and re-entering the main river about one third of the way down. It lies 3-5 m lower than the banktop of the main river channel and takes overflow drainage from it. There are times, however, when the Agu becomes a lake rather than a flowing river if water levels on the main river are high enough to block its lower end. There is also a major non-channelised floodway on the western side of the Lower Middle Fly connecting a series of blocked valley lakes from Bosset Lagoon to Lake Daviumbu which operates during wet episodes.

There are two distinct reaches on the Middle Fly in sedimentary terms (Fig. 2-10): a *sand zone* and a *backwater zone* (Pickup 2001; Bolton, *et al*, 2009). Prior to mining, the sand zone had a riverbed consisting of well-sorted fine to medium sand and extended as far downstream as Manda (Fig. 2-8). This reach has a steeper water surface slope than the backwater zone, which extends from Manda downstream to Everill Junction (Fig. 2-8). The pre-mining backwater zone had a bed composed of mainly fine sand but with an increasing proportion of silt-clay particles further downstream until less than 20% sand was present. A localised body of medium sand occurred in the reach immediately upstream of the junction with the Strickland and is probably associated with the intermittently slightly steeper river gradient there when water levels on the Strickland are low. It may also have originated from the catchment of the blocked valley lake of Bosset Lagoon. The effect of this was to increase the amount of both fine sand and silt present but the original sand and backwater zones were maintained despite the increase in sediment load

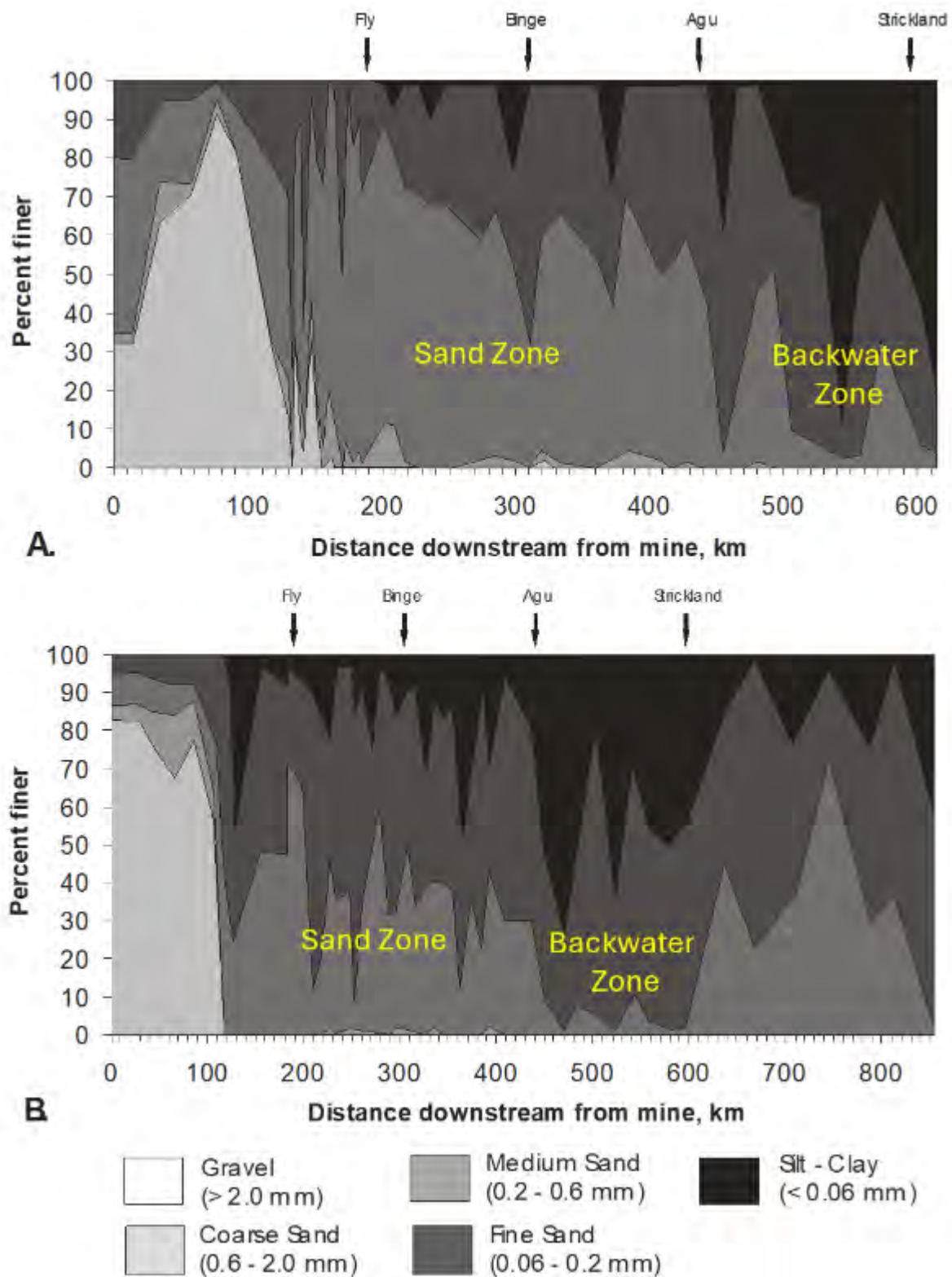


**Figure 2-10. Downstream variation in grain size distribution. A) Bed samples collected before the start of mining operations (Pickup et al. 1979; Maunsell & Partners, 1982; OTML, 1986), B) Bed samples collected in 2001-2003 during mining operations (OTML, 2004a, b).**

The upper Middle Fly (Fig. 2-7) extends from D'Albertis Junction to Manda. It is a sand-bed, slowly meandering river with an 8 km-wide floodplain (Fig. 2-11). The channel is partly contained between discontinuous levees and arrays of point bars on the inside of meander bends marking previous river courses. There are many examples of meander cutoffs on the floodplain which form oxbow lakes. These vary in age and degree of subsequent filling by river sediment and organic matter. The oldest ones are now only visible as traces while the newer ones form deep lakes.



**Figure 2-11. The Upper Middle Fly at Carlton Island, a recent meander cutoff. Note the levees with tree cover and the flooded meander scroll complex which holds clean water while the cutoff contains sediment-laden water from the main channel.**

The Lower Middle Fly extends from Manda to Everill Junction, where it joins the Strickland, and is very different style of river when compared with the upstream reach. The reason for the difference is the Strickland River which is much larger than the Fly and is closer to its mountain sediment load sources. This has caused the Strickland to build up its floodplain faster than that of the Middle Fly which it partially blocks, creating a 180 km long backwater zone on the Middle Fly.

The gradient on the Lower Middle Fly is about half of that on the Upper Middle Fly making it a much slower flowing river. The floodplain is also wider (10-15 km) and surrounding relief is lower. Much of the sand load of the river drops out by Manda so the Lower Middle Fly largely transports silt. The river no longer has the energy to meander, a process which normally destroys outer bank levees and replaces them with lower, inner bank point bars. Instead, a more continuous, narrower and higher set of levee banks has developed. These block many off-river water bodies (ORWBs) and, at times allow them to retain water levels higher and for longer than the main river (Fig. 2-12).

Figure 2-13 shows a series of water surface profiles derived from cross section surveys in 2000, 2001 and 2002 in the dry season. No more recent data are available. All profiles were measured in reaches of 40-60 km over multiple days so water flow and river heights may have changed before a profile covering the whole of the Middle Fly could be measured. Flows were low or moderate when the surveys were carried out.

The various water surface profiles have been compared with *HEC-6* model results for mean flow and the 10% flow duration for the year 2000 when the surveys were carried in Fig. 2-13 (Pickup and Marshall, 2023). Profiles for these two model flows set an envelope which all these survey profiles lie within.



**Figure 2-12. The Lower Middle Fly near Everill Junction. Note the main river channel on the upper right, the narrow levees and the overflow of water loaded with fine sediment into the lake occupying the floodplain behind the levees.**

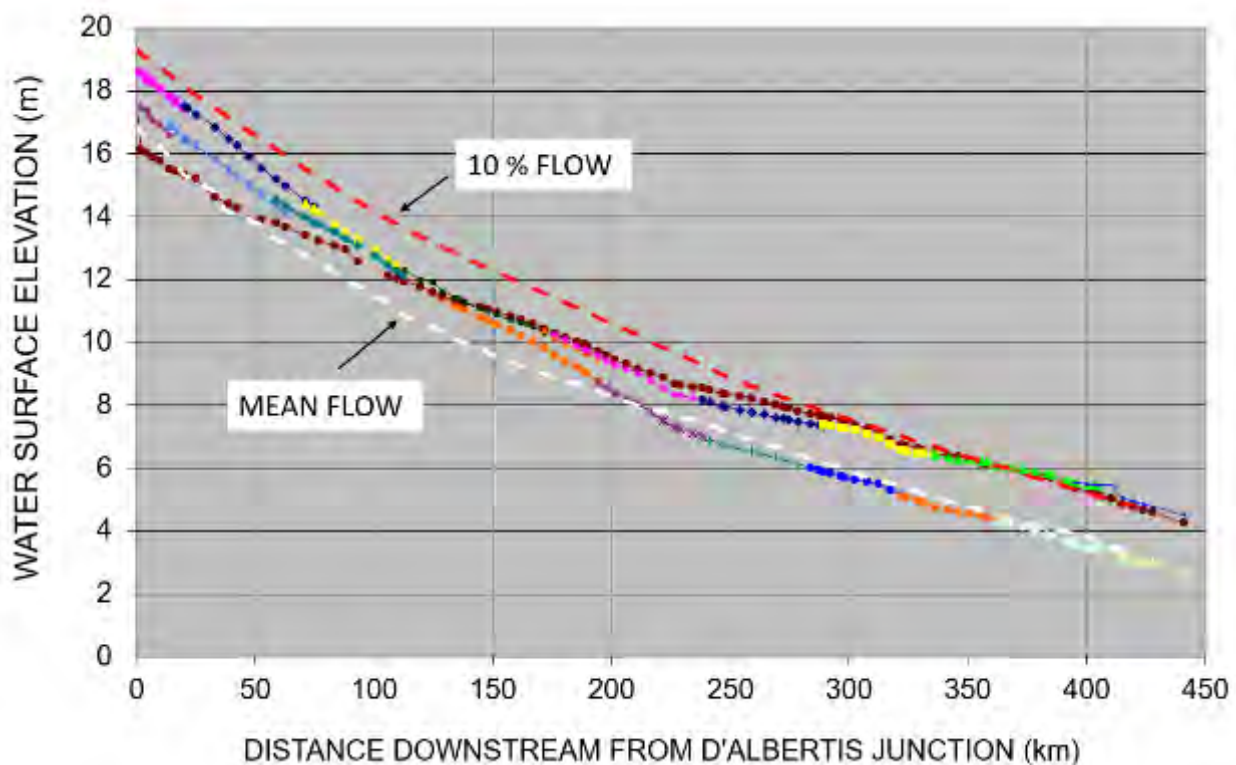


**Figure 2-13: Water surface profiles for the Middle Fly from cross sections during 2000-2002 compared with model profiles for mean flow and the 10% flow for the same period.**

## OFF-RIVER WATER BODIES (ORWBS)

Under natural conditions, the Fly receives most of its sediment load from the landslide-prone mountain catchments of the Upper Fly and the Ok Tedi. Over the long term, this has caused the inner floodplain to build up and block the tributary valleys, creating shallow lakes, most of which dry out during periods of low rainfall although some of the larger ones may retain small bodies of water during drought. A few are also sufficiently blocked off to retain much

larger bodies of water through moderate El Niño events. Most ORWBs are connected to the main river by narrow tie channels, some of which may become blocked (Figs. 2-7 and 2-8). In a number of cases, blocked tie channels have been cleared by local villagers seeking to maintain canoe channels and access to the main river. In a few cases, the tie channels are completely man-made.

A second type of ORWB is the Oxbow Lake. Meander migration on the main river channel creates channel cutoffs leaving the abandoned cutoff channel section as a lake on the floodplain. This is an important biological process because it provides deep and long-lasting water bodies. These are refuge areas for aquatic species when most other water bodies dry out in the severe droughts that occur every 10-20 years. While the Middle Fly contains spectacular evidence of meandering in the form of cutoffs and scroll bar complexes, there is minimal lateral migration in its lower half. Pickup *et al* (1979) found that only three loops were cut off between 1899 and 1979 on the whole of the Middle Fly.

Bank erosion and meander migration rates have increased in response to post-mining sediment input and are highest close to D'Albertis Junction (the zone of maximum mine-related deposition). There have been five cutoffs in the Upper Middle Fly and two in the floodplain reach of the Lower Ok Tedi between 1987 and 2020. However, there has been little lateral migration on the lower two thirds of the Middle Fly in the last hundred years and virtually all modern-day meanders can be identified on the 1920 sketch map produced by the Drexler-Bell Expedition<sup>4</sup> (Fig. 2-14).

While there are oxbow lakes on the Lower Middle Fly, new ones are not being created since meandering has largely ceased. Existing oxbows are essentially fossil features with some being 2,000-4,000 years old. The fact that they have survived rather than becoming infilled indicates that very little river sediment reaches them.

The Lower Middle Fly floodplain is less prone to drying out during all but the most severe droughts. Much of the main floodplain is swamp or shallow lake with *phragmites* and floating grass mats. When it does dry out, fires are common.

Backwater effects from the Strickland and generally lower surrounding terrain has created larger blocked valley lakes on the Lower Middle Fly than on the upstream reach. While shallow, these lakes seem to retain water longer during droughts but they do dry out in moderate El Nino events. This is partly due to backwater from the Strickland which reduces water level variability on the Fly.

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<sup>4</sup> The Drexler Bell Expedition Map is the earliest one with reasonably accurate coverage of the river channel. An earlier map from the D'Albertis Expedition in the steamship *Neva* is of historical interest rather than being accurate.

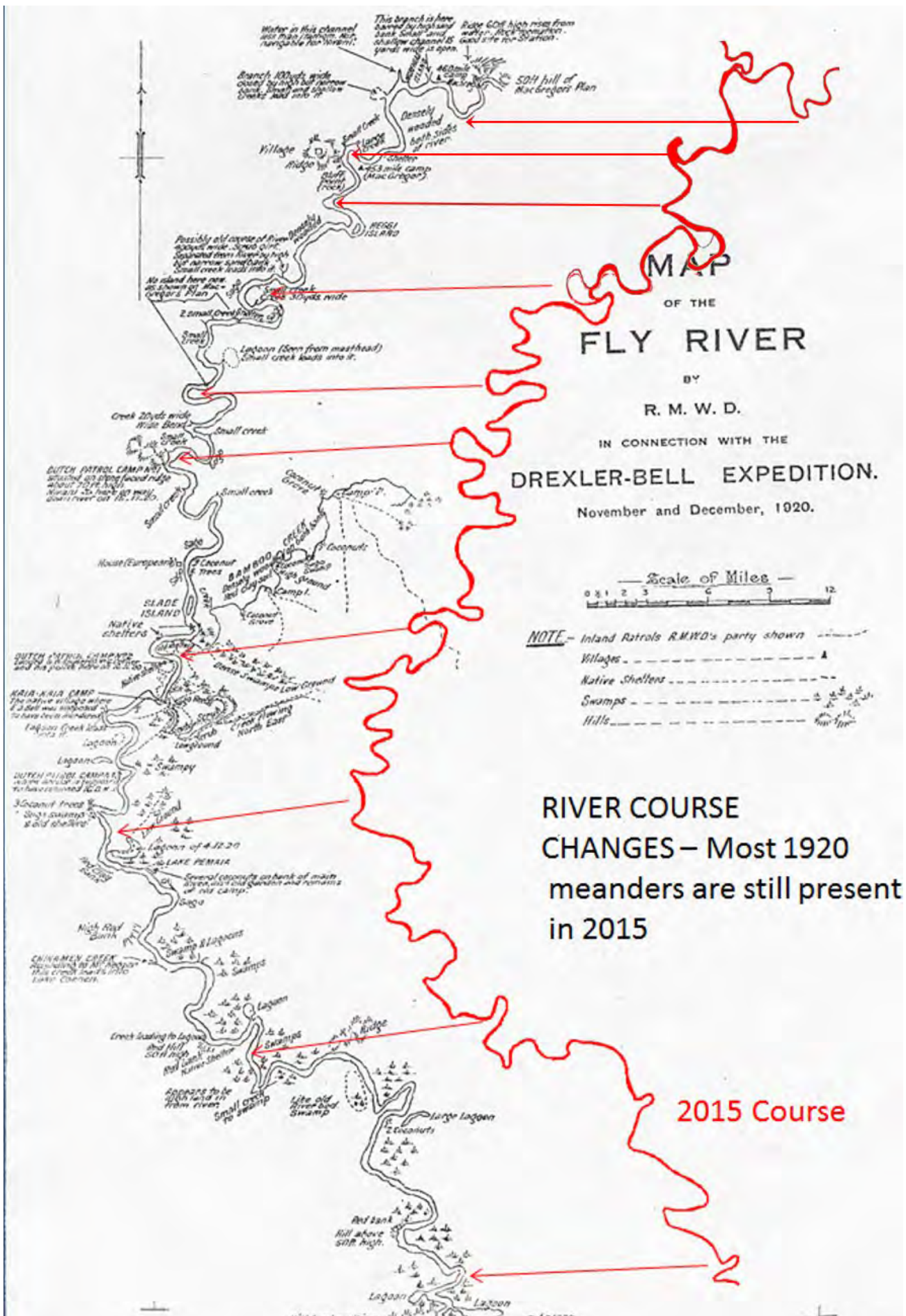


Figure 2-14: Middle Fly River map from the 1920 Drexler-Bell Expedition. Courtesy National Library of Australia.

## RELATIONSHIP BETWEEN THE MAIN RIVER AND THE FLOODPLAIN

There is some evidence that the inflow of mine-derived material has affected the behaviour of the floodplain which we explore in more detail in Chapter Three. In this section we describe the main characteristics of the floodplain and the interactions between it and the main river channel.

The off-river water bodies can hold perhaps 2% of the annual flow of the Fly before general flooding occupies most of the floodplain. However, because there is continuous inflow and outflow between the floodplain storages and the main channel during floods, a much larger proportion of flow is cycled through them. Dietrich & Day (2004) have suggested that at least 20% and possibly up to 40% of Fly River water passes through the floodplain. Model calculations and recent inundation frequency mapping developments (Pickup, 2009; Pickup and Marshall, 2019) suggest that the value is closer to 15%, because once water bodies close to the river are full, further inflow is limited. However, rising water levels due to deposition have by now probably increased the amount of inflow even closer to Dietrich's lower estimate.

Besides the oxbows and blocked valley lakes, two other types of ORWBs can store water and sediment. Both flood when river water levels are high, but once flooded, they may not drain back into the main river and thus provide a sink for delivered sediments. These include:

- Small waterbodies trapped in levee backplains. The backplains occupy narrow areas behind levees which have been isolated as levees have rapidly risen, especially in recent years. For much of the time these areas are isolated from the river and contain clear water. River water usually reaches them through breaches in the levee created by bank collapse or overflow at lower points. Levee back plain ORWBs may also survive on the margins of former meander cutoffs. There may be substantial deposition in levee backplains close to levee breaches. The levee backplain ORWBs on the Lower Middle Fly provided the location for acid breakouts that developed in the early 2000's in response to the high sulphur content of mine-derived material (OTML, 2005; Figs. 2-15, 2-16).
- Point bar fields created on the inner side of laterally migrating meanders consist of ridges and swales which gradually become blocked off by sediment deposition and may contain bodies of clear water. These are often zones of intense deposition of main river sediment and can become isolated from the main river inflows over time.



***Figure 2-15. Vegetation impact on levee backslope due to high acidity water seepage. Photo from 2006, site is now NAF.***



***Figure 2-16. Sampling oxidised mine-derived levee backplain sediments in an acid breakout zone in the Lower Middle Fly. Photo from 2006, site is now NAF.***

## PERSISTENCE OF OFF-RIVER WATERBODIES

While virtually the whole floodplain may be inundated during floods or extended wet periods, the Middle Fly is subject to occasional droughts, many of which are associated with El Niño events. During these times, much of the

Upper Middle Fly floodplain dries out. The Lower Middle Fly floodplain retains water over a much larger area and for much longer periods, but it too eventually dries out.

In severe droughts, such as in 1972, 1997-1998 and 2015, only the main river channel, the lower and middle Agu and most of the main floodplain oxbows held water of any depth. A few of the largest and most distant blocked valley lakes also retained small waterbodies but they were likely to be shallow.

Excluding the main Fly channel, a total area of 83 km<sup>2</sup> held water on the floodplain in 1998 with only 39 separate waterbodies (including oxbow lakes) holding 0.5 km<sup>2</sup> or more (Dietrich and Day, 2004). In a moderate drought such as 2015, 229 km<sup>2</sup> of water remained with 65 areas holding more than 0.5 km<sup>2</sup> and 8 holding more than 5 km<sup>2</sup>. When the blocked valley lakes are full but water levels on the Middle Fly are not high enough to inundate the floodplain, they cover an area of 677 km<sup>2</sup>.

This behaviour has substantial implications for aquatic species survival. Few, if any of the blocked valley lakes offer secure refuges for species that cannot tolerate the high sediment concentrations in the main river in a severe drought. Only the oxbows and the Agu retain enough water for this role and most of them occur in the lower and middle reaches of the Fly. However, behaviour may be changing as there is increasing evidence that many ORWBs are surviving for longer periods during droughts (see Chapter Five, section dealing with connectivity with off-river water bodies).

On the Lower Ok Tedi, the Ok Mart may play a similar role as a refuge.

In the uppermost 80 km of the Middle Fly, about ten large oxbows held water in the 1998 drought, yet this is the reach that has experienced the most mine-related deposition and water level rise. Most of these oxbows have or have recently had a connection with the main river via a tie channel. Some of them are experiencing infilling from sediment inflows. The main form of infilling appears to be progression of the sediment plug blocking the oxbow mouth further into the lake itself. Lake infilling beyond that occurs at an unknown rate but it is likely to be less. It is worth noting that the five oxbows experiencing most rapid infilling were also infilling before significant mine sediment had entered the river.

In the Lower Middle Fly, below Manda, the situation is somewhat different (Fig. 2-8). Only about ten oxbows are or have recently been connected to the main river. Of these perhaps three or four have recently lost that connection by either tie channel blocking or by build-up of sediment in levee breaches. The remaining fourteen are only connected by overbank flow. These are likely to be the least disturbed oxbows in the system and some may be very old.

## THE UPPER (NORTH) FLY

The Middle Fly has two main tributaries: the Ok Tedi and the Upper (North) Fly. The Upper Fly does not receive mine inputs. Prior to mining, it probably made up about 50% of the natural sediment load of the Middle Fly or about 2-5 Mt/year. In its lower section, the Upper Fly had similar characteristics to the Middle Fly, i.e. a broad floodplain and a meandering habit with 3-4 channel cutoffs from the 1960s in the lowest 25 km. Since the start of mine waste discharge, rising water levels on the Ok Tedi have had a substantial backwater effect, also raising water levels on the Upper Fly, causing extensive flooding and forest dieback in its lowest reaches. The impact of the backwater effect is discussed in Chapter Five.

# CHAPTER THREE - INPUTS AND OUTPUTS – PAST AND FUTURE

In this section we describe historical waste rock and tailings input values to the river system as reported by the mine and projected future values from the Case 240822 Mine Plan. We also report on landslide inputs and sediment extraction by dredging.

## WASTE ROCK

Waste rock inputs to the river system via failing dumps on the south side of the mine have varied over time (Fig.3-1). Inputs started around 1990 when dumping into Sulphide Creek on the north side of the mine ceased after the Vancouver Landslide (see below). Over the next five years, values increased to around 30-40 Mt/year before declining to very low values around 2010 and then increasing once more. In recent years, inputs climbed as high as 80 Mt/year, about twice the magnitude of the largest known landslide input. During this period, the Harvey Creek valley increasingly filled and, whereas previously sediment retention rates in the combined Harvey Creek-Ok Mani system averaged around 30-40%, they now climbed to 60% (Marshall, 2025). It is likely that this retention rate will be maintained for the next 4-5 years after which waste rock will be mostly stored in an EWRD in the Sulphide Creek system.

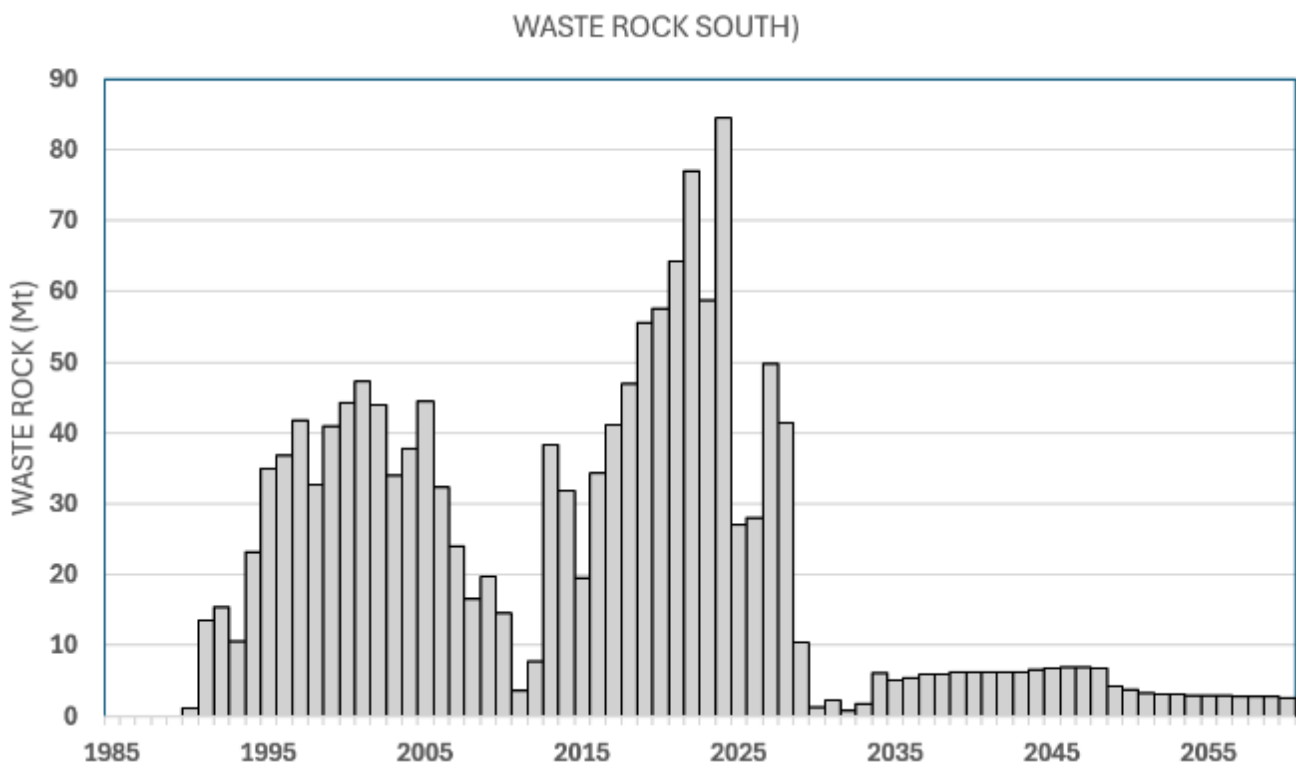


**Figure 3-1. Observed and planned waste rock inputs to the river via the Ok Mani system on the south side of the mine. Grey bars indicate inputs to the failing dump and ultimately to the river system. The lower rates from the early 2030s occur when southern waste rock is directed to the second EWRD from which stored material slowly erodes, a process which continues beyond the mine closure date.**

There are two waste rock dumps on the north side of the mine, The Vancouver Dump and the Taranaki Dump.

Waste rock inputs on the north side began in 1985, climbed to around 30 Mt/year but then fell to very low levels after the Vancouver Landslide. From around 2010 most material went to the Vancouver Dump which had a valley head location, so runoff was limited, minimising gully erosion and sediment loss to the river. However, as the dump extended downslope, its surface catchment area increased, and gullies began to form in the lower sections. Once

the dump toe reached the valley floor, undermining by the creek that occupies the valley began, providing a mechanism for continued removal of sediment. This area is now the location of construction activities in preparation for the construction of an EWRD. Projected dumping rates in this area are expected to be high over the next few years until around 2029. As we have no information on loss rates from the proposed EWRD, we estimate annual values of between 5% (pessimistic case) and 2% (optimistic case) of inputs plus dump contents after successful construction. This suggests slowly declining input rates to the river system of 5-10 Mt, declining to around 3-4 Mt by 2060.

The Taranaki Dump is a failing dump with a high loss rate for most of mine life but with relatively low input rates until 2020. Thereafter they mostly increase, reaching up to 50 Mt/year in 2026 before declining until 2033 after which no more dumping is planned,

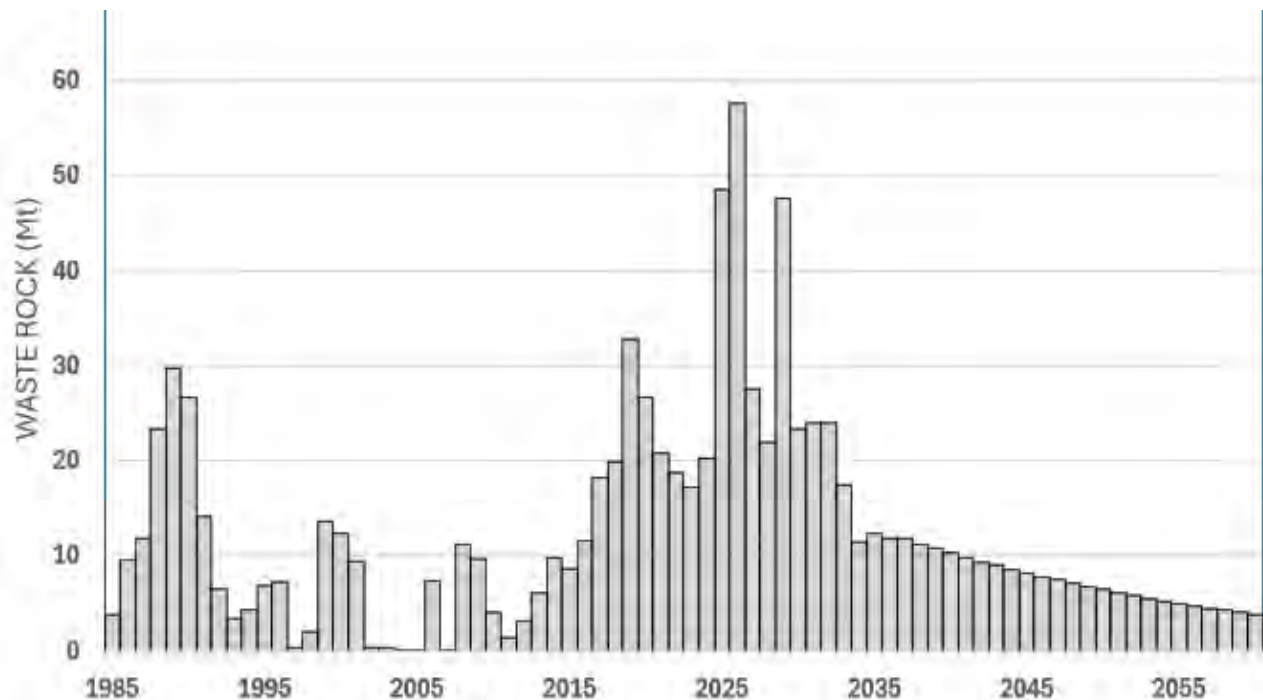


**Figure 3-2. Observed and planned waste rock inputs to the river via the Sulphide Creek system on the north side of the mine. The slower rate from the late 2020s assumes 5% loss rate from the northern EWRD which is still under construction. Erosion of stored material continues beyond the mine closure date even though no new material is added.**

## TAILINGS

Figure 3-3 shows tailings inputs from the start of mine life and identifies the impact of having a TSF on the input of fine sediment to the river system.

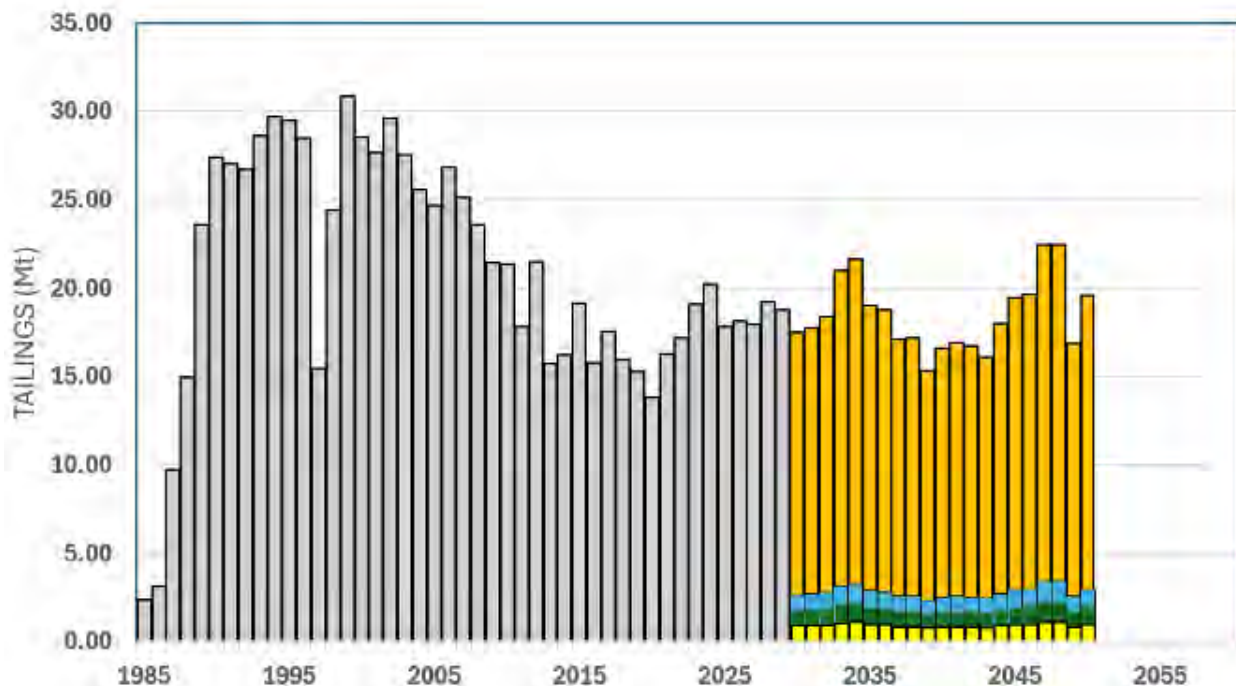


**Figure 3-3. Observed and planned tailings inputs to the river system. Orange bars indicate tailings input if no TSF was built, blue bars indicate 15% of total tailings discharged to the river. Green and yellow bars indicate 10% and 5% of total tailings discharged to the river respectively.**

The overall trend has been for tailings output to decrease over the last ten years by about one-third compared with production levels in the first twenty years of mine life. At the same time, the volume of waste rock production increased. This reflects the increased difficulty of exposing enough ore and having to mine and mill harder rock types as the mine pit becomes deeper.

Mine plan 240822 makes allowance for a limited proportion of tailings to be discharged to the river for several possible reasons. These include periods when the pipeline and associated infrastructure require maintenance or repair. While the mine plan suggests up to 15% of tailings may be diverted to river disposal, values of 5% and 10% have also been suggested. We have taken a middle course and used a figure of 10% which is consistent with the tailings pipeline downtime in TSF Concept Design C5 (Klohn Crippen Berger, 2025) However, as Fig. 3-3 shows,  $\pm 5\%$  only involves a small tonnage which is likely to be within the range of modelling uncertainty.

Figure 3-4 shows the particle size distribution of suspended sediments at Bige and compares this with data from tailings and from suspended sediments at the Lower Ok Tedi Bridge. Data were obtained during an intensive sampling campaign to investigate the effectiveness of adding ground limestone to tailings as a means of increasing acid neutralisation capacity (Pickup, 2011). Tailings contain more coarse material than at either downstream site. This suggests that that a small part of the coarsest fraction of tailings is trapped within gravel deposits in the Ok Mani. Particle size distribution curves for Ok Mani deposits (OTML, 2006) point to the latter case.

Changes in the particle size distribution of the sediment load occurs as the tails mix with the natural sediment load of the system plus the material generated by losses from the waste rock dumps and abrasion of the sediment deposits that make up the riverbed. Once in the river, and after initial mixing with tailings, the particle size distribution of suspended sediment undergoes only limited change. The coarse tailings fraction is increasingly diluted by finer material and at the Lower Ok Tedi Bridge below where the Ok Mani meets the Ok Tedi, the sand/silt ratio has halved. This pattern is maintained down as far as Bige with the sand dilution effect being most pronounced in the coarser fractions. Diverting tailings to a TSF will increase this effect and the river will transport an even finer sediment load.

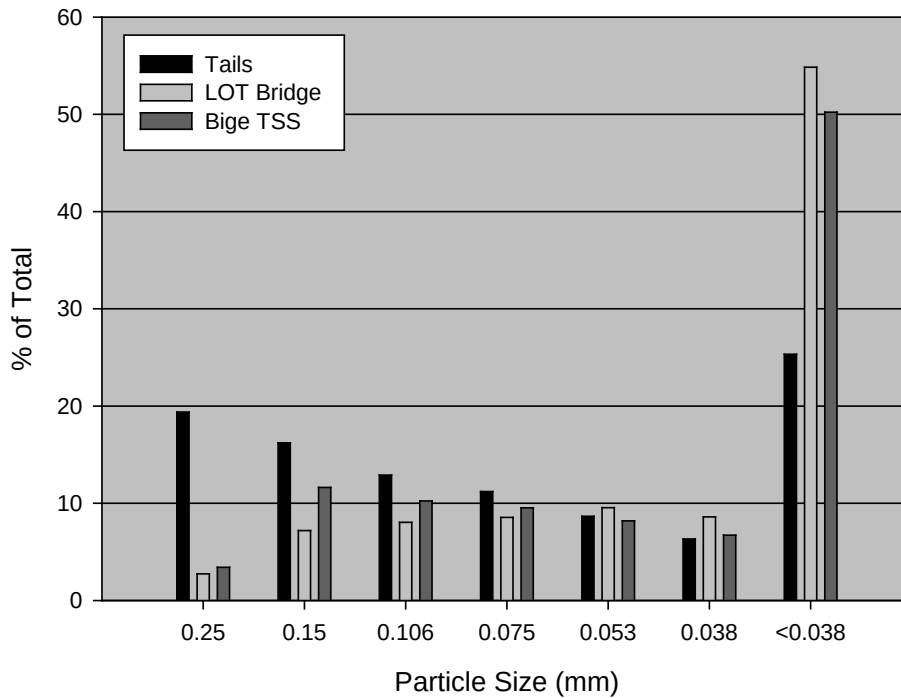


**Figure 3-4: Particle size distribution of suspended sediments at Bige compared with tailings and suspended sediments at the lower Ok Tedi Bridge near the Ok Mani junction.**

At present, sediment delivered to the Lower Ok Tedi and the Middle Fly is a sand-silt mix. While this will continue once a TSF is operating, the ratio between the two will change. Comparing the observed particle size distributions (PSDs) in Fig. 3-4 gives an indication of what will occur. The tailings have an artificial PSD created by grinding. The PSDs at both the lower Ok Tedi Bridge and at Bige are composites of the tailings PSD and a more natural PSD generated by abrasion during transport downriver which tends to generate more silt (Parker, 1991a, b; see also Appendix One, Part Two ). Waste rock also includes a large proportion of limestone, siltstone and shale, all of which have a fine grain structure that naturally breaks down to silt. The effect that combining tailings and waste rock has on the composite PSD is apparent from the doubling of the 0.038mm fraction. Removing tailings by diversion to a TSF would have an even greater effect.

## SEDIMENT INPUTS FROM ROCK AVALANCHES AND LANDSLIDES

Pulses of sediment from landslides are to be expected in the mine area and the Upper Ok Tedi catchment and can influence suspended sediment loads well downstream. Indeed, the effect of a major landslide on the scale of the Vancouver Avalanche (see below) may outweigh the reduction in suspended sediment concentration resulting from tailings disposal in a TSF for a short period.

Some examples of landslides (some recent) are shown in the images below (Fig. 3-5 and Fig. 3-6).



**Figure 3-5. Significant landslides in the mine area. (A) a mudslide from weathered material on the Ok Kam (B) a rock avalanche from probable old Hindenburg Wall landslide debris flow deposits north of Tabubil which cut the mine access road and caused damage to pipelines. (C) the massive 1989 Vancouver Ridge slope failure which caused waste rock dumping to shift from the north side of the mine to Harvey Creek on the south side. (D) the ongoing New York Ridge rock avalanche.**



**Figure 3-6. Recent landsliding on a northern tributary of upper Sulphide Creek. Note the helicopter for scale. Photo: A. R. Marshall.**

The upper river sediment transport model, *OKTUGS*, already includes major landslide inputs based on events that occurred during the early stages of dumping on Harvey Creek and Sulphide Creek. Pickup and Ridd (2022) have also developed *OKTUGS* model scenarios for future landslides on Sulphide Creek based on the Vancouver Rock Avalanche of 1989 (Fig. 3-5C), and early mine life landslides on Upper Harvey Creek (Fig. 3-7).

## HARVEY CREEK

The early history of landsliding on Harvey Creek was closely monitored (Marshall; 2001, 2006). Side wall erosion was produced by valley side undermining as the creek bed rose due to deposition but also by slope destabilisation due to dumping (Fig. 3-7). The data below are derived from high quality surveys and the Parker-Dietrich (1999) model and were used in early modelling (Fig. 3-8). We currently use the actual values in the *OKTUGS* sediment model for Harvey Creek.



**Figure 3-7. Extensive landslide activity on upper Harvey Creek resulting from waste rock dumping.**

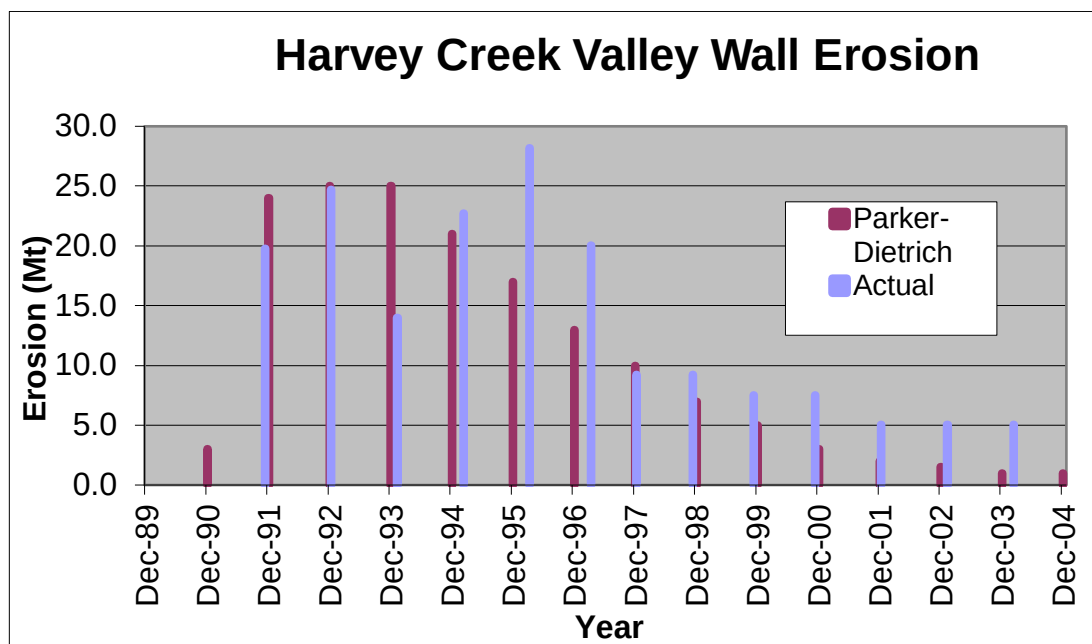


**Figure 3-8: Harvey Creek sidewall erosion losses (from Marshall, 2004).**

## SULPHIDE CREEK

The Vancouver Avalanche on Sulphide Creek shed 60-70 million m<sup>3</sup> of material over a matter of days with a travel distance and a runout zone of 3.5 km (Dietrich and Parker, 1989; Blong and Hearn, 1991).

Once the avalanche material was deposited in the runout zone, its fate gives an indication of the sediment transport capacity of Sulphide Creek. Blong & Hearn (1991) report that 57% of the surface deposit had been eroded within three months indicating the very high transport capacity of Sulphide Creek and the resultant loss of material from the runout zone into middle and lower Sulphide Creek and beyond. Also of note is the mention by Dietrich and Parker (1990)) that the bed of the Ok Tedi at Pratts Crossing, some 9.0 km downstream of the landslide, rose by 13 m between September and November 1989, leading to concerns about bridge safety and indicating

substantial downstream sediment transport well beyond the runout zone. Indeed, monitoring of TSS values at the time shows that the sediment pulse raised TSS values by a factor of 3-4 over the year following the event as far downstream as Obo at the lower end of the Lower Middle Fly (Figs. 3-10 – 3-12).

The Vancouver Rock Avalanche is likely to have released a considerable amount of fine surface material and weathered rock including siltstones, mudstones, and brecciated limestone, much of which would quickly break down to silt.

Limited information exists on the longer-term rate of release of material from the avalanche runout zone. While surveys were done, we have been unable to recover the data directly but site visit reports by Dietrich and Parker (1989; 1990) show how quickly deposited slide mass material was removed from the runout zone.

In their 1989 report Dietrich and Parker note that 26 days after the rock avalanche, a 55 m deep gully had developed in the slide mass. They also report that a survey of twelve cross sections showed that there had been a loss rate of **2.5 – 3.0 Mt over 26 days** even though rainfall had not been particularly high and suggest that the whole deposit could be removed in two years. A subsequent report (Dietrich and Parker, 1990) based on a series of surveys (which sadly appear to have been lost) provides more detail on cumulative erosion rates and the pattern of erosion through time (Table 1). It was also possible from a figure in that report to reconstruct a series of runout zone long profiles that show how quickly deposited material was removed (Fig. 3-9).

| TABLE 1. CUMULATIVE EROSION LOSSES FROM THE VANCOUVER AVALANCHE RUNOUT ZONE |              |                                      |
|-----------------------------------------------------------------------------|--------------|--------------------------------------|
| DATE                                                                        | DAYS ELAPSED | CUMULATIVE EROSION $10^6 \times m^3$ |
| 22 Aug 1989                                                                 | 0            | 0                                    |
| 17 Sept 1989                                                                | 26           | 3                                    |
| 2 Nov 1989                                                                  | 72           | 24                                   |
| 14 Nov 1989                                                                 | 84           | 26                                   |
| 11 Jan 1990                                                                 | 142          | 30                                   |
| 21 Apr 1990                                                                 | 242          | 35                                   |

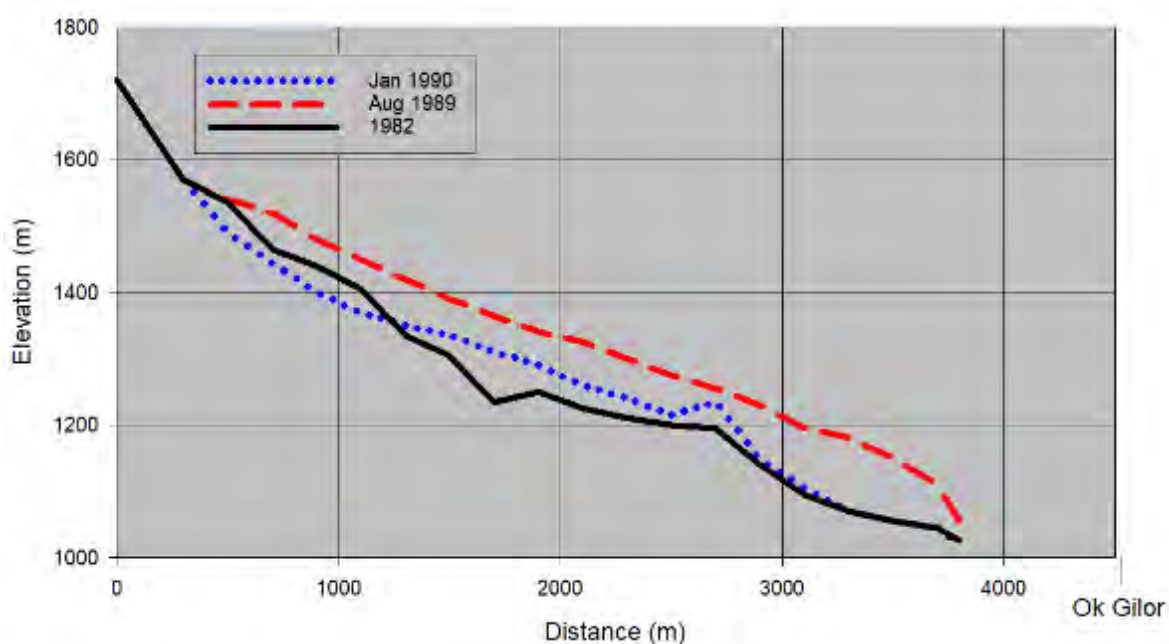


**Figure 3-9. Vancouver Avalanche runout zone long profiles reconstructed from data in Dietrich and Parker (1990).**

The above data and subsequent surveys produced the loss rates used in most sediment transport modelling efforts for the Sulphide Ck system since 2001. Dietrich and Parker (1989) also derived an exponential decay model for estimating the delivery rate of material from the landslide to the Ok Gilor and we have adapted this model for sediment delivery from the Vancouver Dump and the planned Northern EWRD.

There is currently no evidence of any residual aggradation resulting from the Vancouver landslide, with most of the material moving downstream by 1992.

## IMPACT OF LANDSLIDES COMPARED WITH WASTE ROCK DUMP LOSSES AND TAILINGS DISPOSAL ON TOTAL SUSPENDED SOLIDS IN RIVER FLOW

Large landslides can have a similar or potentially even greater effect on water quality down the length of the Ok Tedi or even the Middle Fly but over a shorter period. Figures 3-10 – 3-12 show TSS values obtained by gulp sampling at Ningerum on Middle Ok Tedi, Nukumba on the Upper Middle Fly, and at Obo at the downstream end of the Middle Fly<sup>5</sup> (see Figs.2-7 and 2-8 for locations). Note that each figure plots TSS on a log scale. In every case, the period of the most active and largest landslides that occurred in the late 1980s and early 1990s coincides with the highest TSS values and this effect extends right down the Ok Tedi and the Middle Fly

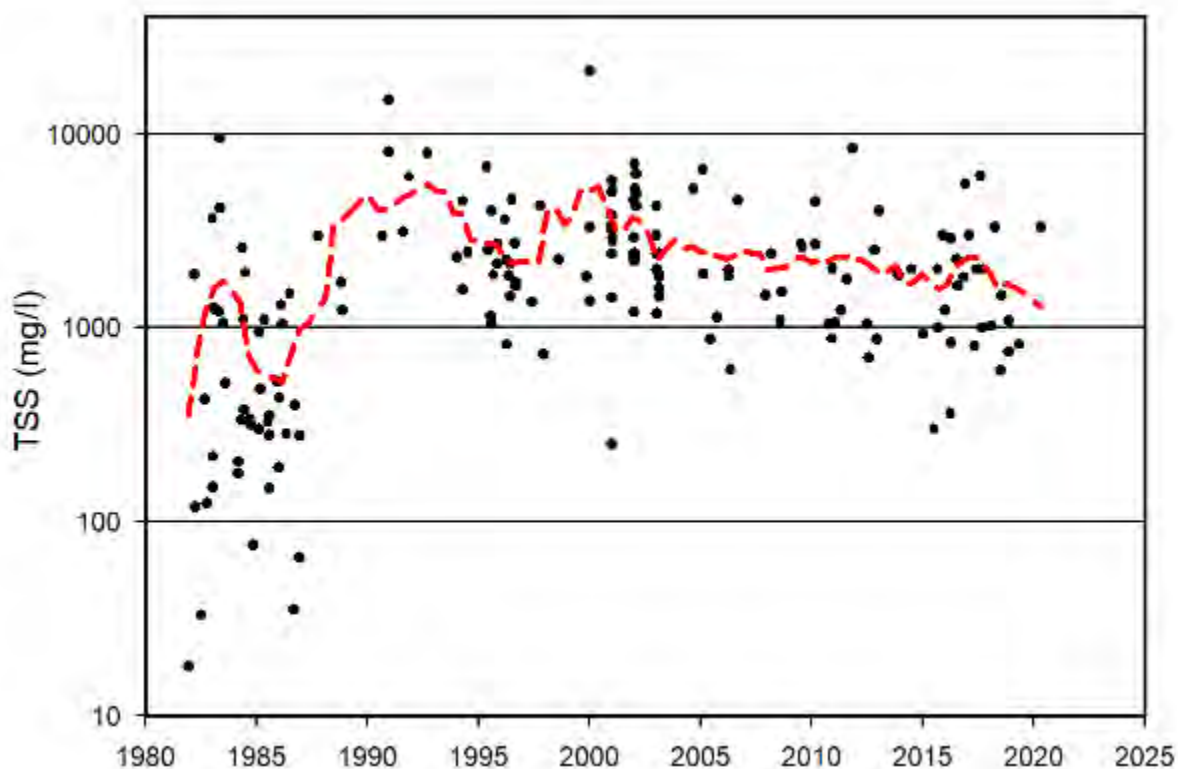


**Figure 3-10. Total suspended solids in water quality samples at Ningerum on the Middle Ok Tedi.**

<sup>5</sup> There is also some uncertainty about sediment delivery from the Middle Fly with mean sediment concentrations of 118 mg/l for OTML Chemistry Section gulp samples, 214 mg/l for OTML Hydrology Section gulp samples, and 342 mg/l for OTML Hydrology Section depth integrated samples (Pickup and Clews, 2002).

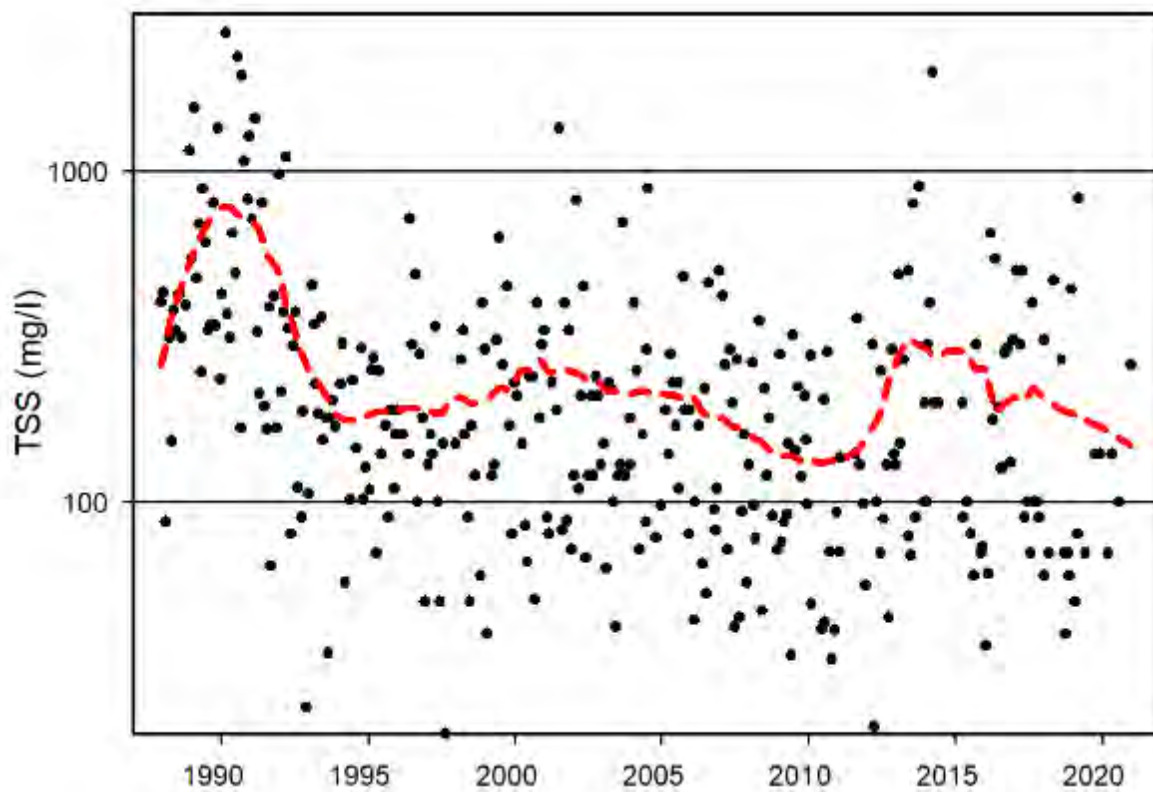


**Figure 3-11.** Total suspended solids in water quality samples at Nukumba on the upper Middle Fly

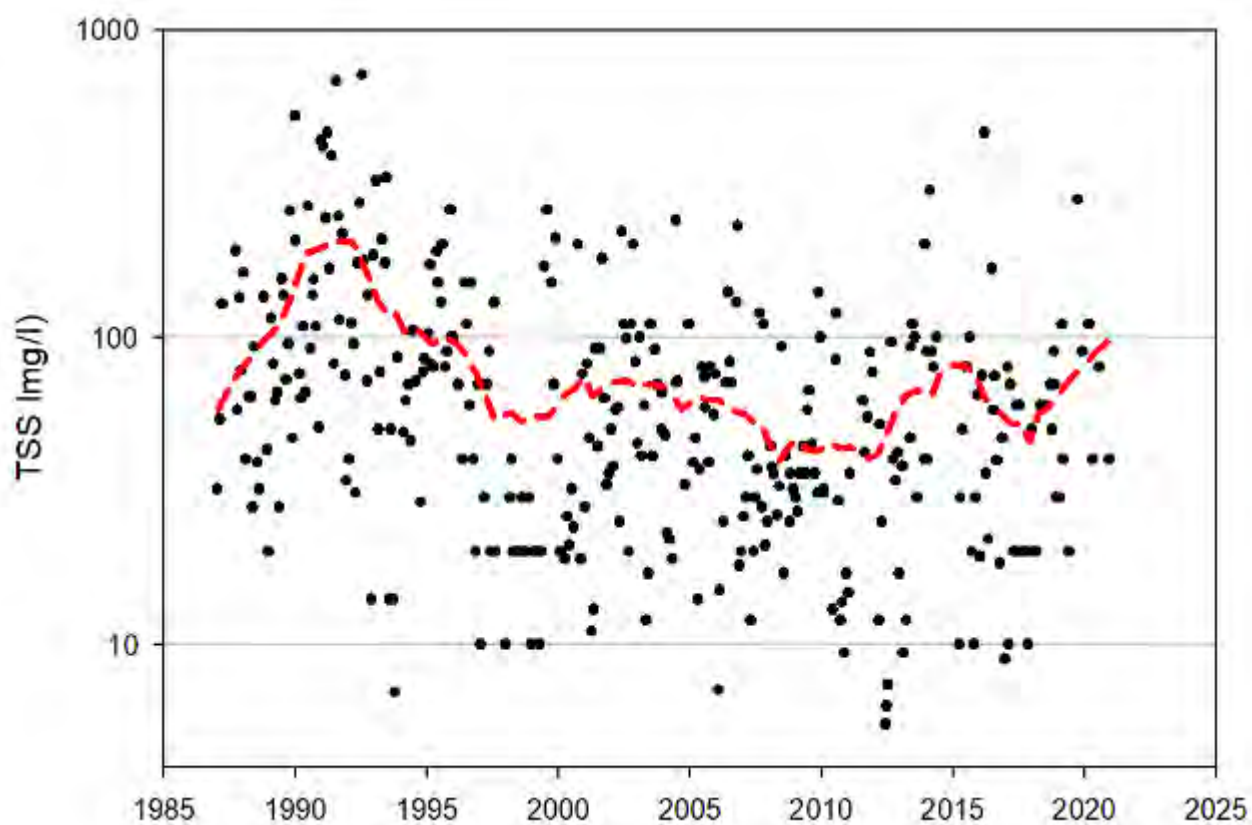


**Figure 3-12.** Total suspended solids in water quality samples at Obo on the lower Middle Fly.

## DREDGE EXTRACTION

Dredging of riverbed sediment at Bige began in 1998 (Fig.3-13) in response to rising riverbed levels, overbank flooding and forest dieback on the Lower Ok Tedi. Riverine disposal of tailings changed the Lower Ok Tedi to a mostly sand bed river but the build-up of sand started further upstream near the end of the braided channel reach upstream of Bige. Dredging has removed an average of 17 Mt/year of sand in most years since then except in 2007-2008 when about 7 Mt/year was removed and the dredge was removed to the West Bank PCon storage then under construction. The silt component of the sediment load is not captured by dredging as it remains in suspension and passes through the dredging reach. Based on data on dredge downtime due to maintenance or dangerous flood conditions, the dredge is estimated to capture about 85% of delivered sand.



**Figure 3-13. Dredging operations at Bige on the Lower Ok Tedi.**

River sediment load reaching Bige is a mix of sand and silt with about 9% more sand than silt until 2013 and then about 20% less sand than silt since 2013 as tailings input decreased from an average of 25 Mt/year to 20 Mt/year. The source of dredged sediment was investigated by Pickup *et al* (2010) as part of a trial of the effectiveness of adding 5,000 tonnes/day of ground limestone to the tailings stream to reduce potential ARD risk in the Bige dredge stockpiles and in the downstream river system more generally. Results from an intensive sampling program at multiple sites indicated that about 2/3 of Bige dredged sands were tailings while the remainder comes mostly from waste rock. Comparisons of tailings geochemistry with that of waste rock over much longer periods supports these values. The limestone trial also showed that the leading edge of a pulse of tailings reaches Bige in about three days.

The effect of dredging is clearly shown in the water level record for the Konkonda Gauging Station (TED25) which is a short distance downstream from the dredging site (Fig. 3-14). The Konkonda record covers the period from the start of mining to the present day. The record shows an increase in water levels of about 3.5m until about the year 2000. They also provide a good guide as to what will happen when tailings are diverted to a TSF. In the twelve years prior to the start of dredging, water levels rose by close to 3.5 m. From 2010, they then started to slowly fall with a more rapid decrease around 2015 when tailings input from the mine fell by around 25%. Water levels have then fluctuated with the amount of waste input and climatic conditions (El Niño and La Niña; Marshall, 2023; and the Madden-Julian Oscillation (Mathews *et al*, 2013).

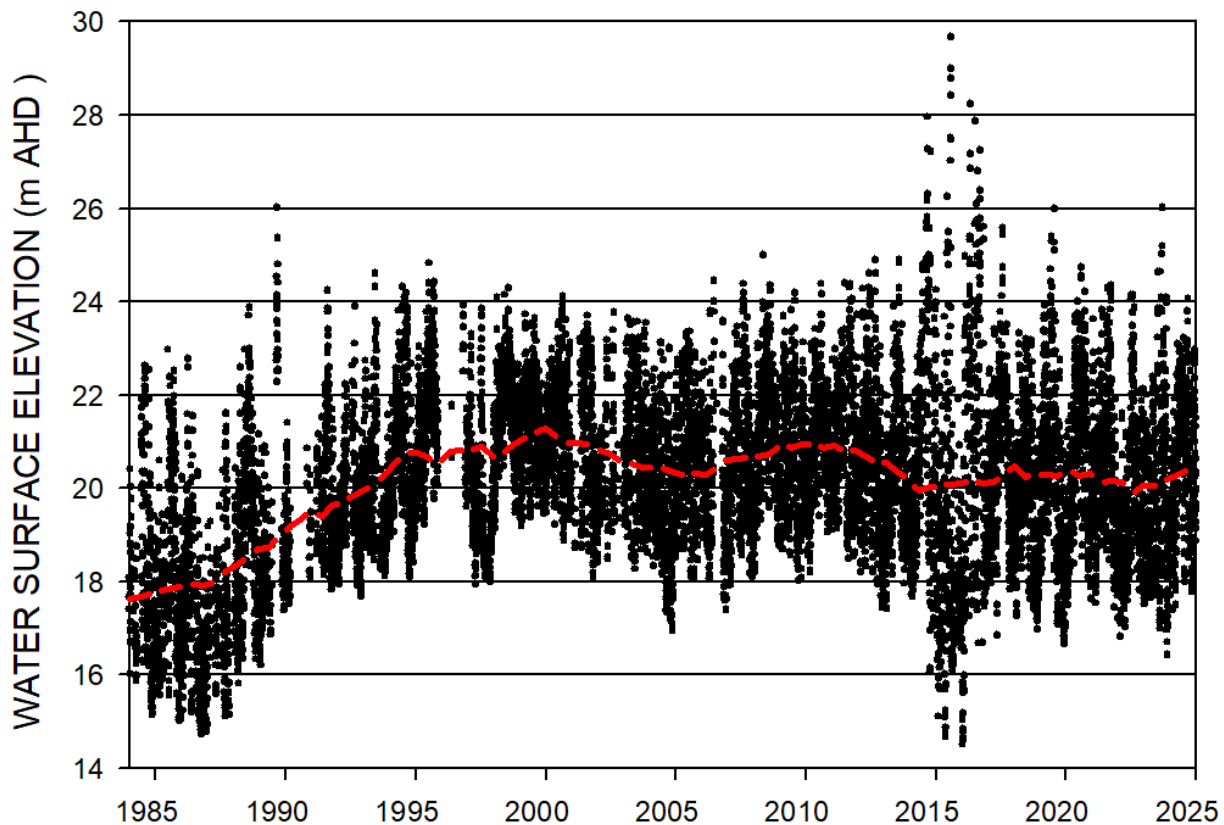


**Figure 3-14. Water surface elevations at the Konkonda gauging station (TED25) at the head of the Lower Ok Tedi. The high and low values around 2016 are due to recorder malfunction.**

Dredge slot excavation created an artificially deep channel and reduced flow velocities sufficient for gravel not to be carried through the dredged slot under most circumstances, creating a largely sand bed reach both within the slot and downstream. Some gravel input could be expected into the upper end of the slot but in the reach upstream, the gravel bed would be shielded to some degree by inflowing sand which begins to behave as bedload as the river gradient declines.

In recent years, increased delivery of gravel to the dredge slot has increased dredging costs and raised the risk of breakdown of dredging equipment. For example, it has been reported that in some sections of the slot, there has been apparently enough gravel to impede dredge operation. The need to remove gravel usually has a substantial effect on weekly sand production, over the last three years reducing weekly production from an average of 365,000 tonnes to 229,000 tonnes. Gravel was extracted 24 weeks out of 152.

Pickup and Marshall (2019) examined the recent behaviour and long term future of dredging at Bige and concluded that delivery of gravel is likely to continue and the river system will eventually evolve into a mixed sand-gravel system not dissimilar to the pre-mine situation and this is without a TSF. Removing the >60% of tailings sand from the river system will accelerate this process.

Several options for future dredging rates after installation of a TSF are under consideration. They include operating a single dredge for the remainder of mine life or running the dredges for a limited number of years after 2030. The aim is to provide material suitable for covering existing dredge stockpiles as well as continuing to reduce impact on the river. The sediment transport models do not set a fixed dredging rate. Rather they extract 85% of available sand delivered by the river as long as there is dredge capacity. The modelling (Chapter Six, Fig. 6-7) suggests that it is the reduced sand supply, if there is a TSF, more than dredge capacity that will determine how much sand may be extracted. In the modelling presented here, we assume a theoretical dredge capacity of 17 Mt/year but it is unlikely that this will be needed after the initial years of TSF operation.

## TAILINGS AND WASTE ROCK GEOCHEMISTRY

This section examines the geochemistry of past and future inputs to the river system using observed data and mine plan 240822. It covers both tails and the waste rock added to both failing and EWRDs and what is required to satisfy the conditions of OTML's Waste Rock Management Plan and Tailings Management Plan required under Environment Permit EP-L3(636). These include:

- that the waste rock entering the river system achieves an end of Calendar Year annual average net acid producing potential of less than minus 150 (NAPP <-150 kg H<sub>2</sub>SO<sub>4</sub>/t) for all failing waste rock.
- the total volume of waste rock discharged does not exceed 70 million m<sup>3</sup>/annum.
- OTML operates and maintains a pyrite concentrate (PCon) circuit in the mill to remove pyrite from the tailings, with a maximum allowable sulfide sulphur content of 1.0%, based on a quarterly average, prior to the discharge of the depyritised tailing to the river system.
- OTML must add sufficient limestone to the mill feed and/or tailing stream so as to achieve a target average net acid producing potential of less than minus 30 (NAPP <-30 kg H<sub>2</sub>SO<sub>4</sub>/t) in the tailings before they are discharged to the river system (based on a quarterly average).
- OTML continues dredging from the slot in the riverbed of the Lower Ok Tedi at an annualised rate of at least 10 Mm<sup>3</sup>/year for as long as mining continues within the project area
- OTML must achieve a target acid neutralising capacity to maximum potential acidity (ANC/MPA) ratio of at least 2.0 in the deposited material comprising the final outer cover for all spoil piles prior to closure; and
- OTML must design and build a final cover system for the dredge spoil piles which supports the sustainable establishment of vegetation and which results in at least an 80% reduction in acid generation rate in the contained material compared with a spoil pile without a final cover.

The TSF will have an influence in meeting these conditions, especially the final three. The 10 Mm<sup>3</sup>/year target may be difficult to meet if tailings are diverted to a TSF. This will occur because future sand delivery will come from tailings currently stored in upstream river deposits which will eventually be exhausted. Only limited sand will be derived from abrasion of waste rock given the high proportion of limestone, siltstone and shale in the material delivered to the river which mostly breaks down to silt (see Fig. 3-4).

The following nine figures illustrate the various combinations of inputs in Case 240822 intended to meet these conditions and balance costs, revenue and the practicalities of mining the ore body. While the amount and concentration of copper delivered to the river system in tailings has decreased substantially since 2000 (the first year regular statistics have become available, concentrations in waste rock have been variable. In the failing Southern Dump, they have been lower than in earlier years. In the planned Northern EWRD, they may become higher in later years but this may be offset by reduced total waste rock losses to the river compare with earlier losses from the failing Taranaki Dump.

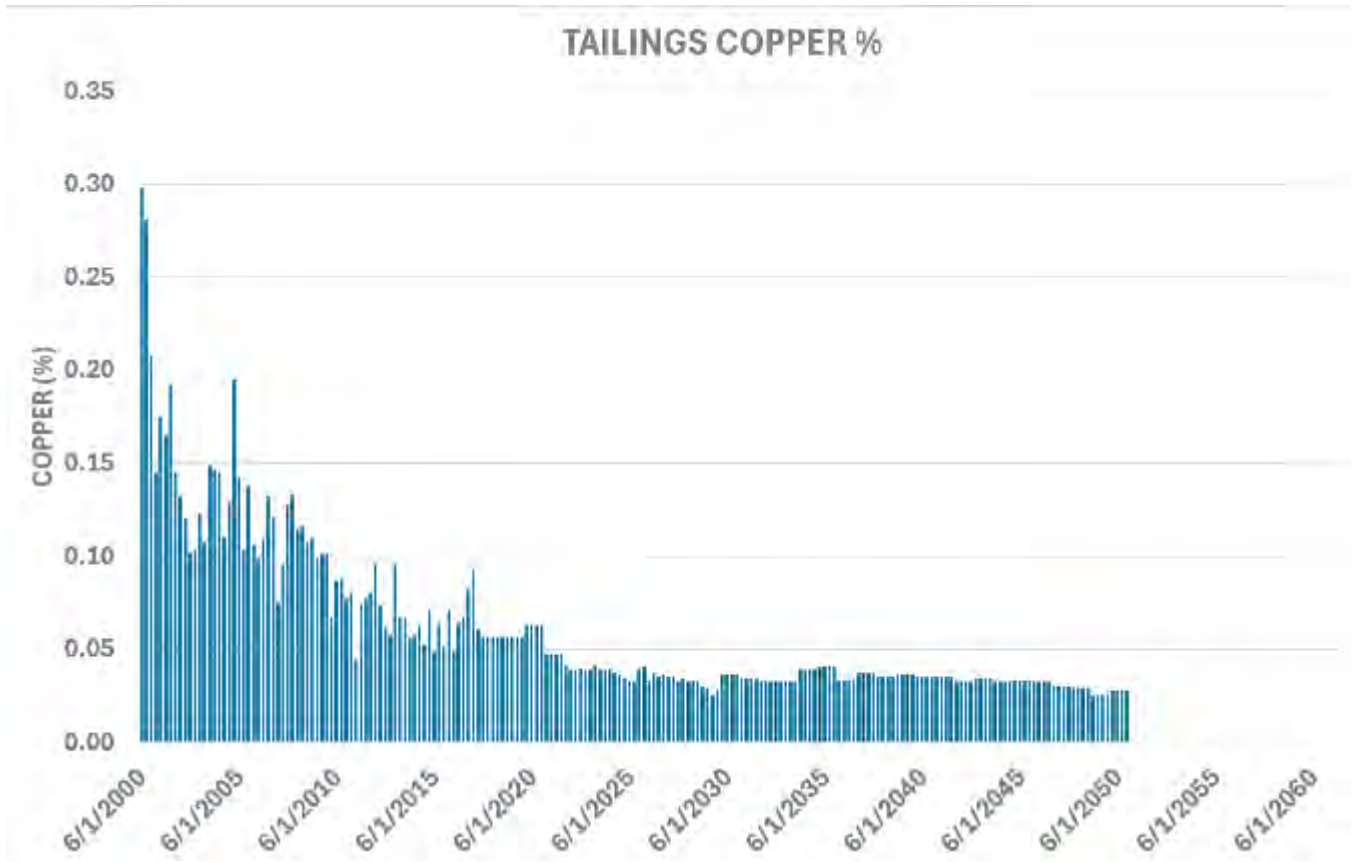


**Figure 3-15. Tailings copper content.**

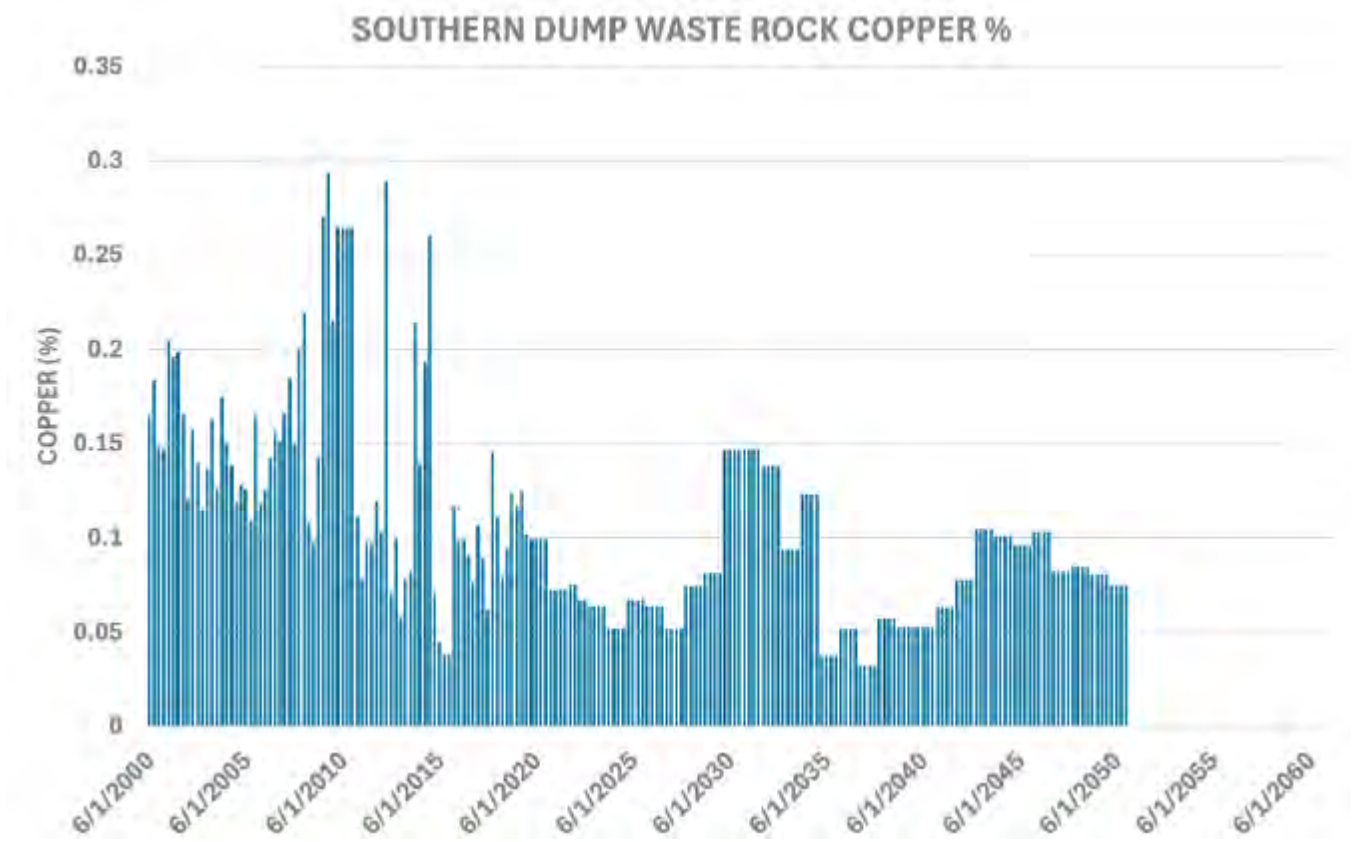


**Figure 3-16. Southern Dumps copper content.**

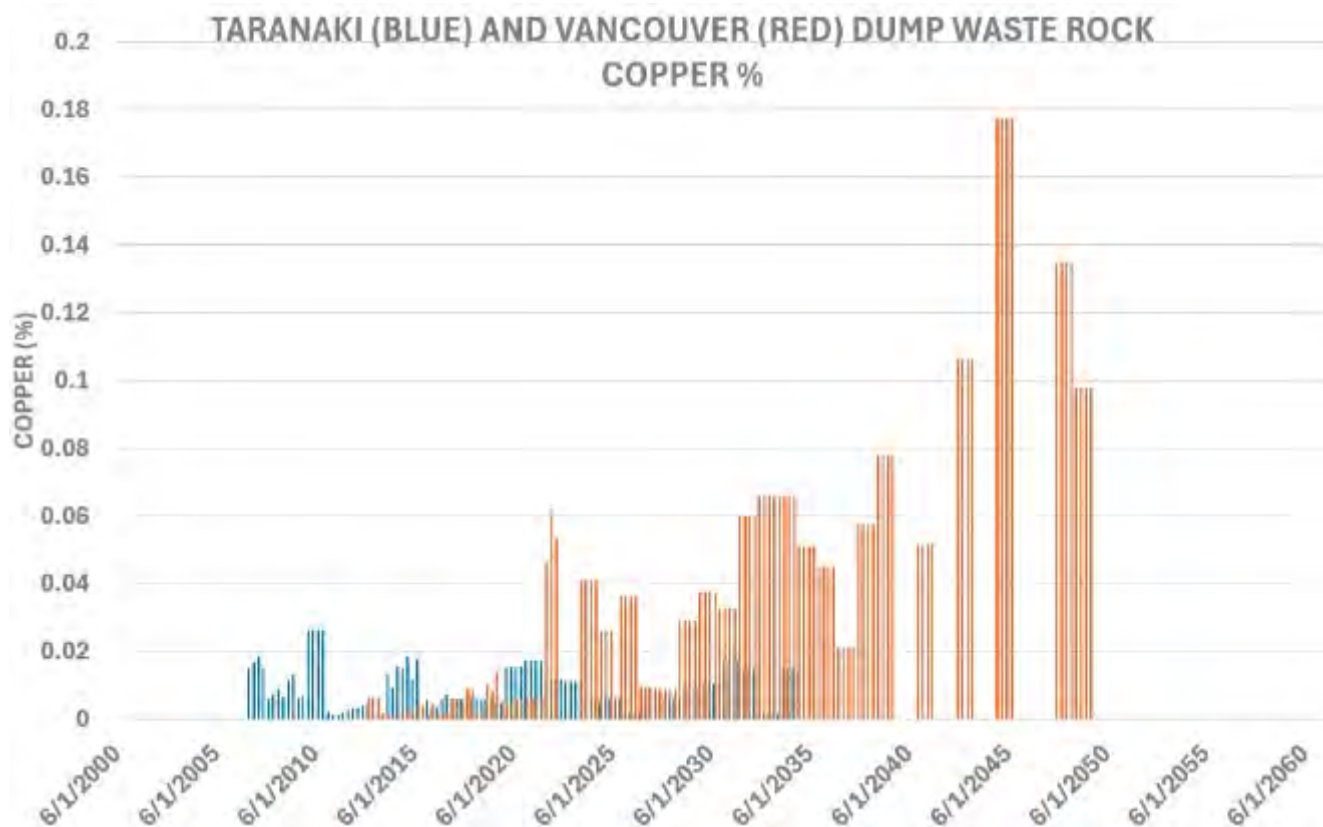


**Figure 3-17. Northern Dumps copper content.**

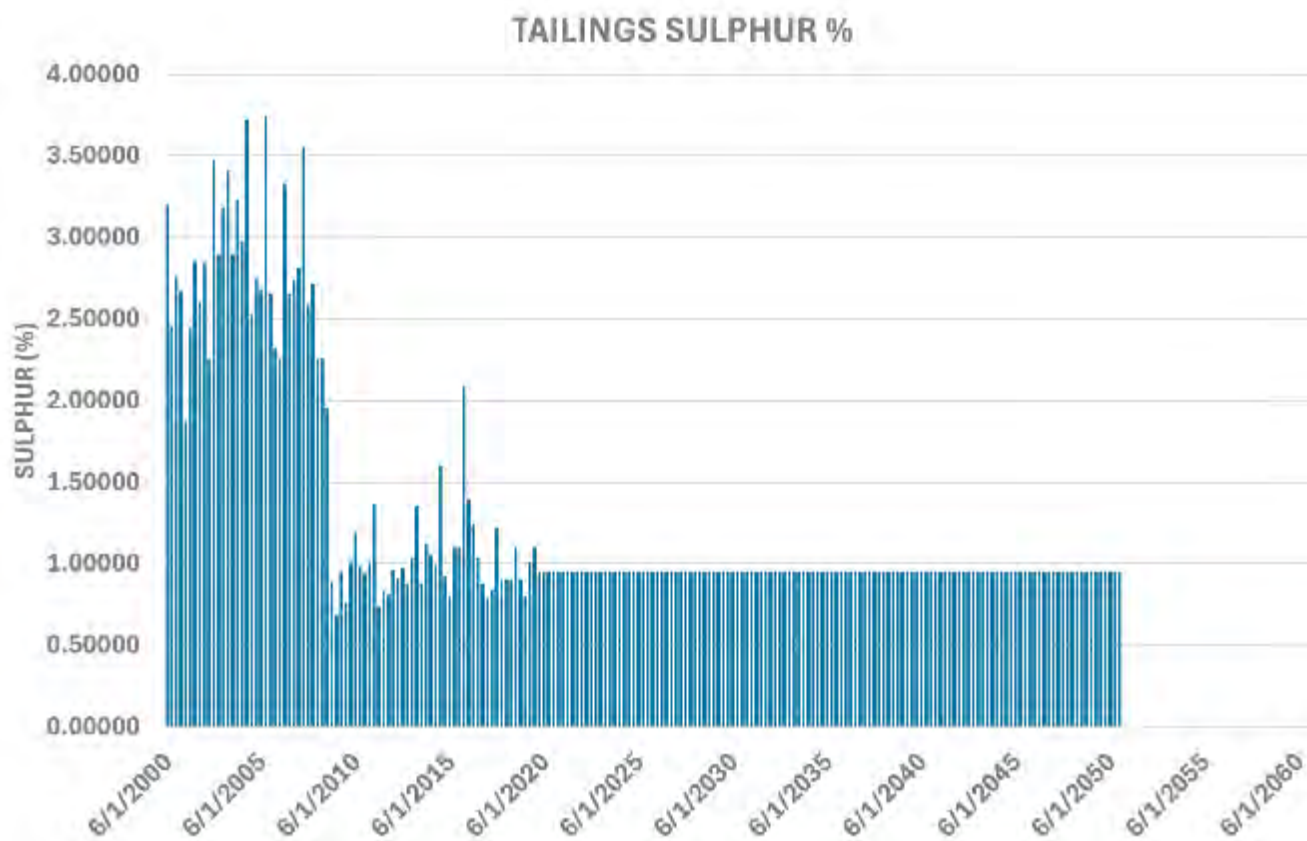


**Figure 3-18. Tailings Sulphur Content.**

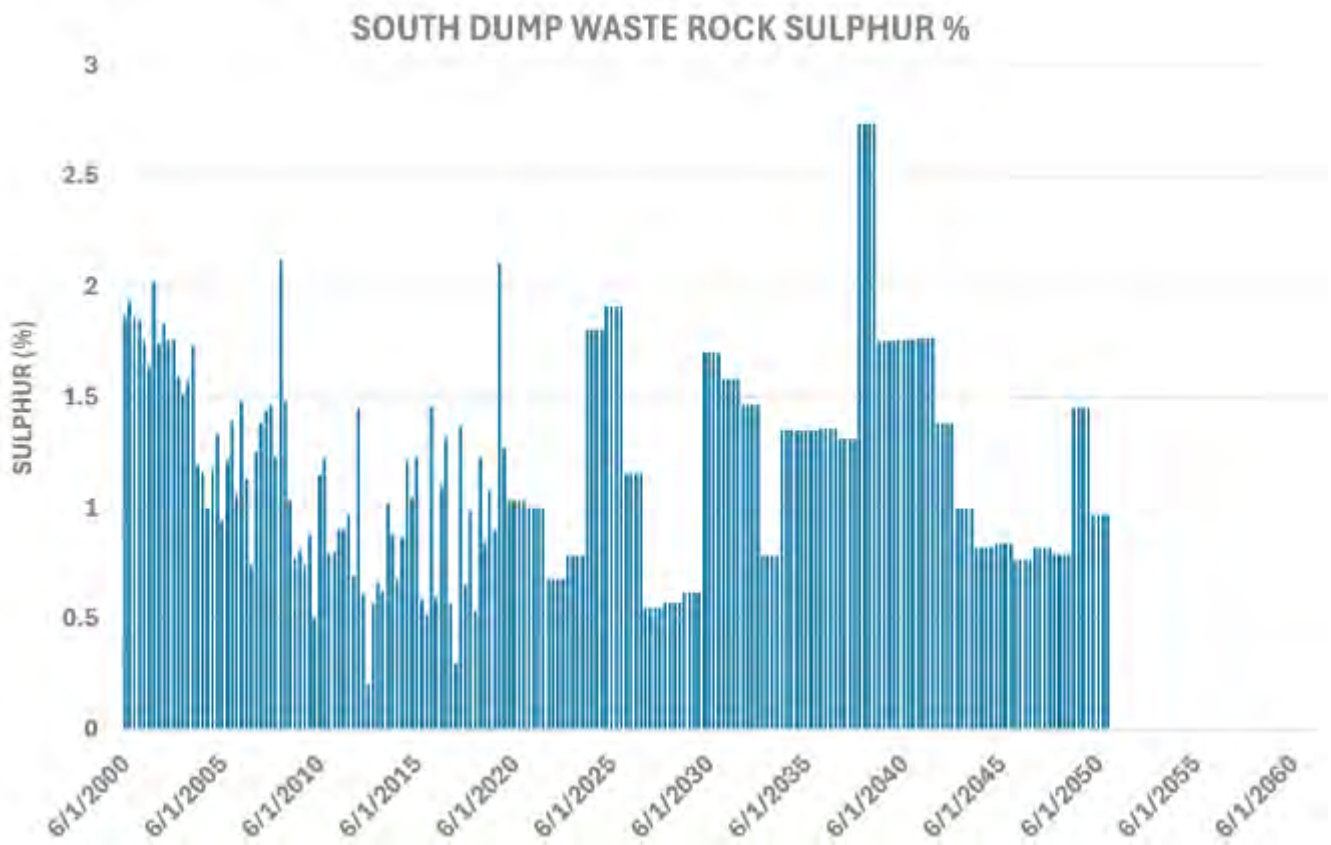


**Figure 3-19. Southern Dumps Sulphur content.**

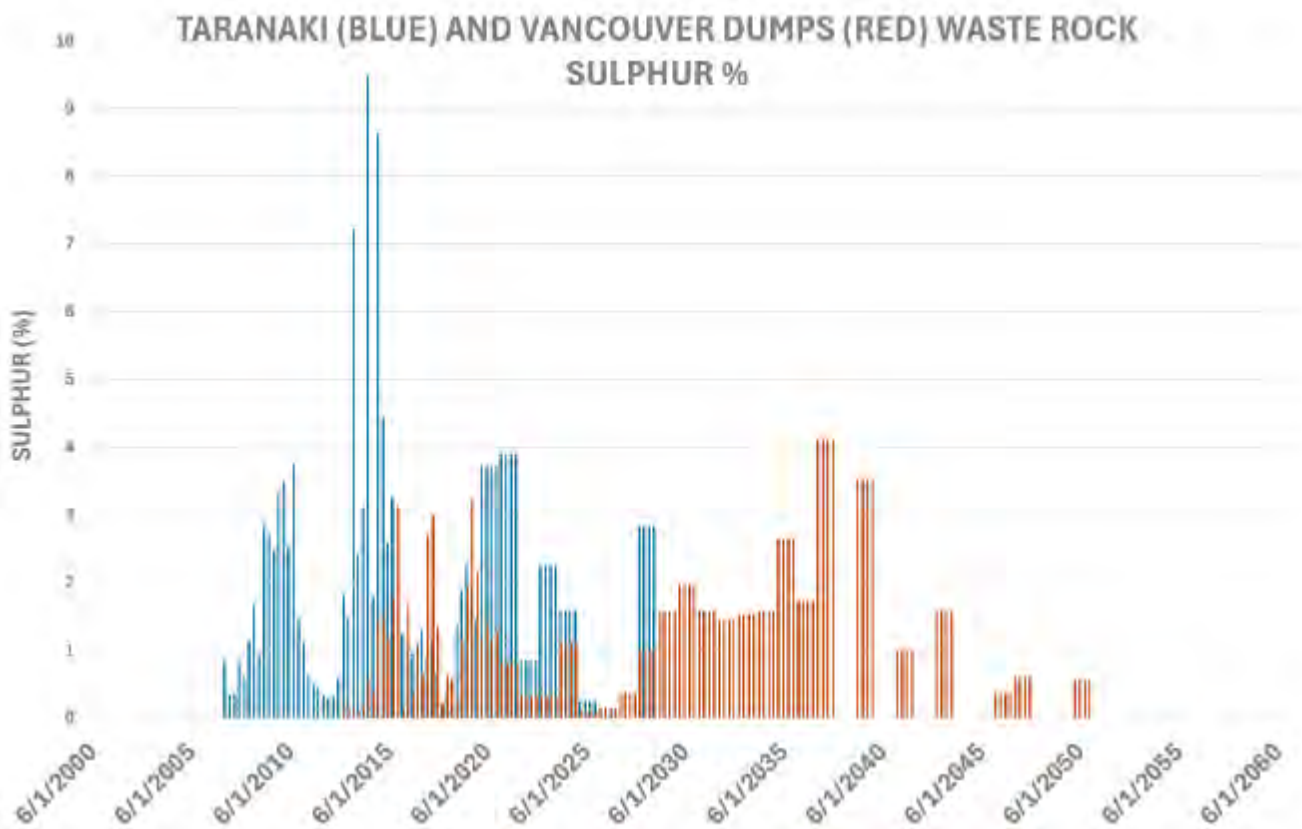


**Figure 3-20. Northern Dumps Sulphur content.**

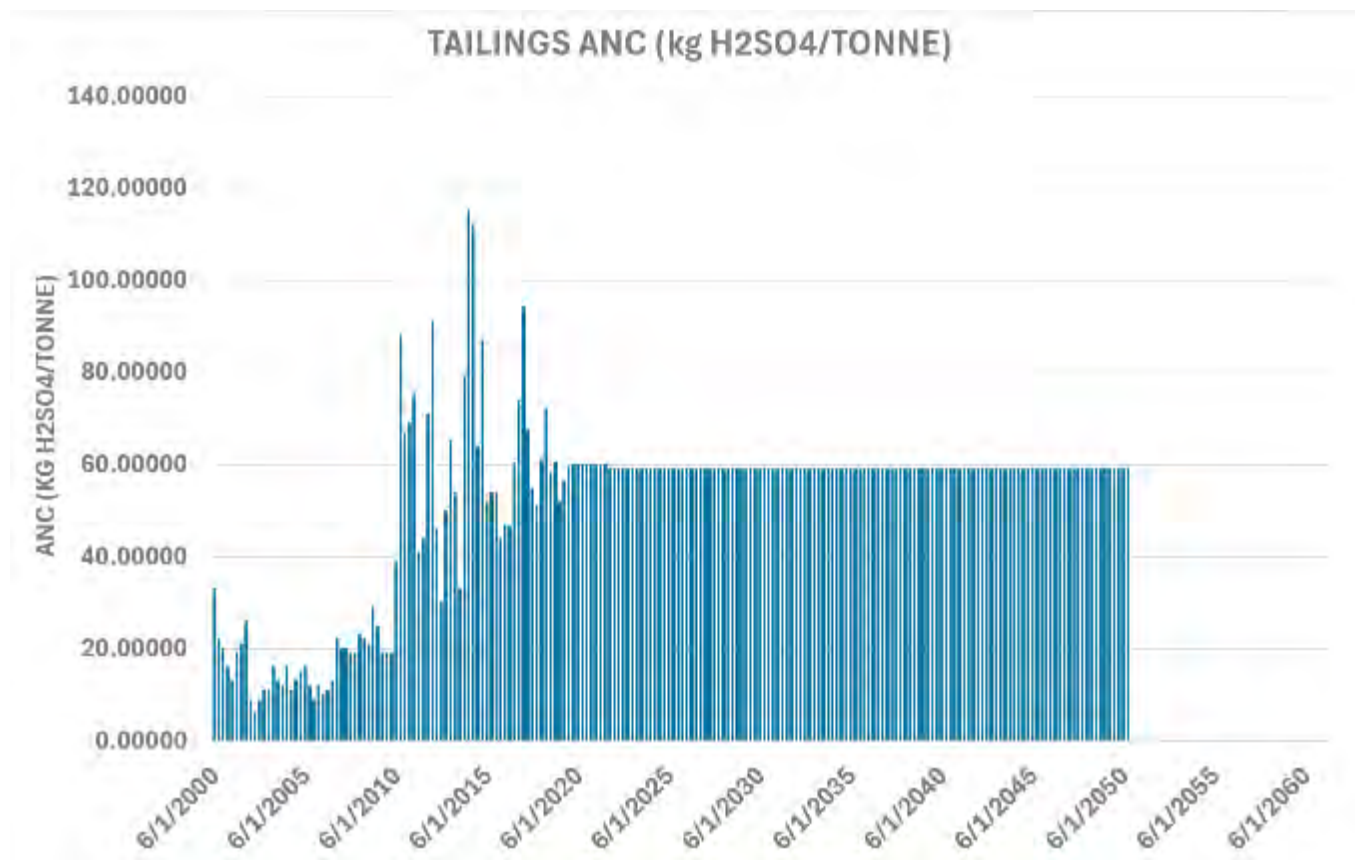


**Figure 3-21. Tailings ANC.**

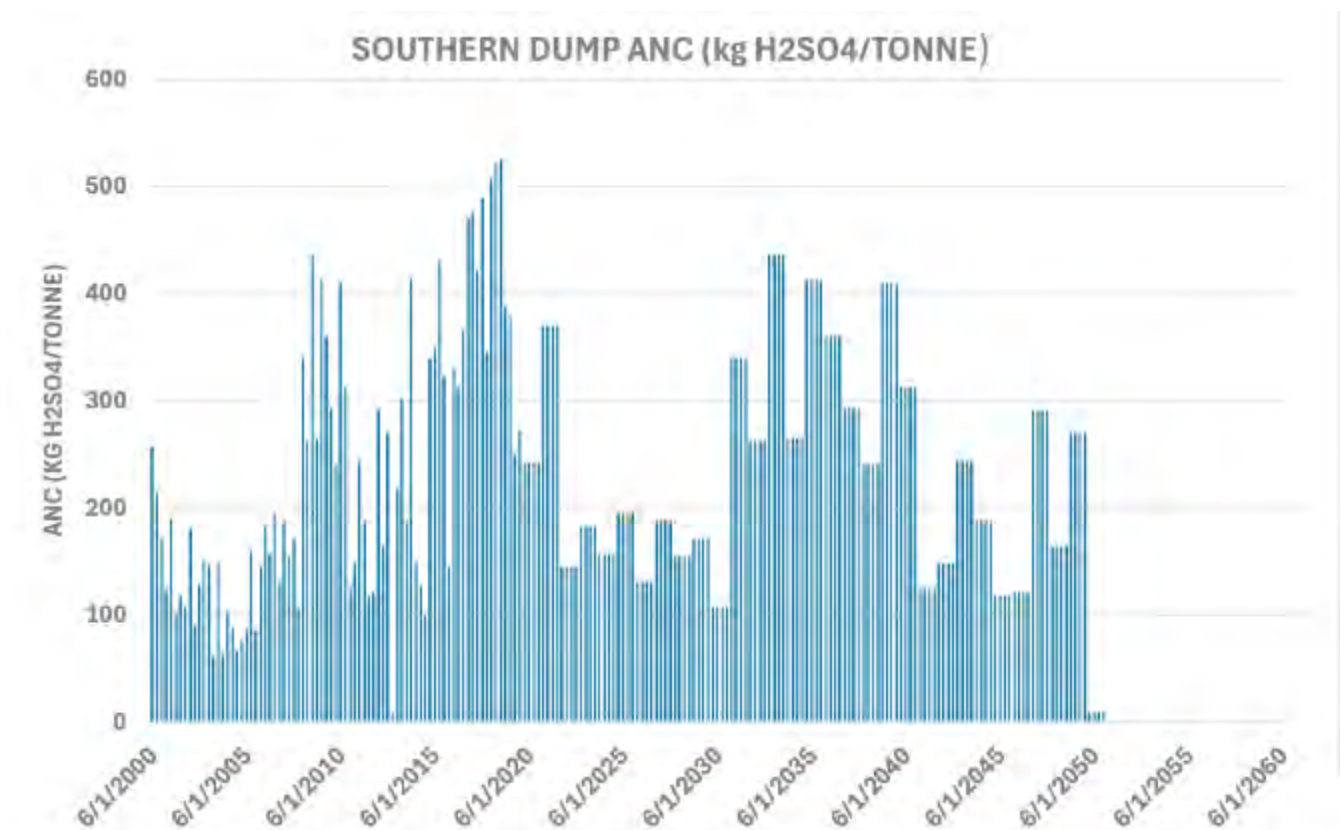


**Figure 3-22. Southern Dumps ANC.**

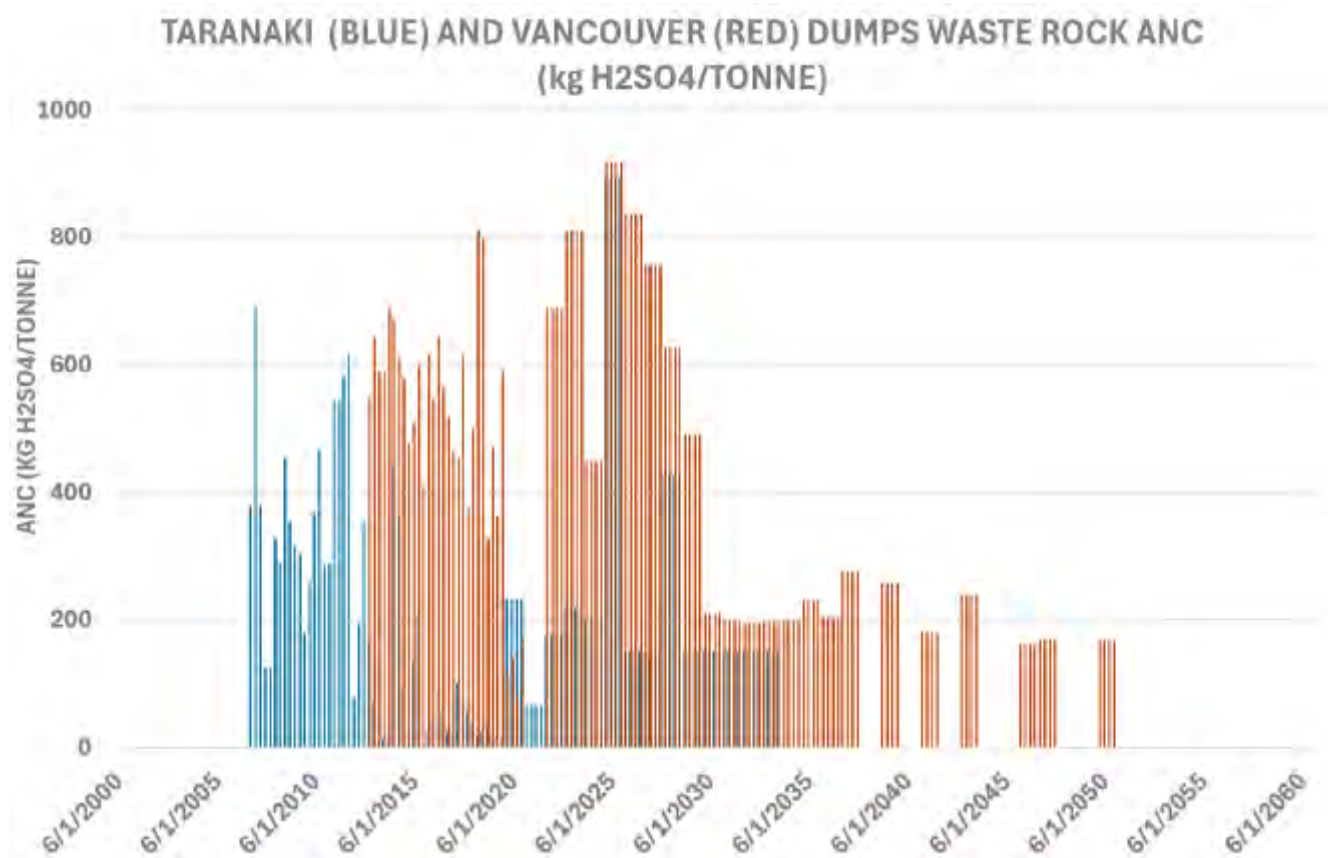


**Figure 3-23. Northern Dumps ANC.**

## CHAPTER FOUR – UPPER RIVER SYSTEM RESPONSE TO WASTE ROCK AND TAILINGS DISPOSAL

This and the following Chapter describe how each reach of river has responded to the input of mine waste and identifies the trends that will determine how they may behave in the future. As such, they provide a guide to some future changes that may occur but that are not directly predicted by the sediment transport models.

While sedimentary processes in the upper reaches of the river system will only experience limited effects from diversion of tailings to a TSF, they will become the only source of sand delivered to the dredge site and thus, the amount of cover material for the PCon storage and Bige stockpiles and the amount of sediment reaching the floodplains of the Lower Ok Tedi and Middle Fly. The latter has potential to affect future patterns of erosion and deposition in the river channel and through them, the pattern of floodplain inundation with its associated biological consequences.

### HARVEY CREEK

Prior to mining, Harvey Creek was a steep, forested mountain gully. Since then, debris flows from the Southern Dumps have gradually filled it up and a large alluvial fan has developed at the downstream end where it joins the Ok Mani (Fig. 4-1). Comparison of 1982 20-m contour maps with 2024 photogrammetry shows that up to 100 m of deposits fill the lower end of the Harvey Creek valley. Comparison with a more reliable 1992 survey suggests a fill of about 80 m. The valley now has a fill extending upslope to the base of the waste rock dump whereas previously the dump ended in a steep cliff face which is now buried (Figs. 3-6 and 4-2). The fill has developed a fan surface

gradient with a constant slope of about 9-10%. This seems to be an equilibrium slope imposed by the sediment transport capacity of the system.

Lateral channel migration in the early stages of dumping has undermined valley sides and there were major landslides. Marshall (2001, 2006) estimated that this process added 160 Mt to Harvey Creek between 1990 and 2000, and a further 15 Mt in the 2000-2004 period. The former landslide zones are now mostly buried by waste rock.



**Figure 4-1. Harvey Creek and the upper Ok Mani 2024 image overlaid on a 2015 image. The Ok Kumuip, which contains the tailings discharge point is the valley on the right. As Harvey Ck filled**

*with waste rock, a large fan developed at the junction with the less steep Ok Mani which was subsequently backed up and also began to accumulate sediment from a small dump to the west.*

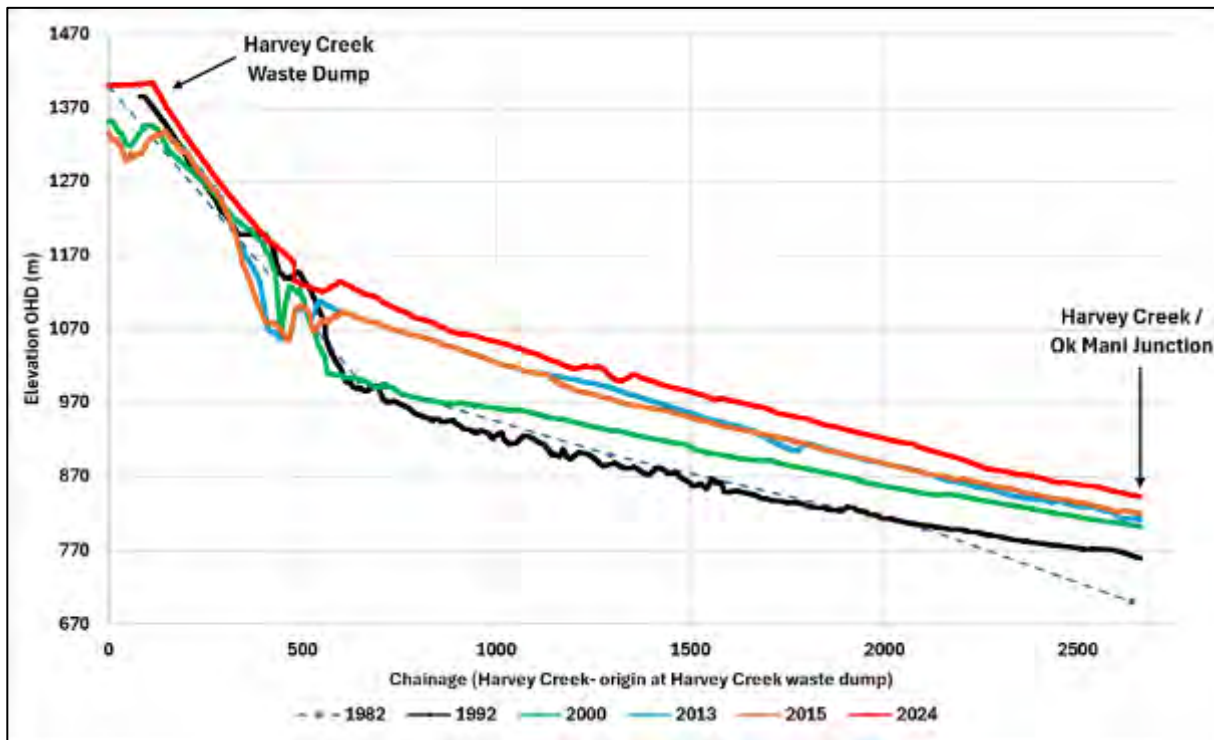


**Figure 4-2. Mine waste deposition in Harvey Creek compared with the pre-mine long profile. Bed levels have risen by approximately 150 metres. While there was little change between 2013 and 2015, the overall bed has risen uniformly by between 20 and 25 metres through to 2024. From Marshall (2025a).**

## OK MANI

The behaviour of the Ok Mani during the period of mine waste dumping is shown by the sequence of long profiles in Fig. 4-3. The river has a concave long profile which, over time, has become steeper as it adjusts to the very large increase in sediment load from Harvey Creek. Deposition is greatest in the upper reaches and the Harvey Creek fan blocks the Ok Mani valley, sometimes leaving a lake in the reach immediately upstream of the junction. Channel form is an extreme form of braiding with many channels which can rapidly migrate across the full width of the valley. Deposited waste thins out towards the Ok Tedi junction at the lower end of the Ok Mani where the larger Ok Tedi is capable of transporting most of the delivered load.

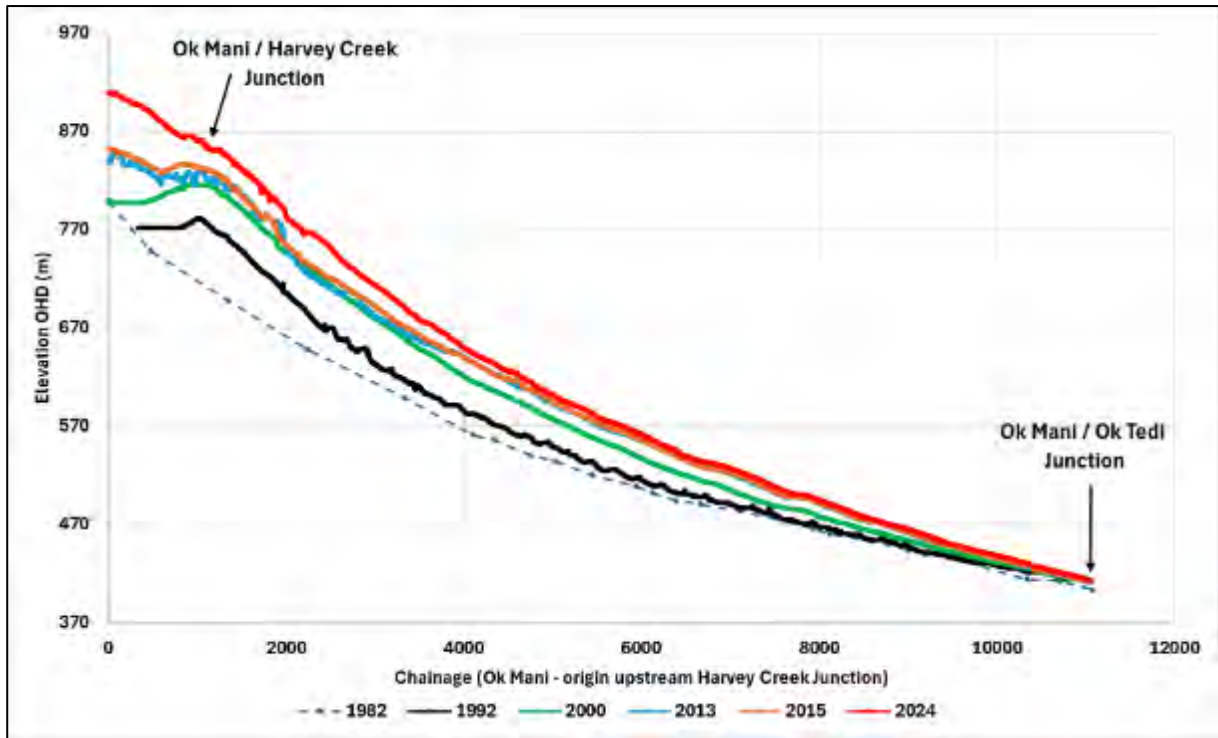


**Figure 4-3. Long profile of the Ok Mani from upstream of the Harvey Creek junction through to the junction with the Ok Tedi. Ok Mani (and Harvey Creek) contribute the vast majority of waste rock storage within the Mine Area Creeks network. Approximately 145 metres of aggradation has resulted in the upper zone compared with the pre-mine state, and this tapers down to approximately 9 metres at the junction with the Ok Tedi (Marshall, 2025).**

The Ok Mani has experienced short periods of erosion such as in 1997, when dumping was greatly reduced because of drought conditions. However, the trend has been for continued aggradation and a gradual steepening of the long profile beginning from the downstream end and progressing upstream. Since 1991 when dumping began, The Ok Mani/Harvey creek system has received about 1.3 billion tonnes of waste rock and perhaps 220 Mt of landslide material.

Marshall (2024) summarises the development of the system as follows:

*“Ok Mani (and Harvey Creek) have contributed the vast majority of waste rock storage within the Mine Area Creeks network. Up to 145 metres of aggradation has resulted through the upper zone of Ok Mani compared with the pre-mine state, and this tapers down to approximately 9 metres at the junction with the Ok Tedi. In Harvey Creek, bed levels have risen by between 115 and 145 metres since mining commenced. Waste storage rates through Ok Mani show a relatively consistent rate of retention at the downstream end junction with the Ok Tedi. This has appeared to be relatively stable since the build-up following the impacts of the Vancouver landslide. .... for the zone upstream of the fan, retention has increased significantly since 2015 in line with increased dumping at the Paris dump, located immediately west of the Harvey Creek southern dump”.*

## SULPHIDE CREEK

There are two failing waste rock dumps on the headwaters of Sulphide Creek: the Taranaki Dump and the Vancouver Dump (Fig. 4-4). Taranaki has been a failing dump from the beginning. The Vancouver Dump was initially more stable until it extended as far as the valley floor further downslope but is now failing. OTML are currently attempting to construct an engineered waste rock dump in this area.

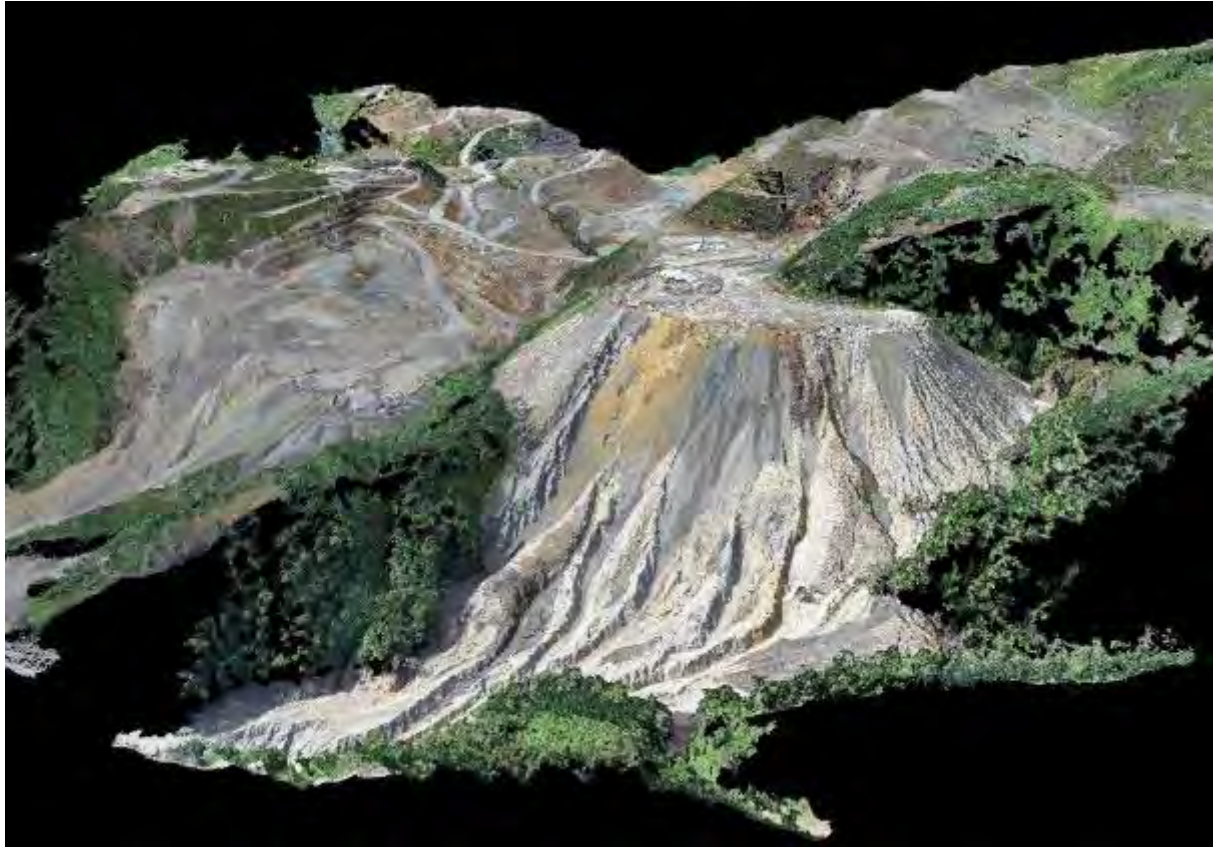


***Figure 4-4. Sulphide Creek waste rock dumps. Lidar image: Steven Aka.***

Sulphide Creek has two reaches separated by a waterfall. Both have a more or less straight long profile (Figure 4-5). There was a limited amount of dumping here in the early years of mine life but a large landslide (the Vancouver Landslide – see Chapter Three) added about 120 Mt of sediment to the system between 1989 and 1992 and waste dumping switched to the Southern Dumps.

The upper reach of Sulphide creek largely operates as a dump runout zone (Fig. 4-6). The lower reach experienced only limited aggradation until 2013 but the addition of 196 Mt of waste rock between 2013 and 2024 resulted in a build-up of material in the upper 1.7 km of the lower zone (Marshall, 2024). The remaining 3 km of the lower zone experienced very little deposition. Indeed, it has hardly changed since 1992 indicating that the system has a very high sediment transport capacity.

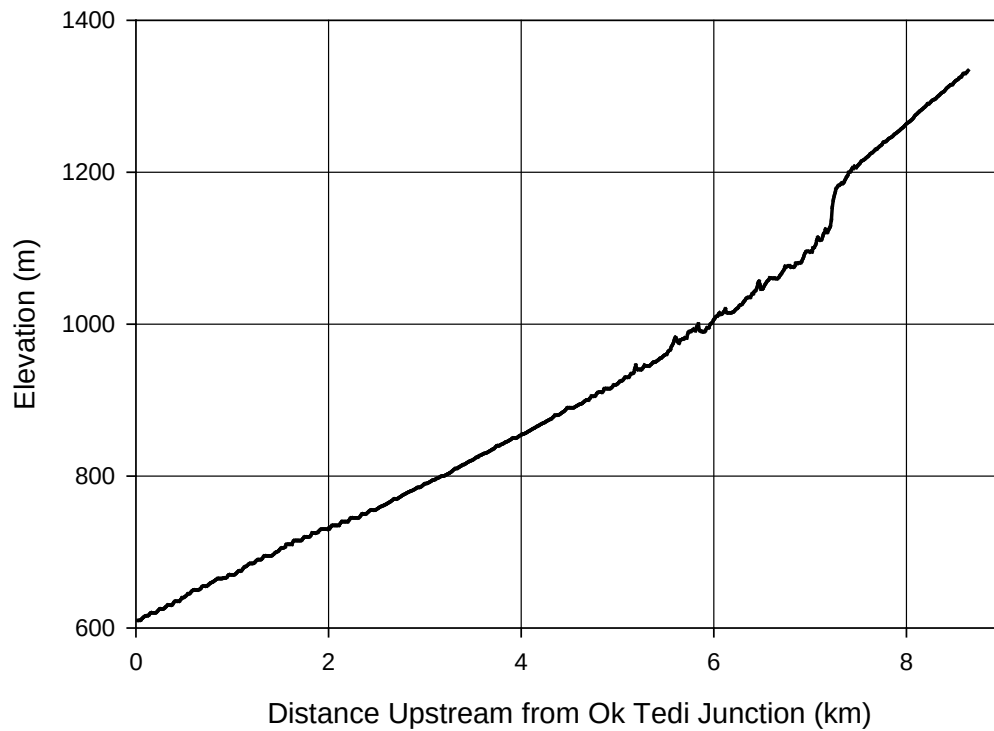


**Figure 4-5. Sulphide Creek long profile (from Cui and Pickup 2009).**

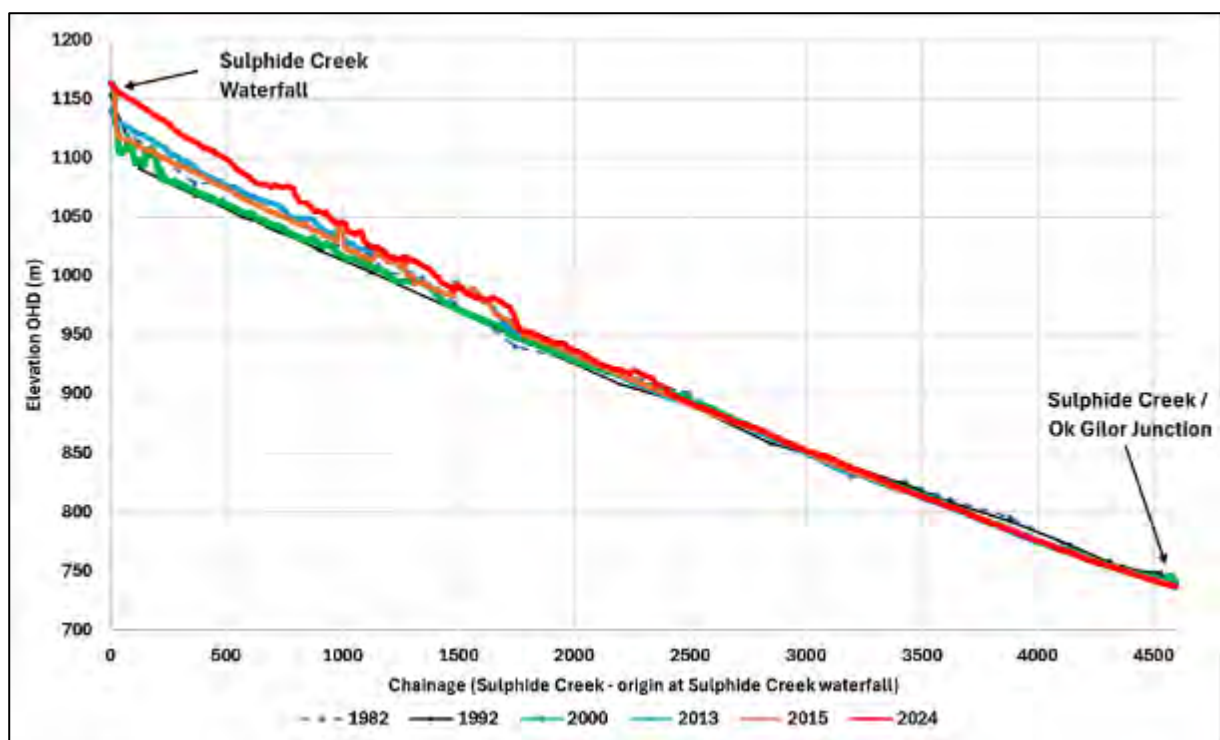


**Figure 4-6. Long profile of Sulphide Creek downstream of the waterfall through to the Ok Gilor junction. Aggradation has increased significantly since 2015, however, there is little net change to bed elevations at the downstream end of the reach. There is no evidence of any residual aggradation resulting from the Vancouver landslide of 1989, with most material mobilising downstream by 1992. From Marshall (2025a).**

We have calculated total storage in the Sulphide Creek system by treating the reach upstream of the waterfall as a mostly eroding dump runout zone and only considering the downstream section as covered by the 2004 survey. Comparing the 1982 and 2004 datasets gives storage of only 1.37 Mm<sup>3</sup> or 2.4 Mt.

Only about a quarter of total waste rock was disposed of at the Northern Dump up until 2006, but the Vancouver Landslide added about 120 Mt of sediment to the system between 1989 and 1992. Material is still being shed from landslide areas on upper Sulphide Creek and this funnels through a narrow valley upstream of the waterfall located approximately 7 km upstream of the Sulphide Creek – Ok Tedi confluence. There was some sediment accumulation in this valley between 1996 and 2000 but since 2000, it has been eroding.

The lower reach of Sulphide Creek has more potential for deposition. Between 1996 and 2000, it was still accumulating sediment from the landslide area upstream. After 2000, however, much of the lower reach began to erode. There was some terrace formation during this process, but the terraces were temporary and the whole valley floor was affected by erosion.

Marshall (2001) estimates that between March 1996 and November 2000, Sulphide Creek received 44.4 Mt from waste rock input and valley wall erosion. It delivered 48.7 Mt to the Ok Tedi giving an annualized transport rate of 10.4 Mt. Sediment transport capacity is therefore greater than delivered load.

Marshall's 2024 data do not cover the period 1982-1996 and end in 2000. We have therefore calculated total sediment storage in Sulphide Creek from digitized 1982 20 m contour data and a photogrammetric survey from 2004. If we treat the reach above the waterfall as eroding and only consider the downstream section covered by the 2004 survey, this gives a storage of only 1.37 Mm<sup>3</sup> (million cubic meters) or approximately 2.4 Mt (Cui and Pickup, 2009).

Comparison of inputs (including the Vancouver landslide) with 2004 storage values gives the Sulphide Creek system a transport rate of at least 15 Mt/year. The rate would be significantly higher than this if more sediment load was delivered. This means that Sulphide Creek will be capable of transporting virtually all delivered waste rock until the end of mine life and will store very little sediment thereafter.

## MIDDLE OK TEDI

Topographic data for the Middle Ok Tedi include spot heights derived by photogrammetry from 1982 and 1992 and aerial photography and a differential GPS survey in late 2008. Elevations are on exposed gravel bars. The 2012 data are from airborne lidar with good ground control. The 2008 and 2012 data are more accurate than the earlier values. Overall, however, a pattern of deposition emerges (Fig. 4-7).

In the upper part of the system, a wedge of mine-derived gravel (A) has accumulated with up to 8 m of deposition in the first 30 km below the Ok Mani although most values lie within the range of 2-7 m. The 1982-2012 points lie above the 1992-2012 values, so the deposition also occurred before 1992. Further downstream, there is 1-4 m of deposition, declining to 1-2 m immediately upstream of the Ok Taub junction (B). Riverbed levels rose in the 80-100 km reach just upstream is what is now the Bige dredging site (C). The lack of change between 2008 and 2012 reflects a decrease in waste rock delivery to the river from about 38 Mt/year to 18 Mt/year. The lack of substantial deposition recently also suggests that much of the 18 Mt is breaking down to sand and silt.

The wedge of gravel deposition at the upstream end of the system reflects two processes. Firstly, as the capacity of the river to move large particles decreases as gradient declines, there is sorting of sediment and preferential deposition of coarse material. Secondly, the supply of coarse particles decreases as larger material is broken down into smaller fragments during transport. Most of the deposited material upstream of the Ok Birim is gravel but there are localized and temporary deposits of sand on many of the gravel bars.

Downstream from the Ok Birim around the 70 km point, deposition begins to increase. Much of the deposited material is sand and reflects the decreasing gradient of the Ok Tedi. The dip around the 100-110 km section (Fig. 4-7) shows the influence of dredging which, since 1998 has removed up to 17 Mt/year of sand from the river.

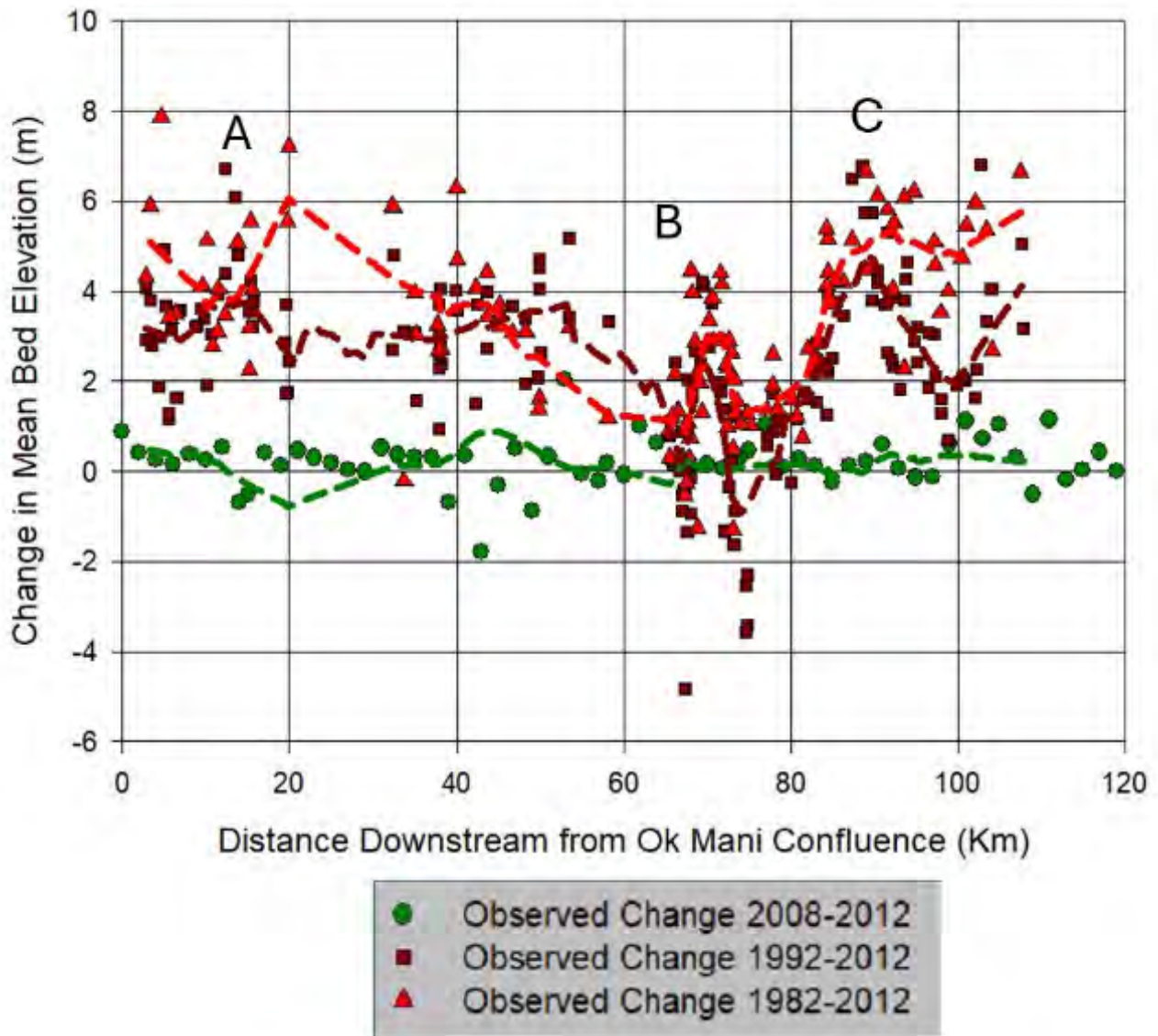


**Figure 4-7. Observed changes in bed elevation in the Middle Ok Tedi. Broken lines are smoothed values. No post-2012 data are available.**

Changes in water level over time illustrate the effect of deposition in the Middle Ok Tedi since mining began more clearly (Fig. 4-8). The record for the Haidauwogam gauging station (TED15) on the gorge section (gravel reach) of the upper Middle Ok Tedi begins in 1990 after five years of waste rock discharge. After the initial water level rise before 1995, there is no clear trend until 2005 indicating that this gorge section was able to transport delivered material downstream. After waste rock input increased post-2005, water levels steadily increased indicating a build-up of deposited sediment.

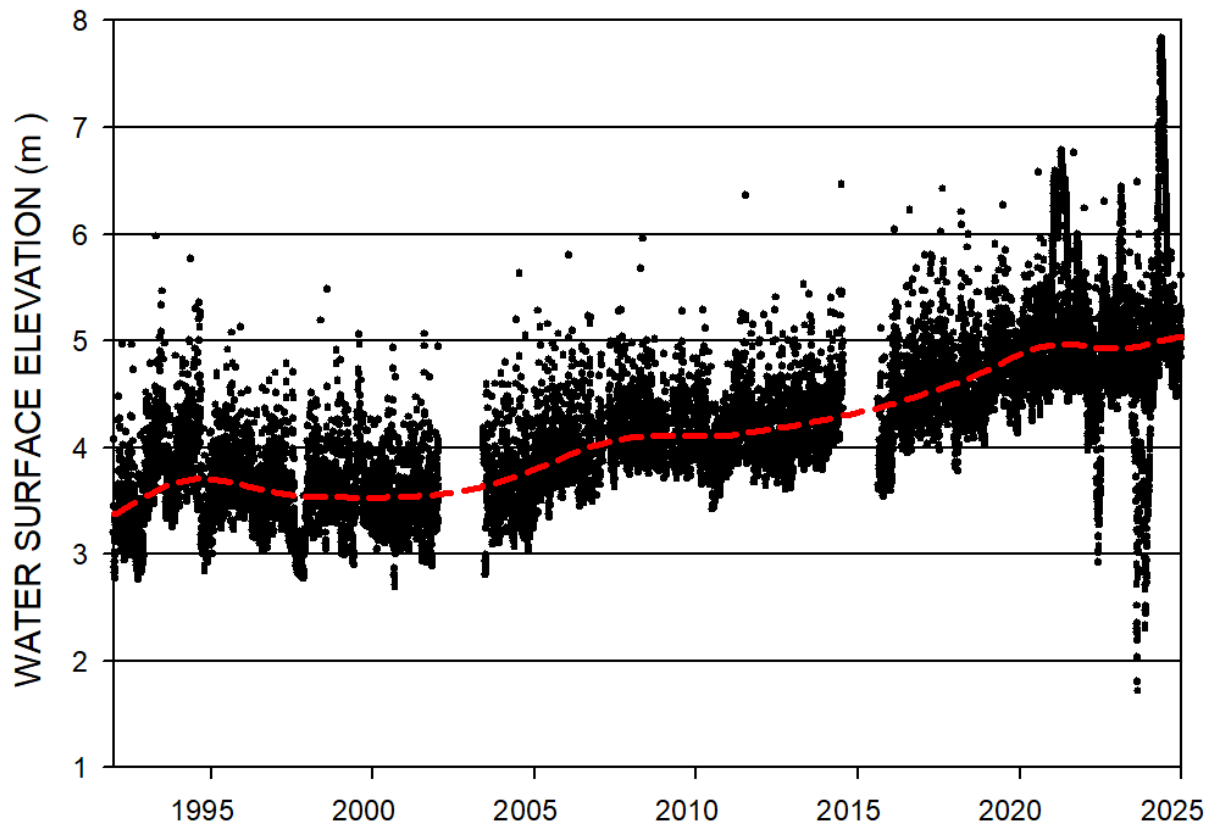


**Figure 4-8. Water levels at Haidauwogam on the upper Middle Ok Tedi. A local datum is used. The very high and low values in recent years are likely to reflect recorder malfunction.**

The progress of recent deposition and the transition from gravel to sand are illustrated by the exposed bank profile in Fig. 4-9. Signs of acid generation are apparent once sediment is deposited and exposed to oxidation. Occasionally, when older tailings are exposed by channel shifting and erosion, oxidised material may be seen on the surface ((Fig. 4-10).



**Figure 4-9.** Exposed riverbank sediment at the lower end of Middle Ok Tedi just upstream of the dredge site but downstream from the Ok Birim. The red stained lower bank material is ancient material of the pre-mine river bank. The red staining indicates oxidation common in such material but it may also reflect acid leaching from the second layer which is mine-derived gravel. The upper layer is sand with lenses of gravel indicating deposition of finer material and is typical of the build-up of sand, mostly from tailings deposition, in this reach of the river in recent times. Prior to 2010 tailings were the principal source of acid-generating material, 2019 photo.



**Figure 4-10.** Heavily oxidised older tailings in sand deposits in the Middle Ok Tedi. Photo: 2007 photo taken prior to addition of milled limestone to tailings and operation of the Tailings Pyrite Plant

## CHAPTER FIVE - MAIN RIVER AND FLOODPLAIN RESPONSE TO WASTE ROCK AND TAILINGS DISPOSAL

The floodplain reaches of the Lower Ok Tedi and the Middle Fly are the main receiving environments for the sand and silt delivered from the mine. As such, they will be the reaches most affected by diversion of tailings to a TSF.

Much of the impact of mine waste disposal was felt before the early 2000s before slowing down as the effects of dredging began to take hold. However, the stored sediment is still moving downriver. The river may respond to tailings diversion in different ways in four distinct reaches: they are the Lower Ok Tedi, the Upper Middle Fly, the Lower Middle Fly and the North or Upper Fly upstream of the confluence with the Ok Tedi at D'Albertis Junction.

### THE LOWER OK TEDI RESPONSE

Prior to the start of dredging there was extensive deposition in the Lower Ok Tedi producing two patterns of river behaviour. The former gravel-sand transition zone (from the river gravel front to Atkamba – Fig. 5-1) remained as a single channel but with up to 7 m of deposition on the bed. This zone has several narrow reaches where the channel is cut into Pleistocene terrace sediments and these create a "choke zone" that has promoted deposition in the reach upstream. Below this zone, in the reach affected by Upper Fly backwater-from D'Albertis Junction, there was extensive channel and overbank deposition. This zone also experienced high water levels and extensive dieback of floodplain forest first recorded in the early 1990s.



**Figure 5-1. 1997 infrared image of the Lower Ok Tedi and lower section of the Upper Fly showing flooded (blue) areas. The yellow outline shows the river course in 2015 and identifies areas of erosion, cutoff meanders and changes in river course at D’Albertis Junction. The Lower Ok Tedi is surveyed annually to meet the requirements for investigations mandated under Condition 37 of Environment Permit EP-L3(636) (Marshall, 2025b).**

As an example of change, Fig. 5-2 shows deposition then erosion in the Konkonda river cross section which was surveyed before the start of mining. Prior to the start of dredging, deposition of sediments from the mine caused riverbed levels to rise by up to 7 m. Figure 5-3 shows the trend in average bed elevation for that Konkonda cross-section once dredging began. There was a steady decline in average bed level until, by 2016, average elevations were 3.7 metres lower than those in 1998. Since then, bed elevation has fluctuated through a range of about  $\pm 1.0$  metre. This may be due to climatic variation and flow conditions.

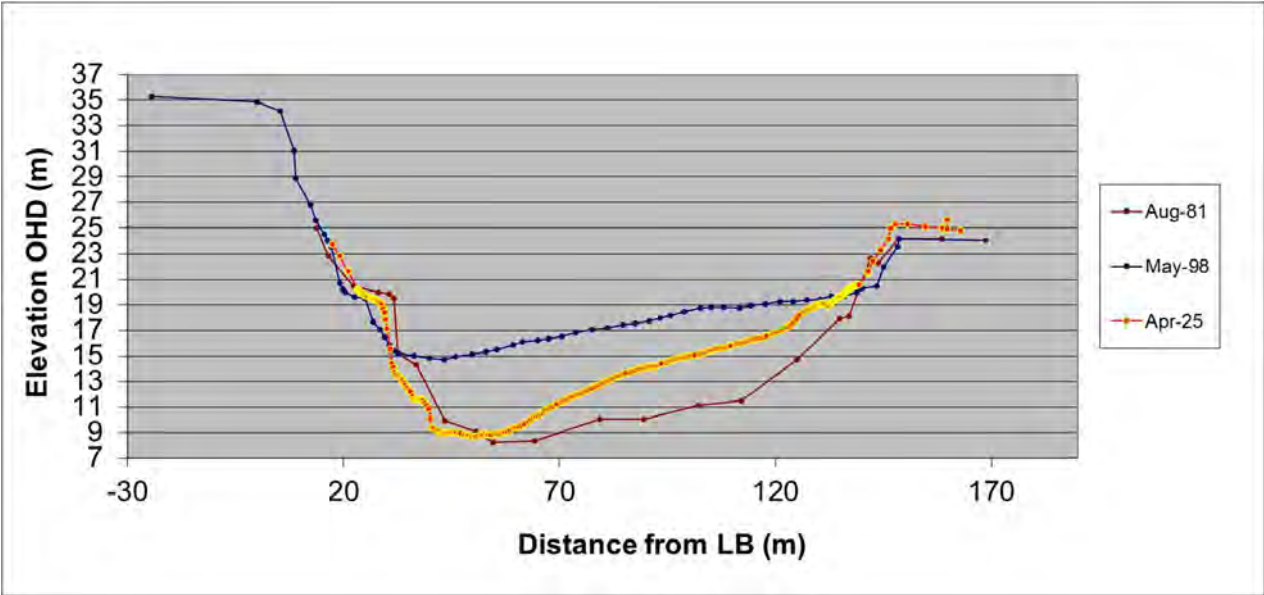


**Figure 5-2. Konkonda cross-section August 1981 (pre-mine), May 1998 (dredging commencement) and April 2025. Channel capacity is currently at approximately 62% of pre-mine levels (from Marshall, 2025b).**

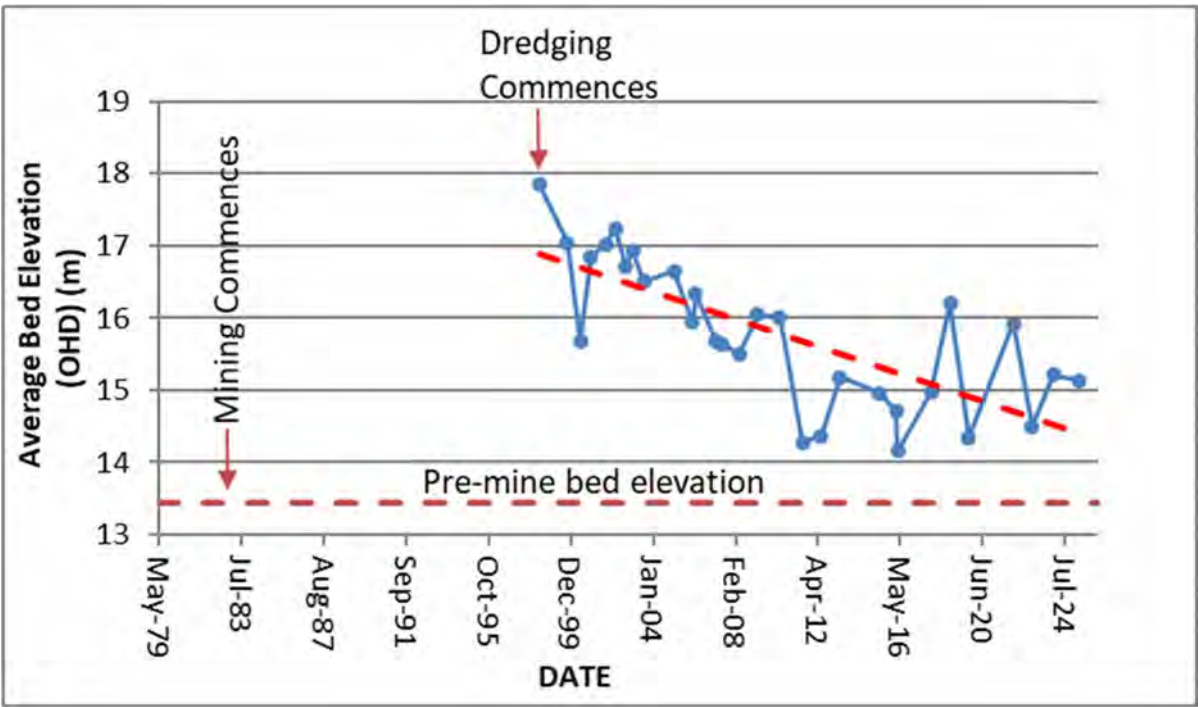


**Figure 5-3. Konkonda cross section average bed level from May 1998 to April 2025 (from Marshall, 2025b).**

The decrease in average bed elevation at Konkonda since 1998 is replicated throughout the Lower Ok Tedi (Fig.5-4) apart from a rise in the D'Albertis Junction area. This is mostly a result of the river cutting through the neck of the meander that had developed there. From 4 km upstream of D'Albertis Junction, the pattern is one of erosion and a decrease in bed levels of 1.5 to 2.0 metres for the next 40 km and an average bed level reduction of between 2.5 to 3.0 metres in the zone immediately downstream of the dredging operations near OKT28.

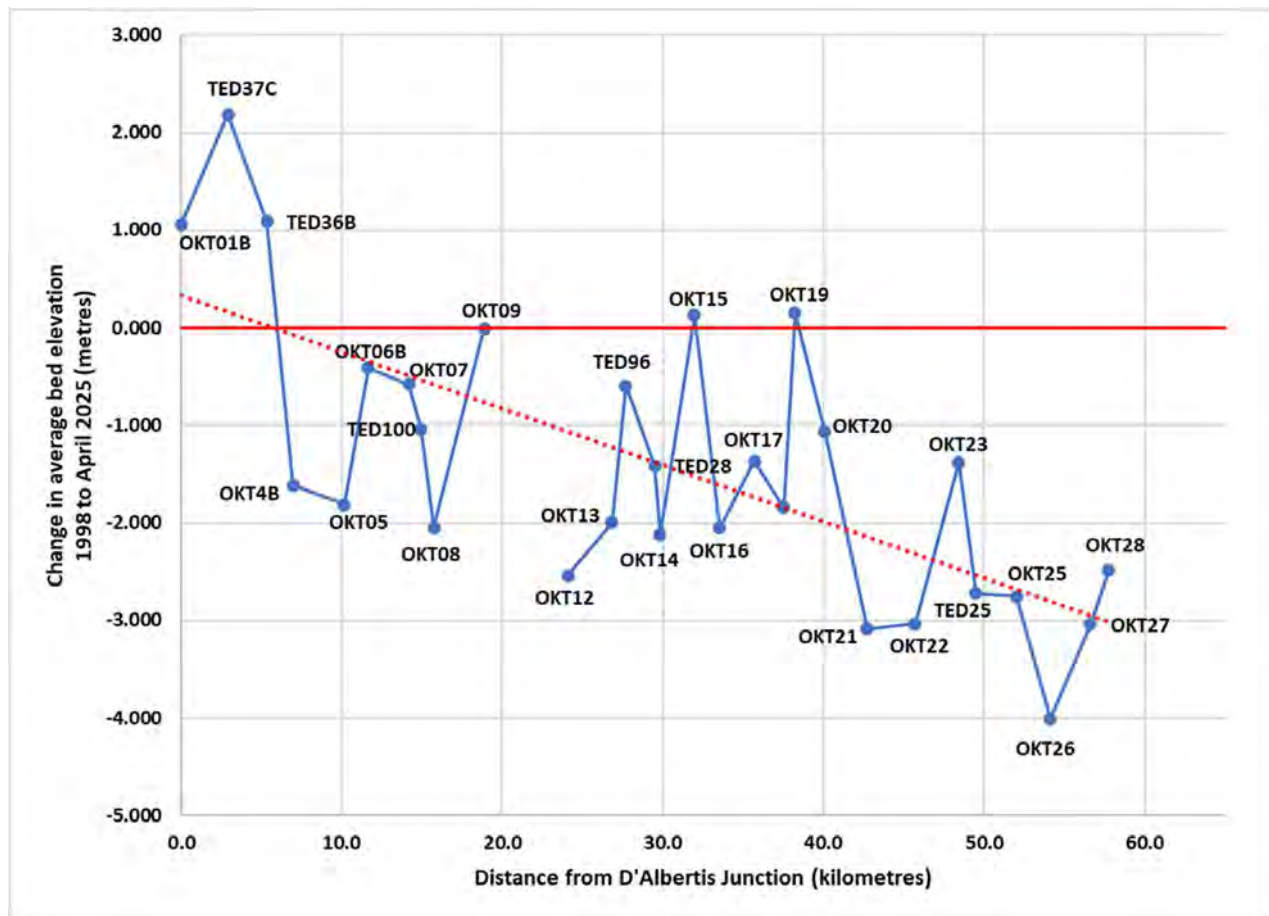


**Figure 5-4. Change in average bed elevation on the Ok Tedi (1998 to April 2025) between D'Albertis Junction and Dome (from Marshall, 2025b).**

Levee heights built up throughout the Lower Ok Tedi and the Middle Fly in the pre-dredging period. Extensive coring programs (reviewed and summarised in Bolton and Pickup, 2021) suggest that deposition of 1.0-2.5 m on main river levees and levee backslopes and tie channel levees was common. Of this, about 1 m occurred after the start of dredging and up to 2002 as it took time for dredging effects on riverbed levels to propagate down the river (Pickup and Cui, 2003).

The behaviour of levees on the Lower Ok Tedi after dredging started is shown in Fig. 5-5. In the upper section, between OKT27 and TED28, where the river is partly confined by high banks cut in resistant Pleistocene sediments, levee bank heights increased by about 1m. In the lower section, which has a less steep gradient, a wider valley and is more prone to flooding, average deposition of 1.5 m and sometimes more than 2.m occurred.

Bed level and levee rise on the Lower Ok Tedi caused most tie channels to become blocked and isolated the associated ORWBs. This largely remains the case except for a larger tributary system just north of D'Albertis Junction.

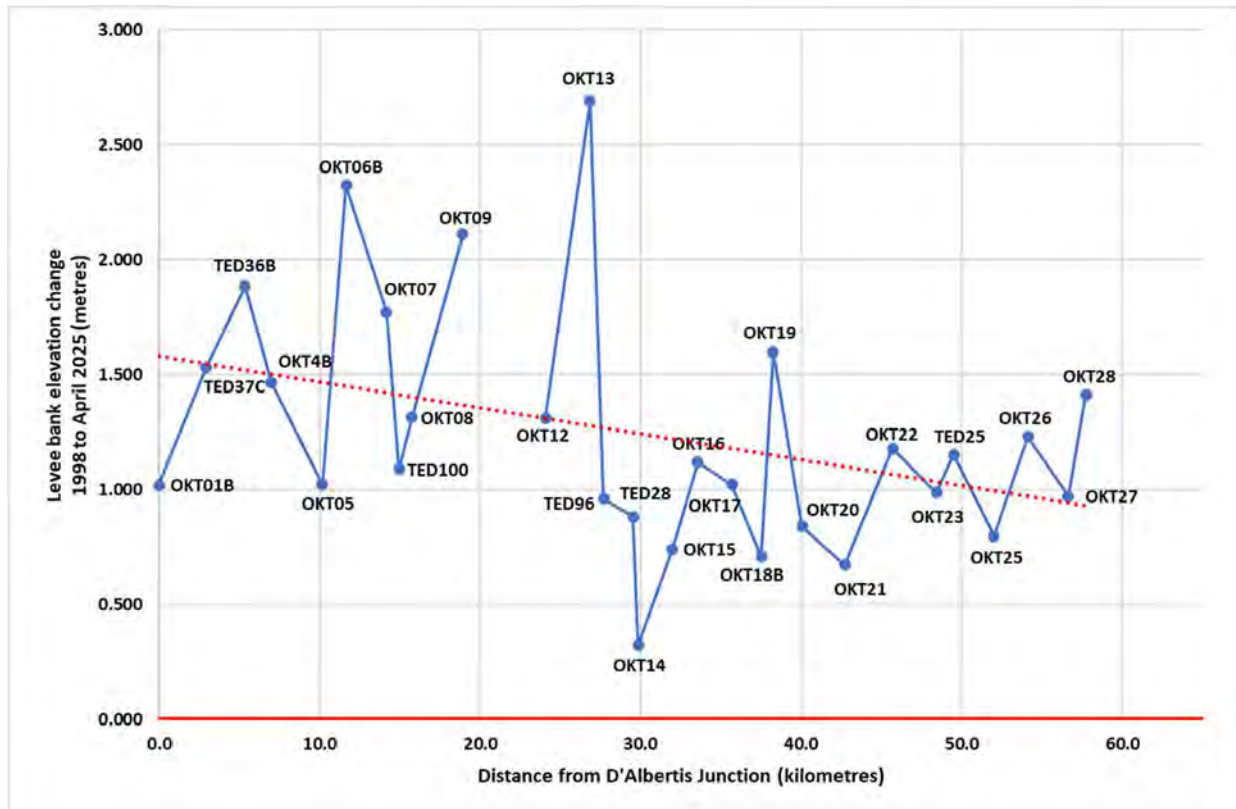


**Figure 5-5. Change in levee bank elevation (1998 to April 2025) between D'Albertis Junction and Dome (from Marshall, 2025b).**

The changes in bed elevation and levee on the Lower Ok Tedi between 1998 and 2025 show how a river may respond after a large initial increase in sediment load followed by a substantial decrease, in this case due to extraction of sediment load by dredging. As such, they provide a guide on what is likely to happen throughout the river system when the decrease in sediment load comes from diversion of tailings to a TSF.

In the period prior to dredging, riverbed levels at the Konkonda monitoring site rose due to 7 m of deposition (Fig 5-2). It is also likely that levee elevations began to rise. Unlike the post 1998 fall in bed levels (Fig. 5-4), the increase in levee elevation has been maintained since bed levels are still higher than in the pre-mine situation (Fig. 5-5). This accords with theory which suggests that levees will continue to grow until they are too high to be flooded or they are destroyed by channel bank erosion. However, the latter process is much slower than the changes that occur on the channel bed. It is therefore likely that the period of levee growth which began as water levels rose prior to dredging has continued and the levee heights have been maintained, even as sediment load has decreased. This behaviour is likely to be repeated, not only on the Lower Ok Tedi but also on the Middle Fly as tailings are diverted to a TSF.

## EXPECTED DREDGING REACH BEHAVIOUR WITHOUT THE INFLOW OF TAILINGS

Once either dredging or tailings input ceases, the river will begin to return to a mixed sand/gravel system. Indeed, after mine closure, it is likely that gravel deposits will start to become common for some distance beyond Bige, displacing the pre-mine mixed sand/gravel system since there is now more gravel upstream than previously given the ongoing inputs of waste rock from the mine waste dumps (Pickup and Marshall, 2019).

The dredge slot lies just downstream of a major break in slope of the Ok Tedi and a transition from a multi-channel braided system with extensive sand and gravel bars to a much narrower single channel system. The reduction in slope that causes this change also caused a decrease in river sediment transport capacity and a change from a largely gravel bedload to a mixed sand and gravel bedload under pre-mine conditions (Fig. 5-6). Sampling

downstream from Bige in 1979 shows that discontinuous gravel remained in the system for a further 27 km (Fig. 5-7) and that this is the natural condition of the river.



**Figure 5-6. Ok Tedi bed sediments close to the upper end of the dredge slot in 1978. Photo C. Cole.**

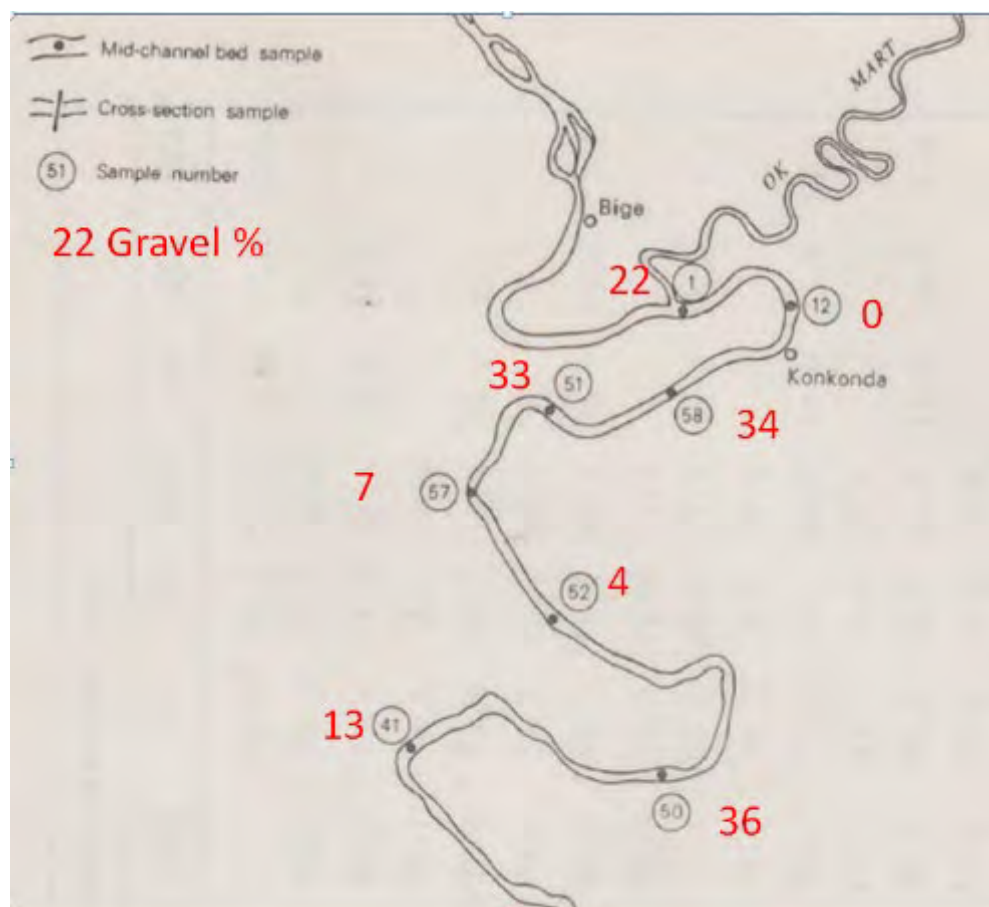


**Figure 5-7: Bed sample locations from the 1979 survey. Samples from circled locations contained 5%-36% gravel with particle sizes up to 64 mm. Red numbers indicate % gravel in riverbed samples.**

## THE UPPER FLY RESPONSE

Higher water levels on the Middle Fly due to mine waste deposition affect the Upper Fly, at least as far as Kiunga. Indeed, the high water levels at the Kiunga gauging station since 1997 have no parallel in the record of the last 30 years (Fig. 5-8). While this regime may be partly related to climate change or variability (Fig. 6-1, Chapter Six), it appears that the increase in water levels begins around 1994. It is therefore likely to be related to deposition of mine-derived sediment in the Middle Fly whereby the backwater effect triggers deposition of the natural sediment load moving down the Upper Fly. This is a process expected to continue but at a slower rate once a TSF is operational.

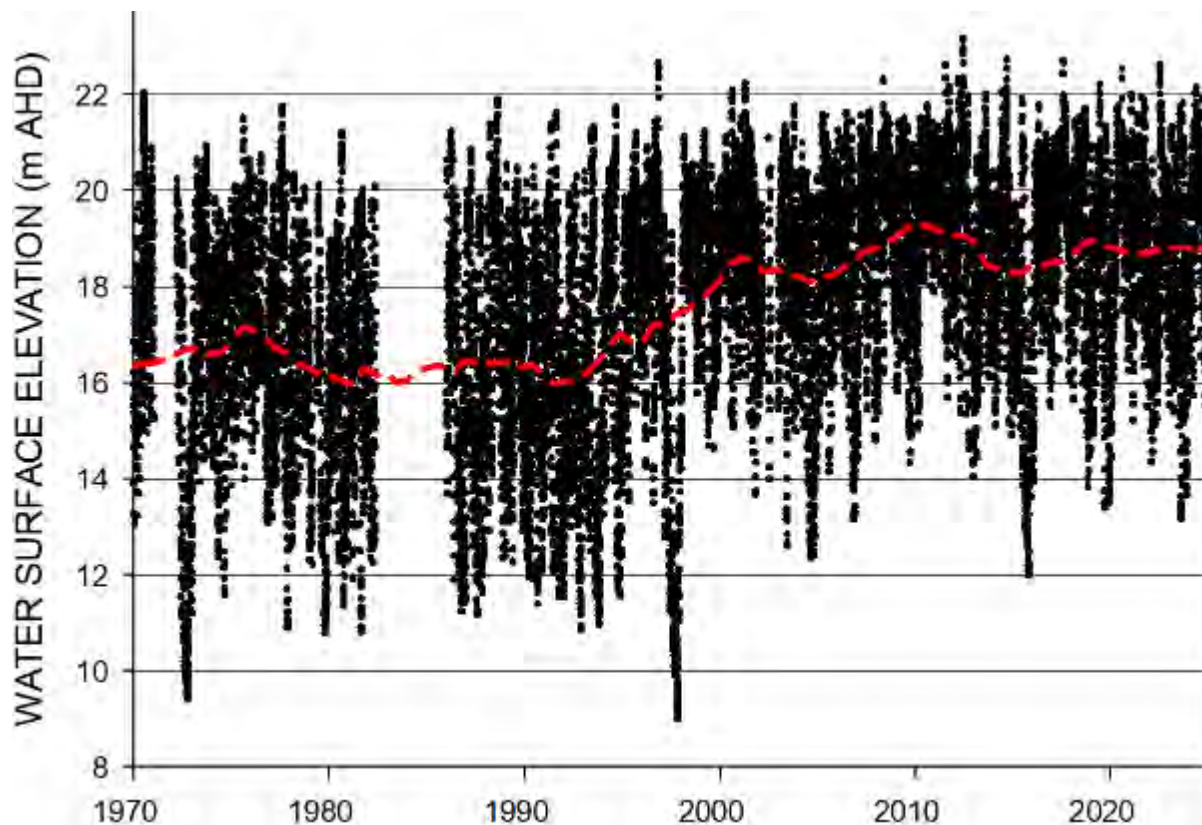


**Figure 5-8. Water levels on the Upper Fly at Gauging station FLY05 just downstream from Kiunga. Red broken line shows smoothed values.**

Pickup and Marshall (2022) made a detailed examination of the backwater effects on the Upper Fly as part of a study of siltation at Kiunga public shipping wharf. They concluded that the factors affecting the degree of backwater are likely to be:

- Generally rising riverbed and water levels at D’Albertis Junction from about 1994 and prior to dredging on the Ok Tedi. This backed up the Upper Fly at least as far as Kiunga.
- Reduced backwater effects from the early 2000s in response to Bige dredging which slowed but not entirely halted bed level rise on the Upper Middle Fly.
- Periods of very high tailings input which partially offset the effects of dredging on the backwater effect.
- Channel straightening which has been occurring on the Upper Fly since the start of tailings discharge with a possible resultant increase in bed levels due to deposition at D’Albertis Junction.

The graphs in Figs. 5-9 and 5-10 describe a rating curve analysis approach to changes in river behaviour at Kiunga using OTML gauging data for station FLY05. The technique is a useful tool for explaining long term river behaviour

in response to external disturbance and/or changes in the river geomorphology. These changes are often subtle and usually do not show up in raw water level data.

The theory behind the analysis states that if a gauging station does not have a stable downstream control, there may be shifts in the average stage-discharge rating curve in response to changing backwater effects from downstream. When there is a strong backwater effect, flow velocity at a given water surface elevation in the upstream channel cross section will be reduced as will discharge. Gaugings under these conditions will plot below the average stage-discharge curve. Where there is a significant reduction in backwater effects, the opposite is true.

Figures 5-9 and 5-10 show the average stage-discharge rating curve and deviations from it over time together with possible explanations.

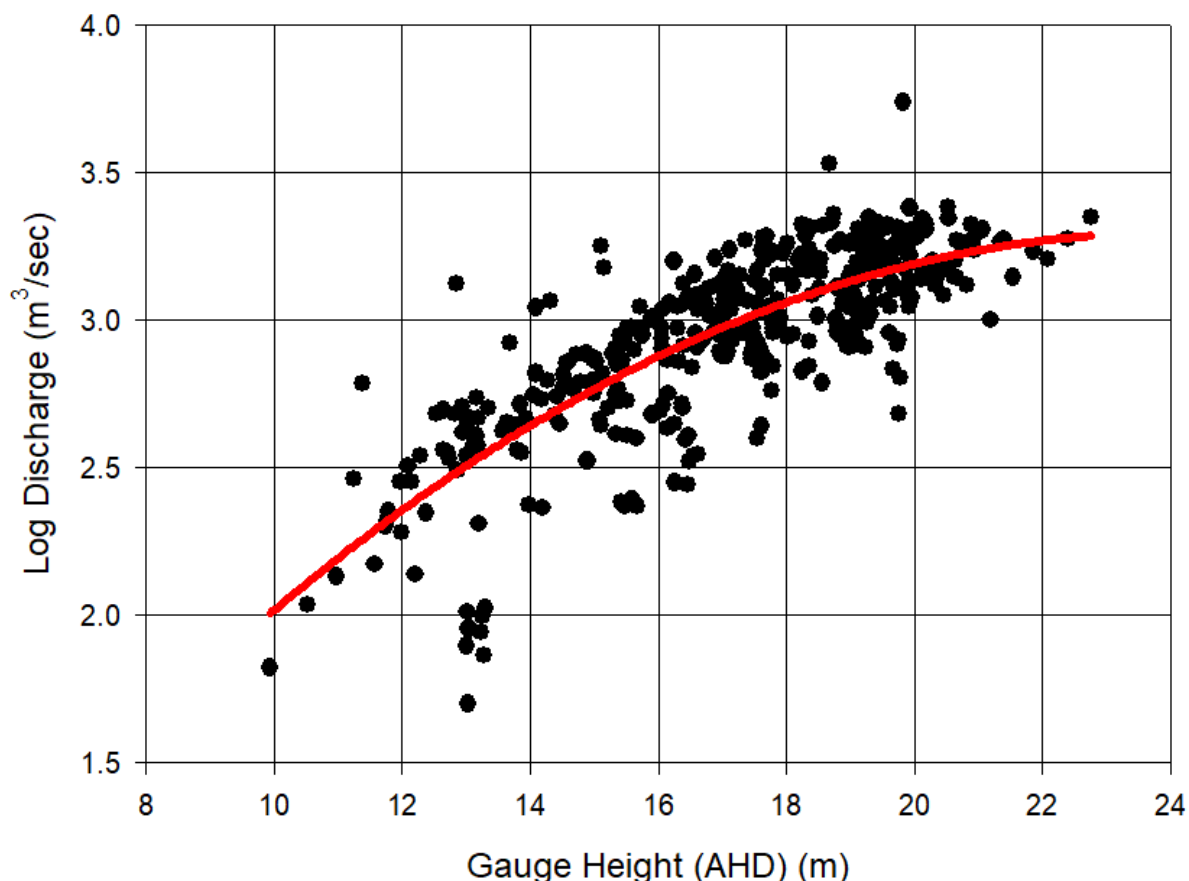


**Figure 5-9. FLY05 gaugings from 1976 to 2021 and the average stage-discharge rating curve.**

The pre-mine period (Fig. 5-10) shows no systematic deviations with time as expected. The main (pre-dredging) deposition period on the Upper Middle Fly shows that backwater effects progressively increased with time at Gauging Station FLY05, a pattern that was reversed once dredging was under way. The early 2000s were years when tailings inputs were high (averaging 25.6 Mt/year) and there was progressively greater negative deviation from the average rating curve. During the decade from 2010 to 2020, tailings input decreased to an average of 16.8 Mt/year and the deviations were progressively reversed. Under these conditions, the sediment transport capacity of the Upper Fly would have increased so it is that backwater effects would not have been as pronounced as previously.

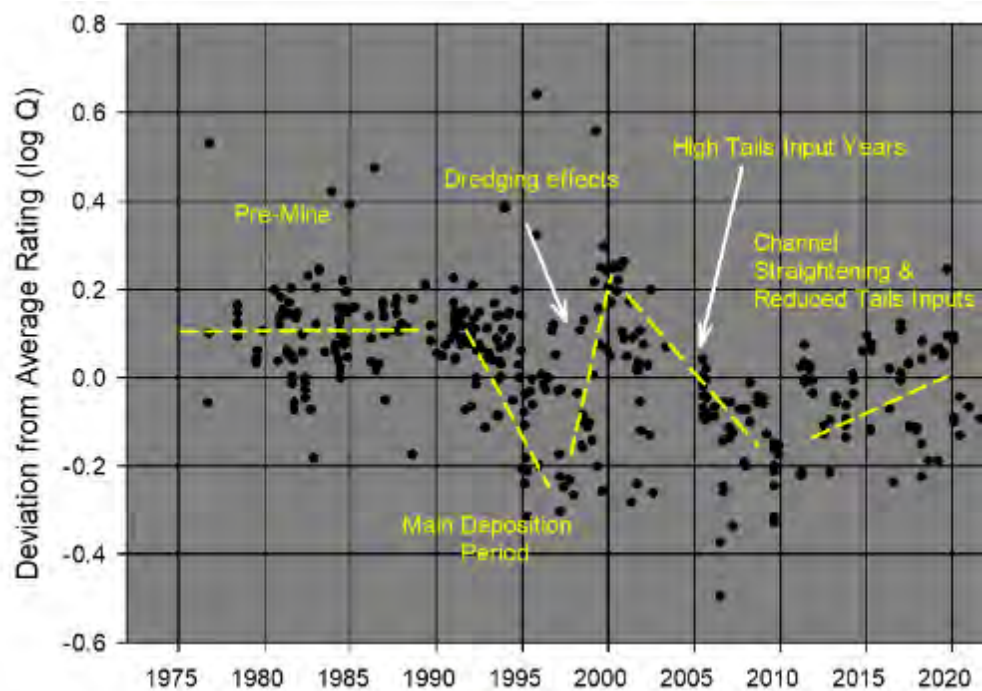


**Figure 5-10. Gauging Station FLY05 (Kiunga) – deviations from the average stage-discharge rating curve with possible explanations.**

The remaining factor affecting backwater and river gradient is channel straightening by meander cutoffs. Figure 5-11 shows the course of the Upper Fly based on the Papua New Guinea 1:100,000 mapping series which was produced from early 1960s air photographs. Cutoff dates were derived from LANDSAT imagery and show that the North Fly has been shortening its course since the early 1960s. Also, between the start of mining and late 2020, the river has shortened its course by close to 30%. The most recent cutoff (CUTOFF 1 on Fig. 5-11) in 2018 was a canoe channel subsequently enlarged by Starwest Constructions as its marine logistics terminal. This reduced the river course length in the Kiunga reach by about 12% which could result in a small increase in the sediment transport rate.

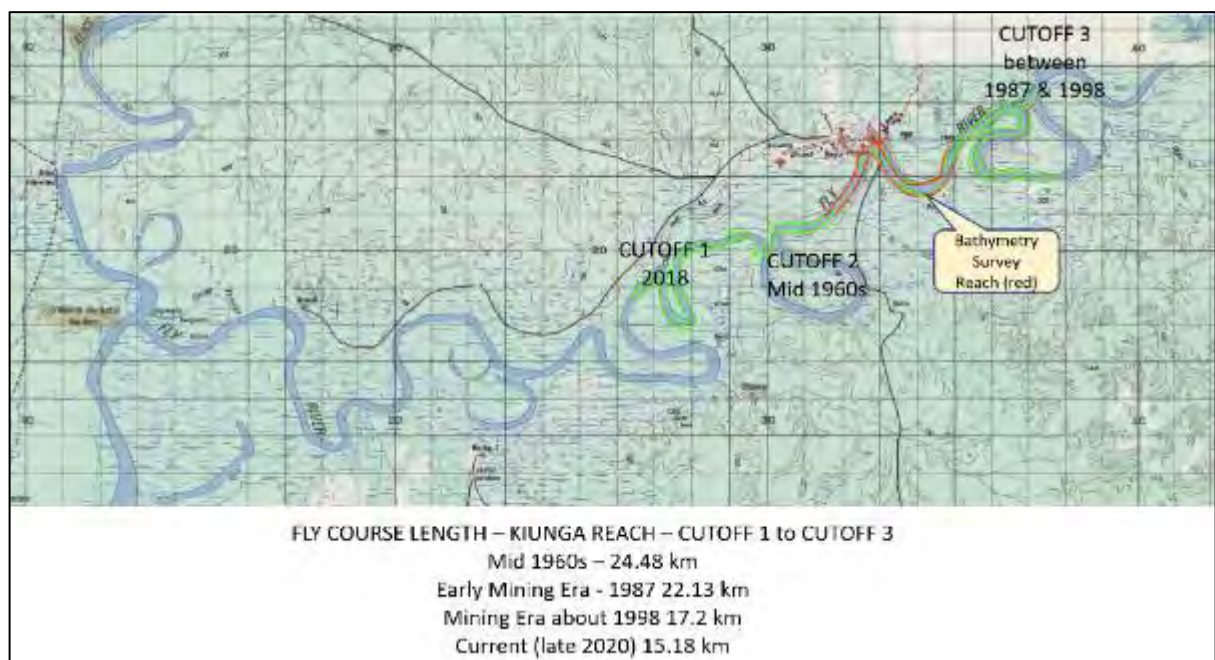


**Figure 5-11. Meander cutoffs and changing river distances on the North Fly.**

Further analysis of the effects of backwater on deposition is shown in changes in riverbed elevation, channel cross section area and levee elevation at gauging station FLY05 about 1.5 km downstream from the Kiunga Wharf (Figs. 5-12 – 5-14). This location has stable banks, and the river channel is confined between indurated and erosion resistant Pleistocene clay soils. Channel width has hardly changed since 2000, although the cross section does occupy a straight section of river with no meandering so lateral erosion would not be expected. However, bed levels rose (reducing cross sectional area) during the period of high tailings discharge from about 2000 to 2010. Since then, cross-sectional area has shown little change and no obvious trend.

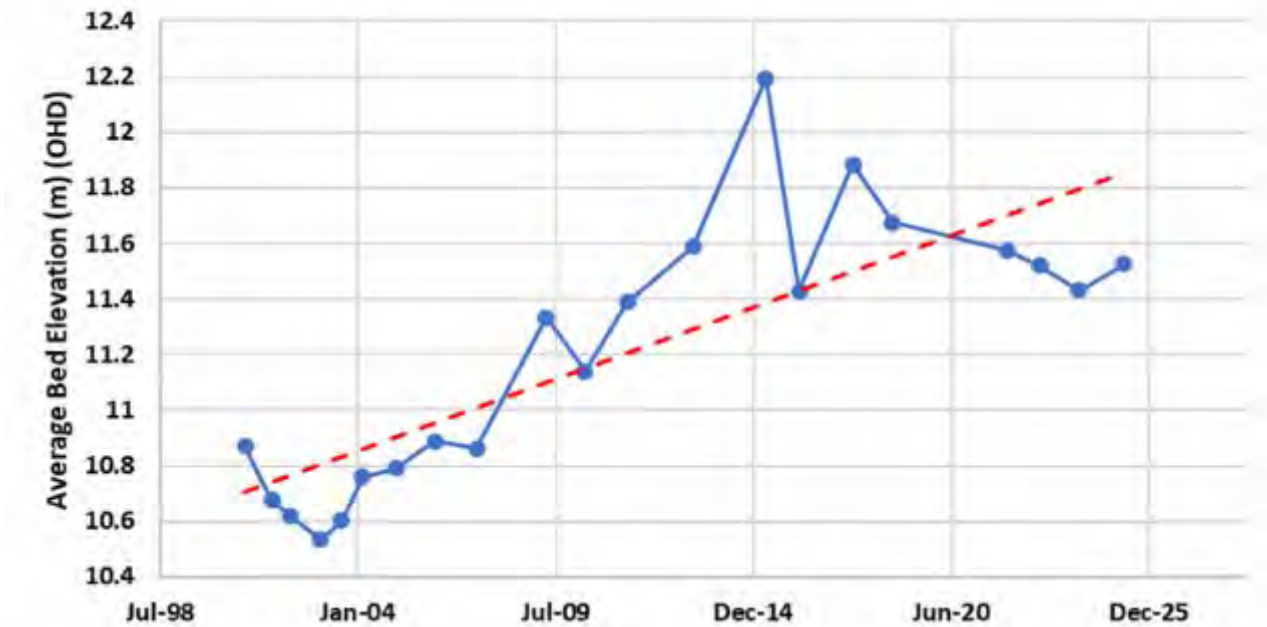


Figure 5-12. Riverbed levels at Gauging Station FLY05 downstream from Kiunga (from Marshall, 2023).

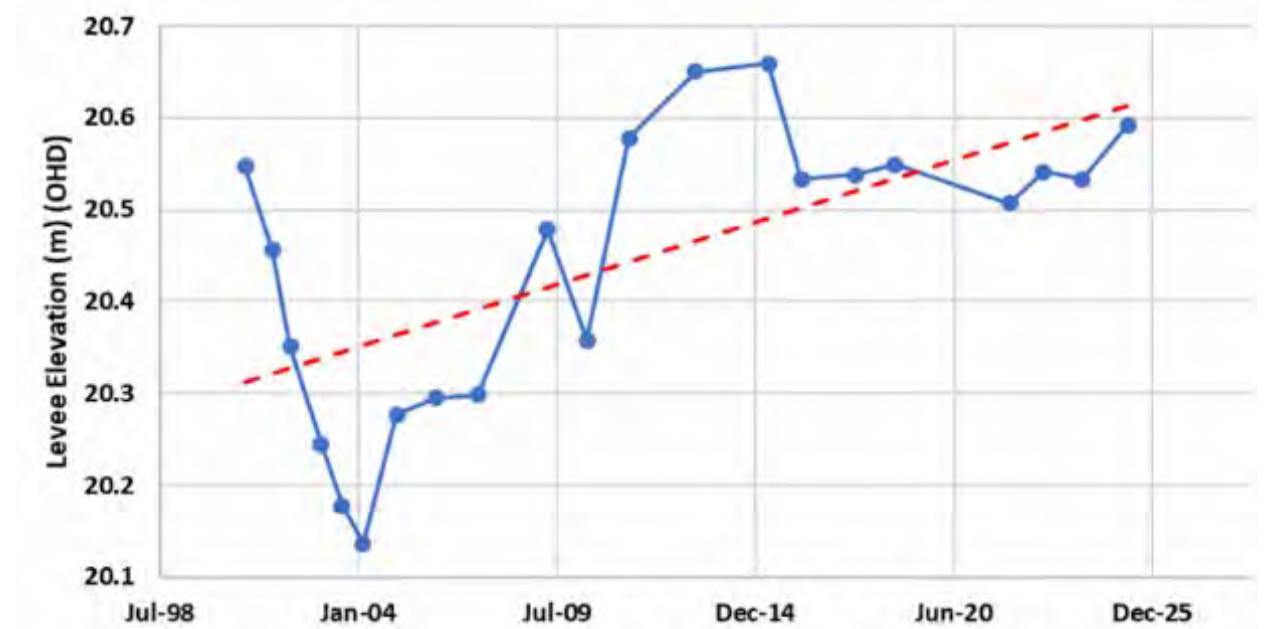


Figure 5-13. Levee elevations at Gauging Station FLY05 downstream from Kiunga (from Marshall, 2023).



**Figure 5-14. Channel cross sectional area at Gauging Station FLY05 downstream from Kiunga (from Marshall, 2023).**

## MIDDLE FLY RESPONSE

The Upper Middle Fly system has a steeper gradient than the Lower Middle Fly and occupies a narrower floodplain. The lower river is a low gradient, slow flowing system occupying a wide and frequently inundated floodplain. Both floodplain reaches are the most likely zones to be affected by diversion of tailings to a TSF. We deal with each in the sections below.

Much of the deposition on the Middle Fly that raised water levels occurred in the early years of mine life prior to 2000. Initially, water levels rose by about 3 m at the upper end of the Middle Fly. After that, the effects of dredging started to be felt and water level rise either slowed, as at Kuambit (Fig. 5-15) or began to slowly fall, as at Konkonda on the Lower Ok Tedi (Fig. 3-14). However, there is a substantial body of sand remaining in the river which is still slowly moving downstream and will be unaffected by diversion of tailings to a TSF.

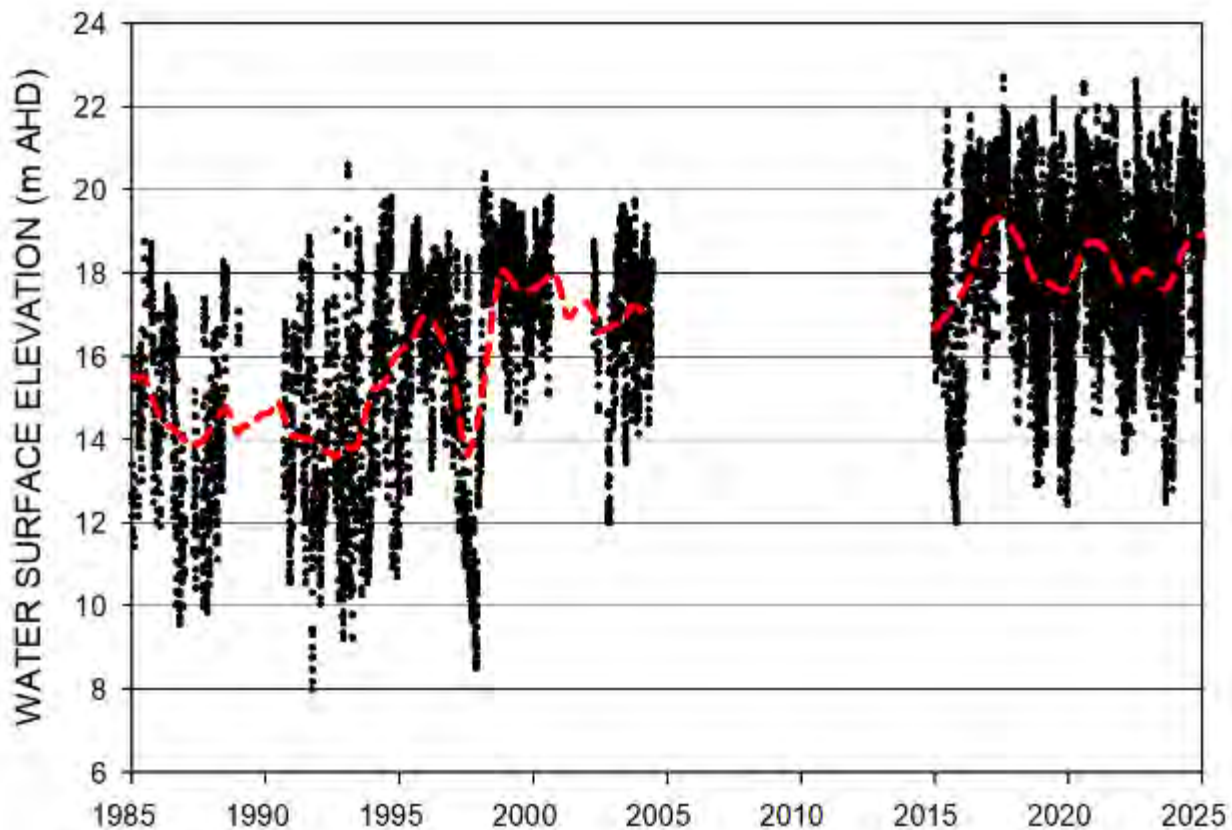


**Figure 5-15. Water levels on the Upper Middle Fly at Kuambit (Gauging station FLY15) just downstream from D'Albertis Junction. Red broken line shows smoothed values.**

Much of the sand and associated bed and water level rise had reached Manda, at the upstream end of the Lower Middle Fly (Fig. 5-16) by around the year 2000. After that, there may still have been slow increase in water levels although it is difficult to separate it from the effects of climate variability on river flow.

At the lower end of the Middle Fly, at Obo (Fig. 5-17), water levels are strongly influenced by backwater from the larger Strickland River. However, the water level record suggests rising water levels up to around 1998. A forensic examination of the gauging station record indicates that until 1998, the gauging station used several local benchmarks but was converted to AHD in either 1998 or 2000 (P. Clews, pers com., 2025). Moi *et al* (2001) did attempt to convert pre 1998 records to AHD but state that the results are not trustworthy. Inspecting the water level record from 2000 indicates that there is no trend and the record largely reflects medium term climate variation.

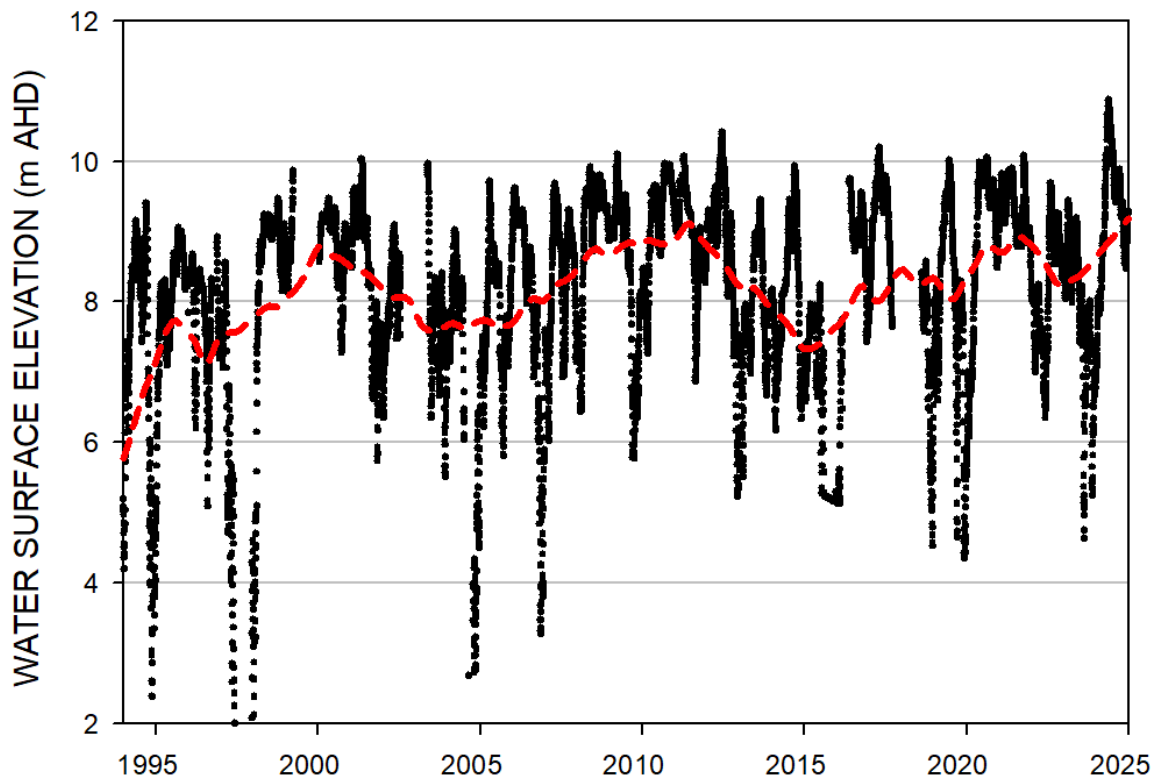


**Figure 5-16. Water levels at Manda (Gauging Station FLY16/17) at the upper end of the Lower Middle Fly. Red broken line shows smoothed values.**

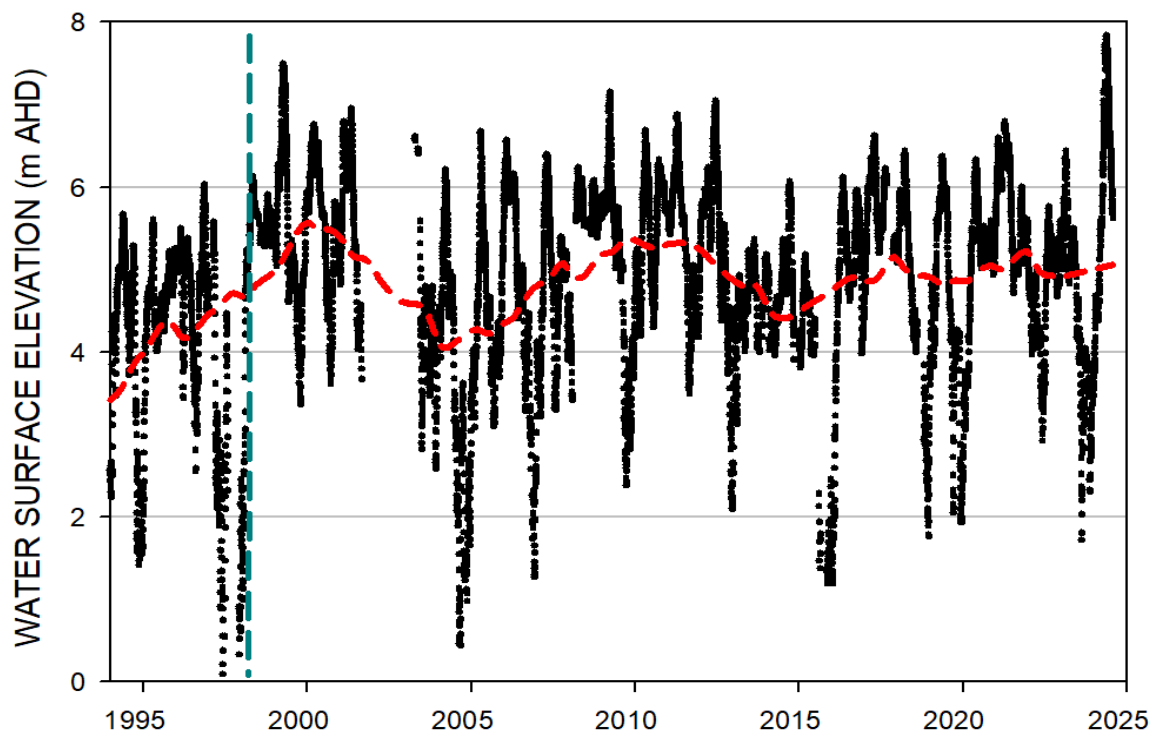


**Figure 5-17. Water levels at Obo (Gauging Station FLY15) at the downstream end of the Lower Middle Fly. The green broken vertical line at 1998 indicates when the gauging station datum is thought to have changed from a local datum to AHD. Red broken line shows smoothed values.**

Riverbed level change has been monitored annually on the Middle Fly at a series of “choke points”. These are locations, typically close to meander bends or in wider shoaling reaches, which ships find difficult to navigate through. While they may not be typical of many of the reaches in the river, they do identify locations of accelerated deposition and channel change and are useful to identify wider trends. Figure 5-18 shows the monitoring results from 2002 to 2023 and mostly confirms the trends appearing in the water level records.

The D’Albertis Junction site showed little change up to 2013 then an increase in bed elevation of about 1 m before stabilising and beginning to erode. This is largely related to channel migration and a shift in the location of the shipping channel over a reach of about 300 m. The remaining 1.5 km shows little change or slight bed elevation decrease. Kuambit, a few km downstream shows little change or slight bed level decrease confirming the trend shown by the water level record. Erehta, Angaramut and Wygerin all show a small increase in bed level of about 1m over the 20 years of record. While this is expected as stored sand gradually moves downstream, there is no nearby gauging station with a comparable water level record. However, the small increase in water levels at Manda accord with this interpretation. The absence of any trend in the Strickland bed levels supports the idea of no change in water levels at Obo.

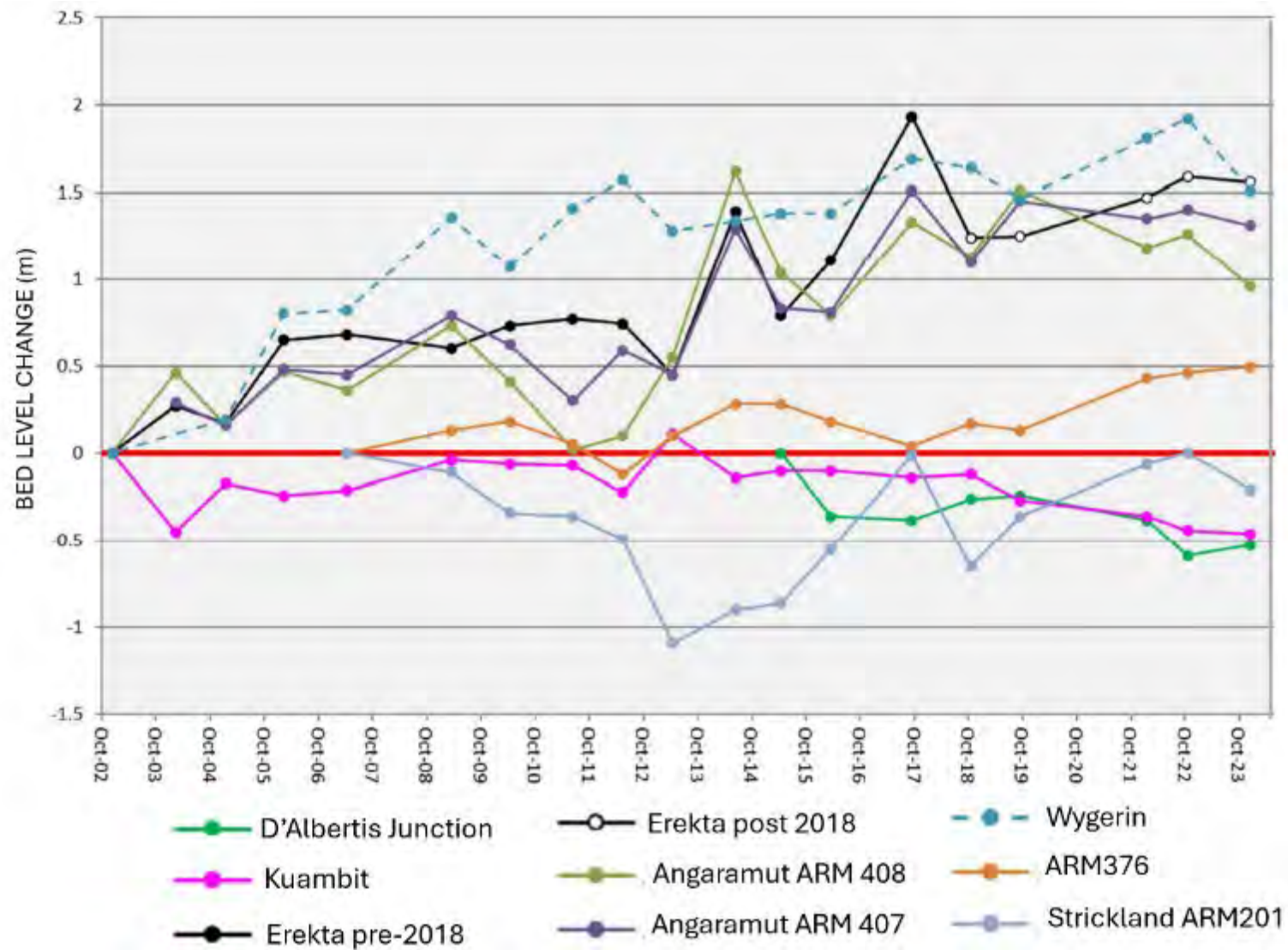


Figure 5-18. Changes in riverbed elevation at navigation choke points on the Middle Fly from 2002 to 2024. (from Marshall, 2024).

Levee heights in both the sand zone and the backwater zones of the Middle Fly increased in elevation by 0.5-1.0 m between 1997 and 2000. While only limited data are available since 2013, levees have continued to rise (Marshall, 2018) (Fig. 5-19). Levee backslopes may also have extended into the adjacent floodplain at many locations

Blocking of tie channels and filling-in of levee breaches also occurred, processes which continue. These processes will make the floodplains subject to inundation for longer periods because water levels on the Middle Fly will be higher than in earlier times, and the floodplains have less capacity to drain local runoff when there is low flow in the main river.

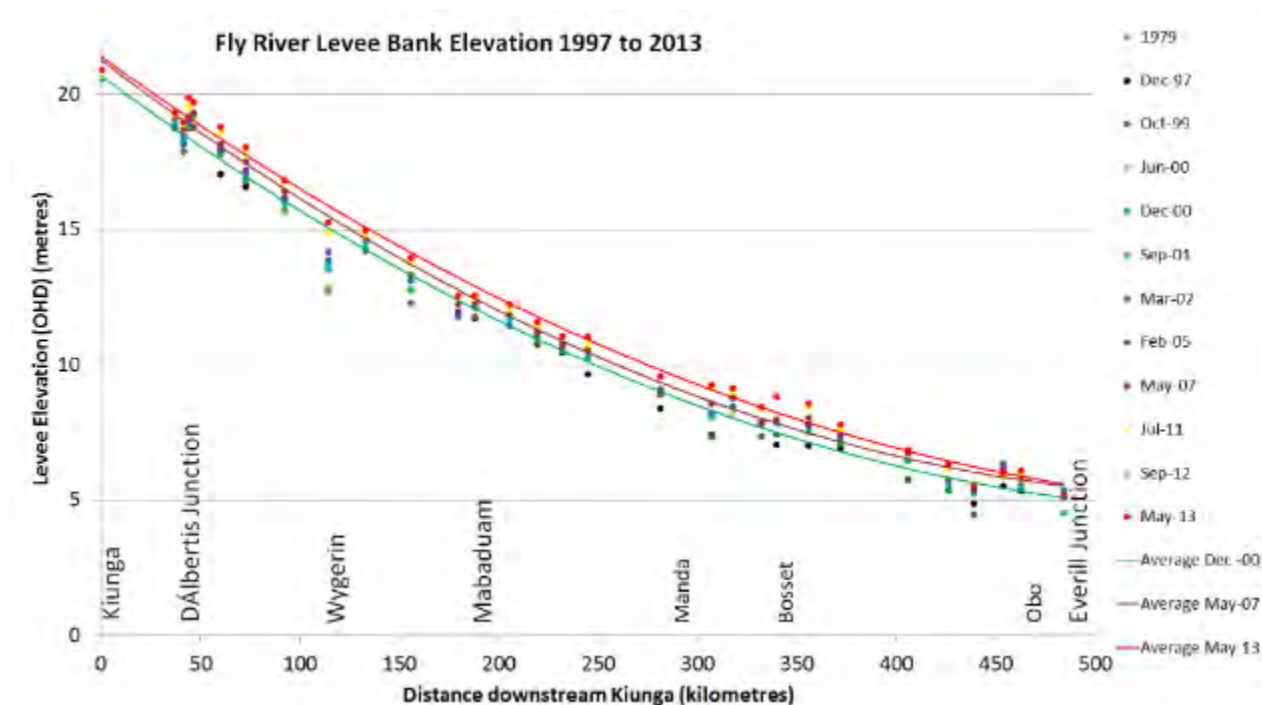


**Figure 5-19. Changes in levee elevation on the Middle Fly, 1997-2013 (data from A. Marshall).**

## THE FLOODPLAIN - CONNECTIVITY WITH OFF RIVER WATER BODIES

The main river carries a relatively high sediment load whereas most ORWBs contain relatively clear water, partly because sediment does not travel far from the main channel, but also because they are fed by rainwater and relatively clean water from adjacent forested lowland tributaries (with some exceptions, notably recently cleared areas in West Papua) as well as by flows from the main river. While the range of aquatic species in the main river and ORWBs may differ, many ORWBs offer refuge from the high sediment concentrations in the main river. They may also retain species that do not survive in the more stressful environment of the main river and could allow recolonization once sediment inputs from the Ok Tedi mine cease or reduce after mine closure. How effective the ORWBs are in this role partly depends on their persistence during drought, maintenance of connectivity with the main channels, and the extent to which they are receiving sediment from the main river which may cause infill (see Bolton and Pickup, 2021 for a detailed review of ORWB infill and examples).

Connectivity between the river and various ORWBs may be maintained in three ways:

- Most ORWBs are directly open to the river during high flow. This may be via levee breaches (especially in the lower river) and through swales in the inner bank point bar complexes in actively meandering reaches of river.
- By overbank flow during large floods when virtually the whole floodplain is inundated. These conditions may persist for months, especially in the Lower Middle Fly. Also, where ORWBs are fed by rainwater or tributary inflow, or hold water from previous floods, sediment load from the main river cannot penetrate because main river inflow is blocked.

Thus, there is a water connection for fish without sediment inflow to ORWBs when main river water levels overtop the levees.

- Via tie channels (which are narrow channels) connecting the main river and ORWBs. Some tie channels may also drain tributaries, sometimes passing through blocked valley lakes and crossing the floodplain. Others connect individual oxbow lakes to the Fly and a few allow drainage from the main river to join the Agu or enter floodways on floodplain margins. Most tie channels experience two-way flow depending on water levels in the main river and the ORWB and depending on whether the ORWB is receiving water or draining. Tie channels provide the only connection between the main river and ORWBs for much of the time when the river is not in flood.

The series of images in Fig. 5-20 show typical features associated with sediment inflow and outflow between the main river and the floodplain.



**Figure 5-20. (A) Blocking of access of main river water by floodplain standing water. (B) Isolated floodplain ORWBs behind main channel and tie channel levees. (C) Inflow of main river water through a levee breach with levee backplain water immediately behind the levee unaffected. (D) Inflow of sediment laden water through a breach in a meander cutoff plug. Note how water in areas behind the cutoff channel levees is largely unaffected and remains relatively clear.**

Figure 5-21 shows examples of blocked or flow-impered tie channels of the Upper and Lower Middle Fly. While most channels appeared to be open on 1987 satellite imagery, by 2015, a number had become blocked<sup>6</sup> by

<sup>6</sup> Given the lack of early high-resolution imagery, tie channel blockage had to be assessed using Landsat TM imagery acquired when the river system was in drought and the floodplain had largely dried out. Imagery for 1987 (a moderate drought), 1998 (a severe drought), 2002 (a moderate drought) and 2015 (another moderate drought) was used. In many cases, water in tie channels could be detected, especially in 1987, 2002 and 2015, and these channels were classified as open if the water extended to the Fly. Also, the behaviour of connected water bodies was examined to see whether they had drained or not. In the case of blocked valley lakes which are normally shallow, where there was a possible tie channel connection but no apparent drainage, the tie channel was treated as being blocked. Most oxbows contain a great enough depth of water to retain it during severe

deposition of main river sediment or build-up of debris and vegetation at low and moderate main river flows. When water levels are high, however, many tie channels do experience flow to or from the main river.



**Figure 5-21. Examples of tie channel and ORWB blocking. Upper left: sediment accumulation and vegetation growth around a trapped log in a tie channel which may clear or may develop further. Upper right sediment plugs blocking access to a lake in a meander cutoff. Lower left: completely blocked tie channel next to the main river. Lower right: infilled former tie channel with tree growth on slightly raised former levees.**

Summary data on tie channel blocking rates is presented in Table 2, including status in 2002. Most tie channels on the Lower Ok Tedi have become blocked or impeded since 2002. On the eastern side of the Upper Middle Fly, most blocking occurred by 2002. On the western side, 8 of the 41 (or about 20%) channels were already blocked in 1987 (essentially pre-mine). Another three were blocked between 1987 and 2002, and five more between 2002 and 2019. The Agu and the Binge show only one blocked channel each by 2002, in both cases close to the Middle Fly itself.

The blocking rates are very approximate given the resolution of the satellite imagery used in assessment, together with differences in the severity of drought in 1987, 2002 and 2015. They should be treated as rough estimates only. There is a clear trend towards more blocking in the last 13 years than previously on the Lower Ok Tedi but no clear pattern on the Middle Fly.

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droughts so this approach would not apply. Instead, the presence or absence of water in the tie channel in the moderate droughts was used to determine blockage.

| TABLE 2: ESTIMATED TIE CHANNEL BLOCKING RATES |       |                    |                    |                    |
|-----------------------------------------------|-------|--------------------|--------------------|--------------------|
| RIVER SYSTEM                                  | TOTAL | BLOCKED<br>IN 2015 | BLOCKED<br>IN 2002 | BLOCKED<br>IN 1987 |
| AGU                                           | 33    | 1                  | 1                  | 0                  |
| BINGE                                         | 9     | 1                  | 1                  | 0                  |
| MIDDLE FLY<br>(East)                          | 35    | 8                  | 6                  | 0                  |
| MIDDLE FLY<br>(West)                          | 41    | 16                 | 11                 | 8                  |
| LOWER OK TEDI                                 | 20    | 7                  | 0                  | 0                  |

Whether a tie channel stays open or becomes blocked seems to follow a pattern. On the Lower Ok Tedi, where sediment concentrations are at their highest, about 30% of channels have become blocked. These tend to drain small tributaries or areas of backswamp. Tie channels that drain larger tributary catchments seem to stay open, indicating that tributary flows are large enough to remove blockages once main river levels drop. Tributary slopes close to the main river also may be steep enough to prevent ingress of large amounts of sediment-laden main river water.

On the Middle Fly, the pattern is similar, with tie channels linking most large tributary catchments remaining open on both the east and west sides of the river apart from one of two links to the Binge River.

The Agu floodplain and channel lie several metres below the elevation of the main channel of the Fly. In the past, there have been up to six links between the Fly and the Agu, all of which initially passed through Fly River meander cutoffs. Given the difference in elevation, Fly-Agu links would normally experience only one-way flow out of the Fly which limits potential for removing meander cutoff sediment plugs and other obstructions. Two links can now only be seen as faint traces and are basically fossil features. Of the four that have functioned more recently, two are now blocked, possibly by meander cutoff entry or exit plugs. The other two are functioning but showing signs of meander cutoff entry plug extension and filling.

Most other blocked tie channels connect small meander cutoffs, small backswamp areas, or blocked valley lakes with small, low-lying catchments. They also often extend across long flat areas of floodplain which means low flow velocities.

Direct observation during river cross section surveys since the late 1990s and from long term satellite image coverage suggests that in many parts of the floodplain, but especially on the lower Middle Fly, levee growth and tie channel blocking are increasingly isolating the floodplain from the river (A. R. Marshall, pers comm). Overbank flows quickly inundate the floodplain, but unless there are levee breaches or open tie channels, the floodplain does not fully drain back to the river as water levels there fall. This suggests that with increased frequency of flooding due to bed level rise; the *duration* of floodplain inundation has been increasing as levee heights increase and levee breaches are infilled with sediment. This also raises the possibility of floodplain waters becoming anoxic if inundation persists for long periods.

Further evidence of increasing floodplain isolation comes from the study by Pickup (2017) comparing the extent of floodplain surface water bodies during the severe 1998 and 2015 droughts. In 1998, river sedimentation in the Middle Fly, levee rise and tie channel blocking were still in the early stages (Table 2, Fig. 5-19). By 2015, most levees were at least 1 m and some 2-3 higher according to core data (Bolton and Pickup, 2021). Both severe droughts resulted in temporary mine closure and while it may be argued that the 1998 drought was more severe than conditions in 2015, there were increases in the extent of ORWBs that survived the dry conditions with a larger body of standing water remaining on the floodplain and in shallow blocked valley lakes throughout 2015 (Fig.5-22). Longer periods of floodplain inundation are likely to have had major effects on floodplain vegetation systems.

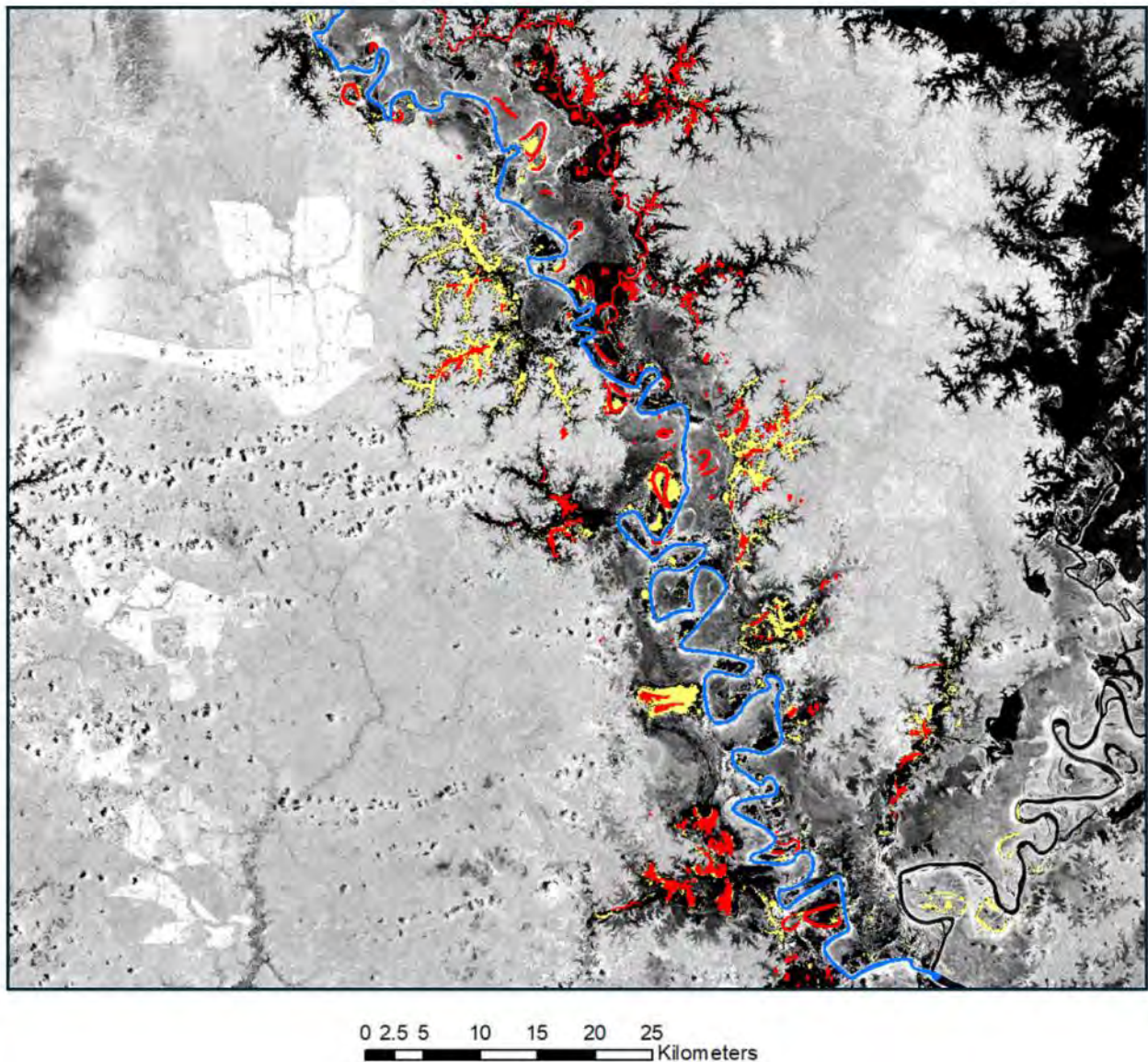


**Figure 5-22. Floodplain off river water bodies containing surface water in the 1998 and 2015 droughts on the lower Middle Fly just north of the Strickland confluence at Everill junction. Red areas contained water in both 1998 and 2015. Yellow areas only held water in 2015. Blue shows the main Middle Fly channel.**

There is also some evidence that isolation of the floodplain from the main river is resulting in increased use of a floodplain overflow system in which flows into the shallow lagoons in blocked valleys on the western side of the lower Middle Fly become connected, bypass Everill Junction and drain back into to the South Fly through Suki Creek, more than 50 km further south (Pickup, 2025).

Further evidence of increasing floodplain isolation comes from Pickup and Marshall (2019). In their study of available synthetic aperture radar for floodplain inundation mapping they examined the northern end of western overflow system zone on the lower Middle Fly using very early PACRIM-2 mid-2000 AIRSAR three band radar data acquired during a specially commissioned mission by NASA's experimental aircraft platform and compared results with May 2024 SENTINEL-1 C-Band enhanced view VV and VH polarised radar. On both occasions, the floodplain was extensively inundated. The closest (Obo) gauge was operational on both image acquisition dates and indicates that in 2024 river water levels were close to 0.8 m higher on the floodplain than in 2000, if the 2000 data are accurate. Figure 5-23 compares the two radar datasets for Bai lagoon and Lake Pangua with arrows identifying the main levee breaches in 2000 when the floodplain was emptying, most of which were apparently no longer active in 2024. The imagery gives some support to the idea of increasing levee heights, levee extension into the adjacent ORWB and increased ORWB isolation (see also Chapter Eight - Tie Channel Blocking Section and Marshall (2018) for a detailed study of the history of these ORWBs).

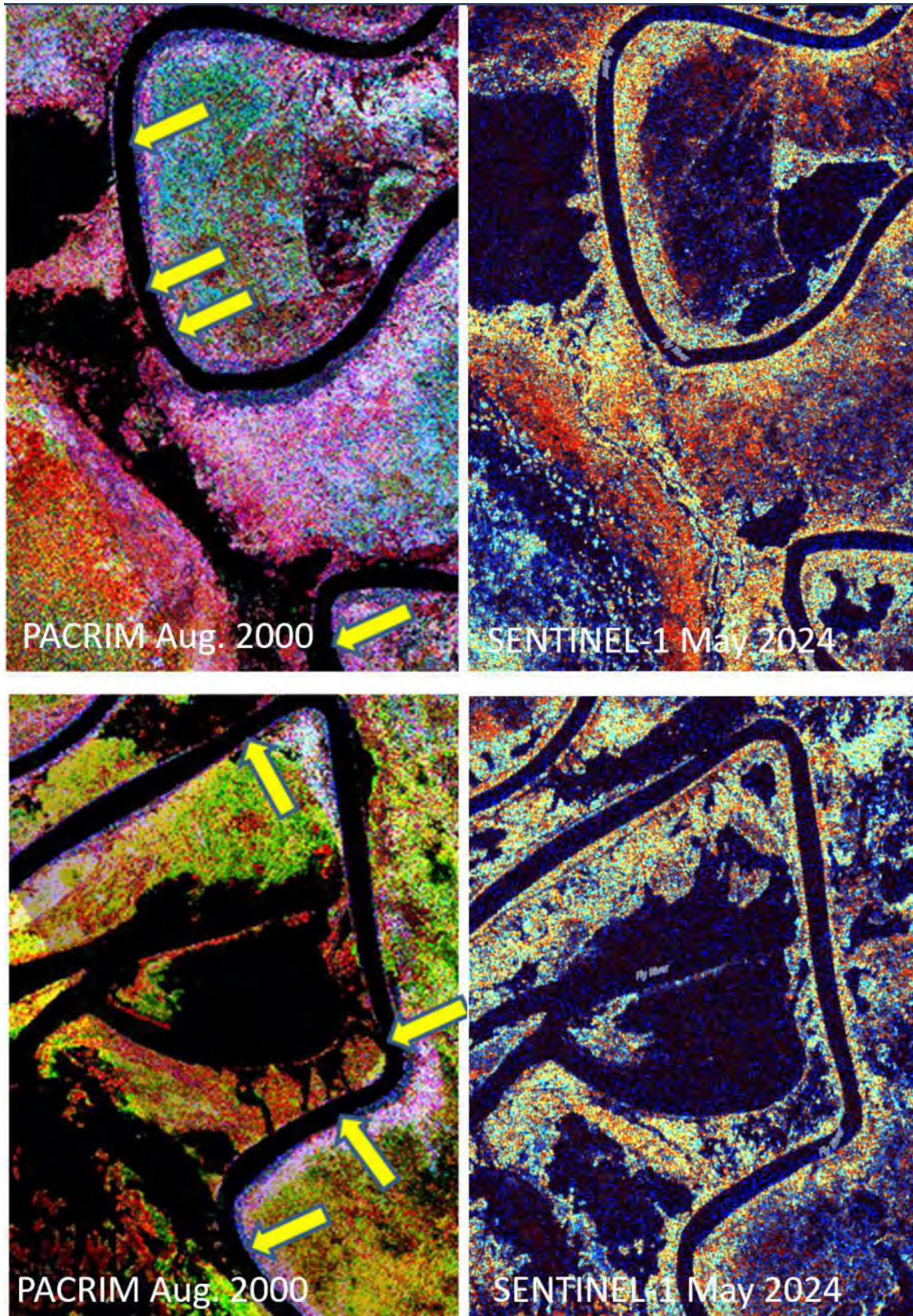


**Figure 5-23: AIRSAR 10m resolution three band synthetic aperture radar from mid-2000 compared with SENTINEL data from May 2024 at Bai Lagoon and Lake Pangua. On both occasions the floodplain was extensively inundated. Black areas on both images indicate water as does red on the SENTINEL images. Water levels appear similar but there was more connectivity between river and floodplain in 2000. Arrows indicate some of the levee breaches at that time when the floodplain was draining back into the river after an extended period of high water levels.**

The impact of increased floodplain inundation and longer periods when the floodplain stays inundated have been monitored since the late 1990s. Marshall (2025c) reports extensive forest dieback, especially between the mid-1990s and the year 2000 but at a lower and continuing rate since then. Rates of recovery from dieback have also been declining. Some areas have also converted from forest to aquatic vegetation. Model results suggest that water levels will continue to increase, especially in the central reaches of the Middle Fly and the upper reaches of the lower Middle Fly (Chapter Seven, Figs. 7-3). It is also likely that existing levee heights will be maintained or will continue to increase (see Chapter 5) suggesting longer periods of floodplain inundation, further increasing stress on flooded forest over much of the floodplain. Comparison of modelled water levels with and without a TSF also suggests that discharging tailings to a TSF is unlikely to make much difference to forest dieback and recovery rates in the medium term (Fig. 7-4). Existing trends related to sediment already in the river system will also continue to exert an ongoing influence on floodplain inundation and the processes that result in forest dieback.

## HOW FAR DOES MINE WASTE PENETRATE THE FLOODPLAIN?

Mine-derived sediment is known to enter most large and connected OWRBs and various coring programs show varying depths of deposition (Bolton and Pickup, 2021). However, the only general models of mine waste deposition across the floodplain date from two decades ago. These are as follows.

The earliest effort to understand deposition on the floodplain was based on the copper content of mine derived sediment being much higher than background levels, making it suitable as a tracer. Initial sampling was carried out by OTML as part of the now discontinued Acceptable Particulate Limit (APL<sup>7</sup>) program and involved the collection of surface grab samples and shallow cores (<1m) from 101 floodplain and 100 ORWB sites scattered between 1989 and 2000.

Using the samples from 1990 to 1994, together with a series of floodplain transects, Dietrich (2000), Day *et al* (2008) and Day *et al* (2009), showed that the bulk of deposition occurs on main channel and tie channel levees and decreases away from them. They also found that the spread of copper-rich, mine-derived sediment across the floodplain was rapid with the copper concentrations far exceeding background values (~30mg/kg) at most sampling sites by 1993.

In the early 2000s, Day *et al* (2008; 2009) went on to build the first floodplain sediment deposition model using the early 1990s data which could also describe the distribution of mine-derived metal pollutants. They envisaged the floodplain as a “*depositional web*” in which tie channels act as feeders to connected river water bodies and more distant parts of the floodplain. Sediment concentrations on the floodplain itself were found to decrease rapidly with distance from the main channel and the tie channels, and when the floodplain is inundated, it is often by clear water. Deposition on the floodplain surface occurs by diffusion out from the various channels and is much slower than on channel levees. Their model was based on a set of empirical regression equations relating depth of deposition, calculated from copper content in shallow cores to distance from source channel. The source channel could be either the main channel or a tie channel. The equations were exponential in form and different coefficients were derived for the Upper and Lower Middle Fly and a transitional zone in between, reflecting a downstream reduction in the amount of deposition. An exponential equation was also derived for deposition outwards from tie channels across the floodplain in the backwater reach of the Lower Middle Fly resulting in a different rate of floodplain sediment accumulation.

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<sup>7</sup> The APL Era began in 1989 when the State agreed to a set of environmental conditions that OTML was expected to meet. Concern focussed on sediment load in the river system and sediment deposition but geochemical pollution by particulate and dissolved copper were also seen as issues. Monitoring schemes were set up including measurement of the sediment load of the Upper Middle Fly at Nukumba to ensure it remained below an acceptable particulate limit (APL) of 940 mg/l. Geochemical monitoring schemes included dissolved and particulate copper measurement at Nukumba and at Obo on the Lower Middle Fly. Copper deposition on the Fly floodplain was also sampled on an annual basis at 200 floodplain surface and off-river water body sites. This was discontinued in 2000 after ten years but remains the only floodplain-wide geochemical dataset.

The Day *et al* (2008; 2009) model was a significant advance in understanding the processes of floodplain deposition on the Middle Fly. However, it did produce excessively high estimates of floodplain deposition especially in ORWB locations and on tie channels far distant from the main river channel. A revised version of the Day/Dietrich model was developed by Pickup *et al* (2008), using both the original Day-Dietrich data but with a longer 1990-2000 data set and this time with the aim of predicting particulate copper concentration in deposited sediments rather than depth of deposition. Other data included airborne gamma ray data for model verification and new sediment cores from levee transects. Distances from the main river channel were calculated from a floodplain inundation model (Pickup, 2005) which uses an unsteady flow hydraulic model to calculate a water surface profile down the Middle Fly. The water surface profile sets water surface elevations which are then extended laterally across the floodplain to identify location and depth of flooding. Floodplain topography came from a digital elevation model (DEM) based on data acquired during NASA's Shuttle Radar Topography Mission in 2000. The DEM was corrected using observed flood extents from a wide range of satellite imagery. Effects of vegetation were also reduced using the same satellite dataset.

The copper model only covers floodplain surface data as the ORWBs and the tie channel linkages between them had not been mapped in sufficient detail at the time. It was also known that some linkages had become blocked, but it was not known when that had occurred. Also, the lack of accurate high resolution floodplain elevation data (which continues to limit progress) meant that flow patterns were only partly understood.

Neither the original Day-Dietrich model nor its successor are suitable for predictive modelling in response to changes in the copper content of delivered sediments. However, they remain the only available method for describing the distribution of mine-derived sediments on the Middle Fly floodplain. Even then, they can only provide a very approximate guide. Figure 5-24 illustrates the quality of predictions and how well Figs. 5-25 and 5-26 illustrate the copper distribution and therefore the mine sediment distribution patterns that result from its application.

It is likely that mine-derived sediments entering the floodplain once the TSF is operational may show a similar distribution pattern to that shown on the maps. However, the reduced amount of tailings in the mix and their much lower copper content during the last decade and in the future compared with the APL period suggests copper concentrations in sediments entering the floodplain will be substantially lower.

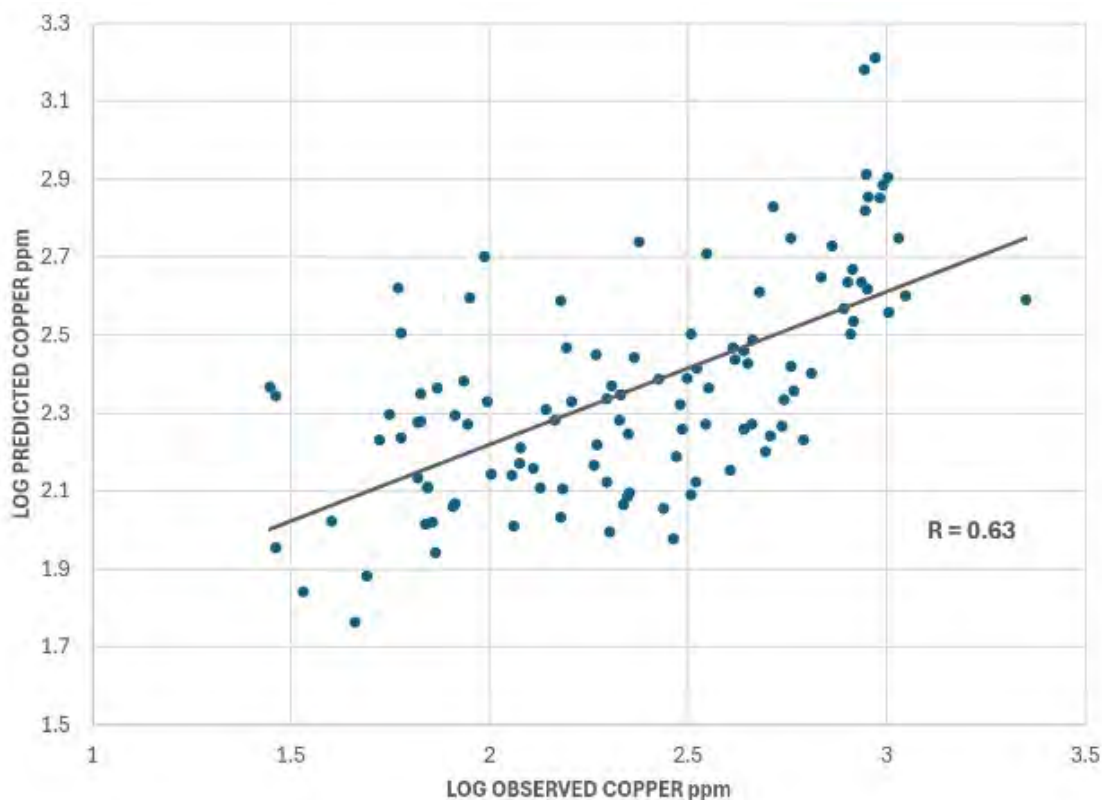


**Figure 5-24. Observed and calculated floodplain sediment copper concentrations from the revised Day/Dietrich model.**

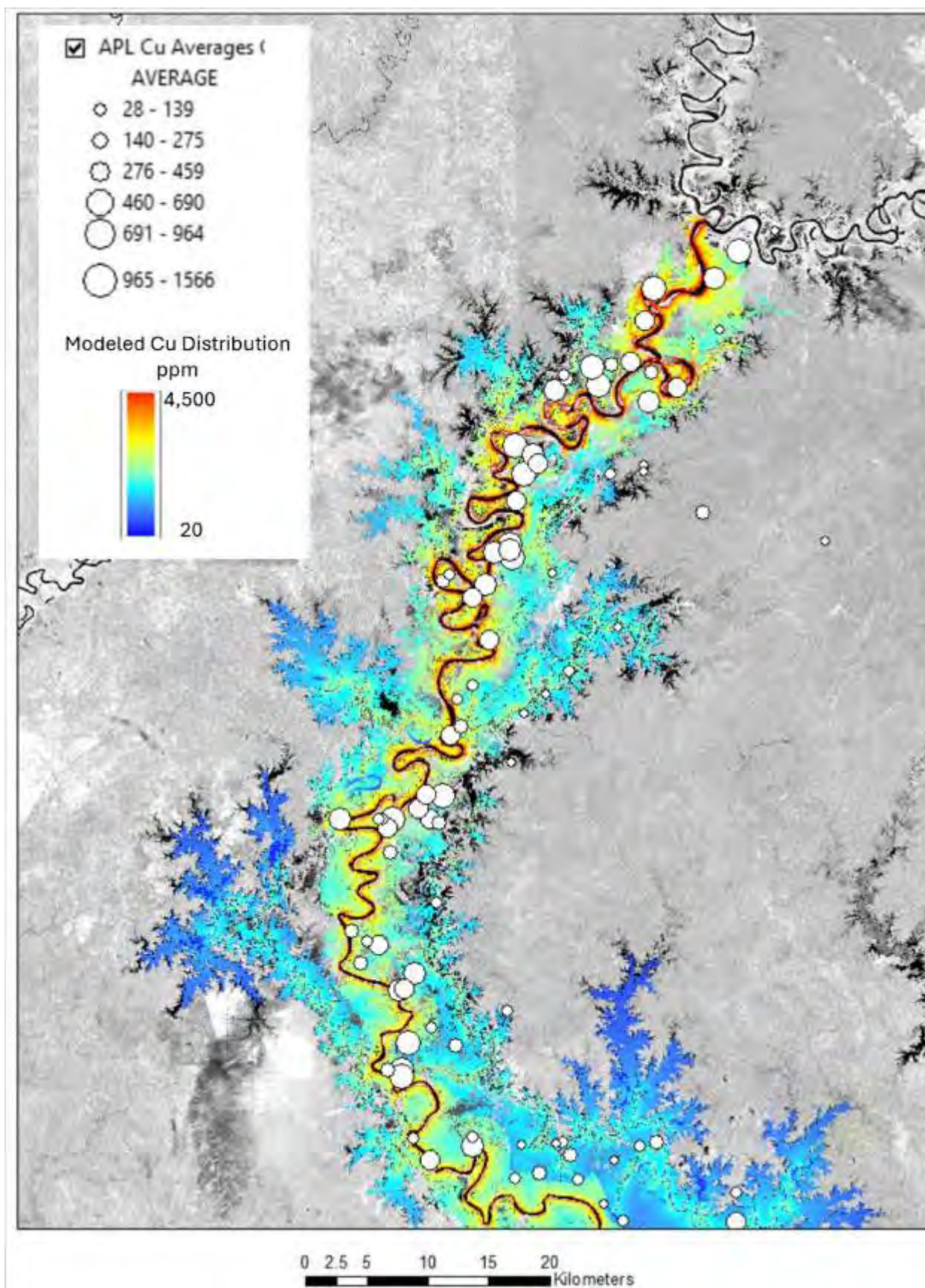


**Figure 5-25. Floodplain sediment copper concentrations from the revised Day/Dietrich model on the sand zone of the Middle Fly. Circles identify the locations of APL samples averaged from 1993-2000. Background is a LANDSAT Band 5 image**

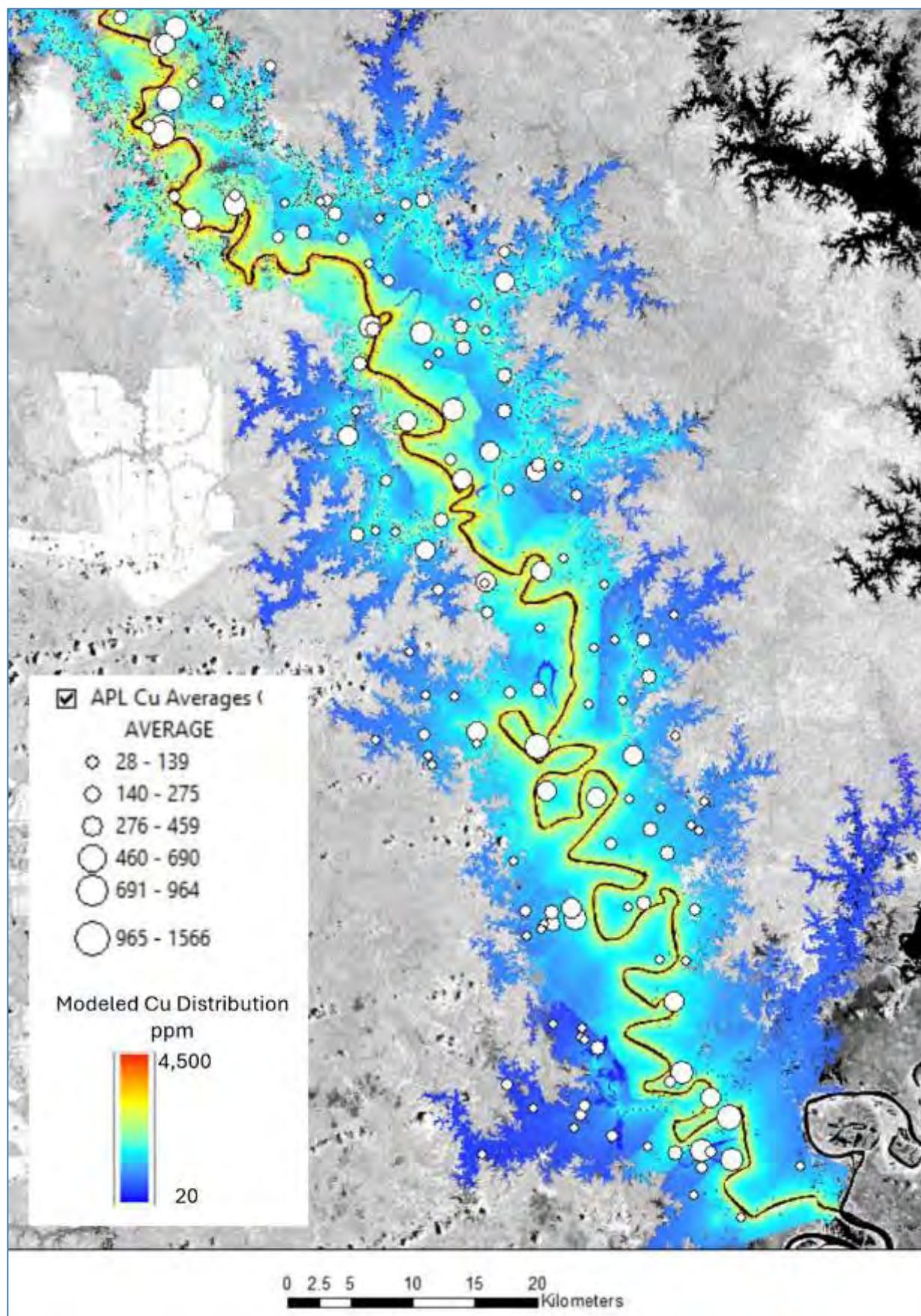


**Figure 5-26. Floodplain sediment copper concentrations from the revised Day/Dietrich model on the backwater zone of the Middle Fly. Circles identify the locations of APL samples averaged from 1993-2000. Background is a LANDSAT Band 5 image.**

The relative importance of levee deposition and why it has been the focus of ARD issues is illustrated by results from multiple coring programs since the early 2000s, mostly on the Middle Fly, aimed at identifying vertical accretion rates of mine sediments across a range of different floodplain depositional environments. These were summarised in the major review of OTML’s floodplain environment geochemical studies by Bolton and Pickup (2021) and are listed in Table 3.

| TABLE 3. MEDIAN THICKNESS OF MINE-DERIVED SEDIMENT AND SEDIMENTATION RATES FOR SELECTED DEPOSITIONAL ENVIRONMENTS BASED ON CORES THAT PENETRATED TO PRE-MINE SEDIMENTS. |                                  |                                 |                                     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|---------------------------------|-------------------------------------|
| DEPOSITIONAL ENVIRONMENT                                                                                                                                                | EST. THICKNESS MINE-DERIVED (MM) | EST. SEDIMENTATION RATE (MM/YR) | EST MAX. SEDIMENTATION RATE (MM/YR) |
| Fly levee                                                                                                                                                               | 1805                             | 69                              | 251                                 |
| Fly levee backslope                                                                                                                                                     | 1340                             | 61                              | 163                                 |
| Fly point bar                                                                                                                                                           | 1570                             | 65                              | 96                                  |
| Tie channel levee                                                                                                                                                       | 2040                             | 59                              | 151                                 |
| Fly backswamp                                                                                                                                                           | 270                              | 12                              | 118                                 |
| Fly scroll bar complex                                                                                                                                                  | 312                              | 15                              | 20                                  |
| ORWB                                                                                                                                                                    | 210                              | 11                              | 46                                  |

Table 3 shows the thickest sections of mine-derived sediment were found in cores taken from the levees of tie channels connecting the main river channel to ORWBs (median of 2040mm). For example, a core taken from the tie channel linking the Fly River to Kemea Lagoon (about 80 km upstream from Everill Junction), recorded 3420mm of mine-derived sediment. Thick sections of mine-derived material were also recorded in Fly River levees (median thickness of 1805mm), main river point bar deposits (median of 1570mm) and levee backslopes (median of 1340mm).

Consistent with the expected decrease in the amount of sedimentation beyond the channels and related levees, mine-derived sediments thin to median values of 312mm, 270mm and 210mm, in main river scroll bar complexes, floodplain backswamps and ORWBs, respectively. In Table3, two estimates of the vertical accretion sedimentation rate are given, and both are based on only those cores that penetrate to pre-mine sediments; the first is the median value for each of the major depositional settings while the second tabulates the maximum value of this rate.

Perhaps not surprisingly, given the thicknesses noted above, the highest sedimentation rates observed, at 69 mm/yr, were in sediments deposited on the levees of tie channels linking the Fly with various ORWBs, such as the Kuambit Oxbow on the upper Middle Fly close to D’Albertis Junction. High rates of accretion were also identified in levee and levee backslope, as well as point bar settings on the main Fly River channel. Much lower accretion rates were determined for sites either further from the channel, such as floodplain backswamps, or at higher elevations, such as in former scroll-bar complexes. The lowest, sedimentation rates were found to occur away from the tie channel in the shallow and open waters of the more distal ORWBs such Bosset Lagoon and Lake Daviumbu.

## FLOODPLAIN LEVEE GEOCHEMISTRY

By the mid to late 1990s, it was known that Ok Tedi tailings were potentially acid forming (PAF) while the waste rock was often strongly acid consuming with an excess of acid neutralising capacity (ANC) due to the high proportion of limestone waste. However, the sandy material (much of which was originally tailings) captured by the Bige dredging operation posed a potential future ARD risk due to mineral segregation in the dredge sand

stockpiles. Also, potentially acid forming (PAF) sediments were found to occur spasmodically in Middle Fly levee deposits between 2003 and 2019 (Bolton and Pickup, 2021).

Based on the investigations of copper in the 1990s, the distribution of mine derived sediments was reasonably well understood and it was known that the highest concentrations occurred on the floodplain levees. From 2000 onwards, most floodplain surface and ORWB sampling ceased and was replaced by regular surveys of levee crest sediments on a roughly annual basis covering copper, sulphur and ANC. The pattern of change in these sediments, both down the river course and over time, as OTML attempted to deal with the acid problem and reduce copper content in tailings, is illustrated in Figs. 5-27 – 5-30 using example data from the 2006, 2012 and 2019 levee surveys. Since 2019, the distribution patterns have remained similar to those shown in the 2019 data.

The copper content of levee sediments (Fig. 5-27) mostly varies as a tributary joins the main river and dilutes the sediment load with natural material and then only after tailings copper content was reduced by about two-thirds over the last decade. Prior to that, levee sediment copper was evenly distributed right down the Lower Ok Tedi and the Middle Fly, only undergoing a substantial reduction when diluted by Strickland River sediment load in the Lower Fly. The even distribution shows how mobile particulate copper is and its wide distribution across the floodplain (Figs 5-25 and 5-26).

The distribution and pattern of change over time of sulphur differs from copper (Fig. 5-28). There was a strong downstream gradient in 2006 which gradually faded over time and since 2012 has largely disappeared. Since then, sulphur concentrations in the Lower Ok Tedi have stayed virtually unchanged, fluctuating randomly between about 0.84 and 1.04% S. This reflects the lack of change in the sulphur content of tailings since 2009 largely due to extraction of pyrite at the mill which is diverted by pipeline to the PCon storage on the west bank of the Ok Tedi at Bige. The limited change after 2012 may also reflect the perched levee effect whereby less new material is added to high levee crests as they grow in height. The Upper Fly does have a dilution effect, reducing sulphur concentrations to some degree but there is little downstream change until dilution by the Strickland.

Over time, ANC has increased by up to 50% in the Lower Ok Tedi reflecting a fourfold increase in the ANC value of tailings due the addition of ground limestone from the mill (Fig. 5-29). There is only limited downstream variation until the beginning of the Lower Middle Fly when a decrease occurs. This is thought to reflect dilution by incoming sediment in flow from large tributaries including the Agu and the Kai which drain lowland catchments in ancient, weathered alluvium and are without limestone.

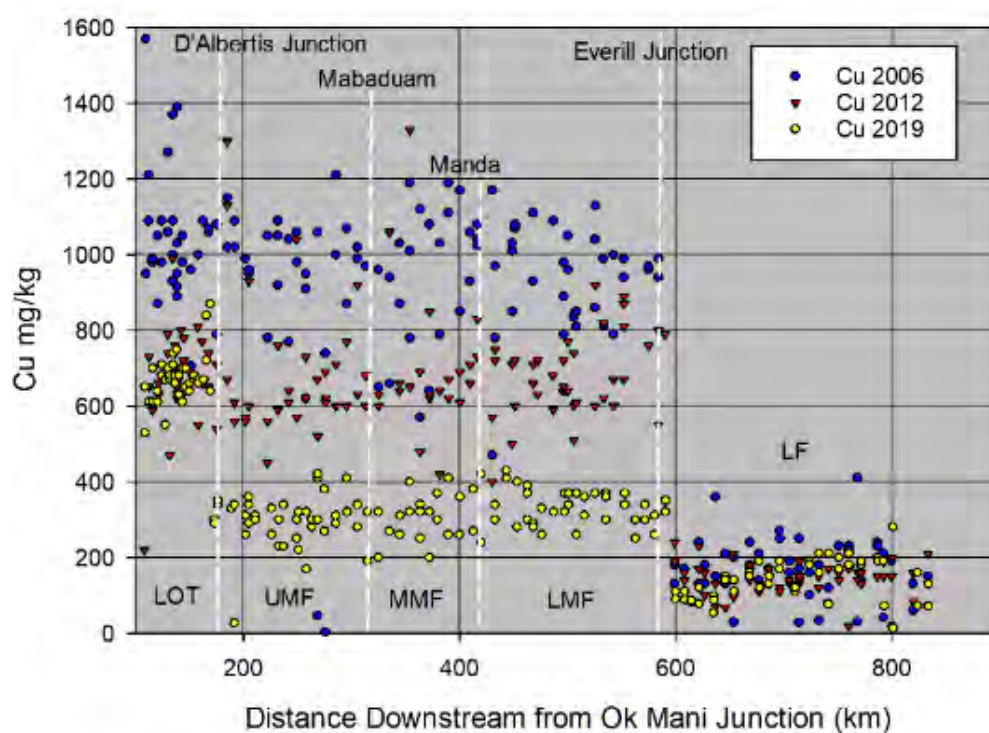


**Figure 5-27. Distribution of particulate copper in levee sediments down the floodplain reaches of the Lower Ok Tedi, Middle Fly and Lower Fly. The letter codes for the various reaches are LOT – Lower Ok Tedi, UMF Upper Middle Fly, MMF – central Middle Fly, LMF – Lower Middle Fly, LF – Lower Fly.**

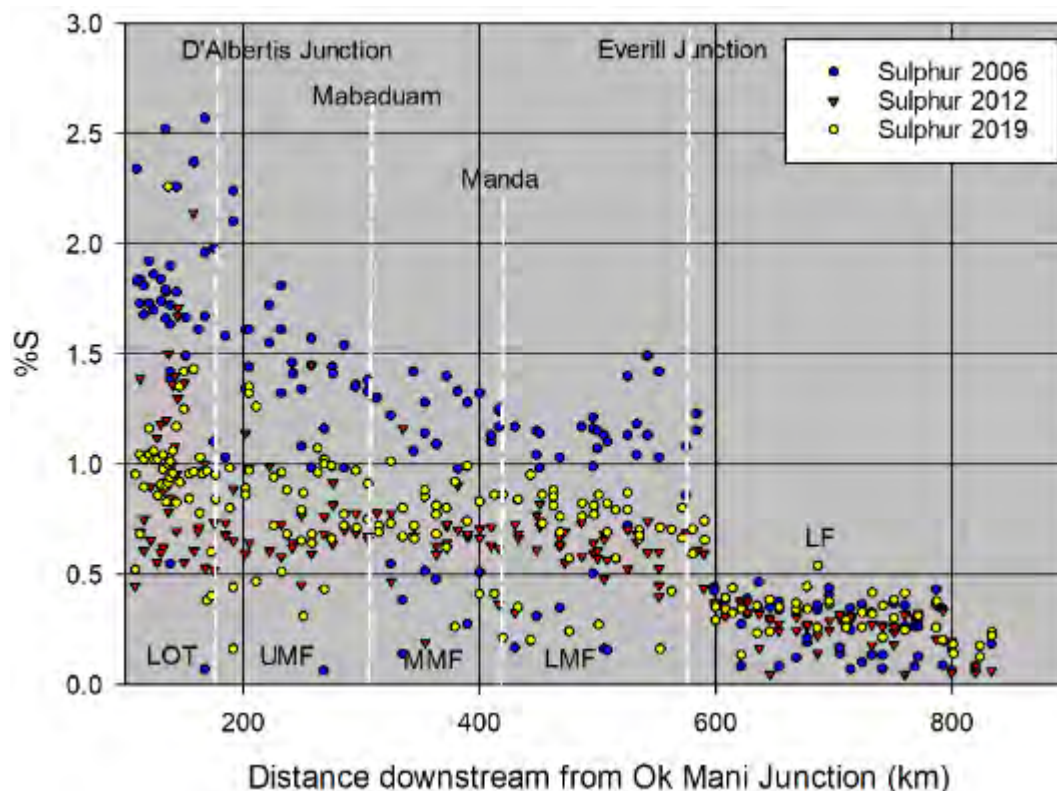


**Figure 5-28. Distribution of particulate sulphur in levee sediments down the floodplain reaches of the Lower Ok Tedi, Middle Fly and Lower Fly. The letter codes for the various reaches are LOT – Lower Ok Tedi, UMF Upper Middle Fly, MMF – central Middle Fly, LMF – Lower Middle Fly, LF – Lower Fly.**

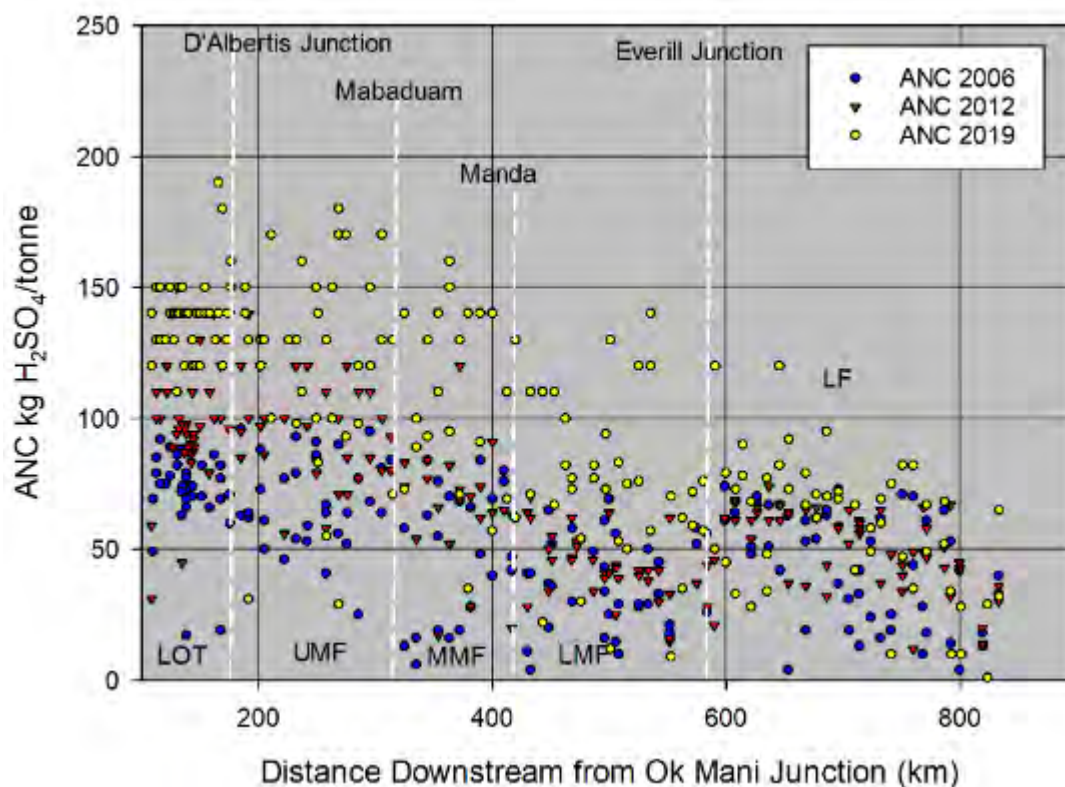


**Figure 5-29. Distribution Acid Neutralising Capacity (ANC) in levee sediments down the floodplain reaches of the Lower Ok Tedi, Middle Fly and Lower Fly. The letter codes for the various reaches are LOT – Lower Ok Tedi, UMF Upper Middle Fly, MMF – central Middle Fly, LMF – Lower Middle Fly, LF – Lower Fly.**

ANC: MPA ratios are plotted in Fig. 5-30 and show a major improvement and a reduction of acid generation risk with time. A value of 2.0 is considered desirable as it allows for some variation among a group of samples. Values of 1.0 or less at Ok Tedi are regarded as being at risk of producing acid. The 2006 data show that the same level of risk prevailed over much of the Lower Ok Tedi and Middle Fly but that risk had been largely reduced by 2012 and remained so.

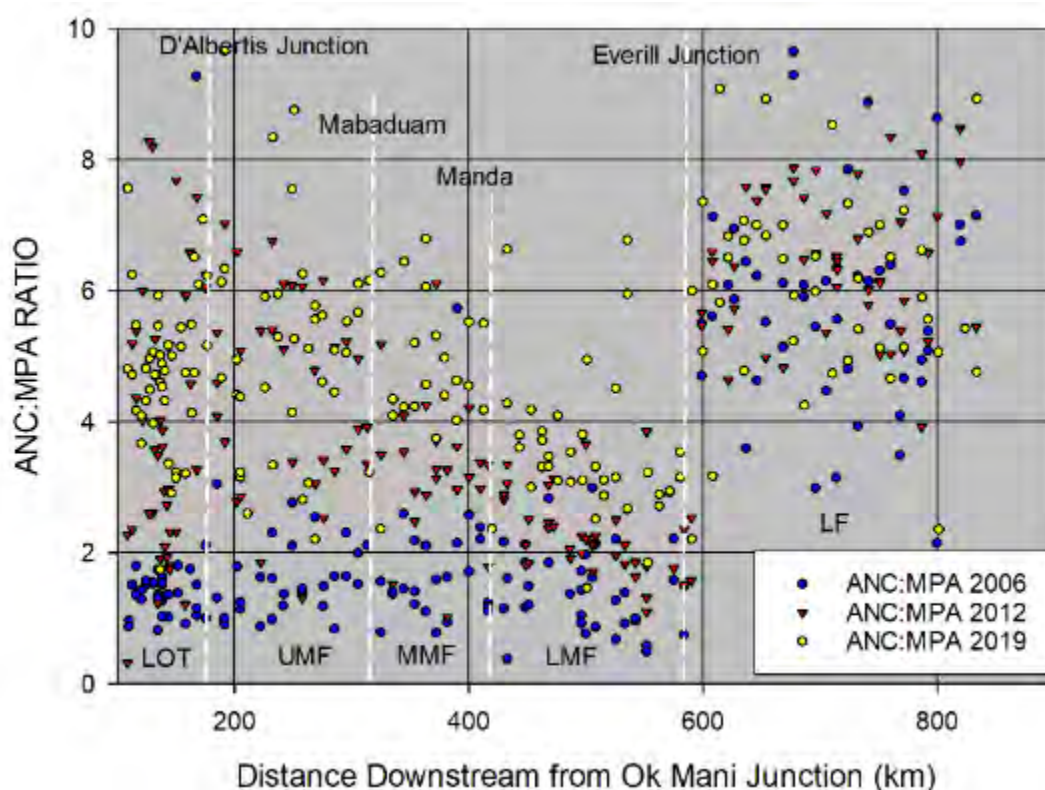


**Figure 5-30. Distribution of ANC:MPA ratios in levee sediments down the floodplain reaches of the Lower Ok Tedi, Middle Fly and Lower Fly. The letter codes for the various reaches is LOT – Lower Ok Tedi, UMF Upper Middle Fly, MMF – central Middle Fly, LMF – Lower Middle Fly, LF – Lower Fly.**

More detail on the trends in ANC:MPA over time is shown in the heat maps shown as tables in Figs. 5-31 to 5-34. Each cell in the table shows the ANC:MPA ratio with cells arranged by site in downstream order and with time. Red cells indicate values of <1.0, hence a clear risk of acid generation. Orange cells show values of 1.0-2.0 and a moderate level of risk. Blue cells mark values >2.0 and locations of minimal risk.

Acid generation risk now appears to be minimal on the Lower Ok Tedi and this trend is likely to be enhanced as TSF construction substantially reduces future tailings discharge into the river system (Fig. 5-31). On the upper Middle Fly a few sites with moderate risk remained for longer than on the Lower Ok Tedi but the risk had largely gone by the drought year of 2015 (Fig. 5-32). On the central Middle Fly localised moderate risk continued for about three more years (Fig. 5-33) This may be because riverbed sediments with high sulphur values from earlier years of mine operation were gradually being excavated from eroding bed sediments on the lower Ok Tedi. A single location at the lower end of the reach did show high risk values in 2020 but these did not persist in later years. On the lower Middle Fly, a few moderate risk values were occurring up to the 2024

sampling mission but the trend has been to decrease slowly over time (Fig. 5-34). Again, this trend is thought to reflect the slow passage of riverbed sediments down through the Middle Fly. A TSF is likely to enhance this trend and continue to extend it over the long term.

| Site   | Ds (km) | 2005_A | 2005_N | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|--------|---------|--------|--------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| OT30-1 | 108.22  | 1.5    | 1.0    | 1.0  | 3.6  | 0.8  | 5.1  |      | 1.7  | 0.3  | 0.4  | 4.1  | 5.3  | 5.3  | 8.7  | 3.7  | 7.6  | 5.4  | 8.9  | 5.4  | 6.6  |
| OT30-7 | 108.27  | 2.2    | 1.7    | 0.9  | 1.1  | 1.4  | 1.0  |      | 5.1  | 2.3  | 2.6  | 2.3  | 7.6  | 7.6  | 5.3  | 5.8  | 4.8  | 8.5  | 3.7  | 3.1  | 6.1  |
| OT28-1 | 112.54  | 1.2    | 1.2    | 1.5  | 1.7  | 3.1  | 4.3  |      | 2.4  | 2.4  | 6.4  | 4.1  | 5.2  | 7.5  | 7.0  | 7.8  | 4.7  | 7.3  | 6.3  | 4.3  | 7.9  |
| OT28-7 | 112.51  | 1.5    | 0.6    | 1.5  | 2.1  | 1.8  | 0.6  |      | 3.8  | 5.2  | 3.4  | 3.8  | 7.5  | 5.2  | 7.7  | 8.4  | 6.2  | 23.6 | 5.7  | 3.8  | 3.9  |
| OT26-1 | 115.72  | 0.9    | 2.0    | 1.8  | 1.0  | 13.1 | 0.3  |      | 5.2  | 4.4  | 4.6  | 5.0  | 23.1 | 23.1 | 5.5  | 7.5  | 4.2  | 4.7  | 8.6  | 6.6  | 3.0  |
| OT26-7 | 115.78  | 2.6    | 0.0    | 1.4  | 1.1  | 1.1  | 4.2  |      | 2.3  | 5.4  | 3.5  | 4.2  | 5.1  | 5.1  | 8.1  | 7.7  | 5.5  | 5.7  | 6.5  | 5.2  | 7.1  |
| OT24-1 | 121.41  | 0.6    | 2.8    | 1.4  | 1.3  | 1.6  | 2.5  |      | 5.9  | 4.0  | 5.4  | 5.9  | 7.4  | 7.4  | 5.1  | 2.6  | 3.7  | 4.1  | 6.4  | 3.0  | 9.9  |
| OT24-7 | 121.41  | 1.5    | 0.3    | 1.3  | 2.7  | 1.4  | 4.3  |      | 3.9  | 6.0  | 9.7  | 4.1  | 5.2  | 5.2  | 14.5 | 7.0  | 4.1  | 4.3  | 4.4  | 5.9  | 5.3  |
| OT21-1 | 126.98  | 1.4    | 0.2    | 1.5  | 1.1  | 2.2  | 1.9  |      | 5.0  | 2.6  | 3.8  | 4.2  | 5.4  | 5.4  | 6.2  | 3.2  | 5.0  | 4.8  | 4.5  | 3.9  | 3.4  |
| OT21-7 | 126.94  | 1.2    | 0.8    | 1.6  | 1.4  | 1.6  | 3.5  |      | 3.4  | 8.3  | 3.7  | 7.3  | 28.8 | 28.8 | 6.2  | 5.5  | 4.5  | 5.1  | 4.2  | 3.2  | 5.2  |
| OT20-1 | 130.07  | 1.2    | 0.7    | 1.5  | 1.1  | 2.6  | 9.4  |      | 2.7  | 8.2  | 4.3  | 4.4  | 4.9  | 4.9  | 7.7  | 8.0  | 5.1  | 5.4  | 4.3  | 5.6  | 4.2  |
| OT20-7 | 129.83  | 1.4    | 0.7    | 1.5  | 1.3  | 2.8  | 2.9  |      | 2.3  | 2.6  | 1.6  | 4.5  | 4.5  | 4.5  | 3.4  | 6.2  | 4.0  | 5.8  | 4.9  | 5.2  | 7.9  |
| OT19-1 | 131.88  |        | 1.2    | 1.3  | 1.6  | 0.6  | 1.0  |      | 2.5  | 5.3  | 4.3  | 5.9  | 10.9 | 10.9 | 8.0  | 5.3  | 4.7  | 4.8  | 6.7  | 4.7  | 3.8  |
| OT19-7 | 131.78  |        | 0.0    | 1.7  | 1.2  | 1.9  | 2.1  |      | 2.0  | 3.6  | 1.4  | 2.9  | 7.3  | 7.3  | 2.6  | 5.4  | 4.7  | 3.6  | 4.9  | 3.7  | 6.9  |
| OT17-1 | 134.61  | 1.0    | 0.0    | 1.4  | 1.2  | 1.9  | 2.5  | 0.9  | 2.8  | 1.2  | 2.3  | 4.2  | 4.3  | 4.3  | 3.3  | 5.8  | 5.5  | 3.2  | 5.5  | 3.2  | 5.4  |
| OT17-7 | 134.56  | 1.1    | 1.9    | 0.8  | 0.9  | 2.1  | 2.3  | 1.5  | 2.3  | 3.5  | 4.1  | 2.0  | 4.3  | 4.3  | 3.6  | 5.9  | 5.9  | 3.2  | 5.0  | 6.5  | 5.8  |
| OT16-1 | 136.65  |        | 0.0    | 1.5  | 1.1  | 1.3  | 10.2 | 6.3  | 2.1  | 1.9  | 1.6  | 2.7  | 3.3  | 3.3  |      | 5.6  | 1.7  | 4.3  | 6.0  | 6.1  | 7.8  |
| OT16-7 | 136.66  |        | 1.2    | 1.5  | 0.9  | 2.5  | 3.8  | 4.4  | 2.2  | 4.0  | 3.7  | 6.2  | 5.1  | 5.1  |      | 5.2  | 4.6  | 4.3  | 4.6  | 7.4  | 4.7  |
| OT15-1 | 138.34  | 1.0    | 1.1    | 1.5  | 1.1  | 2.4  | 2.4  | 28.0 | 2.8  | 3.9  | 2.3  | 6.2  |      |      | 12.0 | 6.8  | 4.5  | 4.3  | 5.9  | 4.8  | 5.8  |
| OT15-7 | 138.34  | 1.0    | 0.4    | 1.0  | 1.2  | 1.6  | 2.7  | 3.8  | 3.0  | 3.6  | 4.2  | 4.3  |      |      | 6.2  | 3.3  | 4.9  | 4.2  | 4.8  | 4.9  | 4.5  |
| OT14-1 | 140.15  |        | 0.0    | 1.6  | 0.7  | 1.6  | 1.1  | 5.1  | 3.0  | 2.9  | 2.3  | 5.4  | 4.3  | 4.3  | 4.6  | 4.4  | 4.8  | 4.2  | 5.6  | 4.4  | 4.6  |
| OT14-7 | 140.24  |        | 0.0    | 1.3  | 0.7  | 1.7  | 0.8  | 5.1  | 3.4  | 2.1  | 3.2  | 5.9  | 5.2  | 5.2  | 6.7  | 5.4  | 4.3  | 4.6  | 3.0  | 4.2  | 5.0  |
| OT13-1 | 142.19  | 1.3    | 1.3    | 1.4  | 0.9  | 1.9  | 4.8  | 1.4  | 4.0  | 2.7  | 3.8  | 4.8  | 3.5  | 3.5  | 6.7  | 5.8  | 5.2  | 5.3  | 4.3  | 4.0  | 4.3  |
| OT13-7 | 142.20  | 4.9    | 0.0    | 1.0  | 0.9  | 3.2  | 4.2  | 4.4  | 2.0  | 1.9  | 2.9  | 3.8  | 4.5  | 4.5  | 2.1  | 5.5  | 3.4  | 2.4  | 11.3 | 3.0  | 6.6  |
| OT10-1 | 143.47  |        |        |      |      |      |      | 6.1  |      | 5.2  | 2.2  | 3.4  | 5.5  | 5.5  |      |      |      | 4.1  | 4.2  | 7.0  | 6.5  |
| OT10-7 | 143.48  |        |        |      |      |      |      | 3.9  |      | 3.0  | 4.7  | 11.1 | 2.7  | 2.7  |      |      |      | 17.8 | 4.9  | 6.3  | 6.2  |
| OT12-1 | 144.58  |        | 0.0    | 1.4  | 1.7  | 2.4  | 0.9  | 6.6  | 1.6  | 1.8  | 1.9  | 3.0  | 7.1  | 7.1  | 2.9  | 5.4  | 2.9  | 4.7  | 4.2  | 7.9  | 4.2  |
| OT12-7 | 144.53  |        | 1.7    | 1.8  | 1.9  | 1.7  | 7.2  | 5.6  | 3.8  | 1.7  | 4.9  | 2.7  | 3.8  | 3.8  | 6.2  | 6.4  | 5.0  | 4.3  | 4.6  | 5.6  | 9.3  |
| OT08-1 | 150.07  | 1.3    | 1.4    |      |      |      |      | 1.4  |      | 7.7  | 4.4  | 6.1  | 5.1  | 5.1  | 8.2  | 7.3  | 5.4  | 6.1  | 6.2  | 5.6  | 9.6  |
| OT08-7 | 150.08  | 1.3    | 2.3    |      |      |      |      | 3.0  |      | 2.3  | 2.2  | 3.6  | 4.9  | 4.9  | 6.6  | 6.6  | 5.1  | 4.6  | 6.4  | 5.9  | 6.0  |
| OT06-1 | 158.02  | 1.1    | 1.0    | 0.9  | 2.0  | 0.0  | 3.1  | 5.6  | 4.3  | 5.9  | 3.5  | 5.1  | 5.9  | 5.9  | 5.8  | 5.2  | 4.7  | 4.5  | 5.8  | 6.1  | 6.2  |
| OT06-7 | 157.92  | 1.0    | 1.6    |      | 0.8  | 1.0  | 4.1  | 4.3  | 1.2  | 1.2  | 2.1  | 2.7  | 4.4  | 4.4  | 4.4  | 6.1  | 3.2  | 3.1  | 5.4  | 4.3  | 6.7  |
| OT04-1 | 162.33  | 2.5    | 3.2    | 1.7  | 2.5  | 2.0  | 5.8  | 4.7  | 3.2  | 4.6  | 4.7  | 6.9  | 4.4  | 4.4  | 5.1  | 5.8  | 4.1  | 5.1  | 4.4  | 6.4  | 6.3  |
| OT04-7 | 161.71  | 2.2    | 1.2    |      | 2.0  | 2.0  | 1.8  | 3.8  | 4.4  | 6.6  | 7.2  | 5.6  | 5.8  | 5.8  | 5.8  | 5.4  | 5.5  | 4.5  | 5.5  | 9.7  | 4.8  |
| OT02-1 | 167.55  | 1.9    | 3.0    | 1.0  | 3.1  | 1.2  | 0.9  | 45.0 | 9.2  | 7.4  | 5.6  | 10.1 | 6.6  | 6.6  | 7.3  | 3.2  | 4.7  | 5.2  | 4.6  | 5.6  | 5.1  |
| OT02-7 | 167.45  | 0.7    | 0.7    | 1.2  | 1.0  | 2.5  | 3.9  | 1.6  | 2.2  | 3.3  | 4.1  | 1.3  | 3.7  | 3.7  | 7.5  | 8.1  | 6.5  | 9.3  | 6.2  | 5.4  | 5.6  |
| LOT2-1 | 169.17  | 1.4    | 1.1    | 1.5  | 3.9  | 1.4  | 3.7  |      |      | 5.1  | 3.8  | 4.4  |      |      | 8.5  | 5.8  | 6.1  | 8.5  | 7.8  | 4.5  | 8.5  |
| LOT2-7 | 170.19  | 1.7    | 1.1    | 9.3  | 2.7  | 1.1  |      |      |      | 4.1  | 2.7  | 10.1 | 26.9 | 26.9 | 4.0  | 7.0  | 10.3 | 6.8  | 8.2  | 7.0  | 7.5  |

**Figure 5-31. Lower Ok Tedi levee sampling site ANC:MPA values arranged by distance and time. Updated from Bolton and Pickup (2021).**

| Site  | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
|-------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| T4-1  | 0.9  | 0.4  | 2.0  | 2.1  | 2.2  | 0.6  | 3.7  | 4.0  | 6.5  | 6.0  | 7.3  | 8.5  | 20.6 | 10.3 | 24.0 | 7.1  | 18.0 | 18.7 | 12.8 | 8.4  | 8.9  |
| T4-7  | 0.8  | 1.4  | 2.0  | 1.0  | 0.9  | 1.9  | 5.7  | 3.8  | 2.0  | 6.2  | 6.3  | 7.0  | 44.9 | 5.0  | 5.1  | 11.4 | 5.9  | 8.7  | 6.1  | 7.3  | 8.0  |
| T5-7  | 1.1  |      | 2.7  | 3.0  | 2.4  | 2.7  | 3.3  | 4.5  | 1.5  | 5.4  | 1.9  | 3.2  | 6.7  | 5.6  | 7.7  | 4.7  | 2.9  | 5.3  | 5.0  | 6.6  | 6.8  |
| T5-1  | 1.9  |      | 1.3  | 1.3  | 1.3  | 2.1  | 4.4  | 3.3  | 2.2  | 4.1  | 3.6  | 7.0  | 12.0 | 6.2  | 5.4  | 6.1  | 7.2  | 5.1  | 4.9  | 7.8  | 7.1  |
| T6-7  | 1.0  | 1.3  | 1.5  | 0.9  | 2.1  | 1.7  | 4.8  | 4.4  | 1.6  | 7.0  | 6.1  | 14.2 | 6.7  | 5.0  | 8.4  | 9.7  | 6.5  | 13.1 | 3.8  | 7.2  | 7.2  |
| T6-1  | 0.9  | 0.7  | 1.6  | 1.0  | 1.4  | 0.9  | 3.4  | 2.1  | 2.9  | 3.7  | 3.0  | 1.8  | 18.6 | 1.1  | 5.9  | 6.3  | 5.4  | 4.5  | 4.8  | 8.3  | 9.5  |
| T7-1  | 1.1  |      | 1.4  | 1.8  | 1.2  | 0.9  | 5.6  | 2.5  | 1.7  | 2.8  | 3.7  | 3.2  | 19.6 | 6.4  | 6.9  | 4.4  | 4.6  | 7.4  | 5.2  | 4.5  | 6.9  |
| T7-7  | 0.9  | 1.7  | 2.2  | 1.8  | 1.6  | 1.6  | 4.8  | 3.3  | 1.8  | 6.6  | 5.2  | 4.6  | 22.1 | 5.2  | 6.0  | 4.9  | 20.2 | 14.8 | 14.2 | 10.1 | 8.8  |
| T8-1  | 1.0  |      | 2.4  | 1.1  | 1.2  | 1.0  | 4.4  | 2.7  | 2.6  | 2.8  | 5.0  | 3.0  | 3.4  | 3.3  | 10.4 | 2.6  | 3.3  | 3.1  | 7.0  | 14.0 | 8.2  |
| T8-7  | 1.0  | 1.3  | 1.6  | 1.2  | 1.6  | 1.2  | 3.9  | 2.9  | 2.1  | 5.1  | 4.1  | 4.8  | 22.5 | 4.8  | 2.2  | 11.9 | 6.4  | 5.0  | 5.0  | 4.7  | 7.8  |
| T9-1  | 6.2  |      | 2.7  | 1.6  | 1.8  | 1.6  | 4.8  | 3.7  | 2.7  | 5.4  | 4.1  | 5.0  | 9.6  |      |      |      |      |      |      |      |      |
| T9-7  | 1.2  |      | 1.7  | 0.9  | 0.8  | 1.5  | 3.1  | 2.1  | 3.9  | 1.8  | 3.4  | 1.2  | 17.0 |      |      |      |      |      |      |      |      |
| T10-1 | 1.3  | 1.3  | 1.5  | 1.0  | 0.8  | 1.0  | 3.8  | 1.7  | 1.7  | 5.4  | 3.3  | 9.4  |      | 3.6  | 5.9  | 4.5  | 2.4  | 6.1  | 4.4  | 7.7  | 6.5  |
| T10-7 | 2.2  |      | 1.4  | 2.3  | 2.2  | 1.1  | 2.2  | 3.9  | 2.9  | 6.8  | 8.6  | 8.4  | 4.4  | 7.9  | 6.5  | 5.9  | 5.8  | 4.7  | 3.9  | 6.0  | 8.1  |
| T11-1 | 1.3  |      | 1.0  | 1.4  | 1.6  | 0.7  | 3.5  | 1.6  | 3.1  | 6.1  | 2.0  | 2.9  | 16.4 | 6.8  | 5.6  | 5.3  | 3.6  | 6.3  | 3.9  | 5.8  | 7.3  |
| T11-7 | 4.4  |      | 0.4  | 1.2  | 1.2  | 1.3  | 3.9  | 2.6  | 3.5  | 5.1  | 4.4  | 5.2  | 2.5  | 10.3 | 6.8  | 5.9  | 8.2  | 5.2  | 3.6  | 7.3  | 6.9  |
| T12-1 | 0.9  | 0.6  | 1.0  | 2.8  | 1.7  | 1.2  | 2.2  | 8.8  | 4.0  | 6.1  | 3.8  | 3.8  | 5.3  | 4.1  | 5.9  | 7.5  | 4.3  | 6.2  | 4.6  | 8.4  | 8.2  |
| T12-7 | 0.9  | 1.4  | 0.7  | 2.1  | 2.2  | 1.4  | 2.7  | 2.3  | 3.1  | 3.4  | 2.8  | 3.8  | 21.1 | 2.8  | 6.4  | 4.1  | 4.8  | 5.7  | 5.9  | 9.1  | 7.3  |
| T13-1 | 1.0  | 0.9  | 1.7  | 1.4  | 1.7  | 2.1  | 3.4  | 1.8  | 2.1  | 6.1  | 6.8  | 7.9  | 17.3 | 6.2  | 5.6  | 6.2  | 5.7  | 5.2  | 4.5  | 6.2  | 11.7 |
| T13-7 | 7.7  |      | 0.2  | 1.4  | 0.7  | 1.3  | 3.9  | 2.8  | 7.0  | 1.3  | 1.2  | 1.9  | 1.3  | 2.2  | 2.5  | 2.8  | 2.8  | 4.5  | 1.4  | 6.1  | 8.9  |
| T14-7 | 0.8  | 1.3  | 1.2  | 1.4  | 1.7  | 1.8  | 4.5  | 2.0  | 2.4  | 4.8  | 5.7  | 6.7  | 27.4 | 8.1  | 7.0  | 5.8  | 4.2  | 6.0  | 3.5  | 3.3  | 8.3  |
| T14-1 | 1.1  |      | 1.0  | 29.0 | 0.3  | 0.7  | 3.4  | 1.2  | 3.9  | 3.0  | 3.1  | 3.2  | 7.1  | 4.2  | 4.9  | 2.2  | 4.0  | 3.9  | 3.2  | 7.7  | 7.7  |
| T15-1 | 1.0  |      | 1.7  | 2.5  | 2.2  | 1.1  | 5.2  | 3.7  | 2.5  | 6.2  | 5.5  | 3.6  | 9.2  | 5.7  | 5.7  | 5.6  | 4.7  | 5.5  | 3.5  | 9.3  | 21.0 |
| T15-7 | 1.1  |      | 1.1  | 1.2  | 1.1  | 1.5  | 3.3  | 1.3  | 4.8  | 3.4  | 2.7  | 3.4  | 5.8  | 4.1  | 3.6  | 4.6  | 10.2 | 10.4 | 5.5  | 7.6  | 5.9  |
| T16-1 | 1.3  |      | 0.9  | 1.5  | 1.6  | 1.3  | 5.0  | 2.8  | 3.1  | 3.2  | 3.1  | 2.3  | 8.7  | 6.9  | 5.1  | 5.1  | 4.4  | 6.5  | 5.2  | 7.3  | 7.1  |
| T16-7 | 1.5  |      | 1.1  | 1.6  | 1.6  | 1.4  | 5.3  | 1.6  | 4.5  | 5.1  | 3.6  | 4.1  | 14.1 | 3.1  | 6.9  | 4.4  | 4.4  | 6.2  | 7.0  | 2.0  | 3.8  |
| T17-1 | 2.2  |      | 0.7  | 0.8  | 0.9  | 1.3  | 2.8  | 2.4  | 3.4  | 5.2  | 1.8  | 3.7  | 3.5  | 1.9  | 2.2  | 5.1  | 4.1  | 4.4  | 3.0  | 10.1 | 7.1  |
| T17-7 | 1.2  |      | 1.8  | 1.6  | 1.5  | 1.1  | 3.6  | 3.2  | 3.0  | 3.6  | 4.8  | 5.4  | 8.3  | 8.3  | 4.7  | 5.5  | 6.8  | 4.9  | 4.1  | 5.2  | 7.5  |
| T18-1 | 1.2  |      | 0.9  | 2.3  | 1.6  | 0.6  | 6.3  | 1.5  | 9.5  | 5.0  | 1.3  | 2.9  | 3.1  | 1.4  | 2.8  | 5.7  | 2.6  | 4.3  | 3.9  | 6.0  | 7.8  |
| T18-7 | 0.3  | 1.7  | 1.1  | 1.5  | 1.7  | 1.3  | 4.7  | 2.0  | 3.9  | 3.9  | 4.7  | 23.7 | 9.8  | 3.2  | 5.6  | 6.1  | 4.1  | 7.6  | 4.1  | 5.9  | 7.9  |
| T19-1 | 1.4  |      | 1.0  | 2.0  | 1.8  | 1.2  | 1.6  | 1.9  | 4.1  | 3.9  | 3.1  | 3.8  | 4.9  | 2.9  | 3.5  | 3.2  | 4.8  | 5.9  | 5.4  | 6.8  | 6.1  |
| T19-7 | 0.9  | 1.0  | 1.1  | 2.1  | 1.9  | 2.4  | 3.5  | 3.5  | 3.4  | 3.4  | 4.4  | 21.4 | 8.5  | 5.8  | 4.9  | 6.2  | 7.7  | 4.1  | 4.9  | 7.7  | 6.4  |

| Site    | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
|---------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| T20-01  | 0.9  | 0.7  | 0.7  | 1.6  | 2.5  | 1.3  | 4.9  | 2.3  | 2.2  | 3.5  | 6.1  | 12.4 | 7.7  | 7.2  | 1.9  | 6.3  | 4.6  | 5.9  | 4.3  | 6.0  | 3.2  |
| T20-07  | 3.9  | 0.8  | 0.9  | 0.8  | 2.7  | 0.7  | 4.4  | 1.4  | 4.9  | 5.2  | 0.9  | 2.3  | 14.7 | 2.2  | 3.9  | 2.4  | 2.8  | 4.9  | 7.6  | 6.5  | 7.3  |
| T21-01  | 1.2  |      | 0.7  | 1.4  | 1.5  | 1.3  | 1.2  | 1.6  | 3.4  | 1.5  | 1.7  | 3.5  | 5.6  | 4.2  | 4.6  | 4.3  | 4.2  | 7.5  | 2.3  | 9.7  | 7.7  |
| T21-07  | 3.8  |      | 1.9  | 1.4  | 2.0  | 1.5  | 3.3  | 1.6  | 2.5  | 4.1  | 3.8  | 6.2  | 10.4 | 4.7  | 4.4  | 4.1  | 4.2  | 5.2  | 6.4  | 7.9  | 5.8  |
| T22-01  | 0.9  |      | 0.7  | 2.6  | 1.7  |      | 3.8  | 3.0  | 3.2  | 3.5  | 3.5  | 9.6  | 16.3 | 12.9 | 5.4  | 6.4  | 4.5  | 4.9  | 5.8  | 15.4 | 7.9  |
| T22-07  | 1.4  |      | 0.8  | 1.4  | 2.1  | 1.2  | 3.2  | 2.0  | 5.4  | 2.5  | 2.2  | 3.5  | 10.1 | 2.7  | 4.1  | 4.2  | 5.0  | 7.2  | 5.7  | 5.8  | 6.1  |
| T23-01  | 1.1  |      | 1.0  | 1.2  | 2.0  | 1.3  | 1.1  | 2.6  | 4.2  | 2.9  | 6.2  | 8.0  | 12.3 | 5.5  | 4.1  | 4.2  | 3.2  | 4.5  | 1.9  | 4.9  | 6.1  |
| T23-07  | 1.1  |      | 0.7  | 2.2  | 1.5  | 1.4  | 3.4  | 2.4  | 2.6  | 4.2  | 4.4  | 4.2  | 8.8  | 3.9  | 4.3  | 5.2  | 4.4  | 5.1  | 3.4  | 6.6  | 5.6  |
| T24-01  | 1.1  |      | 0.7  | 1.1  | 1.6  | 1.3  | 1.5  | 0.9  | 1.2  | 2.9  | 1.4  | 6.2  | 17.9 | 3.7  | 5.9  | 4.6  | 4.8  | 5.0  | 3.6  | 5.9  | 4.8  |
| T24-07  | 1.7  |      | 1.4  | 2.1  | 3.0  | 1.6  | 2.6  | 3.7  | 5.3  | 3.7  | 4.6  | 5.3  | 9.9  | 4.8  | 4.0  | 6.8  | 5.2  | 4.3  | 3.9  | 5.2  | 6.9  |
| T25-01  | 1.0  | 1.0  | 1.8  | 1.6  | 2.1  | 2.4  | 3.0  | 3.2  | 2.8  | 6.1  | 5.2  | 6.7  | 14.4 | 6.3  | 3.2  | 5.3  | 4.5  | 12.7 | 4.2  | 5.8  | 6.8  |
| T25-07  | 0.8  | 1.8  | 0.7  | 0.8  | 0.3  | 1.1  | 3.2  | 1.5  | 3.6  | 3.1  | 1.8  | 3.1  | 2.5  | 3.4  | 5.9  | 3.7  | 3.4  | 7.8  | 2.8  | 10.1 | 6.7  |
| T25B-01 |      |      | 2.1  | 1.6  | 1.4  | 0.7  | 2.0  | 2.6  | 3.7  | 3.3  | 5.1  | 6.5  | 14.2 | 4.8  | 4.4  | 5.0  | 4.5  | 8.7  | 1.5  | 3.6  | 5.3  |
| T25B-07 |      |      | 1.0  | 0.9  | 0.2  | 2.1  | 1.2  | 0.9  | 4.7  | 1.0  | 2.2  | 4.2  | 12.1 | 9.2  | 5.3  | 4.4  | 4.1  | 7.0  | 2.4  | 5.2  | 5.2  |
| T26-01  | 0.8  | 1.8  | 4.5  | 5.7  | 1.6  | 1.6  | 4.4  | 2.7  | 6.2  | 3.6  | 2.7  | 6.8  | 4.6  | 4.1  | 2.8  | 4.0  | 2.3  | 5.6  | 3.6  | 6.6  | 6.6  |
| T26-07  | 1.4  |      | 0.8  | 2.1  | 1.7  | 1.3  | 2.1  | 3.5  | 3.7  | 3.0  | 3.1  | 4.5  | 10.1 | 3.6  | 5.0  | 4.6  | 5.5  | 5.4  | 3.8  | 5.7  | 5.4  |
| T26B-01 |      |      | 0.6  | 2.6  | 1.4  | 1.2  | 2.3  | 1.7  | 3.3  | 3.1  | 2.8  | 3.8  | 4.2  | 2.5  | 3.3  | 4.5  | 4.9  | 19.1 | 3.5  | 5.3  | 5.5  |
| T26B-07 |      |      | 4.6  | 1.7  | 1.3  | 1.5  | 2.3  | 2.9  | 2.7  | 4.2  | 2.7  | 4.7  | 7.3  | 5.9  | 7.0  | 5.5  | 5.7  | 11.9 | 3.6  | 2.8  | 4.9  |
| T26C-01 |      |      | 2.4  | 2.4  | 1.5  | 1.4  | 0.7  | 3.6  | 3.7  | 3.4  | 7.1  | 7.8  | 9.1  | 4.0  | 5.4  | 5.5  | 1.3  | 10.6 | 6.1  | 6.3  | 4.2  |
| T26C-07 |      |      | 98.0 | 2.2  | 1.5  | 1.3  | 1.4  | 1.9  | 5.9  | 3.0  | 3.1  | 6.1  | 8.7  | 4.0  | 5.4  | 4.2  | 1.5  | 9.2  | 2.7  | 4.8  | 6.6  |
| T27-01  | 0.8  | 2.6  | 2.1  | 1.2  | 1.4  | 0.3  | 1.7  | 4.0  | 4.8  | 3.3  | 2.3  | 6.5  | 14.9 | 4.0  | 4.5  | 2.4  | 0.5  | 11.6 | 3.8  | 4.3  | 8.0  |
| T27-07  | 2.1  |      | 0.0  | 1.2  | 0.0  | 0.0  | 1.4  | 0.0  | 2.4  | 1.8  | 4.5  | 4.9  | 7.7  | 5.0  | 3.3  | 20.2 | 1.5  | 7.5  | 3.3  | 2.4  | 9.0  |
| T27B-01 |      |      | 1.3  | 2.2  | 1.0  | 1.2  | 21.6 | 1.6  | 1.3  | 2.8  | 2.3  | 8.2  | 11.3 |      |      |      | 1.6  | 5.4  | 3.4  | 4.2  | 5.7  |
| T27B-07 |      |      | 0.6  | 1.1  | 1.4  | 1.5  | 1.2  | 3.1  | 4.1  | 2.9  | 5.6  | 3.7  | 5.2  |      |      |      | 0.4  | 7.1  | 3.2  | 3.0  | 5.3  |

**Figure 5-33. Central Middle Fly (Mabaduam to Manda) sampling site ANC:MPA values arranged by downstream distance and time. Updated from Bolton and Pickup (2021).**

| Site   | 2000 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
|--------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| T27B-1 |      |      |      |      |      |      |      |      |      |      |      |      |      |      | 4.4  | 4.4  | 4.3  | 5.7  | 5.4  | 3.4  | 4.2  | 5.7  |
| T27B-7 |      |      |      |      |      |      |      |      |      |      |      |      |      |      | 4.0  | 3.1  | 6.6  | 5.3  | 7.1  | 3.2  | 3.0  | 5.3  |
| T28-1  | 3.3  | 1.6  |      | 0.9  | 0.4  | 1.4  | 1.7  | 1.5  | 1.5  | 71.9 | 3.1  | 2.2  | 4.0  | 9.4  | 3.5  | 3.9  | 3.8  | 6.6  | 5.4  | 1.9  | 3.9  | 6.6  |
| T28-7  |      | 1.1  |      | 2.9  | 1.6  | 1.2  | 1.9  | 1.1  | 1.2  | 1.6  | 3.3  | 3.1  | 3.8  | 8.7  | 5.8  | 6.0  | 3.6  | 2.8  | 12.0 | 3.1  | 5.6  | 2.8  |
| T28C-1 | 3.8  |      |      | 1.7  | 1.2  | 2.1  | 1.6  | 1.2  | 2.0  | 4.0  | 2.1  | 2.7  | 4.6  | 7.1  | 3.2  | 1.8  | 4.2  | 3.8  | 7.9  | 3.1  | 2.3  | 3.8  |
| T28C-7 |      |      |      | 4.7  | 2.1  | 1.1  | 1.3  | 1.1  | 1.6  | 2.4  | 1.8  | 2.1  | 3.9  | 1.3  | 2.6  | 1.7  | 3.0  | 3.7  | 6.5  | 3.1  | 3.6  | 3.7  |
| T29-1  |      | 1.2  |      | 1.8  | 1.8  | 1.1  | 1.6  | 1.3  | 1.2  | 2.6  | 2.5  | 2.0  | 4.3  | 5.1  | 2.8  | 5.7  | 3.7  | 11.0 | 14.1 | 2.9  | 3.7  | 11.0 |
| T29-7  |      | 1.1  |      | 1.3  | 1.2  | 1.1  | 1.4  | 1.6  | 1.5  | 2.3  | 1.8  | 1.9  | 5.2  | 8.8  | 6.5  | 3.8  | 3.3  | 7.9  | 7.4  | 2.6  | 5.2  | 7.9  |
| T30-1  | 3.6  | 1.9  |      | 1.7  | 1.5  | 1.1  |      | 0.9  | 1.7  | 2.0  | 3.0  | 3.9  | 8.6  | 16.6 | 5.8  | 3.6  | 3.3  | 4.3  | 6.9  | 3.8  | 5.9  | 4.3  |
| T30-7  |      | 0.9  |      | 2.2  | 1.8  | 1.1  | 1.7  | 1.3  | 1.3  | 3.2  | 2.5  | 3.4  | 2.9  | 3.7  | 3.2  | 5.0  | 3.5  | 2.8  | 9.3  | 3.1  | 6.3  | 2.8  |
| T30B-1 |      |      |      | 1.4  | 2.8  |      |      | 3.3  | 0.6  | 2.9  | 3.1  | 4.6  | 3.1  | 4.8  | 4.2  | 1.4  | 3.1  | 3.9  | 2.8  | 3.2  | 2.9  | 3.9  |
| T30B-7 |      |      |      | 1.3  | 1.4  |      |      | 1.1  | 1.4  | 1.7  | 2.4  | 2.8  | 4.3  | 12.6 | 4.6  | 2.0  | 4.1  | 4.0  | 4.3  | 5.8  | 4.0  |      |
| T31-1  |      | 3.0  |      | 1.6  | 1.4  | 0.9  | 1.5  | 2.3  | 1.7  | 2.1  | 2.1  | 2.2  | 3.6  | 4.2  | 8.7  | 2.2  | 3.1  | 4.2  | 3.6  | 5.3  | 7.1  | 4.2  |
| T31-7  |      | 2.1  |      | 1.1  | 1.7  |      | 1.3  | 1.5  | 1.7  | 2.1  | 1.9  | 2.6  | 4.2  | 11.6 | 5.4  | 2.2  | 3.5  | 3.6  | 3.2  | 3.8  | 4.3  | 3.6  |
| T31B-1 |      |      |      | 0.7  | 1.0  | 0.9  | 1.1  | 2.2  | 1.6  | 1.3  | 2.3  | 3.2  | 5.4  | 5.7  | 12.7 | 4.4  | 3.8  | 4.0  | 4.5  | 5.4  | 7.7  | 4.0  |
| T31B-7 |      |      |      | 1.2  | 0.9  | 0.6  | 1.3  | 1.1  | 2.1  | 1.7  | 2.0  | 2.1  | 3.2  | 9.3  | 5.0  | 4.9  | 3.1  | 3.3  | 5.1  | 4.7  | 4.3  | 3.3  |
| T31C-1 | 3.1  |      |      | 0.8  | 2.0  |      |      | 1.7  | 1.6  | 1.9  | 2.2  | 2.2  | 4.1  | 6.1  | 3.7  | 5.1  | 1.5  | 3.8  | 3.6  | 3.2  | 5.7  | 3.8  |
| T31C-7 |      |      |      | 1.0  | 0.8  |      |      | 1.2  | 1.3  | 1.2  | 3.7  | 4.3  | 3.6  | 7.5  | 2.0  | 4.0  | 4.9  | 2.0  | 4.3  | 3.7  | 3.4  | 2.0  |
| T32-1  |      | 1.4  |      | 1.5  | 1.6  | 1.2  | 1.2  | 1.0  | 0.8  | 2.5  | 2.1  | 2.9  | 2.2  | 4.7  | 4.1  | 3.9  | 2.5  | 3.3  | 5.4  | 2.9  | 7.0  | 3.3  |
| T32-7  |      | 1.0  | 0.7  | 2.5  | 3.0  | 0.8  | 1.1  | 3.3  | 1.7  | 0.8  | 2.1  | 1.9  | 6.8  | 6.4  | 5.0  | 3.3  | 3.3  | 3.8  | 5.2  | 4.9  | 3.3  | 3.8  |
| T33-1  | 2.3  | 1.4  |      | 0.8  | 0.9  | 1.1  | 0.7  | 1.6  | 1.8  | 1.2  | 1.7  | 2.3  | 3.5  | 4.0  | 2.9  | 5.7  | 3.1  | 6.9  | 3.5  | 3.1  | 5.7  | 6.9  |
| T33-7  |      | 1.5  |      | 0.7  | 2.2  | 1.1  | 0.6  | 2.2  | 1.4  | 1.6  | 2.3  | 2.2  | 5.2  | 6.7  | 3.0  | 2.0  | 2.9  | 8.2  | 3.5  | 9.0  | 9.7  | 8.2  |
| T33B-1 | 2.1  |      |      | 1.1  | 1.3  | 0.9  | 1.1  | 1.2  | 3.5  | 3.4  | 2.0  | 2.9  | 3.7  | 8.9  | 5.9  | 4.2  | 4.5  | 4.9  | 5.0  | 6.1  | 4.0  | 4.9  |
| T33B-7 |      |      |      | 0.9  | 0.7  | 0.9  | 0.9  | 0.5  | 1.3  | 1.6  | 2.5  | 2.4  | 3.2  | 4.3  | 2.5  | 3.1  | 3.7  | 3.5  | 2.0  | 5.0  | 5.0  | 3.7  |
| T34-1  | 2.8  | 0.8  | 0.6  | 0.7  | 1.4  |      | 0.8  | 1.4  | 1.4  | 3.5  | 1.8  | 1.5  | 1.6  | 5.6  | 3.5  | 3.7  | 2.7  | 4.1  | 3.7  | 4.6  | 5.6  | 4.1  |
| T34-7  |      | 0.9  | 0.5  | 0.8  | 0.9  | 0.8  | 1.2  | 3.3  | 1.2  | 1.6  | 2.1  | 2.0  | 4.1  | 4.9  | 1.8  | 4.6  | 5.9  | 2.6  | 3.8  | 3.4  | 6.0  | 2.6  |
| T34B-1 |      |      |      | 0.9  | 1.0  | 0.8  | 1.0  | 0.8  | 1.1  | 1.2  | 1.6  | 1.8  | 3.1  | 4.9  | 1.4  | 4.2  | 1.8  | 4.0  | 3.6  | 2.6  | 8.4  | 4.0  |
| T34B-7 |      |      |      | 0.7  | 1.0  | 0.8  | 1.1  | 1.0  | 2.1  | 2.3  | 1.9  | 2.3  | 3.1  | 4.1  | 3.4  | 3.1  | 3.2  | 4.1  | 4.5  | 4.7  | 7.1  | 4.1  |
| T35-1  | 1.8  | 1.0  | 1.8  | 2.2  | 0.6  | 0.5  | 0.8  | 1.3  | 2.7  | 5.0  | 1.8  | 2.0  | 3.4  | 5.4  | 5.8  | 4.1  | 2.7  | 4.0  | 3.3  | 3.5  | 4.3  | 4.0  |
| T35-7  |      | 0.9  |      | 0.7  | 0.5  | 0.7  | 1.2  | 1.0  | 1.1  | 2.3  | 1.1  | 1.5  | 2.3  | 4.4  | 4.2  | 5.8  | 2.9  | 4.1  | 3.8  | 2.8  | 4.8  | 4.1  |
| T35B-1 | 2.8  |      |      | 1.4  | 1.6  | 0.5  | 1.1  | 1.0  | 2.5  | 1.9  | 3.8  | 2.8  | 2.8  | 1.0  | 11.9 | 3.9  | 2.9  | 4.9  | 4.1  | 4.0  | 3.3  | 4.9  |
| T35B-7 |      |      |      | 0.9  | 2.2  | 1.1  | 1.2  | 1.1  | 1.1  | 3.4  | 1.8  | 2.7  | 0.8  | 4.5  | 3.4  | 2.6  | 2.9  | 1.7  | 3.6  | 1.9  | 4.9  | 1.7  |
| T36-1  | 2.6  | 0.9  | 2.8  | 0.9  | 1.5  | 0.8  | 1.1  | 2.8  | 1.1  | 1.7  | 2.4  | 2.4  | 0.6  | 6.0  | 2.2  | 3.3  | 3.1  | 8.9  | 4.2  | 2.4  | 3.1  | 8.9  |
| T36-7  | 3.6  | 73.5 |      | 1.0  | 0.7  | 0.6  | 1.1  | 2.0  | 1.4  | 3.5  | 1.5  | 0.9  | 0.7  | 1.4  | 2.7  | 2.7  | 3.5  | 3.8  | 4.1  | 2.4  | 3.9  | 3.8  |
| T36B-1 |      |      |      | 1.5  |      | 0.7  | 1.2  | 1.7  | 1.0  | 1.4  | 2.5  | 2.6  | 5.5  | 2.9  |      | 3.6  | 6.0  | 4.3  | 3.6  | 1.5  | 2.8  | 4.3  |
| T36B-7 |      |      |      | 0.8  |      | 0.5  | 0.6  | 1.8  | 4.7  | 0.9  | 1.6  | 0.0  | 2.2  | 1.8  | 3.0  | 1.9  | 2.2  | 7.9  | 3.3  | 3.6  | 8.0  | 7.9  |

**Figure 5-34. Lower Middle Fly (Manda to Everill Junction) sampling site ANC:MPA values arranged by downstream distance and time. Updated from Bolton and Pickup (2021).**

# CHAPTER SIX – MODELLING THE IMPACT OF A TSF ON THE UPPER RIVER SYSTEM

## DEALING WITH UNCERTAINTY IN INPUT VARIABLES

Models are approximations of physical systems and processes and are also subject to the limitations of imperfect science. As such, model predictions are subject to error. We examine the potential range of model errors in the Appendices which describe model development and, as part of the calibration process, compare observed and predicted results as part of the validation process. Other sources of uncertainty derive from the input data used to drive the models. In this section, before presenting model predictions of TSF impact, we describe five main sources of uncertainty resulting from unknowns in model input data and how they are dealt with. These are:

- Future changes in the mine plan affecting inputs of waste rock and tailings including amounts, timings and geochemistry.
- Assumptions about EWRDs, notably whether there will be one or two after 2030.
- Assumptions about EWRD loss rates, i.e. whether to use a 5% rate or a 2% rate.
- The magnitude, impact and likelihood of a major landslide. We have modelled a case with a single landslide based on early Harvey Creek measured sidewall erosion (Marshall, 2004), (Pickup and Ridd, 2022), (Fig. 3-8). However, we have reduced the inputs to the Ok Mani system by an arbitrary 50% because the most likely site for a new EWRD is the Ok Kumuip (see Fig. 2-2 for location) which has a smaller catchment area and therefore less runoff.
- Potential effects of climate change.

## MINE PLAN

We have used Mine Plan 240822 (AMC, 2024) as a firm prediction of future events and have built the modelling studies on that basis. However, plans do change and minor variations are expected. Overall, however, over the last 20 years, mine life has been extended by up to 40 years. Further extensions may well occur based on ore availability, metal prices and many other factors. Material changes in mine life and associated issues will be dealt with between OTML and the Government of PNG at the appropriate time.

## EWRD ASSUMPTIONS

While this study is concerned with identifying the impact of a TSF, there are two waste rock management plans which may have a simultaneous impact on the relative effectiveness of a TSF in reducing the supply of tailings-size material. These involve construction of an engineered waste rock dump (EWRD-1) on the Sulphide Creek system on the north side of the mine (currently in progress) and a second engineered dump probably on the Ok Mani system on the south side of the mine (EWRD-2). This dump is currently only in the conceptual stage but will probably be built on the Ok Kumuip if it proceeds (see Fig. 2-2 for location). Both involve significant construction challenges and effective runoff management if they are to retain the major proportion of delivered waste for a long period of time. As we do not have sufficient information to model the effectiveness of these dumps, we have assumed an annual loss rate of 5% of delivered material for that year plus 5% of total dump contents. Based on behaviour of the failing dumps and the location of the EWRDs, we have used a 5% rate and this has been the practice in upper river system modelling over the last decade. Using the Vancouver Dump inputs plus EWRD-1 for ten years of dumping from 2025 to 2030 as a model adds 270 Mt of waste rock to the EWRD of which 81 Mt is lost. This includes two years of 10% loss to cover the construction period. We have previously trialled a 2% loss rate on the Vancouver Dump (Pickup and Ridd, 2024) which gives a loss of 35 Mt which we consider very optimistic for an early stage dump in a landslide-prone area.

## POTENTIAL LANDSLIDE IMPACT

In Chapter Three we report the occurrence of large landslides, especially in the early stages of waste rock dump development when potentially unstable hillslopes with weathered regolith lose their stabilising forest cover and are disturbed by access road construction and activities such as tipping on head slopes. The largest landslides have been known to match annual waste rock production but over a shorter period, even when erosion of runout zones is accounted for. To compare the increase in landslide-generated sand and silt production on the reduction in river sediment load once a TSF is operational, we have run the *OKTUGS* model with a set of landslide inputs based on those occurring in the early development of the Southern Dump and Harvey Creek (see Chapter Three for details).

## EFFECTS OF CLIMATE CHANGE

There is very limited information on the impacts of climate change in Papua New Guinea. Year to year variation is strongly influenced by the El Niño-Southern Oscillation of which there are two extreme phases: El Niño and La Niña. There is also a neutral phase. Generally, in Papua New Guinea, El Niño years are usually drier than normal while La Niña events are usually wetter but not always. La Niña-associated prolonged rainfall has led to flooding and landslides, whilst El Niño-associated droughts have also taken a toll on Papua New Guinea generally, including disrupting navigation on the Fly River (Marshall, 2024). The Indian Ocean Dipole may also have an effect but this is not as well understood (Mathews *et al*, 2013). The strong topographic influences which affect river flows in both the Upper Fly and the Ok Tedi and reaches downstream are also significant

The methods used to generate flows for modelling in this study (see Appendices One and Two) have been derived from river flow sequences largely from the current period and include both wet and dry sequences.

Observations of recent climate change and future predictions are summarised in the PNG Country Report ([www.pacificclimatechangescience.org](http://www.pacificclimatechangescience.org), 2013). They indicate that temperatures have warmed and will continue to warm. Annual and seasonal rainfall is projected to increase by the end of the century, along with extreme rainfall events. Drought frequency is projected to decrease by the end of the century but there are no clear trends in rainfall since 1945. However, predictions are not specific enough to be used in this modelling exercise.

Australia's State of the Climate Report (CSIRO and Bureau of Meteorology, 2024) where recent climate change is much better understood than in PNG, reports above average to very much above average rainfalls across much of northern Australia. Rainfall decile ranges (a measure of variability) have also been very much above average. However, rainfall during the last decade has been closer to the long-term average than in the previous two decades.

Extrapolating trends from Northern Australia with its flat topography to mountain areas in Papua New Guinea is questionable. To see if any trends can be detected from a more localised analysis, five of the longest records from OTML-operated recording sites in the Fly River region have been plotted in Fig. 6-1 covering mountain environments (Falomian, Kumkit and Tabubil), the piedmont zone (Kiunga) and the coastal region (Obo). Data are presented as cumulative totals, with extrapolated trends from apparent pre-change periods plotted as dotted lines. Lines of constant slope indicate no long term variation. Dotted trend lines identify changes in slope and if marked on a single station record, may or may not indicate a change in long term rainfall regime. Kumkit and Kiunga show a break in slope, both starting around the same time in the year 2000 which coincides with the time when reports of increasing rainfall in northern Australia began<sup>8</sup>. Kumkit suggests an increase in rainfall, as do Kiunga and Obo. Tabubil and Falomian show no break in slope and therefore no change in rainfall regime so the regional pattern of change is contradictory. However, the rainfall records contain gaps which can affect the slopes of the trend lines to varying degrees. While small gaps can be infilled using various statistical techniques, this did not prove feasible on rainfall records with longer gaps. Data gaps are greater in early rainfall records which suggests

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<sup>8</sup> See <https://www.csiro.au/en/research/environmental-impacts/climate-change/climate-change-information>

that some of the slope changes in Fig. 6-1 result from missing records rather than real change. This means that we have no consistent means of modifying hydrology model inputs (especially for extreme events) to accommodate a possible change in climate. However, given the likely importance of the mountain stations of Falomian and Tabubil in determining flows in the Ok Tedi and the Fly and given that these stations have minimal or no data gaps and no slope changes, we have treated the current river flow regime as being sufficiently representative of conditions in the near future when generating sediment and geochemistry model predictions over the next 20-30 years. We do not regard either mine inputs or model accuracy as being reliable beyond that time scale.

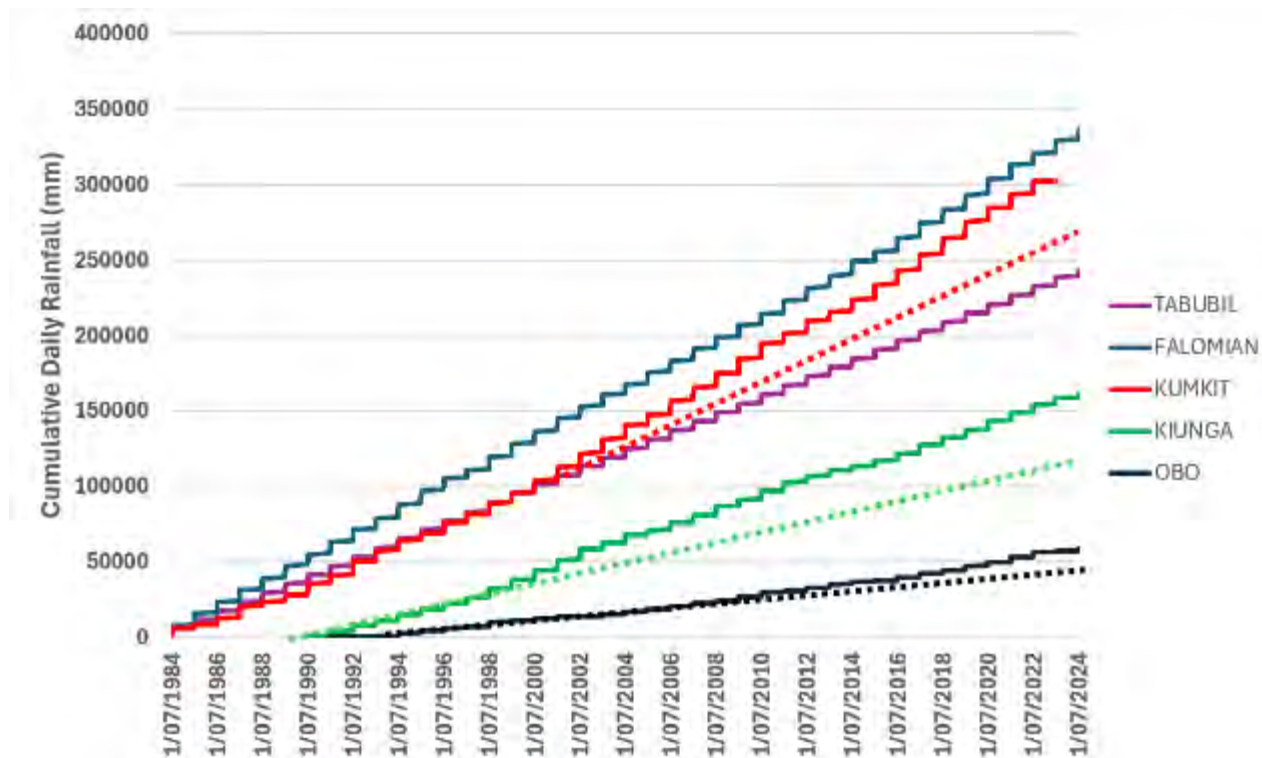


**Figure 6-1. Long term rainfall sequences for Fly River region rainfall stations.**

We have also conducted a preliminary analysis of water level records to test for indications of increases in the magnitude and frequency of extreme events (i.e. high water levels) over time in the existing record. Overall, we are unable to detect trends in either the number or the magnitude of extreme flood events. If there is a trend, it is masked by the water level changes that have occurred in response to deposition of mine waste. Recent record water levels on the lower Middle Fly in May 2024 are suspected to be related to backwater effects from a very large flood on the Strickland River rather than being generated by flows from within the catchment of the Ok Tedi and the Upper and Middle Fly River system (Pickup, 2025). It is not feasible to establish a link between these flows and climate change. A recent record water level at Haidauwogam in the upper Middle Ok Tedi appears to be due to instrument malfunction.

## SELECTING MODEL SCENARIOS

Given the uncertainties associated with these options, we have selected six scenarios to run through the upper river model, *OKTUGS* before eliminating those scenarios that give very similar rates of sediment discharge to the floodplain reaches of the Lower Ok Tedi and beyond. The remaining cases are then run through lower river model, *HEC-6* and then the particulate geochemistry mass balance models. The full range of scenarios is listed in Table 4. Where a scenario does not include an EWRD, the material is deposited in the failing dumps.

Of these cases, C is the Base Case while comparison with Case D allows for an assessment of the impact of a TSF. Cases A and B explore variations with and without a TSF assuming only one EWRD is constructed. Case E is used

to explore long term changes in the river system while the landslide case examines what impact a large landslide might have if a TSF is operating.

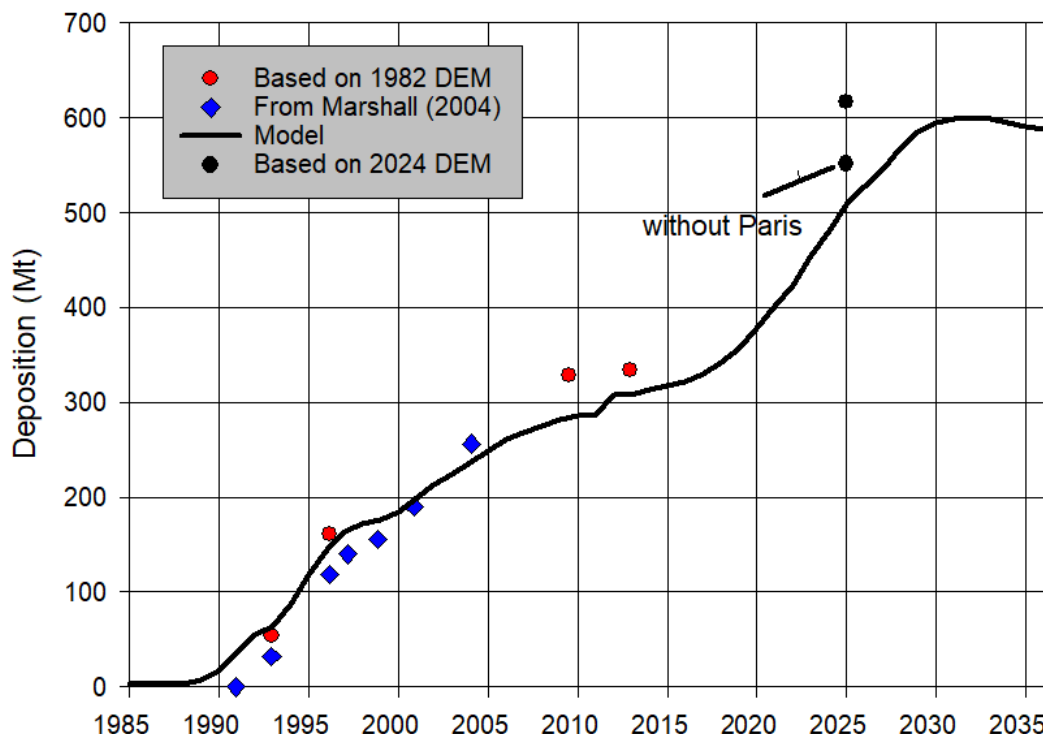
| TABLE 4. UPPER RIVER SEDIMENT TRANSPORT MODEL SCENARIOS |     |        |        |                              |
|---------------------------------------------------------|-----|--------|--------|------------------------------|
| CASE                                                    | TSF | EWRD-1 | EWRD-2 | EWRD LOSS <sup>9</sup>       |
| A                                                       | No  | Yes    | No     | N/a                          |
| B                                                       | Yes | Yes    | No     | 5%                           |
| C                                                       | Yes | Yes    | Yes    | 5%                           |
| D                                                       | No  | Yes    | Yes    | 5%                           |
| E                                                       | N/a | N/a    | N/a    | N/a                          |
| LANDSLIDE                                               | Yes | Yes    | Yes    | Landslide Case <sup>10</sup> |

## UPPER RIVER SYSTEM – MODEL RESULTS

### DEPOSITION PREDICTIONS

The Sulphide Creek system only retains very limited amounts of waste rock due to its steepness (Marshall, 2025) and, historically, has only retained large masses of runout material in its uppermost section (see Chapter Three). *OKTUGS* model results also show minimal deposition so are not presented here.

The Ok Mani System has retained 30-60% of delivered material with more in heavy dumping years, notably when surface flow tends to infiltrate deposits and moves downslope as throughflow which greatly reduces surface erosion. In the last few years, when annual dumping rates have increased from a long term average of 27 Mt/year to 52 Mt/Year, increased throughflow has been the norm and the model has underestimated the rate of deposition as Fig. 6-2 shows. Long term model predictions are shown in Fig. 6-3.



<sup>9</sup> EWRD loss refers to the rate at which material placed in a constructed dump is lost to the river system by erosion, slope failure etc. It is calculated as rate x input for each year plus rate x total dump contents in the previous year. The rate may vary over time and is higher in early years of dump construction. In this study we use a rate of 5%.

<sup>10</sup> See section above on Dealing with Uncertainty in Input Variables for detail on this special case,

**Figure 6-2. Observed and modelled deposition in the Ok Mani system. The Paris dump is fairly recent and lies outside model boundaries.**

The upper Ok Mani system does receive tailings but they are stored in limited amounts in gravel deposit interstices and mostly pass downstream as washload without deposition. Diversion to a TSF will thus have minimal effect on Ok Mani deposition. The observed and predicted rates of deposition in the Ok Mani system have been fairly constant until recently, apart from a period of less dumping from 2009 to 2018 when sediment transport rates were overestimated and deposition underestimated. Deposition reduces after 2030 in Plans C and D when an EWRD begins to operate whereas sediment continues to build up to a maximum around 2040 under Plans A and B, neither of which have an EWRD on the Ok Mani. Once dumping ceases, accumulated sediment begins to be removed in all Plans but at a slower rate than deposition during the accumulation period. Plan E gives an indication of the longevity of the Ok Mani system deposits. If no material was added after 2025, about 40% remains after 35 years.

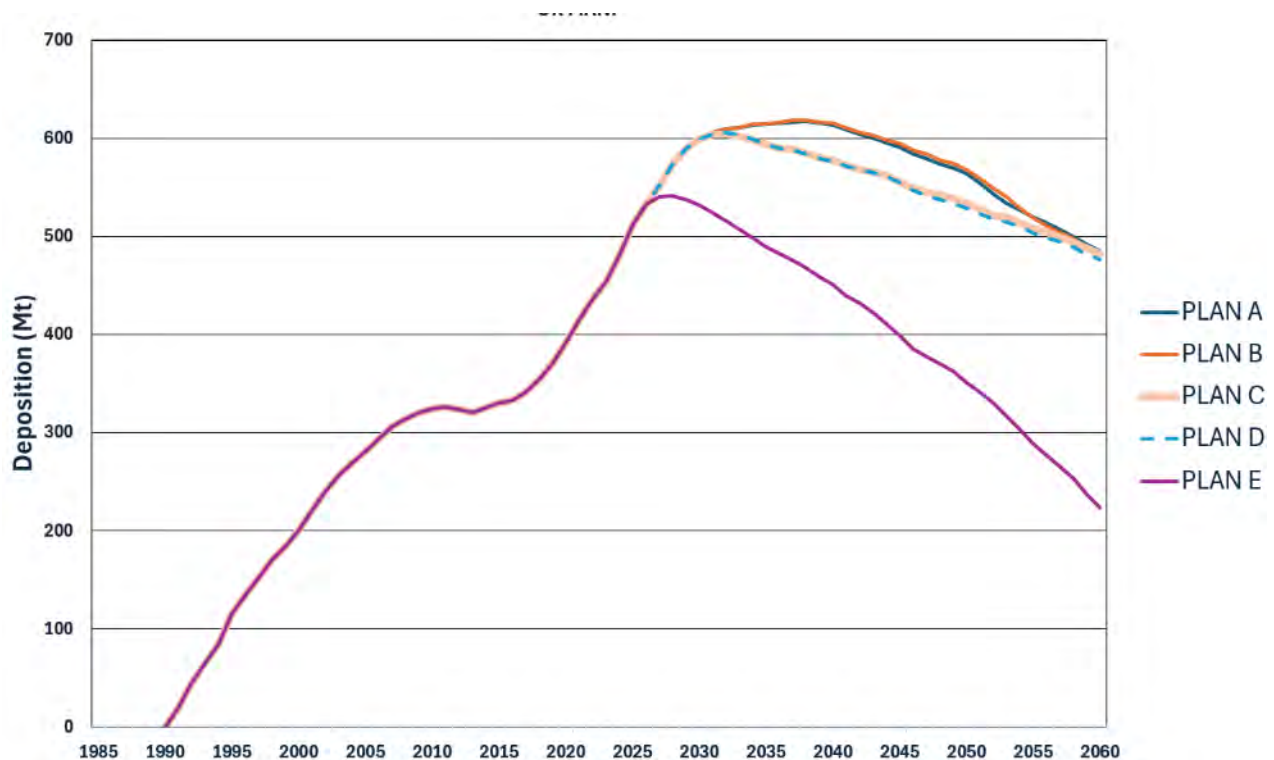


**Figure 6-3. Predicted deposition in the Ok Mani System. PLAN C is the scenario on which the permit request is expected to be based.**

The Middle Ok Tedi (Fig. 6-4) receives a continuing supply of material from the slowly eroding EWRD-1 on Sulphide Creek and from the Ok Mani system to the end of mine life and beyond, but at a reduced rate from around 2030 as waste rock inputs are reduced (see Chapter Three). Plan E indicates that, after about 25 years, the rate of accumulation approaches zero, probably because the rate of sediment loss by gravel abrasion to finer material which is then transported downstream begins to match inputs from the Mine Area Creeks. There is little difference between the amounts of deposition generated by each of Plans A, B, C, and D indicating that the Middle Ok Tedi is basically a gravel system and tailings mostly pass through as washload apart from at the downstream end of the lower braided reach (Fig. 2-5) when sand accumulates in the dredge slot reach at Bige.

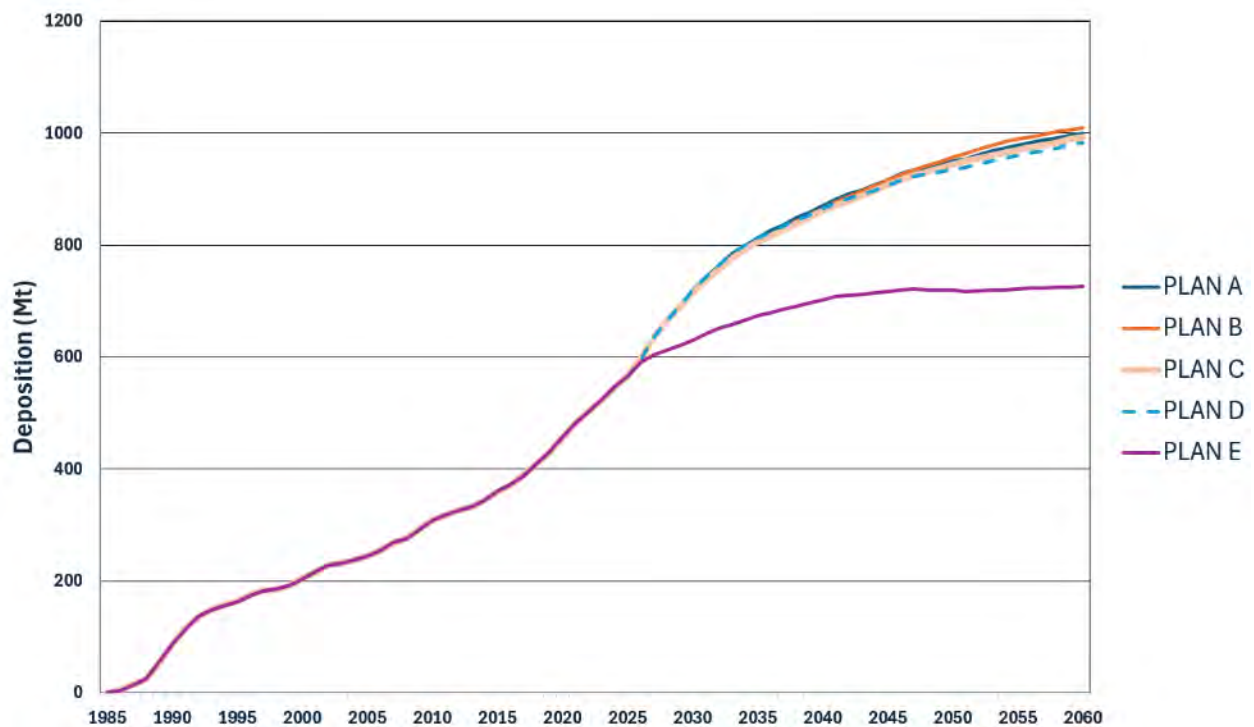


**Figure 6-4. Predicted deposition in the Middle Ok Tedi System. PLAN C is the scenario on which the permit request is expected to be based.**

## SUSPENDED SEDIMENT LOAD PREDICTIONS IN THE MIDDLE OK TEDI AND THE INFLUENCE OF THE TSF

The deposition predictions in the previous section largely describe the behaviour of the gravel component of the river sediment load. The diversion of tailings which are made up of sand and silt will not be reflected in gravel behaviour. However, both sand and silt will continue to be produced in the Mine Area Creeks and the Middle Ok Tedi as the outcome of gravel particle abrasion. Comparing behaviour both with and without a TSF in the suspended sediment load of the Middle Ok Tedi thus can still be done using TSS samples from the Middle Ok Tedi.

TSS sampling has been carried out at Ningerum about 2/3 of the way down the Middle Ok Tedi since the start of mine life. The method is mostly shore-based gulp sampling which produces results about 1/3 to 1/2 of the more representative depth integrated sampling procedure at Ok Tedi (Pickup and Clews, 2002). However, the Ningerum gulp sample dataset does give an indication of how sediment load is changing and will change into the future.

Figures 6-5 and 6-6 show gulp sample equivalents from *OKTUGS* model runs with Plans C and D. Note that the observed values are from instantaneous samples from one or a few points in the channel cross section whereas the model results are daily averages for the whole cross section and therefore show much less scatter.

Both Plan C and Plan D values show the increase in sediment load early in mine life and correctly reflect the increase in load after the Vancouver Landslide and the high valley wall erosion on Harvey Creek in the late 1980s and early 1990s. Thereafter, model values occupy a relatively narrow band (noting that a log scale is used) reflecting a relatively constant input of tailings until either the end of mine life or diversion of tailings to a TSF. TSS then decreases sharply before settling to a gradually declining trend. In terms of TSS at least, the TSF, once operational, changes values to a similar range to that experienced post mine closure.

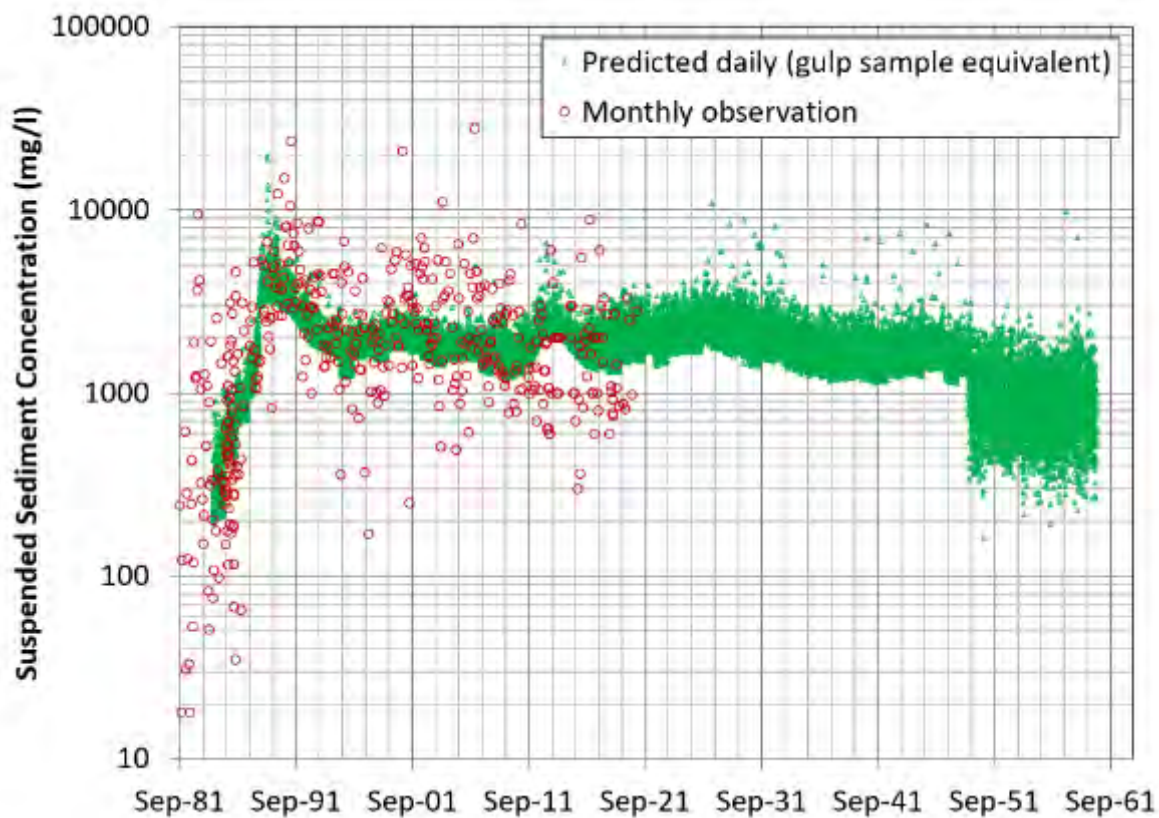


**Figure 6-5. Daily TSS PLAN D model predictions for Ningerum compared with monthly gulp sample values.**

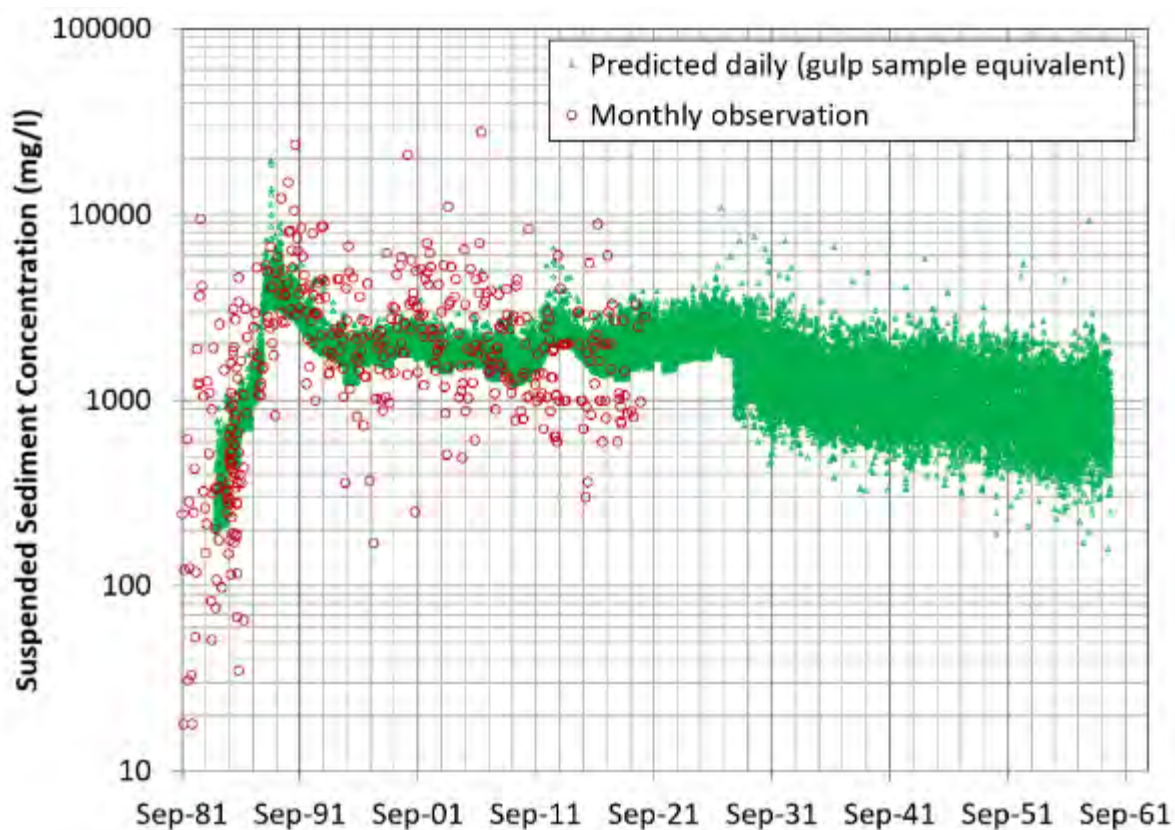


**Figure 6-6. Daily TSS PLAN C model predictions for Ningerum compared with monthly gulp sample values. PLAN C is the scenario on which the permit request is expected to be based.**

## SEDIMENT OUTPUT TO THE LOWER RIVER AND THE DREDGE FROM THE MIDDLE OK TEDI

Figures 6-7 and 6-8 show total output of sand and silt to the dredge site and the lower river system for Plans A to E. Note that all the amounts from 2030 for Plans A and D which do not include a TSF are very similar. Whether there is one EWRD or two only makes a small amount of difference in sand supply since the models tend to produce mostly silt either by direct loss from waste rock dumps or subsequent abrasion of river deposits. This reflects the large proportion of limestone and siltstone or mudstone in the waste rock.

Sand discharge is relatively high in the early years of mine life reflecting an average tailings discharge of 25 Mt/year but subsequently decreasing to an average of 17 Mt/year. The effect of the TSF in both Plans B and C (Fig. 6-7) results in a decrease in sand output to the lower river system and the dredge from around 17 Mt/year to an average of 6-7 Mt/year. Given a dredge sand capture efficiency of 85%, there may be issues for capping of the PCon store on the Ok Tedi west bank at Bige and closure of the dredge stockpiles on the east bank.

Silt load predictions (Fig. 6-8) follow a similar pattern over time to the sand predictions reflecting both higher tailings and waste rock input in the earlier years of mine life. While the total silt load decreases from about 23 Mt/year to 17 Mt year after 2013, the sand: silt ratio only declines from about 0.9 to 0.7 for Plans without a TSF. For plans with a TSF, the ratio declines to about 0.45 (Fig. 6-9) The effect of having a TSF not only means a substantial reduction in total sediment load but also a shift towards more silt in the load. Most of this material will remain in suspension during downstream transport and will form a major part of the sediment load delivered to the floodplain reaches downstream. This may have biological consequences as there are implications for aquatic biota, not just in water quality but also in less smothering by sand deposition in shelter and breeding areas on channel margins.

The long-term recovery pattern, after the cessation of riverine tailings disposal and waste rock dumping after mine closure shown in PLAN E, indicates a rapid recovery of both sand and silt delivery to lower levels over 5-6 years. This results from the removal over time of the most accessible material on the surface and in the upper layers of gravel deposits. There is little subsequent decline in sediment load which remains at a level perhaps 50% greater than estimated pre-mine levels.

The Landslide Case has been modelled given the observed impact of the Vancouver Landslide on TSS values in the Middle Fly (Figs. 3-11 and 3-12). However, a more suitable model associated with an EWRD on the Ok Mani system such as in the Ok Kumuip is the behaviour of sidewall erosion during the early years of waste rock dumping on Harvey Creek. Given the steepness of the area, this is thought to have released more relatively fresh rock than the Vancouver Landslide which may have contained more weathered material, hence the elevated TSS values down through the Middle Fly. As Figs. 6-6 and 6-7 show, the impact on sediment load delivered to the lower river is relatively small and unlikely to compromise TSF performance in reducing sediment load.

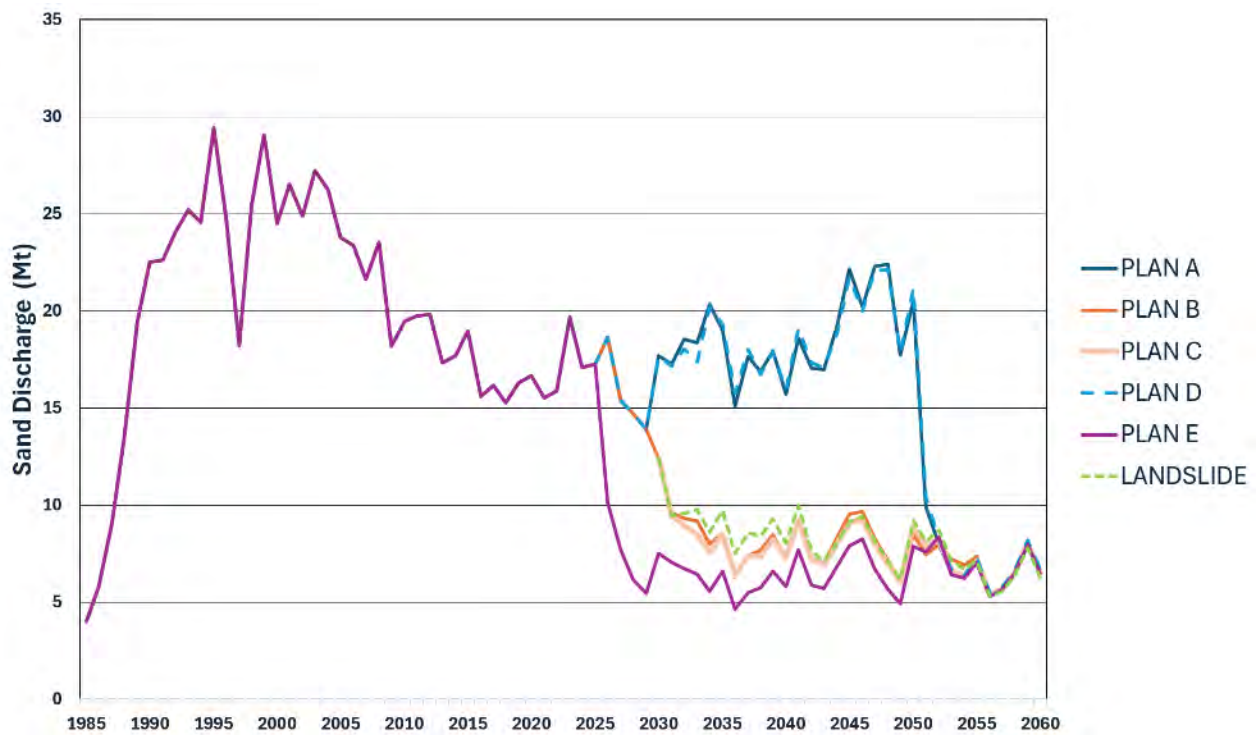


**Figure 6-7. Predicted sand output to the Dredge and the Middle Fly from the Middle Ok Tedi. PLAN C is the scenario on which the permit request is expected to be based.**

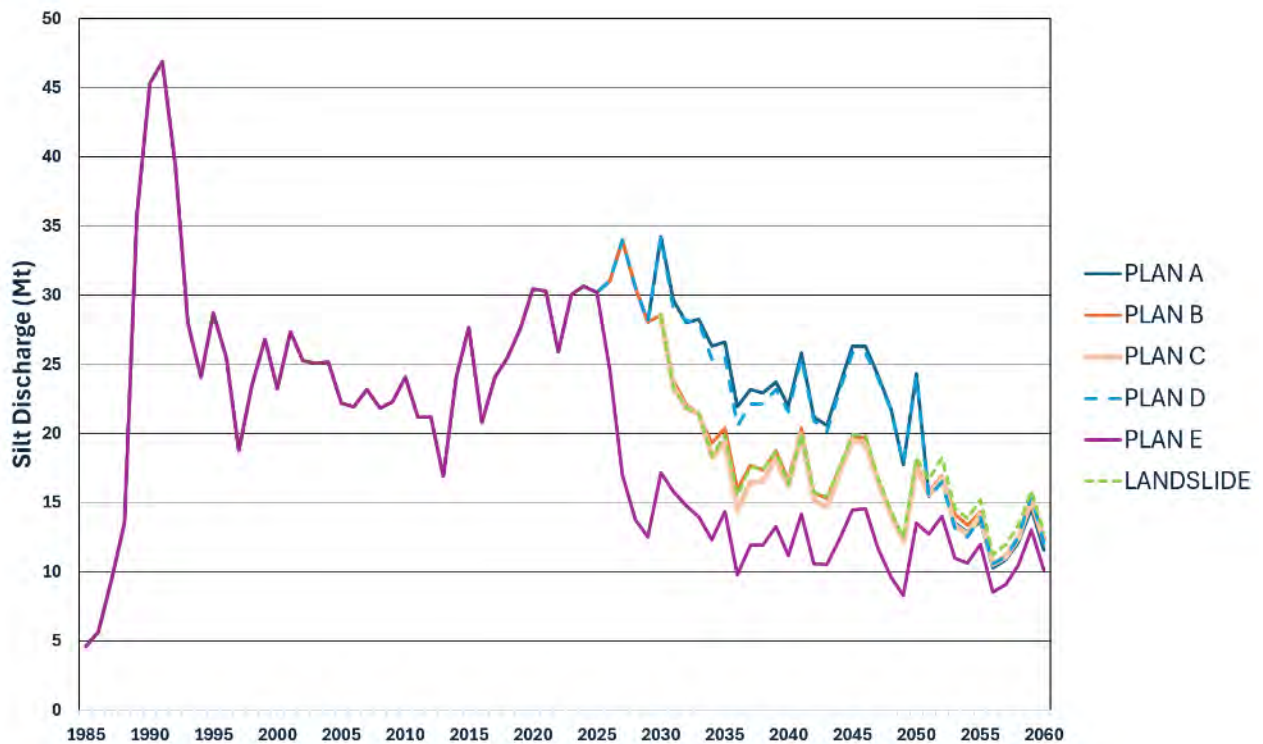


**Figure 6-8. Predicted silt output to the Dredge and the Middle Fly from the Middle Ok Tedi. PLAN C is the scenario on which the permit request is expected to be based.**

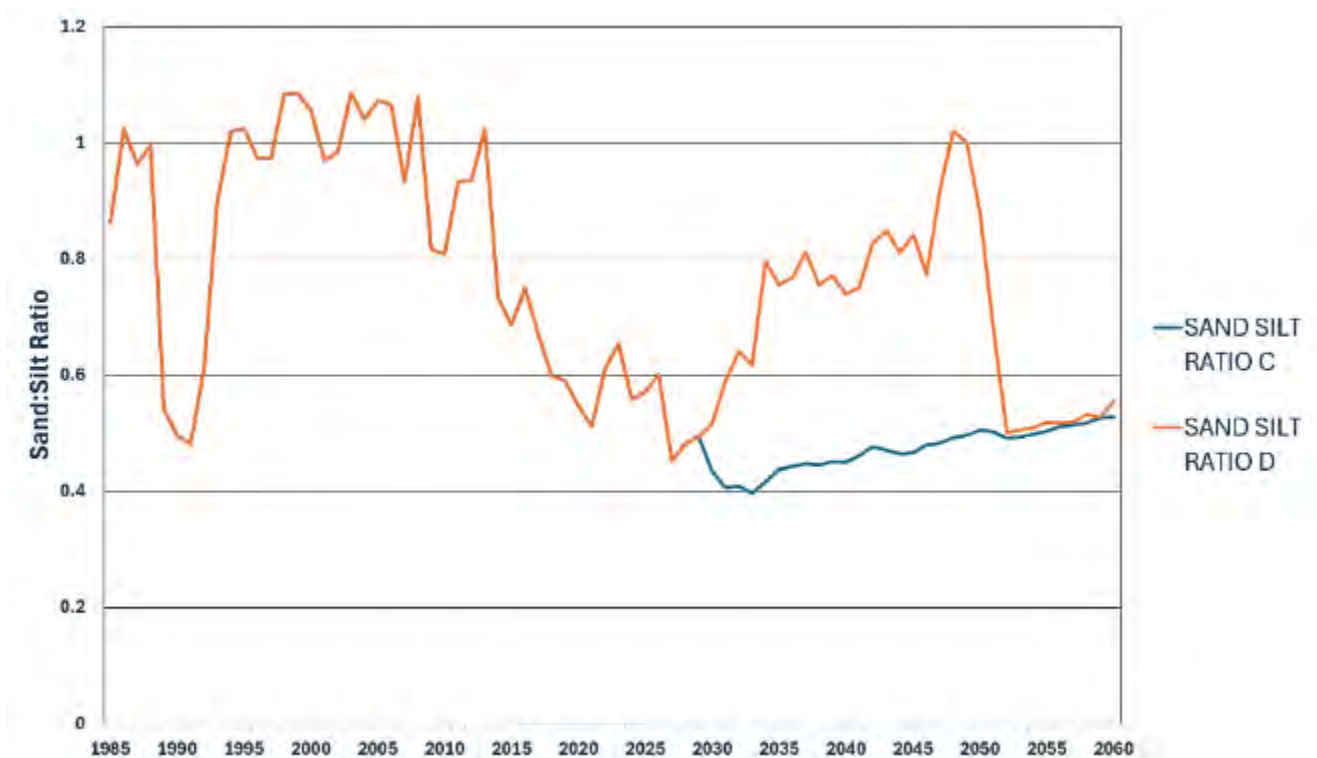


**Figure 6-9. Predicted sand: silt ratios in sediment delivered to the Dredge, the Lower Ok Tedi and the Middle Fly from the Middle Ok Tedi. PLAN C is the scenario on which the permit request is expected to be based.**

## EFFECTS OF A TSF ON THE UPPER RIVER SYSTEM SEDIMENTATION – A BRIEF SUMMARY

The behaviour of the Mine Area Creeks will continue to be largely governed by coarse waste rock inputs from failing dumps and the movement of already deposited coarse material moving down the system into the Middle Ok Tedi. Engineered waste rock dumps, if successfully constructed and operated, will substantially reduce new inputs to the system but will have minor effects on existing riverbed deposits and the downstream transfer of material.

The main body of material in the Ok Mani/Harvey Creek system will peak in 2030-2035 and will then slowly reduce as it is discharged to the Middle Ok Tedi.

The Sulphide Creek system will continue to discharge most delivered material quickly and will only store limited amounts.

The Middle Ok Tedi will continue to accumulate deposited material to 2060 and beyond.

At present, most tailings pass through the Mine Creeks and the Middle Ok Tedi as wash load and there will be limited deposition and storage except in the interstices of existing gravel deposits. However, there may be some sand build-up in the reach immediately upstream of the dredge site at Bige.

A TSF will divert most tailings from the mine site to the TSF but stored material in existing riverbed deposits will continue to be delivered to the lower section of the Middle Ok Tedi where there will be limited deposition, as at present. Otherwise, no significant effect on the upper river system deposition is expected.

Direct discharge of about 10% of tailings into the river rather than to the TSF will have very little effect on upper river system sediment load as it will only make up about 7% of total sediment discharge and will be mostly transported downstream as wash load.

A TSF will make a substantial difference to the suspended sediment load of the Middle Ok Tedi and the particle size distribution of material discharged to the Lower Ok Tedi from 2030. That effect will continue up to mine closure in 2050 and for a few years beyond that.

Post mine closure sediment concentrations will slowly fall but will remain well above pre-mine levels for decades to centuries.

While a number of scenarios were run through the models, the main differences in sediment load effects were between those with and without a TSF. These are illustrated by differences between results from Plans C (with TSF) and Plan D (no TSF).

For Plan C, predicted mean annual sand discharge to the dredge reach and the Lower Ok Tedi for the 2031-2050 period averaged 7.96 Mt. For Plan D, the equivalent value is 18.7 Mt. For silt discharge (which is not captured by the dredge) the equivalent values are 17.6 Mt/year (Plan C) and 23.8 Mt/year (Plan D).

The substantial reduction in sand discharge to Bige and possible dredging may create issues for supply of stockpile cover material.

Having an operational TSF will change the sand: silt ratio of the sediment load discharged to the Lower Ok Tedi after 2030 from about 0.8 to 0.45. Dredging of the remaining sand reaching Bige under Plan C will reduce the ratio even further. This suggests some transition of the floodplain reaches of the river from a sand bed type towards a silt dominated system. However, there is sufficient sand already in the system for the river to continue to behave mostly as a sand bed system for a considerable time.

## CHAPTER SEVEN – MODELLING THE IMPACT OF A TSF ON THE LOWER RIVER SYSTEM

### LOWER RIVER SYSTEM MODELLING RESULTS

Given the similarity between results from the various plans, we have applied the lower river sediment and geochemistry models only to PLANS C and D. PLAN C was selected because it is the most likely future condition. PLAN D was used because it has the same EWRDs as PLAN C but no TSF. The two provide the best datasets showing the net effect of a TSF. Modelling results are predicated on continued dredging to 2050.

#### DEPOSITION

Figure 7-1 shows modelled deposition for Plans C and D (i.e. with and without a TSF) in the Lower Ok Tedi and Middle Fly. Figure 7-2 shows the difference between the two. The results are plotted as space-time diagrams where the colour displays the magnitude of the effect. Viewing along a horizontal line shows the magnitude of deposition along all locations at a point in time. Viewing along a vertical line shows the magnitude of deposition at a single location over time.

The pattern of deposition may be seen as a flow of material with a discontinuous wave-front that gradually moves down the system over time. This behaviour shows as a prominent diagonal break between the green (little or no deposition) feature in the lower left of the image and the red and yellow (greater deposition) zones. The sediment flow attenuates downstream with distance but only slightly with time indicating that deposited sediment is staying in place. This is also supported by the large difference in sediment concentrations shown between Nukumba and

Obo in Figs 3-10 and 3-11, a difference which led Day and Dietrich (2009) to conclude that at least 40% of suspended load is being trapped upstream in the Middle Fly.

Initially, heavy sediment accumulation occurs in the upper part of the Ok Tedi between logi Village and D'Albertis Junction. This deposition is subsequently reduced by dredging. The Lower Ok Tedi holds material for longer and deposition persists in some reaches to at least 2060. There is a pattern of long term sediment accumulation and retention over most of the Middle Fly which, once sediment is in place shows little tendency to clear except in the uppermost section.

Table 5 illustrates the pattern of deposition by reach from 1990 to 2060 for Plan C and includes the influence of a TSF but also dredging at 17 Mt/year up to 2030 followed by a lesser rate thereafter dictated by sand availability. Table 6 shows the amount of deposition from 2030 onwards for Plan D and reinforces the pattern of less sediment loss in the upper reaches of the river and more deposition downstream. Upstream from D'Albertis Junction and, to a lesser extent Wygerin, accumulated deposition is being removed beginning in 2015 or 2020. There is little change downstream beyond Wygerin and deposition continues to increase right up to 2060 but at a slower rate from 2045.

The effect of a TSF on deposited sediment is best shown in the difference image in Fig. 7-2. There is less deposition, initially at the upstream end of the system which gradually progresses downstream and attenuates. Below the 250 km point (i.e. beyond Manda), the effect is minimal. The small differences between the two datasets that occur before 2030 reflect differences in the two Plans probably arising from roundoff differences when transferring data between Plans, software programs and graphics packages.

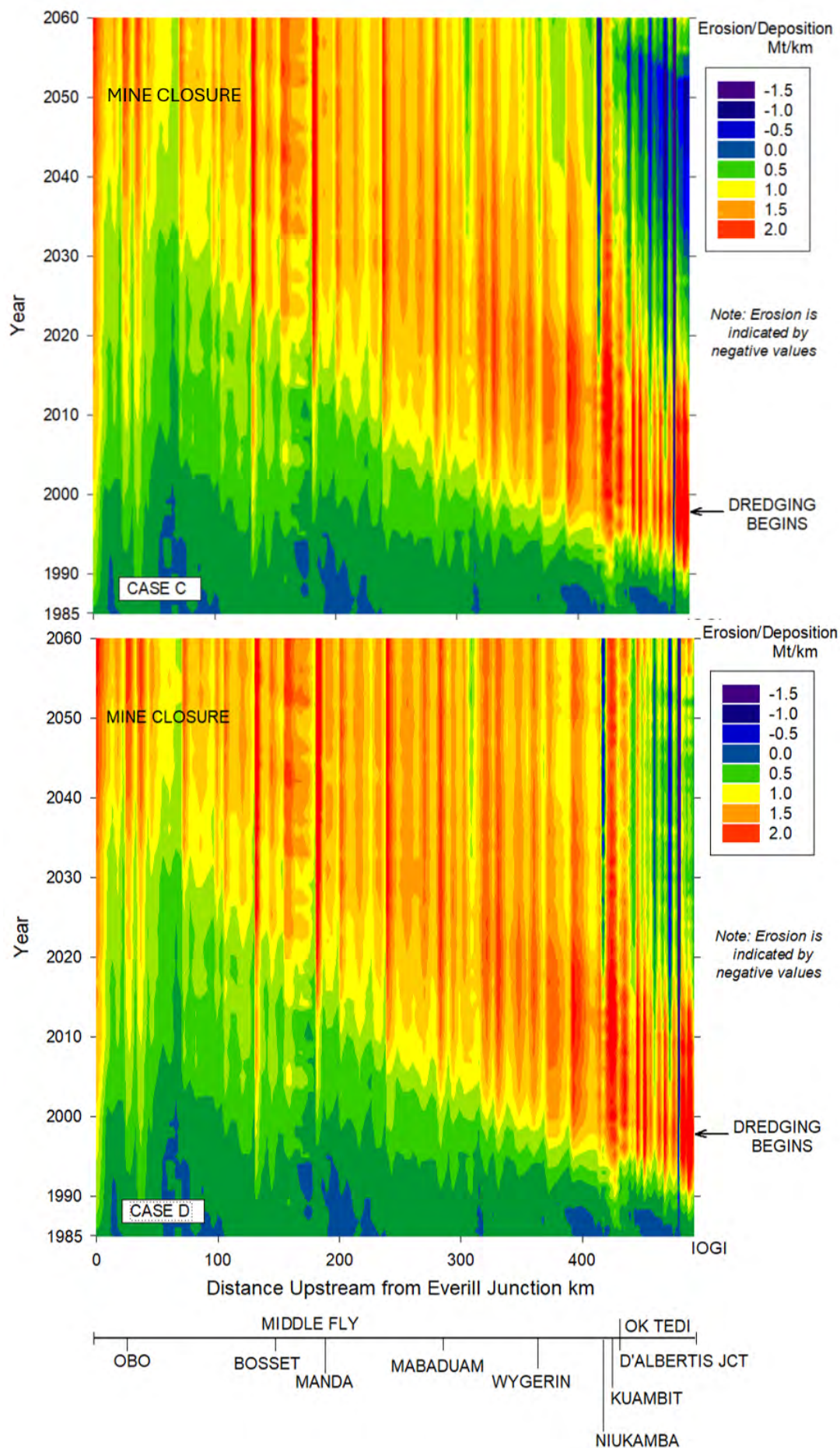


**Figure 7-1. Space-time image of modelled deposition in the Middle Fly for Plans C (upper image) and Plan D (lower image).**

| YEAR | TABLE 5: PLAN C CUMULATIVE DEPOSITION BETWEEN<br>1990 AND 2060 Mt (PLAN C AND D ARE IDENTICAL UP TO 2030) |                      |                        |                      |                    |           |
|------|-----------------------------------------------------------------------------------------------------------|----------------------|------------------------|----------------------|--------------------|-----------|
|      | BIGE-IERAN                                                                                                | IERAN-<br>D'ALBERTIS | D'ALBERTIS-<br>WYGERIN | WYGERIN-<br>MABADUEM | MABADUAM-<br>MANDA | MANDA-OBO |
| 1990 | 4.9                                                                                                       | 6.8                  | 10.3                   | 6.6                  | 4.1                | 9.6       |
| 1995 | 18.3                                                                                                      | 31.4                 | 42.2                   | 14.3                 | 13.3               | 18.8      |
| 2000 | 18.3                                                                                                      | 42.9                 | 79.9                   | 32.3                 | 27.8               | 31.6      |
| 2005 | 11.1                                                                                                      | 40.8                 | 83.8                   | 50.7                 | 39.7               | 54.2      |
| 2010 | 9.1                                                                                                       | 38.5                 | 92.9                   | 59.4                 | 59.2               | 58.0      |
| 2015 | 0.4                                                                                                       | 32.0                 | 91.2                   | 63.5                 | 71.5               | 69.9      |
| 2020 | -4.3                                                                                                      | 23.7                 | 82.6                   | 67.3                 | 81.7               | 80.7      |
| 2025 | -6.9                                                                                                      | 17.2                 | 72.1                   | 66.1                 | 88.1               | 97.6      |
| 2030 | -10.1                                                                                                     | 13.0                 | 70.5                   | 63.0                 | 95.5               | 106.9     |
| 2035 | -13.4                                                                                                     | 9.0                  | 63.4                   | 60.3                 | 93.0               | 124.1     |
| 2040 | -15.4                                                                                                     | 5.2                  | 56.0                   | 58.3                 | 92.7               | 132.8     |
| 2045 | -16.9                                                                                                     | 2.1                  | 48.1                   | 53.8                 | 91.8               | 141.2     |
| 2050 | -19.0                                                                                                     | -2.0                 | 45.4                   | 51.6                 | 91.2               | 143.7     |
| 2055 | -12.6                                                                                                     | -2.7                 | 41.6                   | 49.9                 | 88.3               | 147.8     |
| 2060 | -8.6                                                                                                      | 11.3                 | 37.1                   | 47.6                 | 86.6               | 152.4     |

| YEAR | TABLE 6: PLAN D CUMULATIVE DEPOSITION BETWEEN<br>2030 AND 2060 Mt |                      |                        |                      |                    |           |
|------|-------------------------------------------------------------------|----------------------|------------------------|----------------------|--------------------|-----------|
|      | BIGE-IERAN                                                        | IERAN-<br>D'ALBERTIS | D'ALBERTIS-<br>WYGERIN | WYGERIN-<br>MABADUAM | MABADUAM-<br>MANDA | MANDA-OBO |
| 2035 | -6.5                                                              | 17.7                 | 71.7                   | 63.6                 | 97.5               | 129.4     |
| 2040 | -8.4                                                              | 17.4                 | 67.7                   | 63.7                 | 97.3               | 142.1     |
| 2045 | -9.9                                                              | 17.1                 | 63.4                   | 61.7                 | 97.3               | 149.3     |
| 2050 | -8.3                                                              | 20.6                 | 68.4                   | 61.6                 | 100.4              | 150.8     |
| 2055 | -7.9                                                              | 18.5                 | 71.9                   | 60.7                 | 98.9               | 159.9     |
| 2060 | -6.0                                                              | 25.9                 | 68.2                   | 62.9                 | 97.1               | 159.8     |

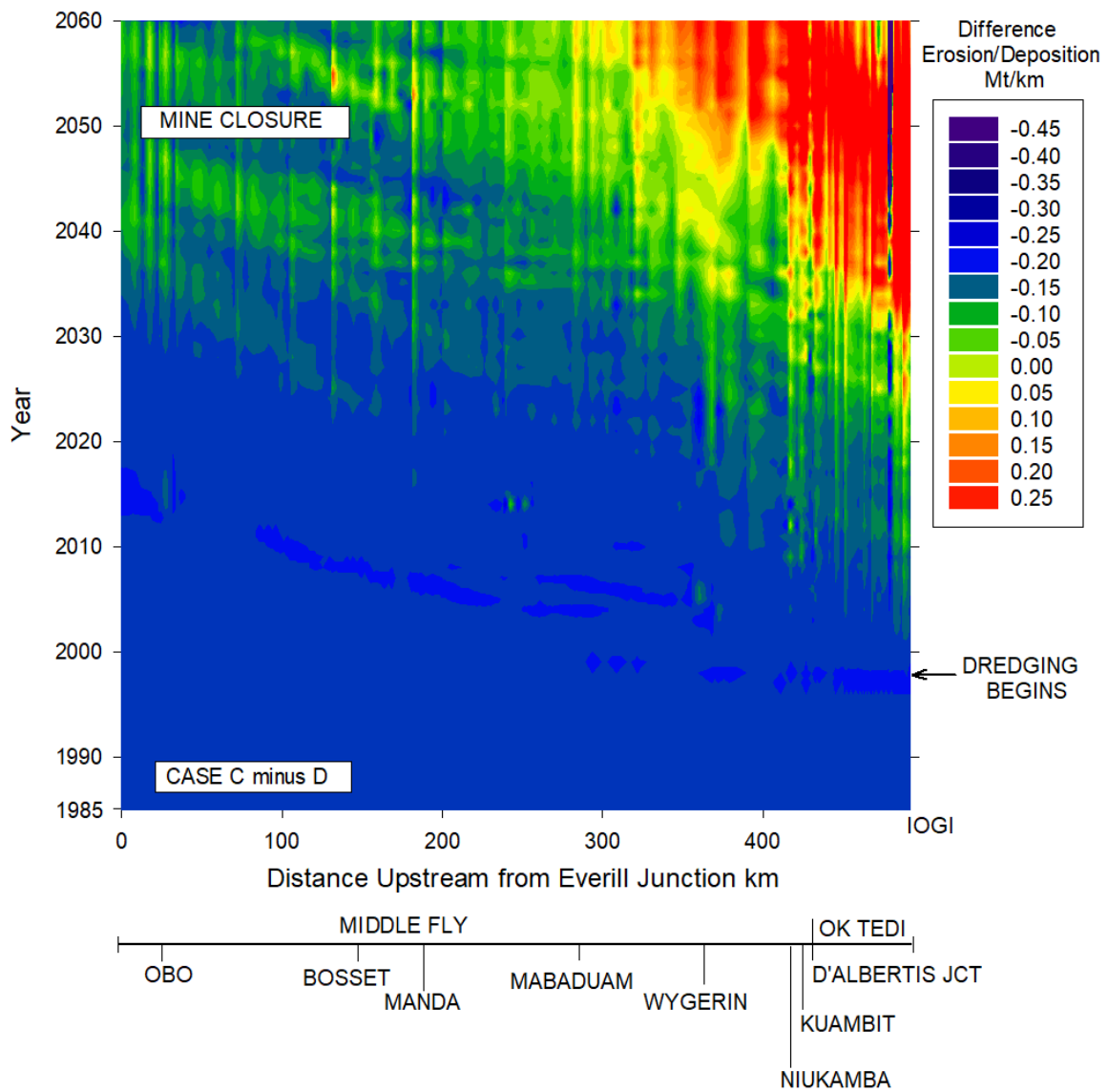


**Figure 7-2. Space-time image of modelled difference in deposition in the Lower Ok Tedi and Middle Fly for Plans C & D.**

## WATER LEVEL CHANGES

The effect of a TSF is greatest at the upper end of the system (Figs 7-3 and 7-4) with decreases in water level of up to 1.5 m but this is not sufficient to offset the increases that occurred in the early years of mine life. However, it does enhance the improvements resulting from dredging and in combination produces a small but useful improvement downstream as far as Wygerin. Further downstream, any changes are small. However, by 2060, water levels are still higher than in the pre-mining situation over most of the Middle Fly and all the Lower Ok Tedi.

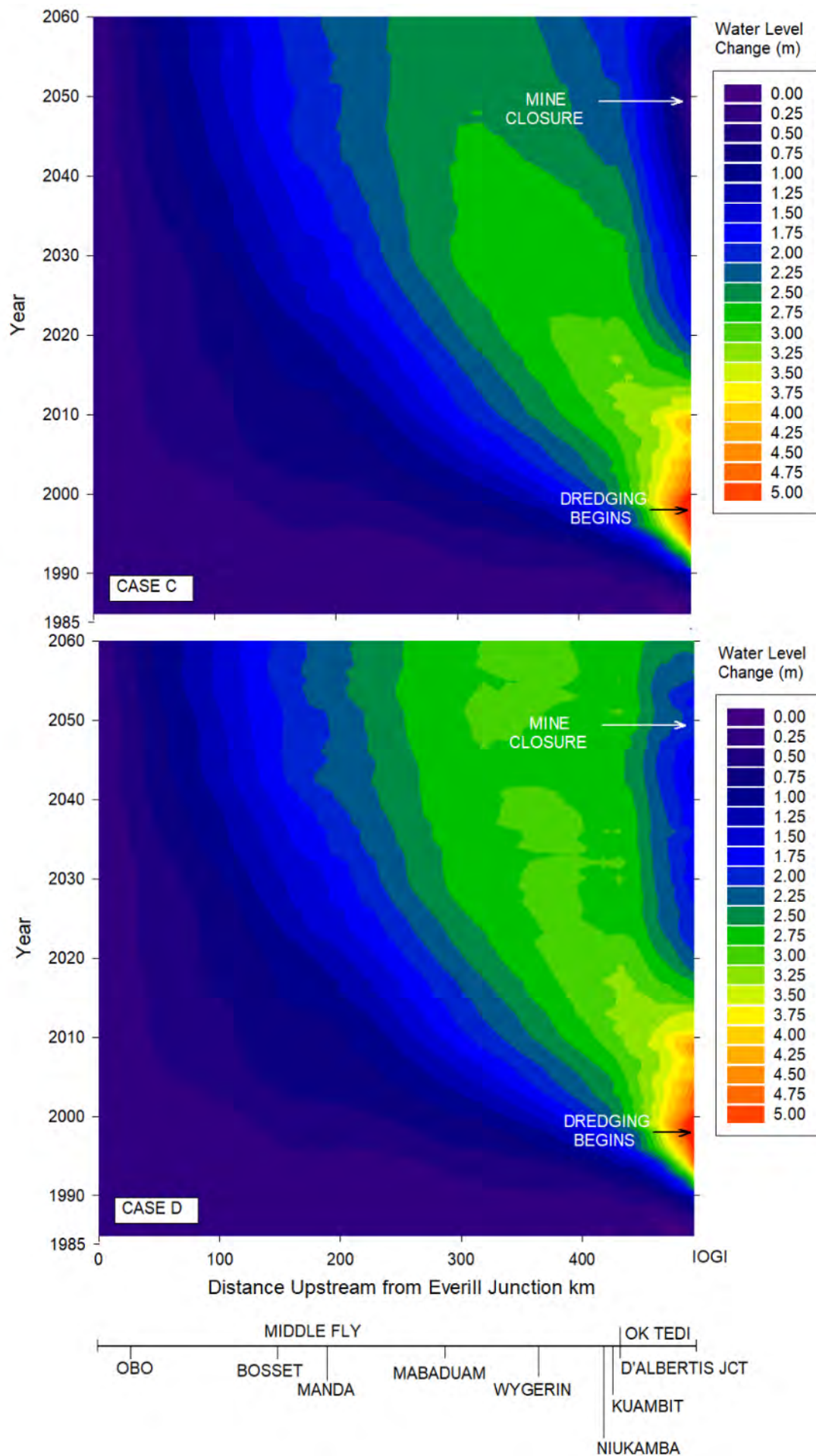


**Figure 7-3. Space-time image of modelled water level change in the Middle Fly for Plans C (upper image) and D (lower image).**

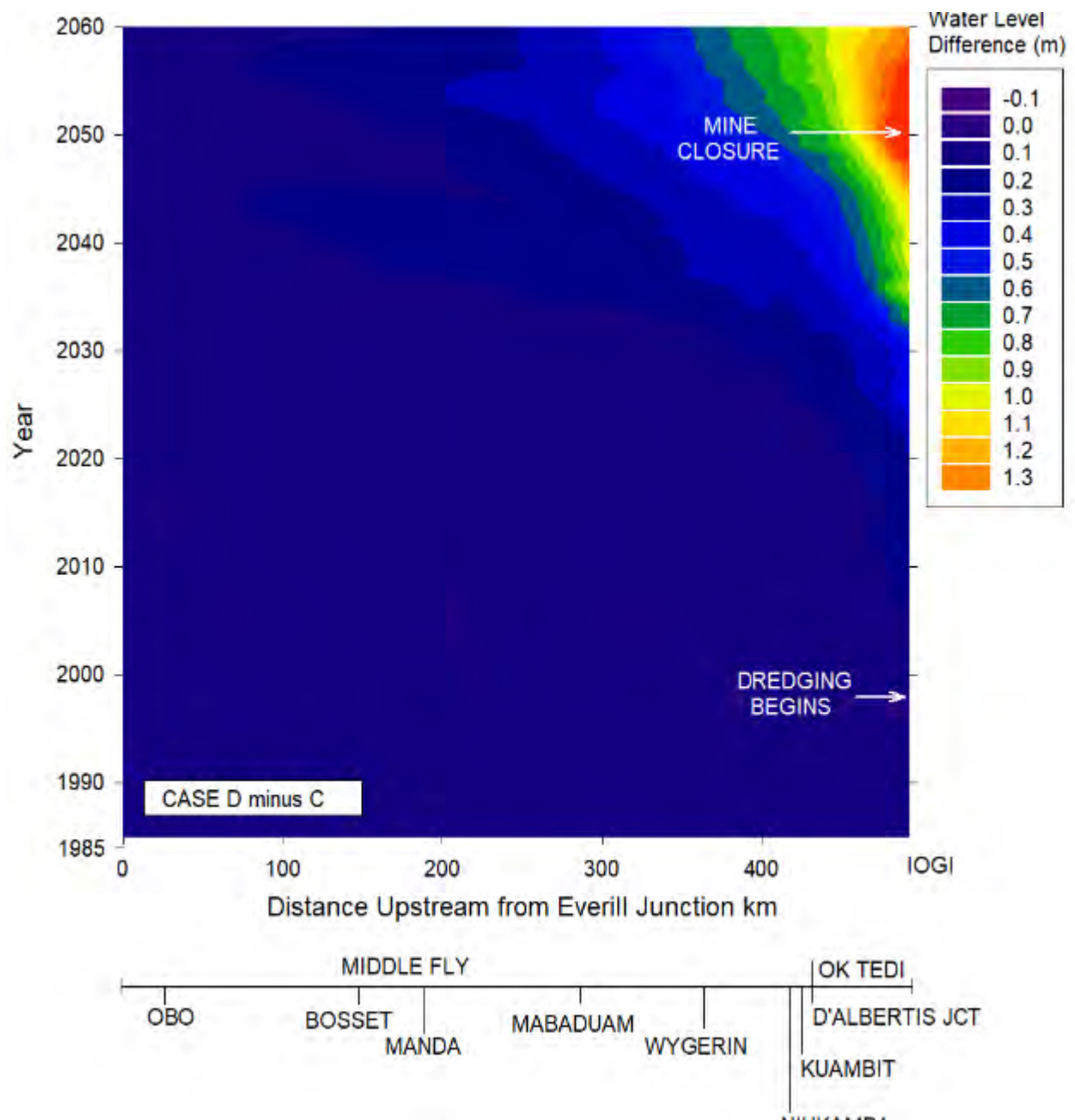


**Figure 7-4. Space-time image of modelled difference in water levels in the lower Ok Tedi and Middle Fly for Plans C & D.**

## CHAPTER EIGHT - CHANGES NOT MODELLED BUT INFERRED FROM OBSERVED TRENDS

The lower river system model does not predict changes in the rate of tie channel blocking, sediment accumulation on levees and the amount and extent of floodplain inundation. These restrictions exist because there is no predictive model available in the technology or the necessary data are not available. In these cases, we can mostly infer the likely effects of TSF from the existing trends described in earlier Chapters of this report.

### TIE CHANNEL BLOCKING

Data on tie channel blocking is very limited so the following conclusions have a high level of uncertainty.

In a draft study based on drought period 2015 LANDSAT imagery Pickup (2017) found that most tie channel blocking had occurred on the Lower Ok Tedi (i.e. the area of greatest deposition of mine-derived sand and silt), and the Strickland backwater zone in the Lower Middle Fly. The locations of problem tie channels are mapped in Figs. 2-7 and 2-8.

Middle Fly tie channel blocking mostly occurred between 1987 and 2008 but with little subsequent increase up to 2015. On the Lower Ok Tedi, most blocking appears to have occurred after 2002 although some early data suggests that it may have been occurring beforehand. Most Upper and Central Middle Fly tie channels have remained open over the same period. Marshall (2018) reported on the status of Lower Middle Fly tie channels joining the main river to three large ORWBs: Bosset Lagoon, Bai lagoon and Lake Pangua. Bosset Lagoon tie channel is reported to be infilling as is the Bai lagoon tie channel. The Lake Pangua channel shows intermittent blocking. These lakes may also connect to the main river through levee breaches when water levels are high.

Once a tie channel is blocked there may still be bidirectional flow through levee breaches during periods of high water. There is clear evidence for this in the May 2024 record flood on the upper reaches of the Lower Fly (Pickup, 2025).

The lower river system water level and sedimentation modelling results do not suggest changes to existing trends in the rate and location of tie channel blocking once a TSF is operating. There is insufficient change in water levels in the Lower Middle Fly. The Upper and Central Middle Fly tie channels in most cases have sufficient catchment area or have large enough ORWB feeders to generate sufficient flow to keep the channels open for most of the time although occasionally blockages may develop around vegetation debris.

The Lower Ok Tedi blocked tie channels are mostly likely to remain closed until water levels on the main river fall sufficiently to allow enough erosion to reconnect the isolated ORWBs. However, these water bodies are relatively small and may not generate sufficiently large flows to cause severe enough channel erosion and reopen the tie channels even with tailings diversion to a TSF.

### LEVEES

Apart from a relatively small number of locations where the main river channel is confined between high banks, levees have been slowly and consistently rising throughout the floodplain reaches. Most sections of river experience overbank flow and levee deposition and this will continue to occur where this is the case. The predicted reduction in sediment load when a TSF is operating may slow this process but the predicted reduction in water levels is unlikely to be large enough to prevent continuing overbank flows except perhaps on limited reaches of

the Lower Ok Tedi. The usual process that limits levee deposition is when the bank is high enough for overbank flooding to no longer occur. This is a gradual process and occurs more slowly than bed level rise in the main channel. Given previous rises in water level on both the Lower Ok Tedi and the Middle Fly, the levees will continue to adjust in spite of tailings diversion to a TSF (see Chapter 5). A second process limiting levee growth is when lateral channel migration erodes banks and where meander cutoffs develop. These processes replace a high surface with a lower one and levee deposition restarts. However, as a comparison of the current river course with that mapped during the Drexler-Bell Expedition of 1920 (Fig. 2-14) shows, lateral migration and the development of meander cutoffs is a very slow process on the Upper and Middle Fly

## FLOODPLAIN INUNDATION

The modelled water level changes mapped in Figs 7-3 and 7-4 describe conditions on the main river channel. However, there is a need to determine what these results mean for floodplain inundation extent and frequency.

There have been two attempts to extend main channel water levels across the floodplain. Pickup and Marshall (2023) using water level gauge data from the 1990s and from private gauges in 2022-2023 have shown that main channel water surface elevations can be extended laterally across the floodplain for considerable distances. However, the lack of a floodplain DEM of sufficient accuracy for this type of extrapolation and for floodplain hydraulic modelling more generally has prevented development of predictive models of mine impact on changes in floodplain inundation extent and frequency. The two attempts so far to develop such models based on extrapolation (Pickup, 2005, 2009 and Pickup and Marshall, 2024) illustrate the limitations of the existing low spatial resolution (30m) DEMs and the problems in correcting elevations for vegetation effects.

Direct mapping of flood extents from visible-near infrared satellite imagery from the various SPOT, LANDSAT and SENTINEL-2 missions on a large scale and over a long enough period of time also proved ineffective because of cloud cover, especially during wet periods. An alternative approach is therefore necessary.

The best floodplain inundation map currently available does not rely on topographic data but uses multitemporal high resolution synthetic aperture radar from the European Space Agency's *SENTINEL-1 Mission* and largely bypasses the problem of not having an accurate DEM. *SENTINEL-1* C-band radar offers 12-day repeat coverage, can see through cloud cover and can detect the presence of surface water to some degree (CEOS-GOFI, 2018).

A systematic evaluation of *SENTINEL-1* C-band inundation mapping potential was carried out by Pickup and Marshall (2019) between 22 and 25 April 2019 by flying twenty UAV high resolution photography transects over the upper Middle Fly and Upper Fly floodplain between Kiunga and Mabaduam. These data closely coincided with a *SENTINEL* descending orbit (i.e. north-east to south-west) pass on 20th April. Comparisons between *SENTINEL* backscatter values and the presence of exposed water in vegetation-water mixes in the UAV imagery suggested that DN (digital number) backscatter values of less than 190 in the *SENTINEL* data indicated the presence of floodwater. Most swamp, grassed and floodplain forest types, including dense sago stands were covered by these transects (Fig. 8-1).

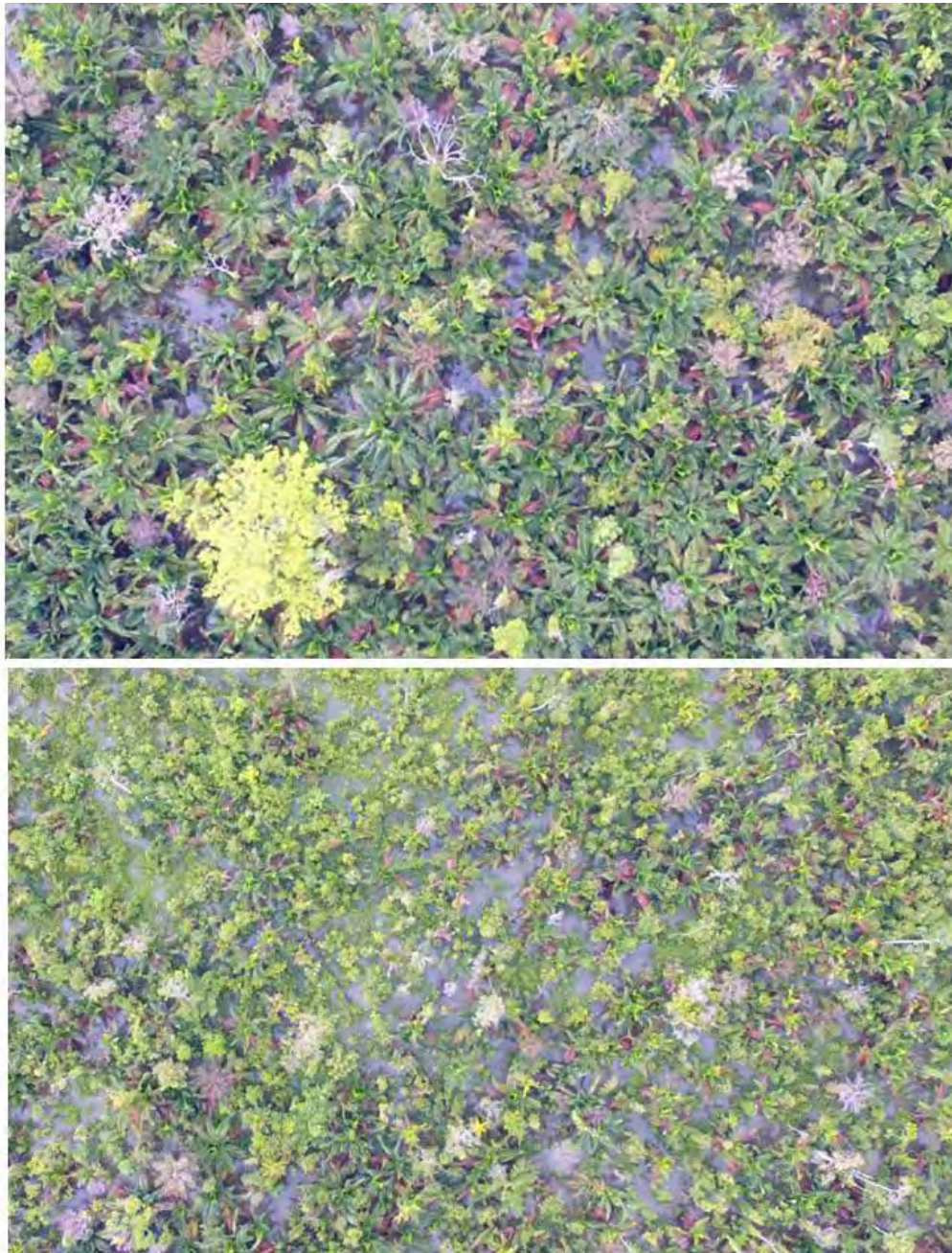


**Figure 8-1. Examples of mixed exposed water and forest types where a cutoff value of 190 successfully identified the presence of floodwater. Upper image is from a mixed forest and mature sago stand; lower image is from a typical floodplain forest stand. Open floodplain cover type is shown in Fig. 8-4. From Pickup and Marshall, (2019).**

Figures 8-2 and 8-3 show the results. The UAV images are larger than the SENTINEL-1 grid cells so initially, we compared the estimated area of exposed water with the mean backscatter value from the corresponding area in the SENTINEL data. Increasing amounts of visible floodwater in the UAV images show as decreasing *SENTINEL* mean backscatter values (Fig. 8-2). The cutoff value for the presence of water was variable but lay somewhere between about 190 to 300. We adopted a conservative cutoff value of 190. Counting the number of SENTINEL grid cells with values less than a DN<sup>11</sup> of 190 within a UAV photo frame is a better predictor of inundation extent with a correlation coefficient of 0.86 compared with 0.78 for the UAV area mean (Fig. 8-3).

<sup>11</sup> Digital numbers (DN) are related to raw *SENTINEL* values as  $\gamma_0 = \log_{10} (DN) [dB]$

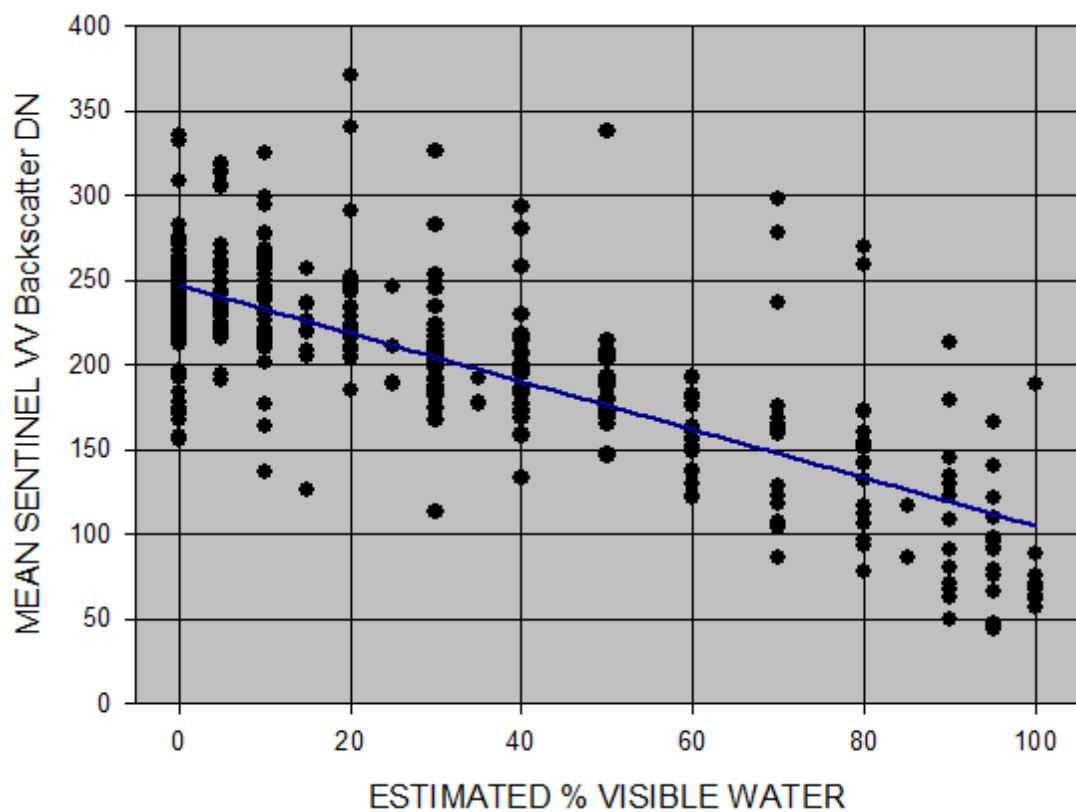


Figure 8-2: SENTINEL mean VV DNs compared with estimated exposed water in UAV images (from Pickup and Marshall, 2019).

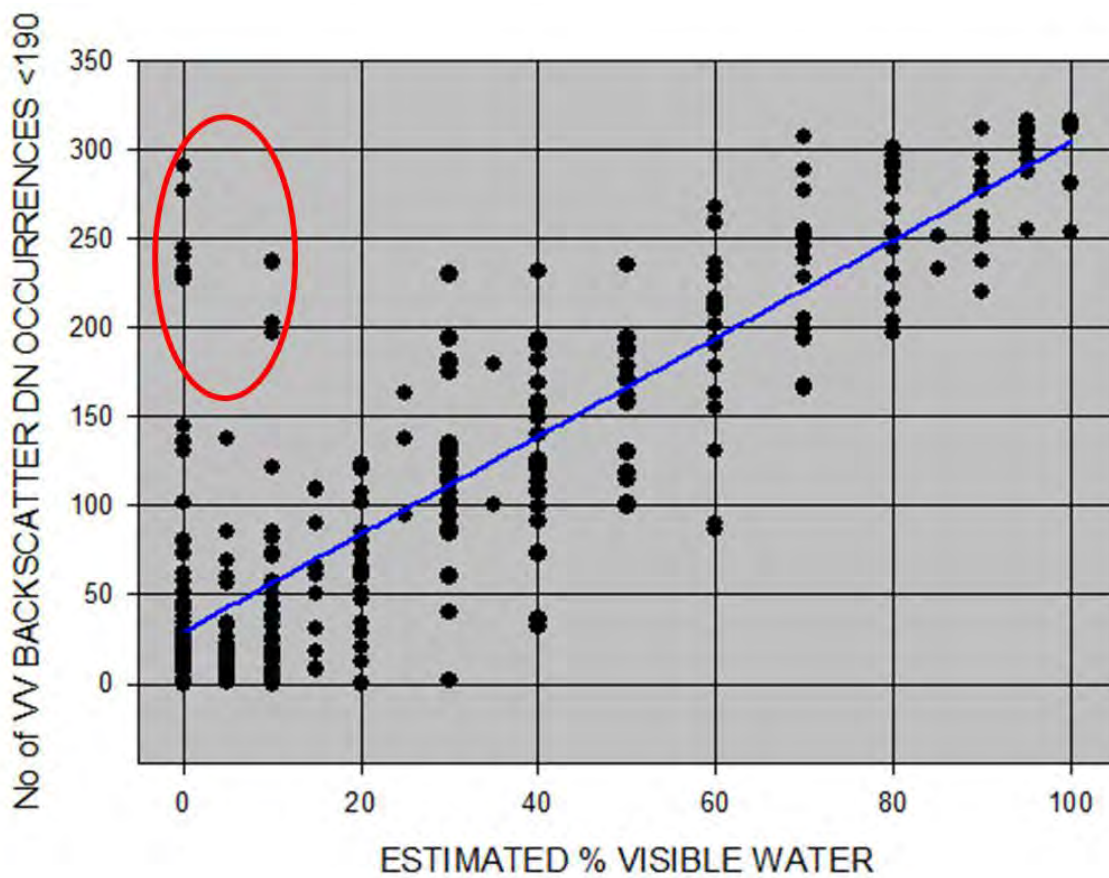


Figure 8-3: SENTINEL VV DNs below 190 compared with estimated exposed water in UAV images (from Pickup and Marshall, 2019).

A small group of values lie well above the regression line in Fig. 8-3 (circled) representing anomalies. These appear to be moss, swamp grass, sedge and bog areas that have a continuous plant cover but are waterlogged even though water cannot be seen over most of the UAV images that include them. Figure 8-4 shows an example with some surface water showing along a discontinuous drainage line. The C-band data appears to penetrate the surface plant cover and the resultant backscatter is closely related to the water within the vegetation mass. Removing these values from the dataset raises the correlation between % visible water and the number of *SENTINEL* values less than 190.



**Fig.8-4:** Swamp area with limited surface water yet showing *SENTINEL* DN values usually associated with 70-90% surface water. *SENTINEL* C-band radar appears to penetrate the plant cover. From Pickup and Marshall, (2019).

Combining *SENTINEL*-1 VV data with a 190 cutoff value provides the ability to create inundation frequency maps with a 10 m grid. Several filtering operations are needed to produce these maps, namely excluding areas of very high radar backscatter in C-band data typical of forest with no surface water present, and areas with significant topography, including locations where available digital elevation model ground surface heights are clearly incorrect because of tree cover. Japanese Space Agency 25m resolution *PALSAR* L-band data, which can discriminate water through forest cover better than C-band data but was only available on an annual basis, were also used to improve results by filtering out unlikely areas

*SENTINEL*-based inundation frequency maps were derived from 180 individual images covering 60 occasions between 2015 and 2019 to provide inundation frequency data. The images were selected to cover the maximum range of conditions from a drought to major floods. Ground truthing using further extensive UAV photography from 2019 shows these maps to be reasonably accurate. *PALSAR* data used for flooded forest discrimination came from 2007-2010 and 2015-2017 regional mosaics produced by Japan's Space Agency.

The inundation maps are shown in Figs. 8-5 and 8-6 and may be used in association with patterns shown in the space-time water level change maps to at least make some qualitative inferences on future patterns of change. The main limitation with these maps is the inability to penetrate stands of dense sago which have a largely closed canopy cover masking water beneath. These are mostly in the upper Middle Fly and are marked on Fig. 8-5 with an S.

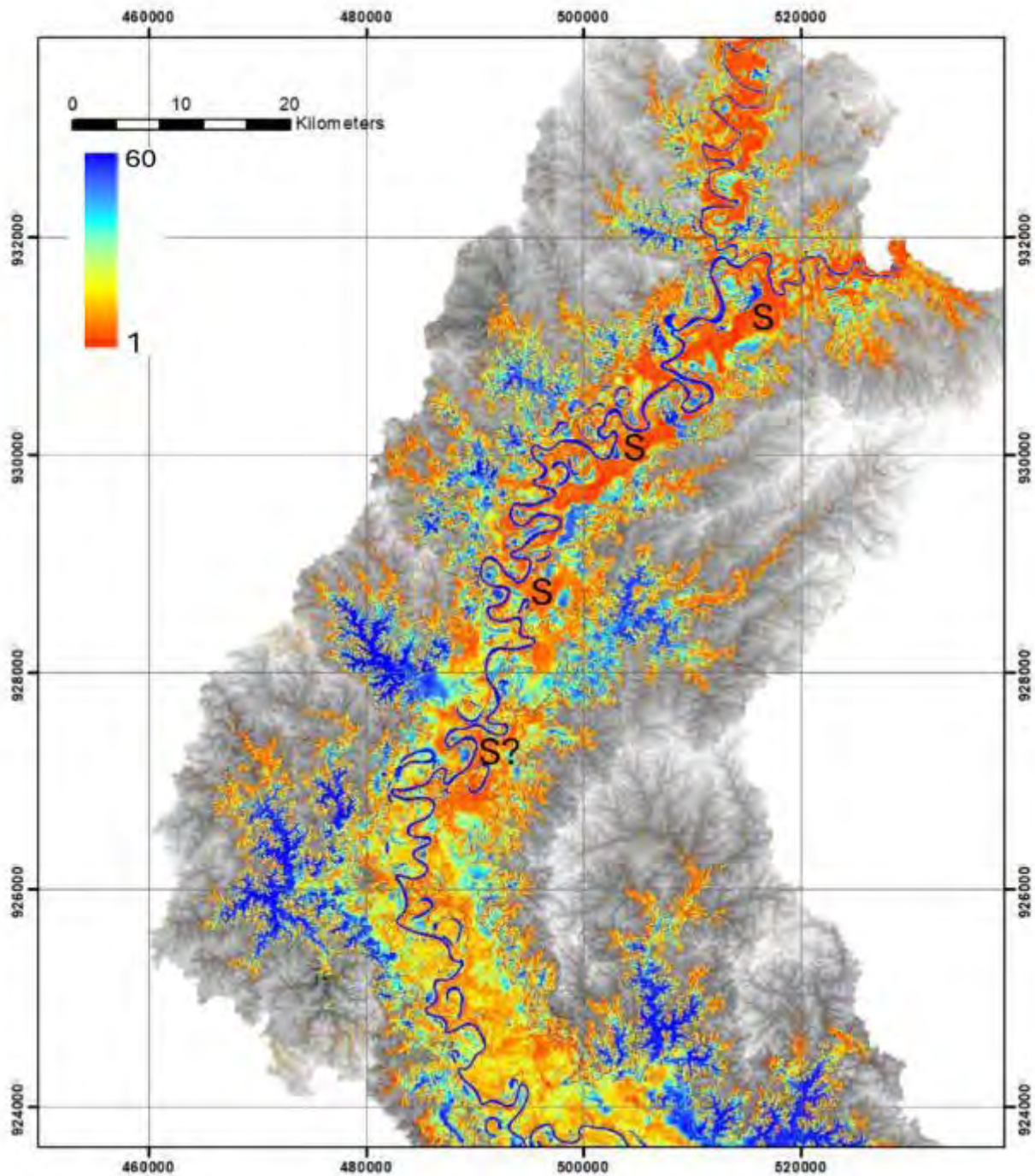


**Figure 8-5. Upper river system floodplain reaches showing the number of SENTINEL-1 DN values of less than 190 from 2015-2019 imagery. Dense sago stands with closed canopies where inundation frequency is underestimated are marked with an “S”. Inundation values are overlaid on a COPERNICUS grey scale DEM image which identifies locations outside the potentially flooded areas.**

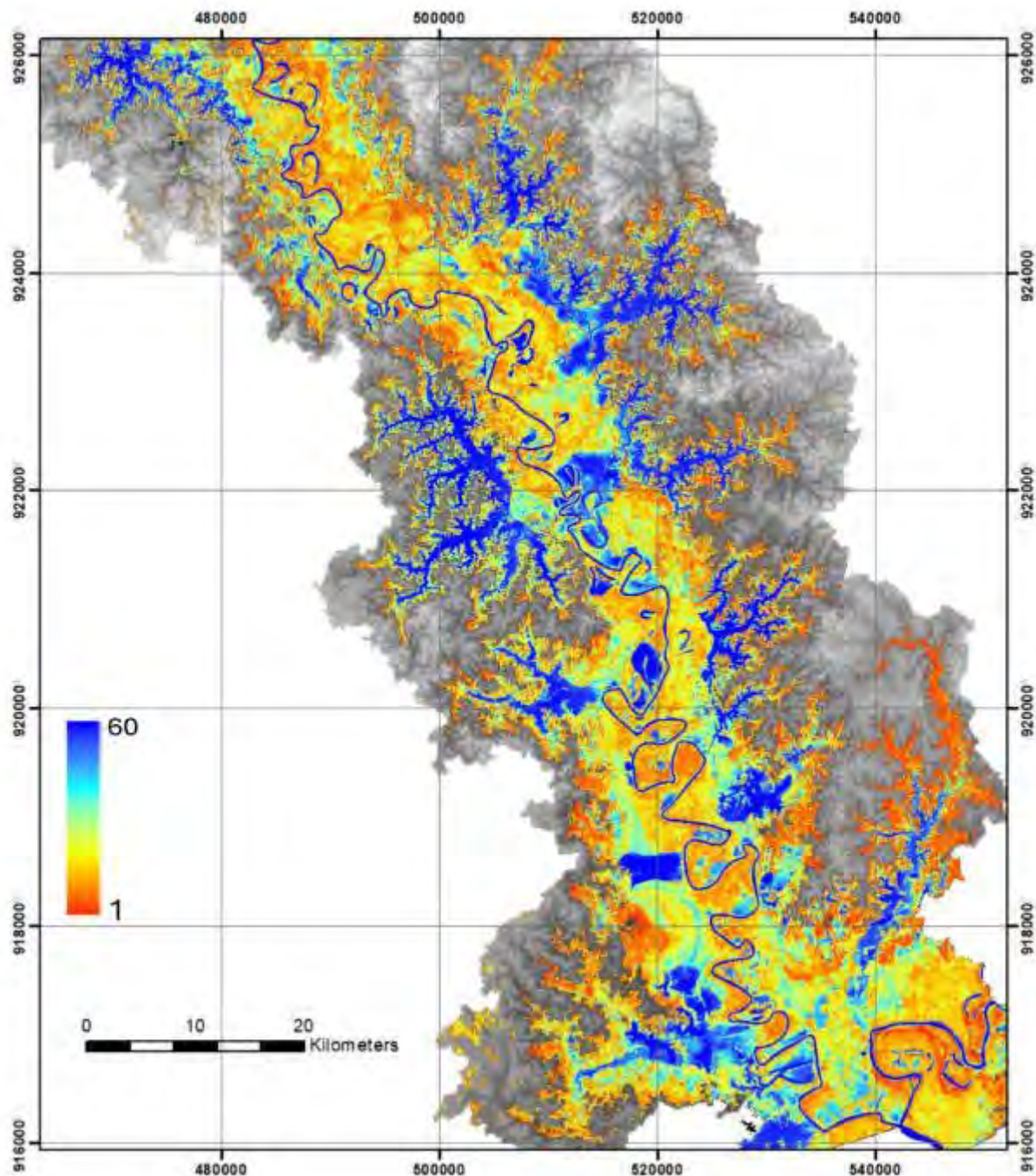


**Figure 8-6. Upper river system floodplain reaches showing the number of SENTINEL-1 DN values of less than 190 from 2015-2019 imagery. Inundation values are overlaid on a COPERNICUS grey scale DEM image which identifies locations outside the potentially flooded areas.**

The inundation maps provide information on the absolute inundation extent and frequency and differ from the space-time graphs in the previous Chapter which provide information on water level change but not its geographical extent, frequency or the water surface elevations. The mapping technology is not accurate enough to represent the relatively small changes in water level generated by the models. However, simulating a water level reduction by mapping with a cutoff value of 150 instead of 190, has minimal effect on inundation extent. A similar exercise by excluding cells with inundation count values of less than 5 rather than 1 also only has a very small effect on inundation extent. Using a cutoff value of 200 rather than 190, simulating a small water level rise, only increases the flooded area by a very small extent, mostly at the edges of flooded tributaries. From these results, we infer that the current extent of inundation is at close to the maximum and further expansion is limited by the elevated topography that makes up floodplain boundaries. There will however be small changes in the

inundation frequency of the existing flood-prone zones. These are likely to occur whether or not there is a TSF. From information in Figs. 7.3 and 7.4, the largest reduction in inundation frequency is likely to occur on the Lower Ok Tedi, gradually decreasing with distance down into the upper reaches of the Middle Fly. Small increases in inundation frequency may occur on the Lower Middle Fly between Manda and Obo but these will be minor, especially if a TSF is operating.

## CHAPTER NINE - UPPER RIVER SYSTEM PARTICULATE GEOCHEMISTRY

The geochemistry models predict particulate copper, sulphur and acid neutralising capacity (ANC) in the sediment load output from the upper river system. Copper is regarded as the main pollutant while the interchange between sulphur and ANC is a major determinant of acid generation which is a significant variable in determining trace metal toxicity and the subsequent loss of biodiversity (Kiwingim *et al*, 2024). Predictions were made using the copper mass balance model and the sulphur and ANC mass balance model which are both described in detail in Appendix Three. In brief, the models use a structure that mimics the river system and integrates the geochemical properties and input amounts of tailings and waste rock with predictions of sediment load, erosion and deposition from the *OKTUGS* sediment transport model. Wherever possible, model results have been compared with observed data noting that some of those datasets are of limited quality because of sampling logistics given the large areas that need to be covered except in the case of the Bige data.

Results from the mass balance models are shown in Figs 9-1 to 9-4 for PLANS C and D. Observed data in the form of monthly averages of dredge material from the operation at Bige are also presented as a measure of model accuracy. Predictions for copper and ANC are reasonably accurate when compared with observed values from Bige. Sulphur is the least accurate but the major trends in concentration over time are correctly reproduced. However, the observed data show extreme variability which remains unexplained.

The patterns of change over time show the ongoing improvement in OTML's environmental performance. Particulate copper concentrations are one third to one quarter of the values in the early 2000s. Without a TSF, they are expected to level off. With a TSF, a further 50% improvement is expected compared with values in the early 2020s. This illustrates the major role of tailings as opposed to waste rock in contributing copper to the sediment load and the benefits of a TSF.

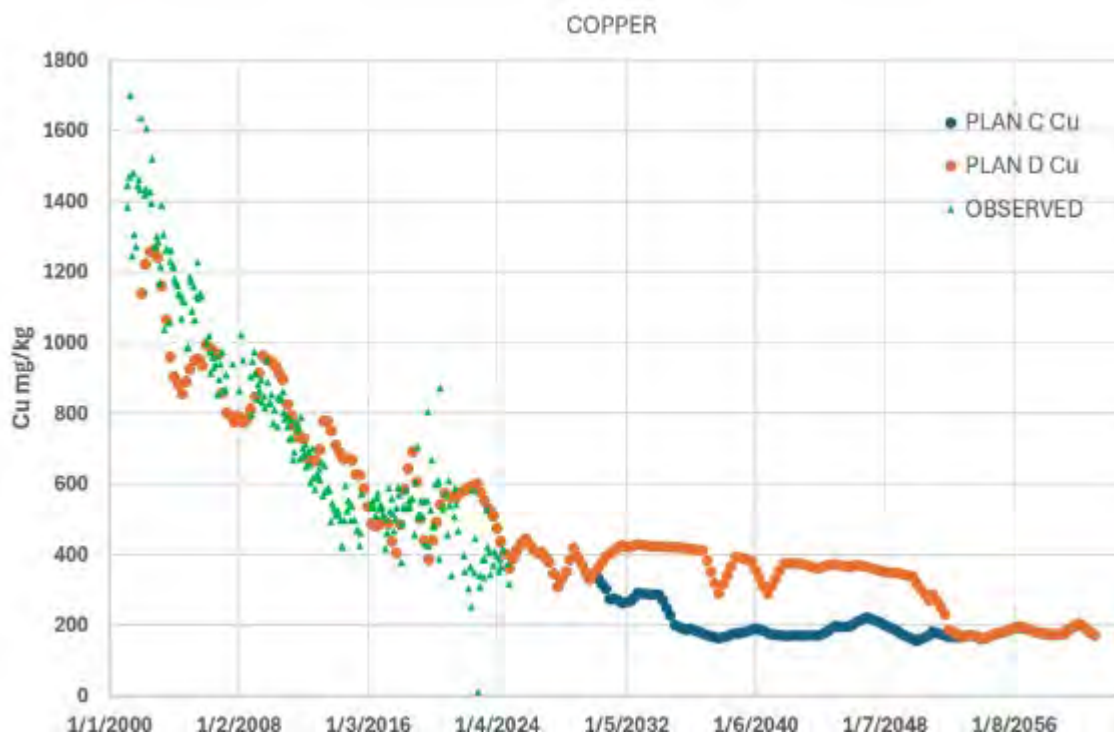


**Figure 9-1. Observed and predicted particulate copper concentrations for sediment delivered to the floodplain reaches of the river system. PLAN C has a TSF and two EWRDs. PLAN D does not have a TSF. PLAN C is the scenario on which the permit request is expected to be based. Plans C and D are identical up to 2030.**

Figures 9-2 and 9-3 illustrate the improvements in reducing the ARD risk at Ok Tedi (Kiingim, 2024). Sulphur is less than one third of the early 2000 values while ANC has doubled. The TSF offers a further 30% reduction over time. ANC values with a TSF increase by about one third and ANC:MPA ratios almost double. However, even without a TSF, by the 2020s, ANC:MPA ratios mostly lie above 2.5 which is well above the high ARD risk values of less than 1.0 which prevailed in the early 2000s.

It is likely that sediment with the higher ANC:MPA ratio will slowly spread more widely across parts of the floodplain as long as there is a connection with the river system. However, the lack of floodplain surface sampling since the early 2000s, apart from on the levees and in a small number of ORWBs, makes it difficult to predict the rate and extent. What data there are indicate highly variable deposition rates and considerable spatial variability in both core and surface sample geochemistry. Bolton and Pickup (2021) provide a very detailed reach by reach review of what is known (also see Table 3). Their results, together with more recent levee sampling (Bolton, in prep.) suggest the lower particulate copper and higher ANC:MPA values associated with a TSF will provide a detectable geochemical benefit on the levees. However, it would be both technical and logistically difficult to identify clear patterns of geochemical improvement across the hundreds of square km that make up the very diverse floodplain environments.

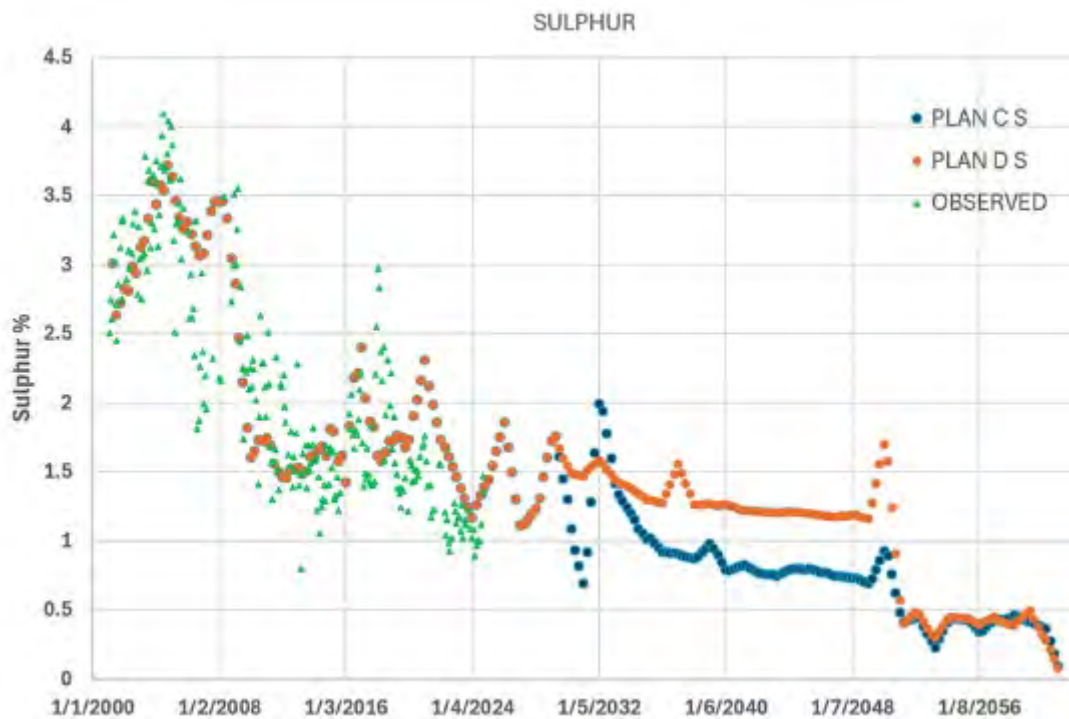


**Figure 9-2. Observed and predicted particulate sulphur concentrations for sediment delivered to the floodplain reaches of the river system. PLAN C has a TSF and two EWRDs. PLAN D does not have a TSF. PLAN C is the scenario on which the permit request is expected to be based. Plans C and D are identical up to 2030.**

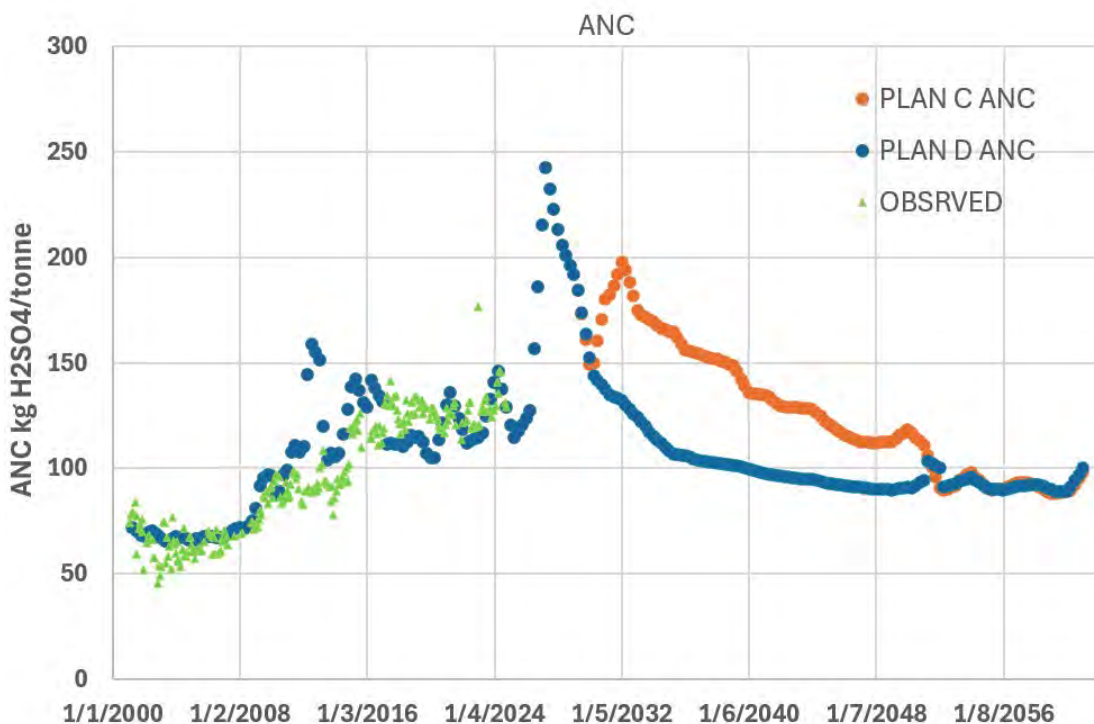


**Figure 9-3. Observed and predicted particulate ANC for sediment delivered to the floodplain reaches of the river system. PLAN C has a TSF and two EWRDs. PLAN D does not have a TSF. PLAN C is the scenario on which the permit request is expected to be based. Plans C and D are identical up to 2030.**

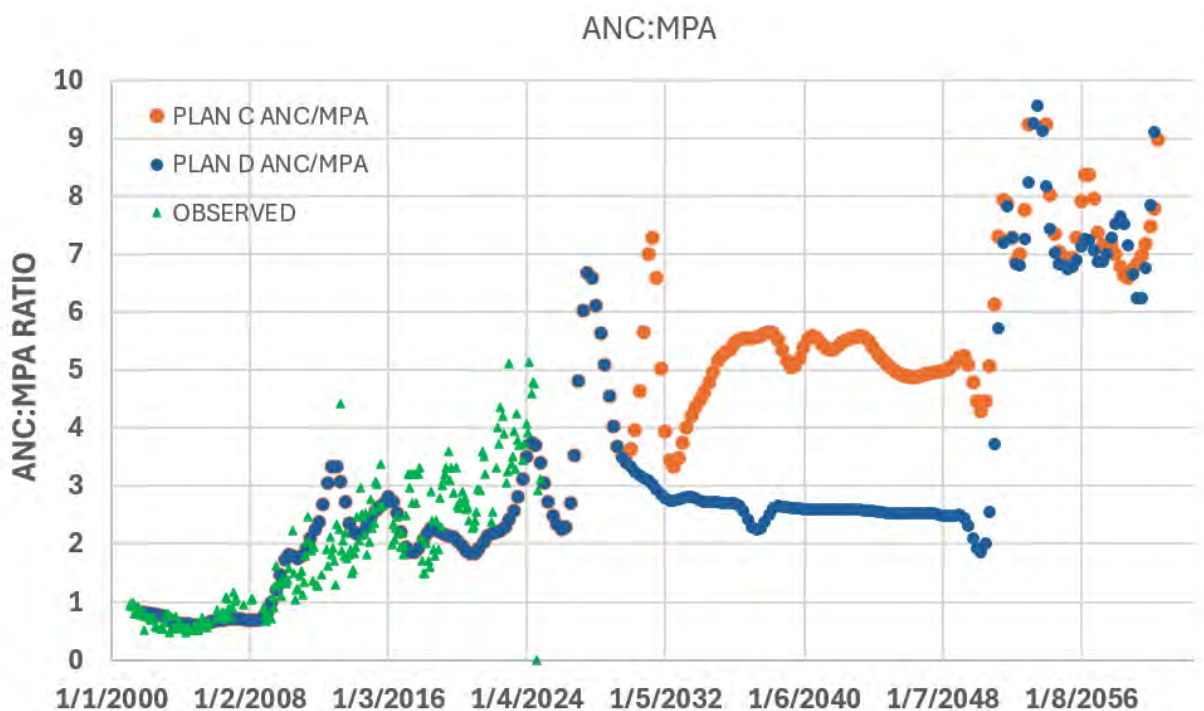


**Figure 9-4. Observed and predicted particulate ANC:MPA for sediment delivered to the floodplain reaches of the river system. PLAN C has a TSF and two EWRDs. PLAN D does not have a TSF. PLAN C is the scenario on which the permit request is expected to be based.**

## CHAPTER TEN - LOWER RIVER SYSTEM PARTICULATE GEOCHEMISTRY

Annual sampling of levee sites for particulate copper content, sulphur and ANC since 2001 makes it possible to derive an empirical relationship in the form of a set of dilution coefficients between reach averaged data and the Mass Balance Model particulate geochemistry predictions for outflows from the upper river system. We have derived these for four river reaches using data from 2001 to 2024 which covers Plans C and D. Both plans are identical up to 2030. Projections beyond 2030 are derived for PLAN C since this is the most likely future condition. The dilution coefficients are listed in Table 7. Differences between Plans C and D are highlighted in Figs 9-1 – 9-4 in the previous chapter.

| TABLE 7. APPROXIMATE DILUTION COEFFICIENT VALUES FOR LOWER OK TEDI AND MIDDLE FLY LEVEE GEOCHEMISTRY |        |         |      |
|------------------------------------------------------------------------------------------------------|--------|---------|------|
| REACH                                                                                                | COPPER | SULPHUR | ANC  |
| Lower Ok Tedi                                                                                        | 1.00   | 0.60    | 1.00 |
| D'Albertis Jct - Mabaduam                                                                            | 0.90   | 0.45    | 0.9  |
| Mabaduam - Manda                                                                                     | 0.90   | 0.35    | 0.6  |
| Manda – Everill Jct                                                                                  | 0.90   | 0.30    | 0.45 |

### COPPER PREDICTIONS

The best results using the dilution coefficient approach come from the copper model (Figs. 10-1 to 10-4). Predictions are close to observed data from the early 2000's to 2019 for all reaches of river reflecting the apparent ease with which particulate copper disseminates through the system. The trend is for both

predicted and observed particulate copper to decrease from the earliest years to the mid-2010s on the Lower Ok Tedi when a drought in 2015 triggered a major dip due to mine closure. Values then increased but have continued to decline until the present time. Forecasts under PLAN C suggest a further 50% decline once the TSF is operational. Both observed and predicted behaviour throughout the Middle Fly mimic the pattern of change on the Lower Ok Tedi.

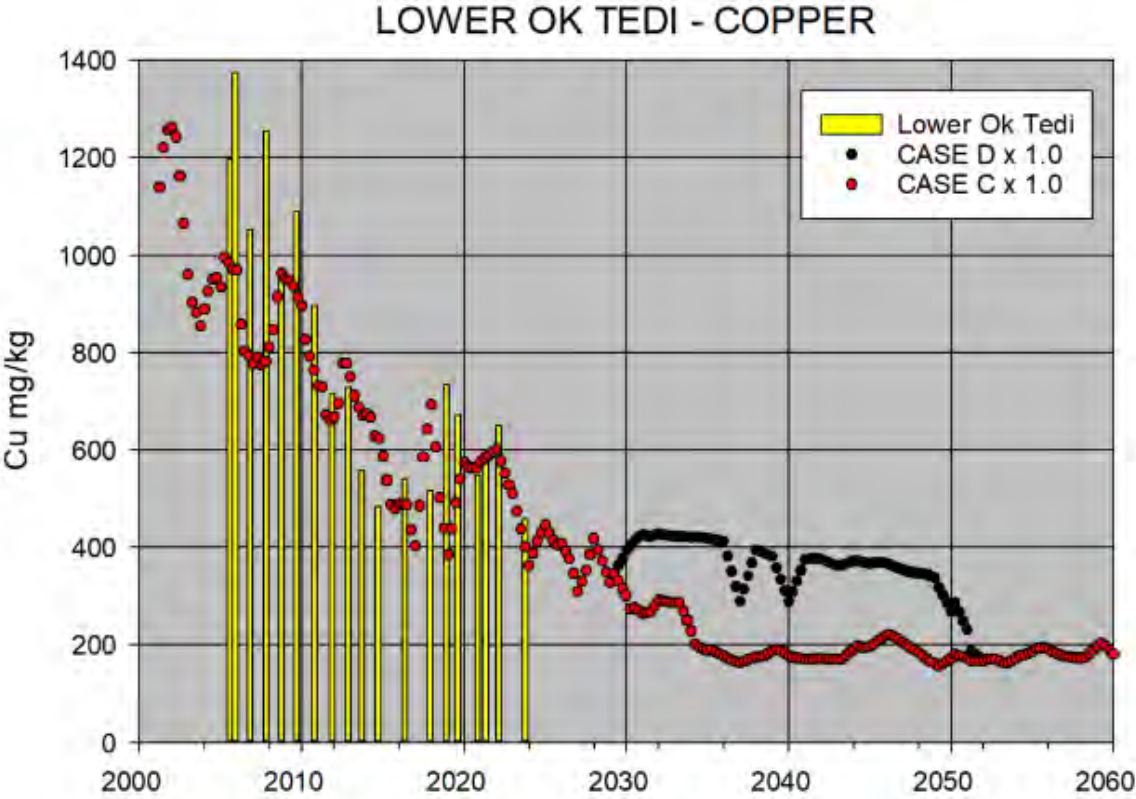


Figure 10-1. Observed and predicted particulate copper in Lower Ok Tedi levee sediments.

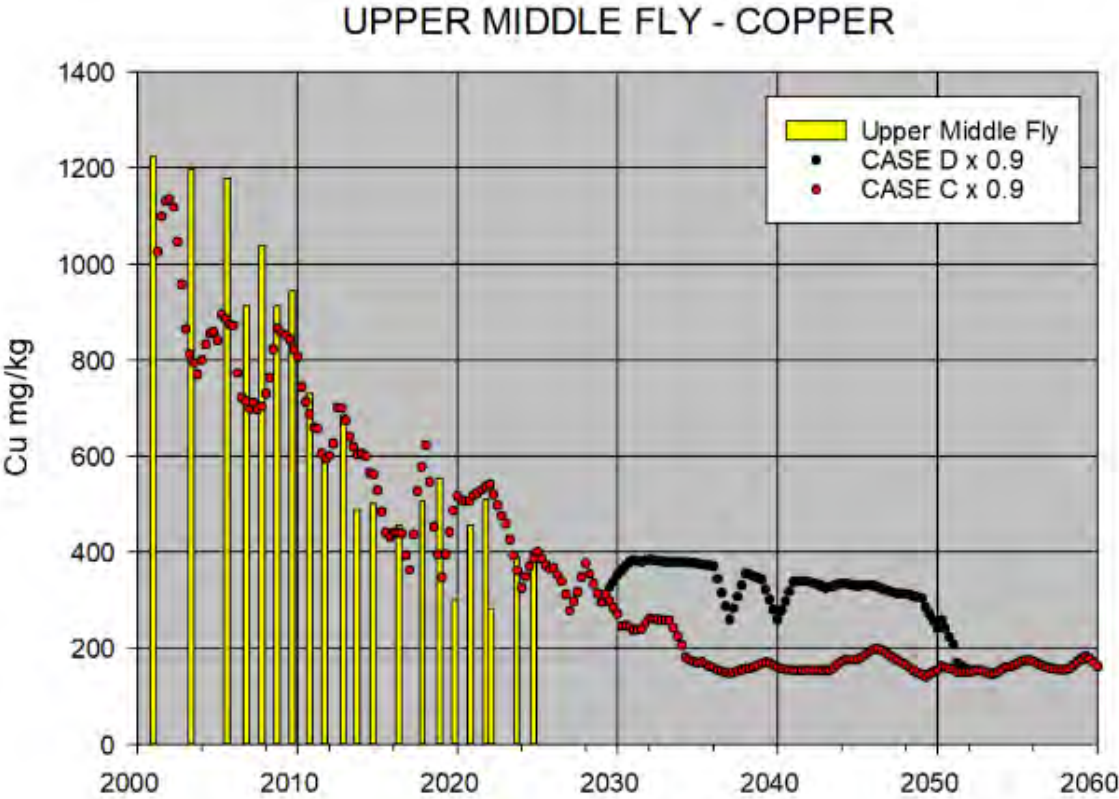


Figure 10-2. Observed and predicted particulate copper in Upper Middle Fly levee sediments.

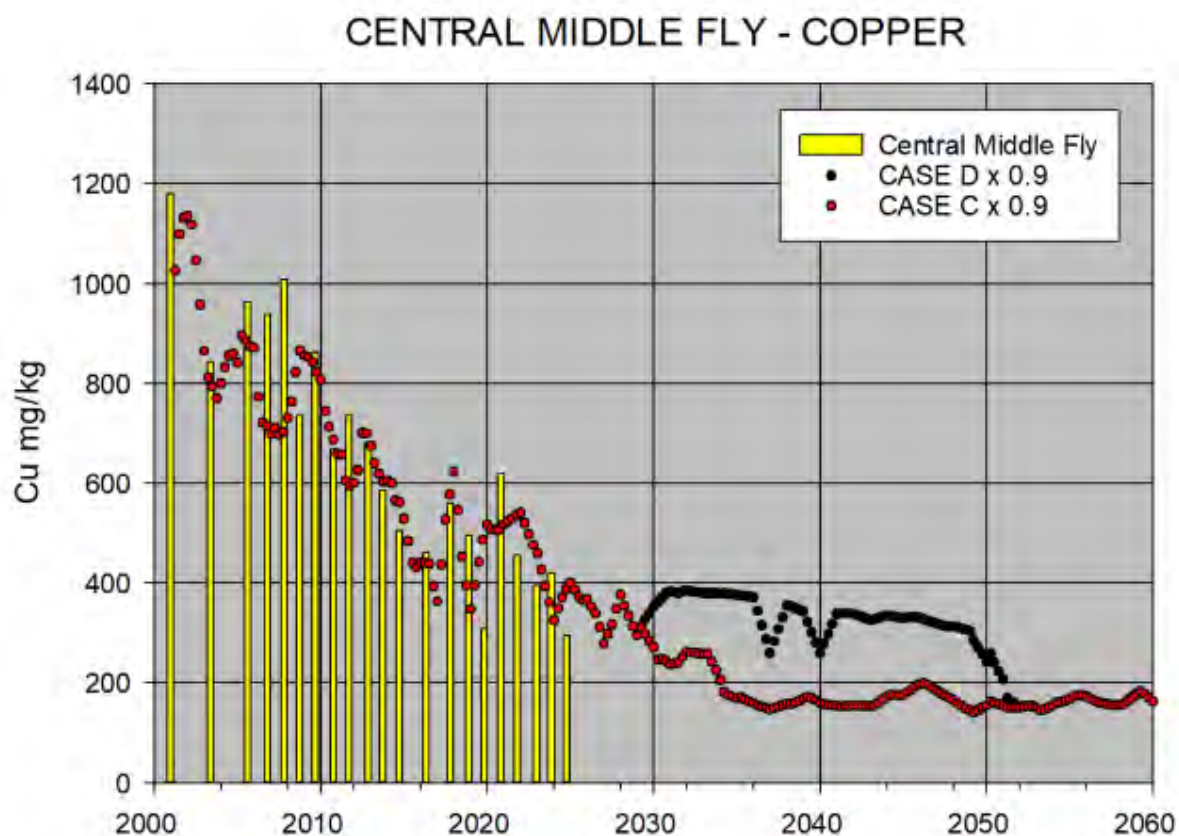


**Figure 10-3. Observed and predicted particulate copper in Central Middle Fly levee sediments.**

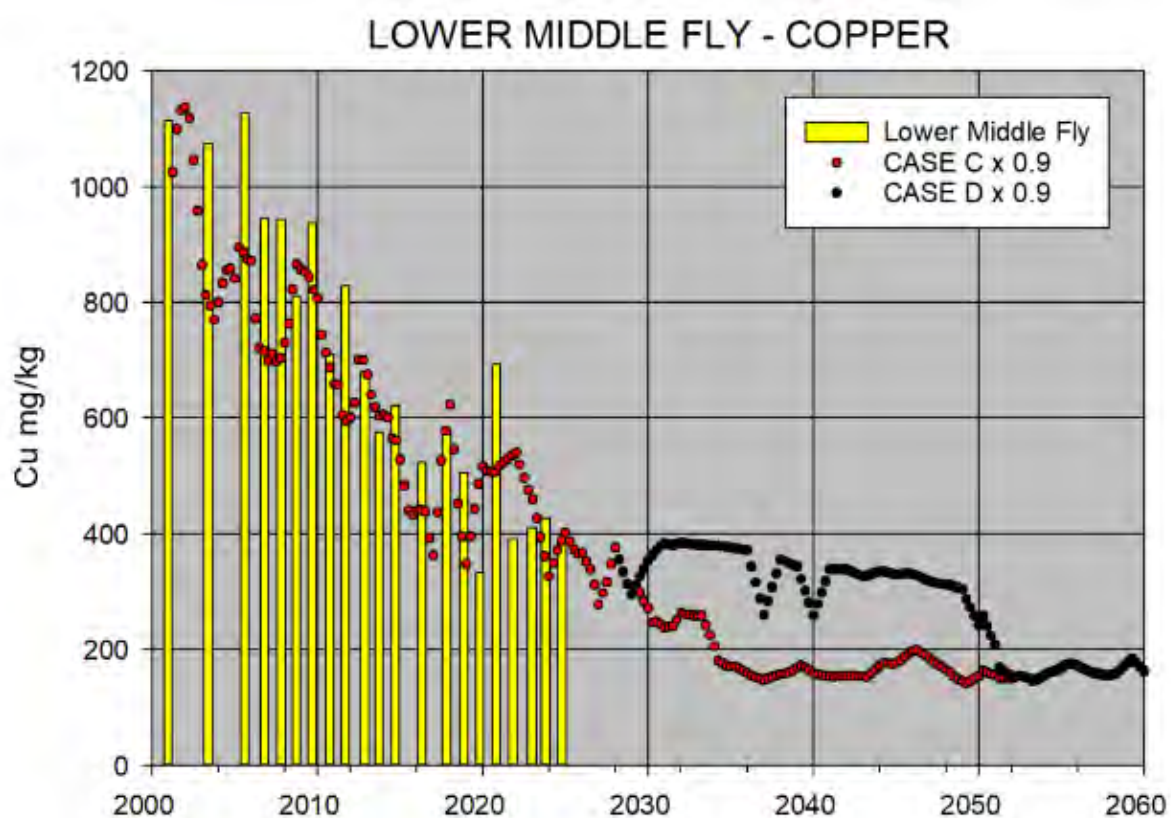


**Figure 10-4. Observed and predicted particulate copper in Lower Middle Fly levee sediments.**

## SULPHUR PREDICTIONS

Sulphur predictions are good when levee sulphur content is high, especially on the Lower Ok Tedi and the D'Albertis – Mabaduam reach of the Upper Middle Fly are overestimated on occasions when the sulphur content of surface levee sediments is low. This is especially true on the mid and lower reaches of the Middle Fly and notably after the 2015-early 2016 period when drought shut down mine operations and there was no discharge of tailings or dumping of waste rock. It therefore seems likely that material deposited on the levees at these times had a larger component of natural sediment load with less sulphur. Sulphur input from the waste rock dumps does tend to be highly variable and more so than copper hence the variability in model predictions from about 2010 to the early 2030s after which there is a gradual decline. It is worth noting that copper, sulphur and ANC waste rock inputs are derived from a mine area geology block model rather than observed inputs which may result in some averaging. In this case, the observed levee deposits reflect a more steady pattern of inputs over time. As with copper, the model predicts a substantial reduction in sulphur inputs right down the system once the TSF is operational. The sulphur dilution coefficients suggest a more substantial rate of decline down through the system. Copper and ANC values show less downstream dilution since more of these materials would travel as fine sediment reworked from upstream mine-derived deposits. Pyrite-derived sulphur, being more dense, would be less able to be transported downstream.

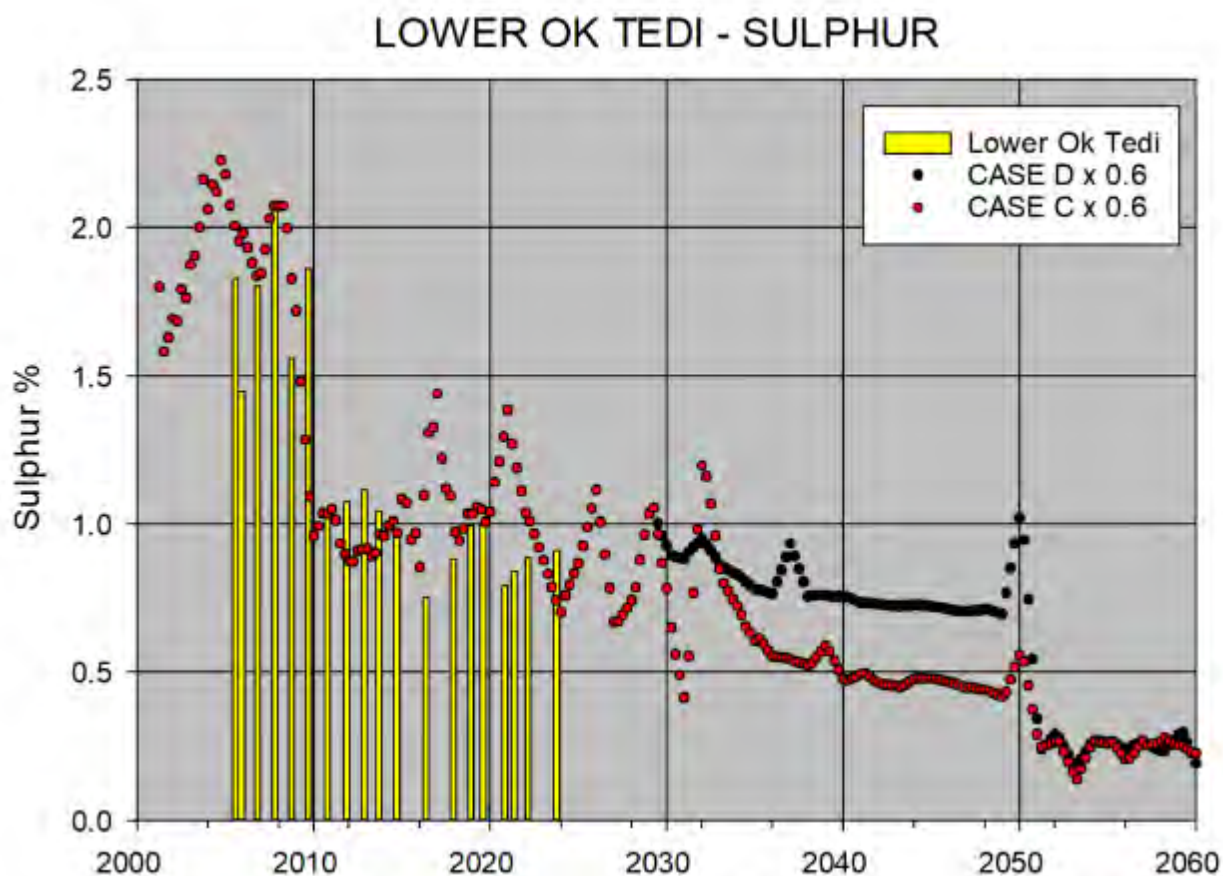


**Figure 10-5. Observed and predicted particulate sulphur in Lower Ok Tedi levee sediments.**

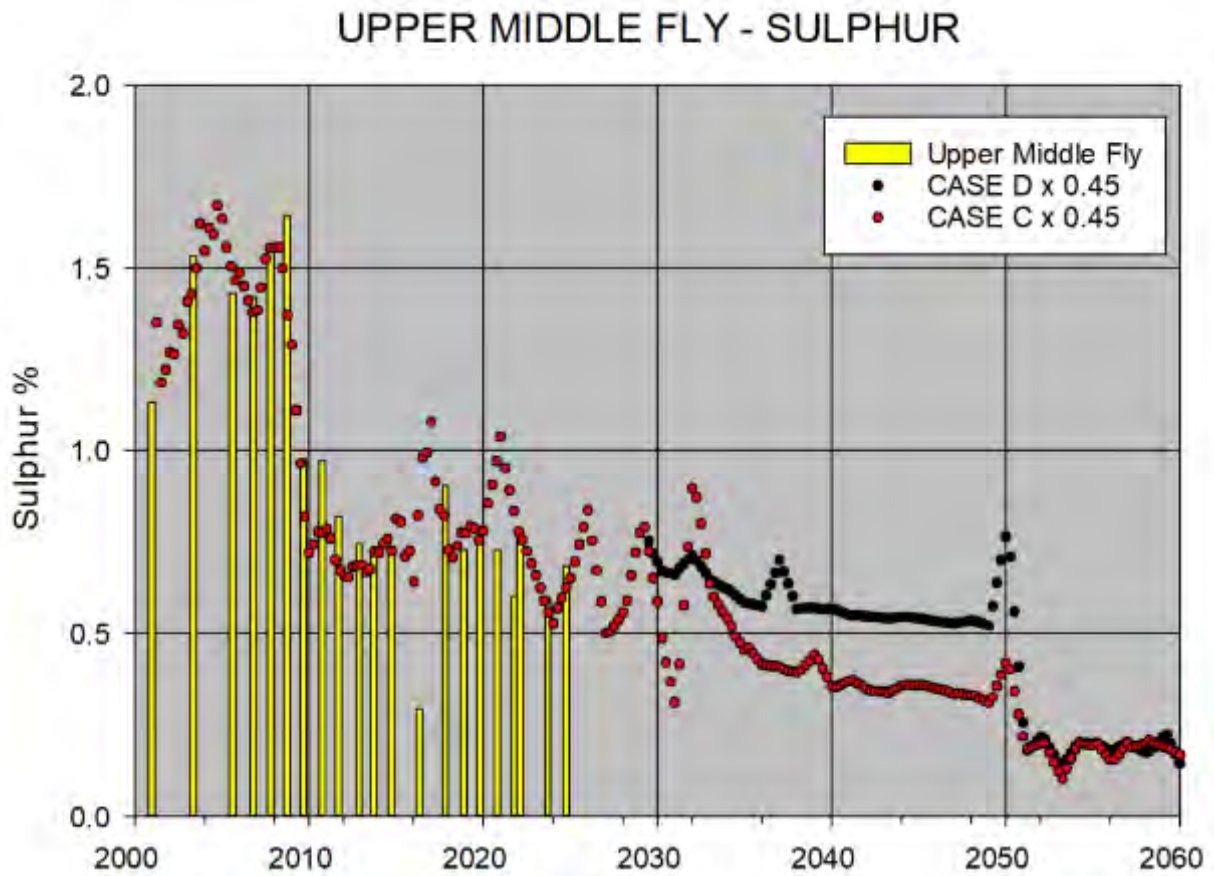
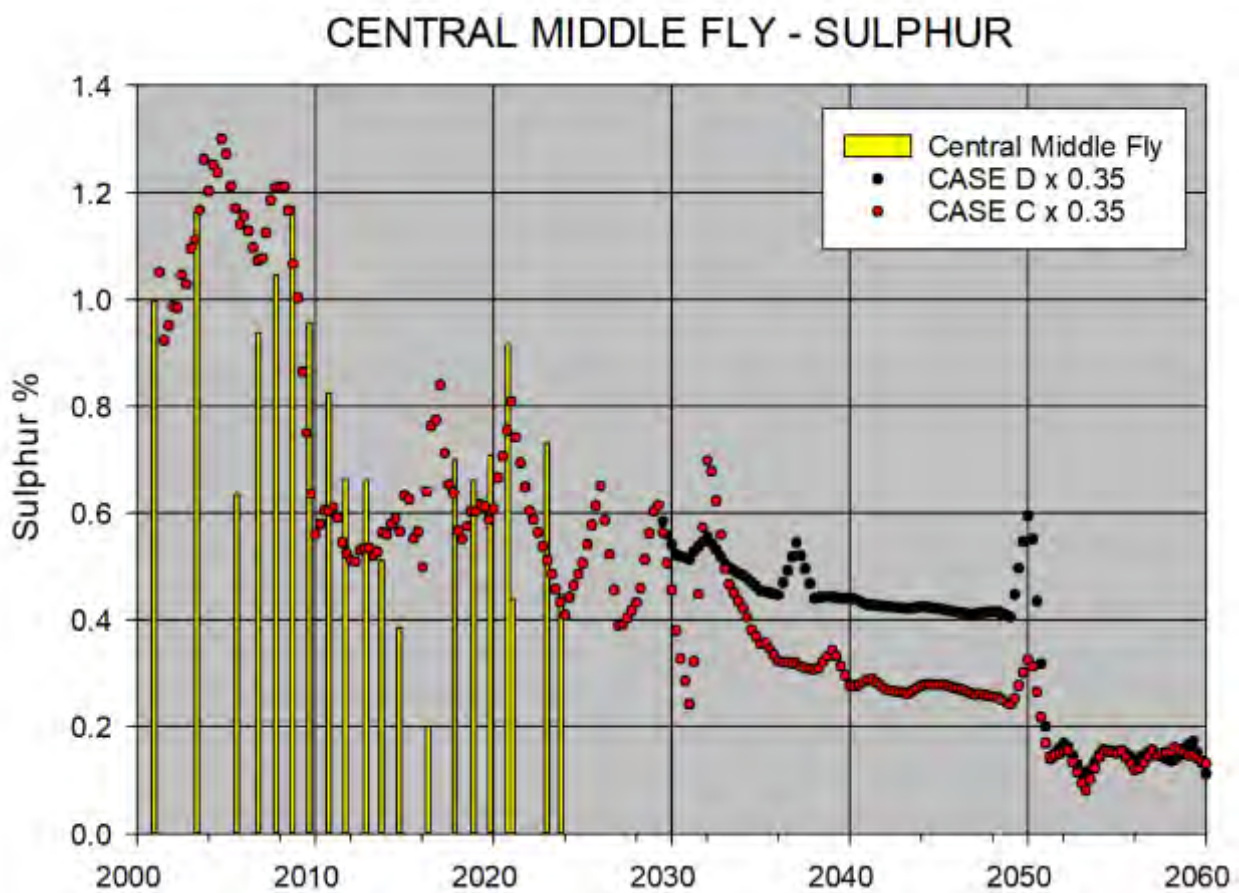


Figure 10-6. Observed and predicted particulate sulphur in Upper Middle Fly levee sediments.



10-7. Observed and predicted particulate sulphur in Central Middle Fly levee sediments.

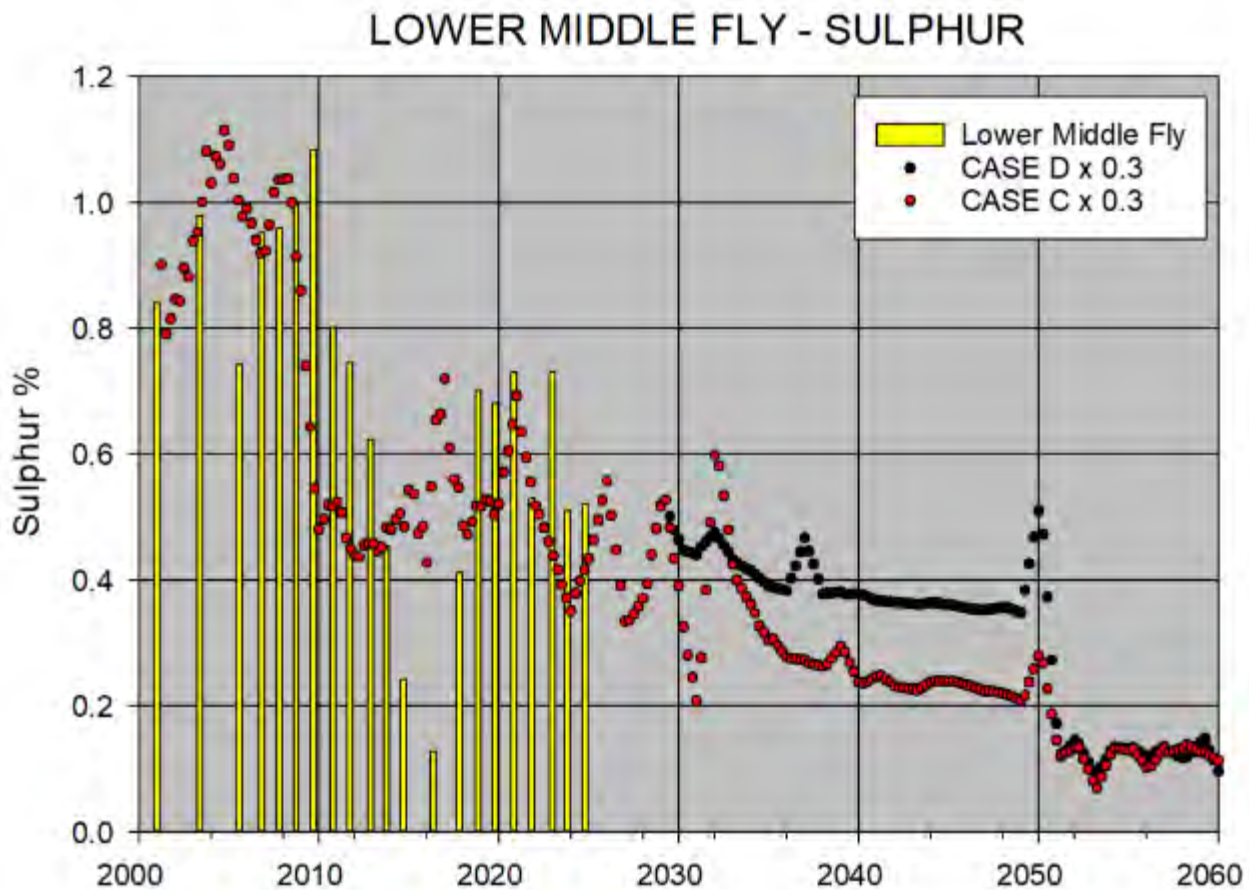


**Figure 10-8. Observed and predicted particulate sulphur in Lower Middle Fly levee sediments.**

## ANC PREDICTIONS

The ANC predictions are fairly close to the observed levee values but show some variability reflecting the waste rock inputs. The trend in both observed data and model predictions is for ANC to increase to the mid 2010s, fall around the time of the 2015 drought and then fluctuate before rising until the early 2030s, mostly in response to some large inputs of waste rock to both the northern and southern dumps. There is also some variability in the predicted ANC of tailings around this time. Once the TSF is in operation, there is a gradual decrease in predicted ANC right down the the system but notable in the Central and Lower Middle Fly. The cause of this remains unexplained but in the Lower Middle Fly it may be due to tributary inflow from catchments draining ancient sediments including the Agu, Kongun Creek and the Kai compared with the large amount of limestone in material derived from the mountains of the upper river system.

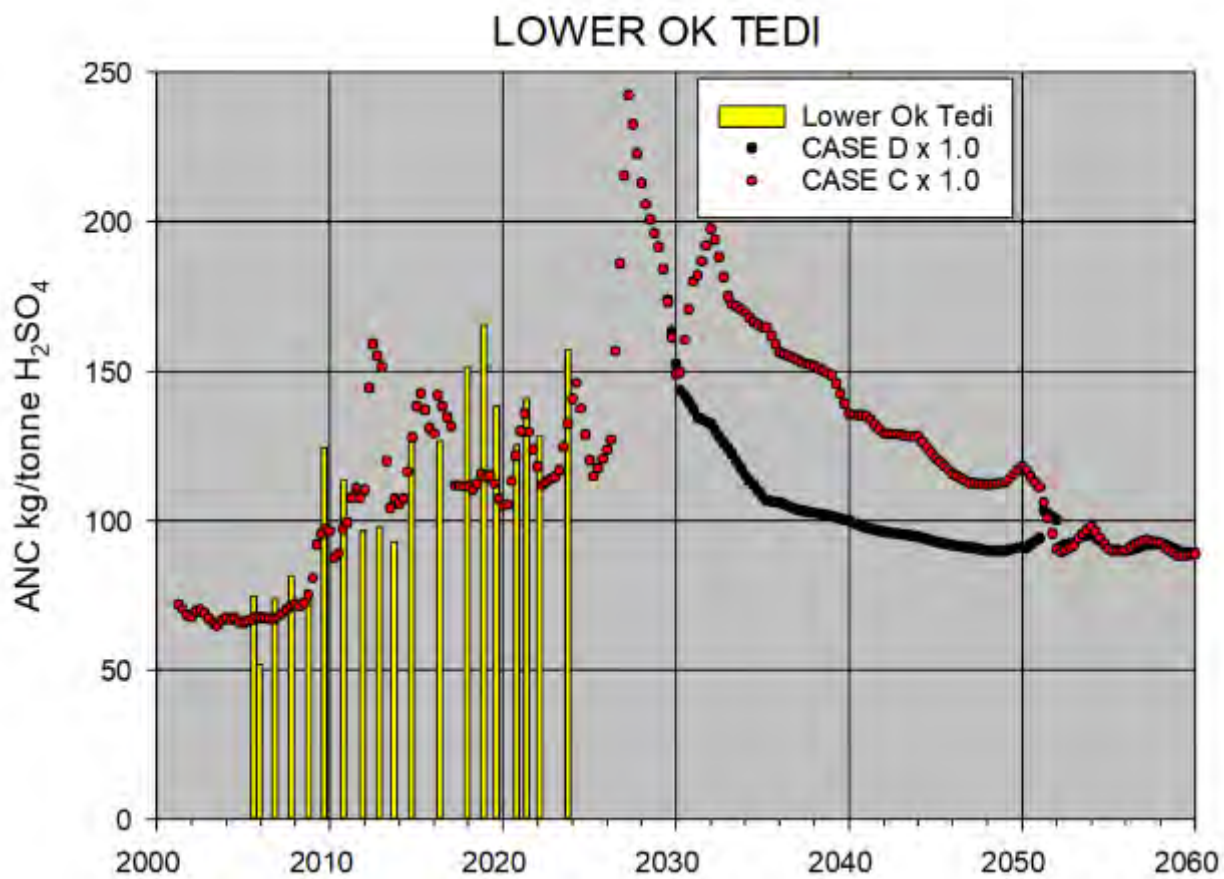


**Figure 10-9. Observed and predicted ANC in Lower Ok Tedi levee sediments.**

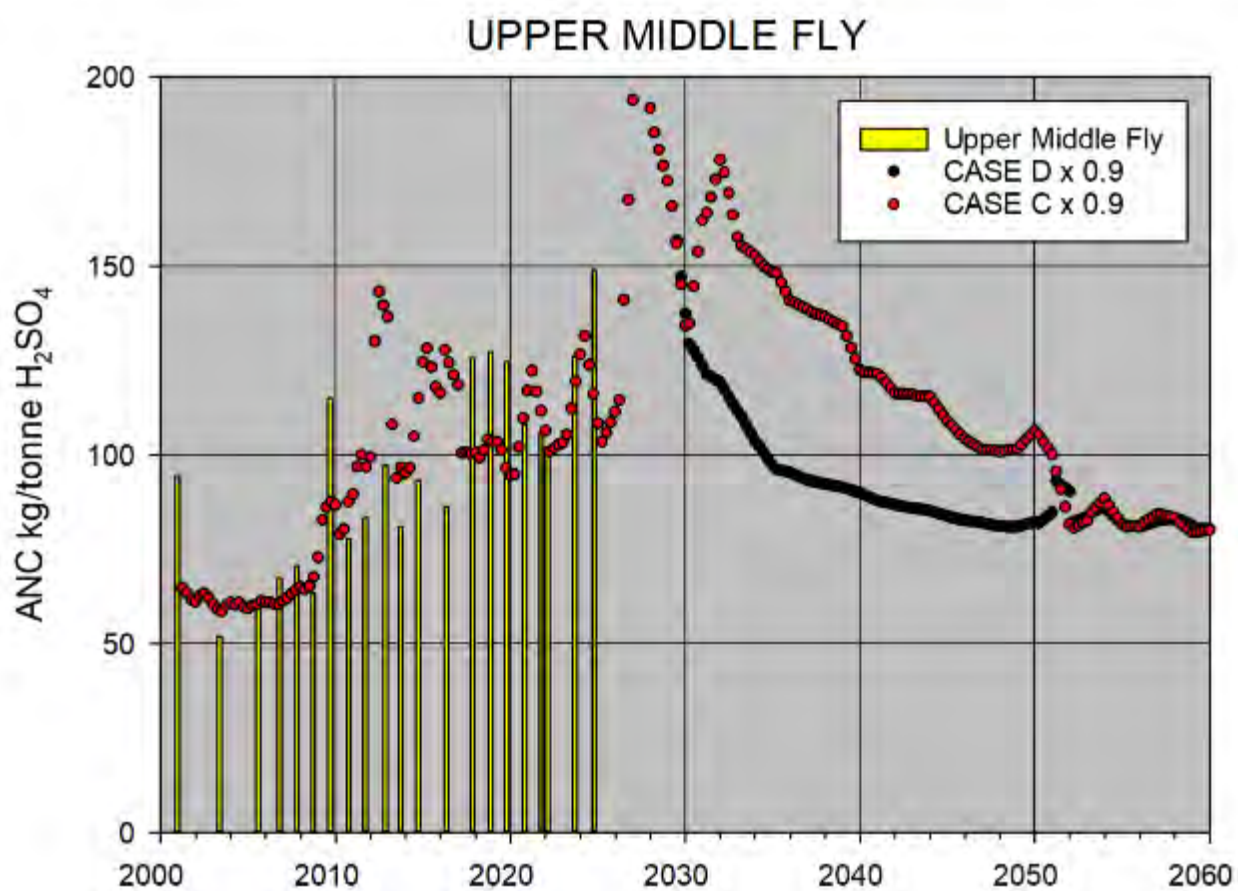


**Figure 10-10. Observed and predicted ANC in Upper Middle Fly levee sediments.**

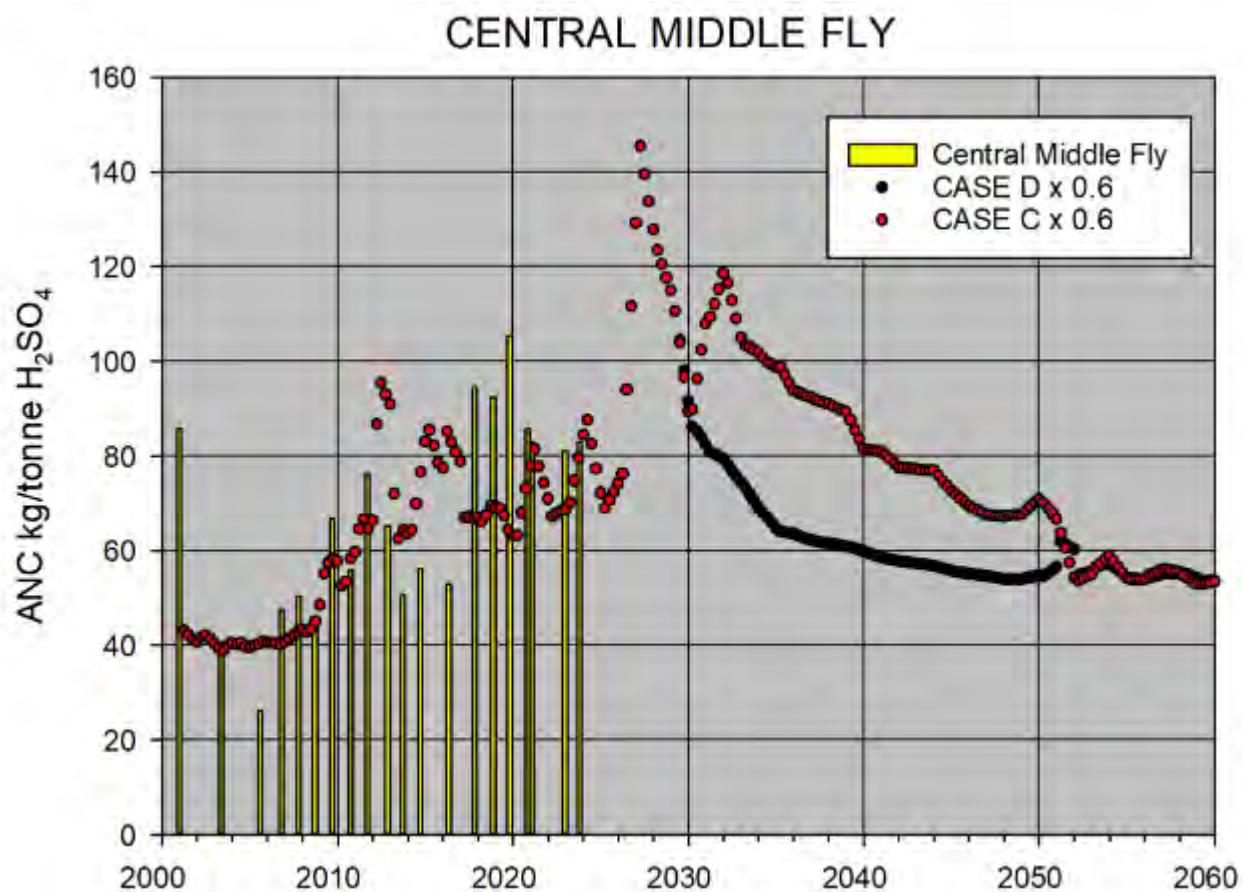


**Figure 10-11. Observed and predicted ANC in Central Middle Fly levee sediments.**

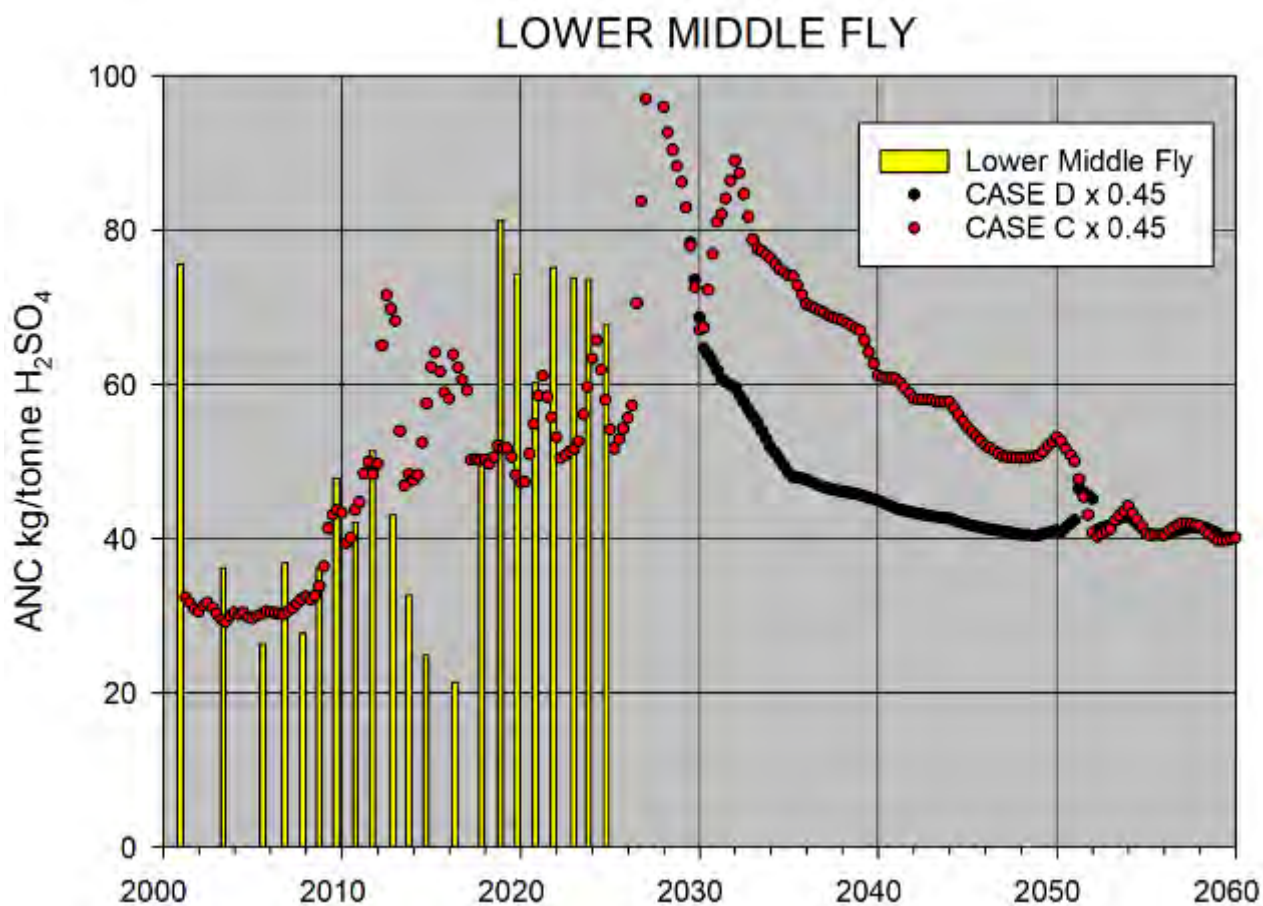


**Figure 10-12. Observed and predicted ANC in Lower Middle Fly levee sediments.**

## CHAPTER ELEVEN – LOCAL AREA IMPACT OF THE TAILINGS STORAGE FACILITY

This chapter deals with the local impact of the TSF on area geomorphology concentrating on drainage lines. TSF operation including hydrology is covered by KCB (2025) in PLAN C5 design documents and many preceding and supporting design documents. TSF geochemistry is the subject of a separate study by Environmental Geoscience International.

The elevations of the TSF and associated features are shown in Fig. 11-1. There are two depositional cells fully enclosed by ring dyke dams. Footprint area is 15.8 km<sup>2</sup> within the ring dyke embankments. The ring dyke follows natural catchment boundaries where possible and appears to avoid any discharge into the relatively pristine Ok Birim. The operating spillway is expected to be on the east side of the TSF and has yet to be modelled but it is likely to follow a short shallow valley into the Ok Tedi. One of the design criteria was to have as much of the TSF as possible confined within a single catchment.

As Fig. 11-1 shows, the footprint covers much of the east branch of the Ok Yep, a small 66.6 km<sup>2</sup> catchment that drains south and joins the Ok Tedi about 4 km south of the TSF. The TSF does cut off some of the upper tributaries of Ok Yep in the north and east but redirects flow back into the western arm of the Ok Yep further south (Fig. 11-2). The overall effect of these diversions and the TSF overflow discharge to the Ok Tedi is likely to reduce flows in the lower Ok Yep.

The effect on sediment load and geochemistry in the lower Ok Yep is unknown. However, the impact on sediment load is likely to be greatest in the construction period. At present, these lowland watercourses carry little sediment load and occupy shallow, well-vegetated valleys. Clearing of the TSF area and that of associated infrastructure during construction is likely to produce an ongoing pulse of sediment load to the Ok Yep, mostly from local sources containing minimal copper and sulphur, especially before the ring dyke dams are completed. This is likely to result in Ok Yep stream bed aggradation which may subsequently flush out to some degree in the post construction period. However, some deposited sediment may remain given the reduction in the post-construction Ok Yep catchment area and reduced streamflow. There may also be continuing sediment delivery to the lower Ok Yep from the constructed flow diversion channels that border the ring dyke and other cleared areas, especially if blocking due to sediment build-up occurs.

Kobom Creek, which borders the Bige West Bank stockpiles provides an example of what may occur once the TSF becomes operational (Fig. 11.3). The creek on the west side has become blocked to some degree, raising water levels and resulting in forest dieback upstream. The drainage line in the south-west has been cleared and opened up in an attempt to reduce upstream water levels. Other areas around the stockpile perimeter have also been cleared. Some of these effects may also occur on the Ok Birim TSF but probably to a lesser degree as there is no blocked and diverted external flow diversion sub-catchment on the scale of Kobom Creek.

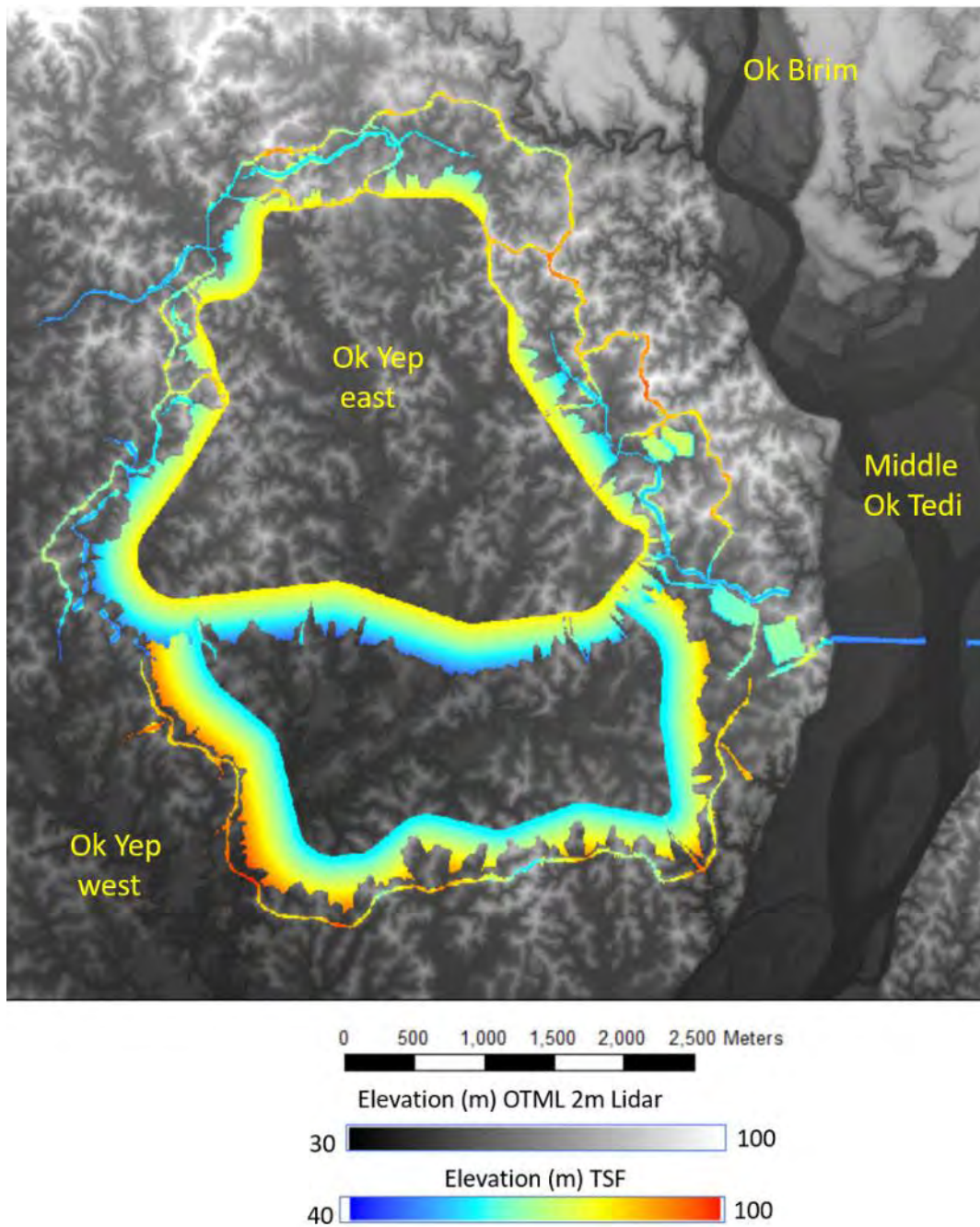


**Figure 11-1.** Digital elevation maps of the proposed TSF embankment, road and boundary flow diversion channels with pre-construction elevations from the OTML lidar elevation model. TSF data from Klohn Crippen Berger, 2025.

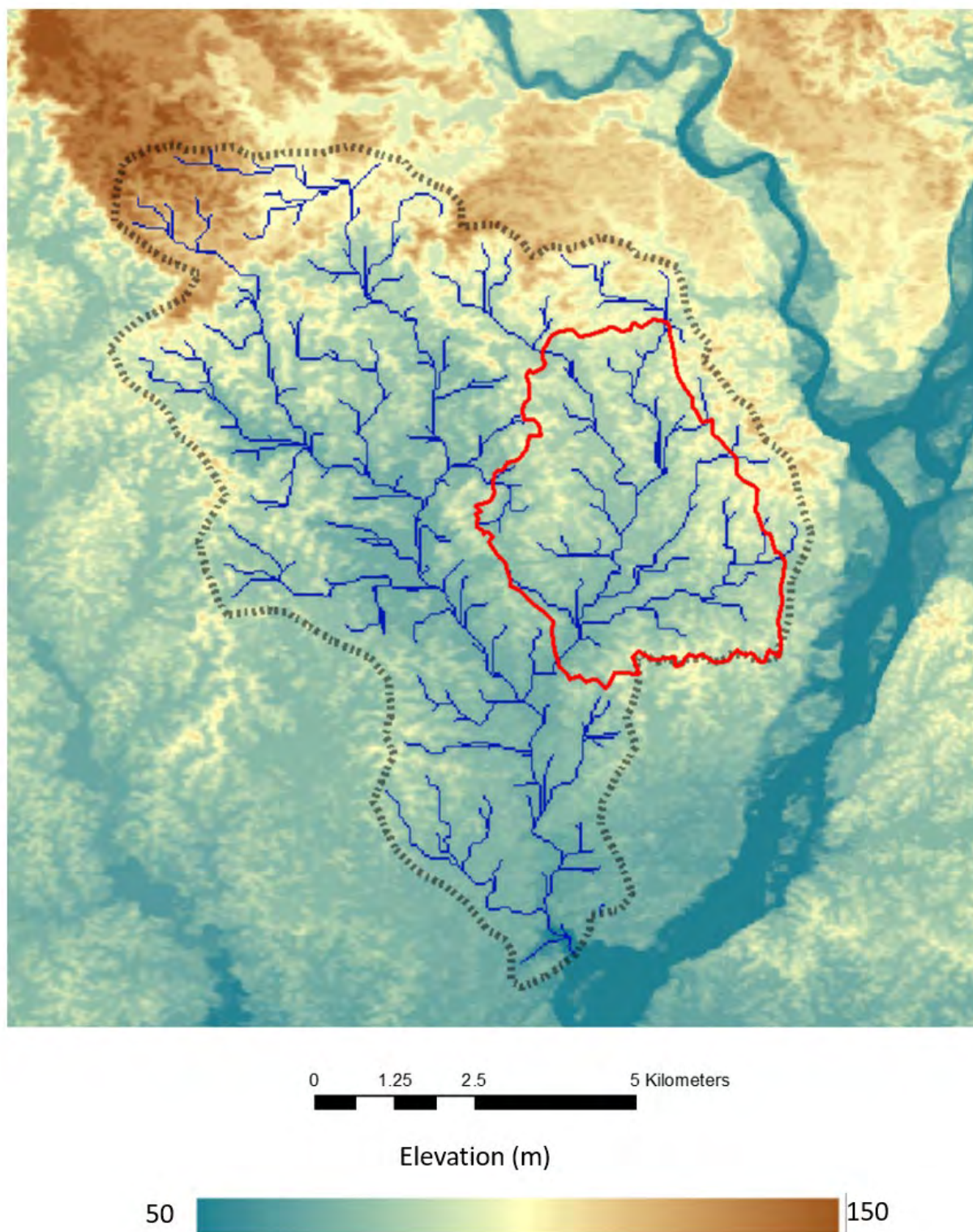


**Figure 11-2. Ok Yep catchment boundary(broken black line) and the Tailings Storage Facility footprint boundary overlaid on pre-construction elevations from the COPENICUS X-band radar digital elevation model.**



**Figure 11.3. Kobom Creek and the Bige West Bank showing cleared areas, opened-up diversion channel and dieback area.**

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**APPENDIX ONE – PART ONE**

**EXTRACTS FROM**

**Modeling Sediment Transport in  
the Ok Tedi Mine Area Creeks and the Middle Ok Tedi  
in Response to Disposal of Rock Waste and Tailings**

**Technical Report**

*Prepared for*

Ok Tedi Mining Limited

P.O. Box 1, Tabubil 333

Western Province, Papua New Guinea

*Prepared by*

Dr. Yantao Cui, Consulting River Engineer

1126 Crowe Place

Concord, CA 94518, USA

&

Dr. Geoff Pickup, Consulting Geomorphologist

1538 Sutton Rd

Sutton, NSW 2620, Australia

**March 2009**

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## SUMMARY

As the Ok Tedi Mine moves towards closure, there is a need to cap the dredged sand stockpiles at Bige. The sandy material required to do this will be dredged from the river. There is also a need to provide better estimates of future erosion in the river system as deposited mine waste moves progressively downstream. The *OKGRAV* sediment model, which has been used to model the Middle and Upper Ok Tedi and tributaries, has performed well in the past but it is not suitable for detailed prediction of sand supply to the lower Ok Tedi. It is also essentially a depositional model and not well-suited to prediction of post-mine closure erosion. We have therefore developed a new upper river system sediment model, *OKTUGS*.

The *OKTUGS* model is based on the Unified Gravel-Sand (*TUGS*) model (Cui 2007a). This is a significant advance in sediment transport modeling technology since it can successfully handle the gravel-sand mixtures delivered to the river system by disposal of waste rock and tailings from the Ok Tedi Mine. These have proved difficult to handle with existing models, including those developed or calibrated specifically for the Middle Ok Tedi and Mine Area Creeks. It also allows two different waste rock lithologies, a useful option since observation shows limestone clasts break down by abrasion more slowly than other material in the waste rock stream (Pickup et al, 2010)

*OKTUGS* uses the surface-based bedload equation of Wilcock and Crowe (2003), and the gravel transfer function of Hoey and Ferguson (1994) and Toro-Escobar et al. (1996). It also includes the sand transfer function of Cui (2007a). The gravel and sand transfer functions link the grain size distributions in the surface layer, subsurface and bedload. Other model components include the ability to handle several different rock types, each with its own specific gravity and rate of particle abrasion during sediment transport. A further development is the ability to simulate how valley and channel forms change under both depositional and eroding conditions and a method for calculating the rate at which stored sediment is released from valley floor deposits. The erosion simulation also includes a method for representing the development of a valley-in-valley form as terraces containing the active channel migration zone are created by channel incision.

*OKTUGS* requires a substantial amount of input data as well as information for model calibration and verification. Input data on waste rock and tailings input comes from OTML operational data. Information on stored sediment for model verification was derived from digital elevation models (DEMs) or spot height data from the river system. These data included two new sources: a DEM of the mine area topography in 1982 derived by digitizing early BHP contour maps; and spot height elevations down the Middle Ok Tedi obtained from 1982 and 1992 air photos together with a differential GPS survey carried out during a small boat transect in 2008. Other datasets included a

new regional hydrology model for generating daily flows throughout the river system and information on channel and valley widths derived from analysis of air photos and satellite imagery.

The Middle Ok Tedi GPS survey provides the first reasonably accurate assessment of deposition in this reach of the river. Specifically, it shows that between 1982 and 2008 about 73 million m<sup>3</sup> of sediment accumulated in the upper Middle Ok Tedi and 89 million m<sup>3</sup> in the lower Middle Ok Tedi. A sediment budget for the whole river system for the period 1985-2004 shows that 319 Mt of sediment had accumulated in the Ok Mani system, 2.4 Mt in the Sulphide Ck. System, and about 200 Mt in the Middle Ok Tedi. Total sediment output to the Lower Ok Tedi was 955 Mt.

*OKTUGS* was designed to represent the river system using fifteen separate reaches, each containing a number of nodes. Both natural sediment load and mine-derived material were routed through the model and deposition was calculated for individual reaches. Observed data were used to calculate particle abrasion coefficients, allowing the model to represent the breakdown of sediment into smaller size fractions during transport. Downstream control of hydraulic conditions was derived from observed changes in water surface elevation at Konkonda.

As in most real-world sediment modeling exercises, *OKTUGS* required calibration to reproduce observed transport and deposition rates. Calibrated parameters included critical shear stress and a factor to allow for sand deposition within the deposited gravel matrix. After calibration, the model calculated total sediment yield from the upper river system to within 3% of the value derived from the sediment budget. Predictions of the location of deposition were also reasonably good. In the Ok Mani system, the model predicted 327 Mt of deposition in 2008 compared with 320 Mt calculated from DEMs. In the Sulphide Ck system, both modeled and observed values were less than 5 Mt. Deposition in the Middle Ok Tedi was modeled with slightly less accuracy, the model yielding 249 Mt of deposition compared with an observed value of 198 Mt. However, it should be noted that the observed value was derived from spot heights and satellite imagery assuming a uniform depth of deposition across the whole valley and would only be an approximation.

Once calibrated, the model was run for a 100-year period. Two different models of channel incision and terrace development were included to represent extremes of behaviour. The model runs show a rapid decrease in sediment delivery to the lower river once dumping of waste rock and tailings disposal ceases. Over the longer term, the release of sediment from deposited material occurs slowly, declining to pre-mine levels after 40-50 years. Much more sediment is released to the lower river system if erosion affects the whole valley floor and terrace development is limited and this is thought to be the more likely case in much of the river system.

Finally, we have examined potential sand supply for dredge sediment storage capping at Bige. Comparison of dredging rates with modeled sand delivery suggests a dredge capture rate of about

85%. From 2010 to 2012, this would yield 8-10 Mm<sup>3</sup>/year, falling to 8.5-9.7 Mm<sup>3</sup> in 2012 and then declining rapidly to 1.8 -3.3 Mm<sup>3</sup> by 2017.

# 1. Introduction

This technical report describes the development of a sediment transport model, *OKTUGS*, and its application to the Ok Tedi Mine Area Creeks and the Middle Ok Tedi (study area hereafter) for simulation of channel responses to mining waste and tailings disposal. Large amounts of rock waste and tailings have been disposed of into the Mine Area Creeks since the start of mining in 1985, resulting in channel aggradation in the study area and downstream. Ok Tedi Mining Ltd. (OTML) has responded with a dredging program on the lower Ok Tedi which extracts about 17 Mt/year of sand from the river which is stored in containments at Bige. Also, pyrite concentrate from high sulphide ores is piped down to Bige and held in a large, excavated storage on the west bank of the Ok Tedi.

As the Ok Tedi Mine moves towards closure, material will be required to cover the dredged stockpiles and the new pyrite concentrate storage at Bige. One possibility is to dredge sand from the river. However, the amount of sand currently stored in the Middle Ok Tedi between Tabubil and Konkonda has remained unknown until now. Also, it was not clear how quickly sand would be released from accumulated deposits in the Harvey Creek Fan, the Ok Mani and the Middle Ok Tedi once waste rock dumping and tailings disposal cease. Professor Gary Parker's *OKGRAV* model (Cui and Parker, 1999), which was used until 2009 on the Mine Area Creeks and the Upper and Middle Ok Tedi, is basically a gravel transport program. As such, it routes sand straight through the system and fails to reproduce the extensive sand deposition which has occurred between Ningerum and Konkonda (Pickup, 2003). A new modeling approach is therefore required to forecast sand deposition and to handle the mixed sand and gravel sedimentary environment of the middle Ok Tedi.

A second issue is the way in which deposited mining waste will begin to erode once waste rock and tailings disposal cease. This will determine sediment supply to the lower river and the development of terraces as the channels of the Ok Mani and the Ok Tedi begin to incise into deposited material. The process will expose deposited material to sub-aerial weathering and acid rock drainage (ARD) issues may develop in some reaches. *OKGRAV* is essentially a depositional model and does not contain the specialized routines required to deal with eroding situations. It has therefore become necessary to develop a new approach.

Modeling the transport of gravel-sand mixtures at high concentrations has proved to be very difficult for existing sediment models. The *HEC-6* Model, which has been used successfully on the Lower Ok Tedi and Middle Fly (Pickup and Cui, 2003, 2009a) does not work on the Middle Ok Tedi<sup>1</sup>. The core of the *OKTUGS* model is the advance in sediment transport modeling offered by the Unified Gravel-Sand (*TUGS*) model (Cui 2007a) which employs the surface-based bedload equation of Wilcock and Crowe (2003), and the gravel transfer function of Hoey and Ferguson (1994) and Toro-

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<sup>1</sup> As recent work has shown, nor does the *CAESAR-LISFLOOD 2-D model* (Coulthard et al) or the 1-D and 2-D versions of *HEC-RAS*.

Escobar et al. (1996). It also includes the sand transfer function of Cui (2007a). The gravel and sand transfer functions link the grain size distributions in surface layer, subsurface and bedload.

The *TUGS* model has been tested with flume experimental data (Cui 2007a) and with field data in two rivers (Cui 2007b; Gomez et al. 2009), all with good agreement. In particular, Cui (2007a) demonstrated that the model can accurately reproduce the depositional patterns and bed material grain size distributions observed in flume experiments; Cui (2007b) demonstrated that the *TUGS* model was able to reproduce the stratification of the sediment deposits upstream of Marmot Dam, Sandy River, Oregon, USA with sufficient detail to reproduce two gravel lenses within a sandy layer. Similarly, Gomez et al. (2009) were able to demonstrate that the model could reproduce aggradation and degradation patterns in the Waipaoa River, New Zealand observed between 1947 and 2002. It was also able to reproduce the reach-averaged bed material median size to within millimeters.

In addition to the techniques used in *TUGS* model, the *OKTUGS* model includes both new components and components adapted from other models to meet the specific requirements for the modeling of the study area. These include a) the expansion of the model to allow for tributaries following the work of Cui and Parker (1999); b) the inclusion of multiple rock types with different abrasion coefficients (Cui and Parker 2005) and densities; c) the concept of valley-wide aggradation during the period of mining operation as in the *OKGRAV* model (Cui and Parker 1999); and d) the concept of valley-in-valley formation in response to channel incision that may leave terraces behind once sediment disposal ceases following mine closure.

The first two parts of the report set the background to the study. They begin with a description of *OKTUGS* model development in Section 2 while Section 3 provides details of the geomorphic and hydrologic conditions in the project area, the disposal of the mining rock waste and tailings, and channel responses to the mining activities. The next part of the report deals with model setup and application to the Ok Tedi and its tributaries. Section 4 describes how the model represents the river system, how model input data were derived, and how model boundary conditions were established. Section 5 deals with model calibration and operation. The final part of the report presents model results and supplementary analysis.

## 2. Model Development

### 2.1 Conceptual Model

The conceptual model used in *TUGS* model and in the *OKTUGS* model is the widely used three-layer model (e.g., Hirano 1971; Ribberink 1987; Parker 1990, 1991a,b; Parker and Sutherland 1990; Wilcock and Crowe 2003; Cui et al. 1996, 2003, 2005, 2006; Cui and Parker 1997, 2005; Cui and Wilcox 2008). According to this conceptual model, a sediment deposit in a gravel-bedded river is composed of a surface layer (or active layer), which lies on top of the subsurface sediment (the second layer). A third bedload layer is composed of the sediment particles transported as bedload over the surface layer. The three layers, along with the concept of the interface layer, are shown in Figure 2. For the simulation of channel bed dynamics, the interface layer was defined by previous researchers (e.g., Hirano 1971; Ribberink 1987; and Parker 1991a,b) as the layer of sediment to be deposited on top of the existing subsurface layer during aggradation (Figure 2a) and the layer of sediment to be released from the top of the subsurface layer during degradation (Figure 2b). Thus, interface sediment becomes part of the subsurface

layer following aggradation and was part of the subsurface layer prior to channel degradation. Note that the interface layer exists only conceptually because, given a time increment  $\Delta t$ , the thickness of the interface layer during this time increment approaches zero when  $\Delta t \rightarrow 0$ , and hence the conceptual model is conventionally named as a three-layer model instead of a four-layer model. The basic concept of the bedload, surface, subsurface

and interface layers will help the understanding of the surface-based bedload equation and the sediment exchange functions presented in detail below. The grain size distribution of the surface layer sediment will be part of the input variables for applying Wilcock and Crowe's (2003) bedload equation. Here it is important to introduce the notations that describe the grain size distributions in the four layers before Wilcock and Crowe's (2003) equation and other relations are described.

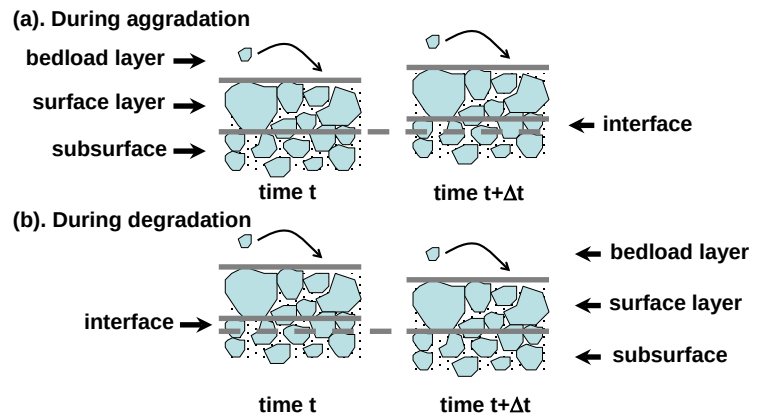


**Figure 2. Conceptual three-layer model in a gravel bedded river showing the bedload layer, the surface layer, and the subsurface layer. The interface sediment is the sediment that becomes part of the subsurface layer during aggradation (a) and the subsurface sediment to be eroded from the subsurface during degradation (b). Sketches are adapted from Parker (1990a, b) by Cui (2007a).**

## 2.2 Notations for Sediment Grain Size Distributions

The existence of both natural sediment and sediment from mining operation necessitates the use of multiple rock types, each with a different abrasion coefficient and density. Notation for grain size distributions used in this technical report is almost identical to that presented in Cui (2007a) except for the inclusion of multiple rock types, as described below. To represent the grain size distribution of a body of sediment, it is first divided into two classes: sediment coarser than 2 mm (gravel and coarser, referred to as gravel hereafter), and sediment finer than 2 mm (sand and finer, referred to as sand hereafter). For simplicity, it is assumed that there is no grain size sorting within the sand class during transport, although each rock type may have its own grain size distribution for the sand class. As a result, sand fractions of different rock types in bedload, surface layer and subsurface will change in space, while the grain size distribution for sand of any individual rock type remains unchanged. The gravel class is divided into  $N$  groups bounded by  $N+1$  grain sizes,  $D_1, D_2, \dots, D_N, D_{N+1}$ , where  $D_1$  is always 2 mm (*i.e.*, the boundary between sand and gravel). The  $j$ -th size group, where  $j$  is between 1 and  $N$ , is bounded by grain size  $D_j$  and  $D_{j+1}$  with a mean grain size  $\bar{D}_j = \sqrt{D_j D_{j+1}}$ . The grain size distribution of the gravel class (*i.e.*, the bulk sediment excludes sand and finer) is then represented with volumetric fractions of the  $N$  size groups. Knowing the fraction of sand of each rock type within the bulk sample, and the fraction of each gravel size group and rock type within the gravel class, we will be able to define the grain size distribution of the combined gravel and sand. For example, we would describe the grain size distribution of the surface layer with sand fraction  $F_{s,k}$ , in which  $k$  denotes the  $k$ -th rock type, and  $k = 1, 2, \dots, M$ , where  $M$  is the total number of rock types. We will then describe the fractions of different gravel size groups and rock types within the gravel class as  $F_{j,k}$ , in which  $j=1, 2, \dots, N$ , and  $k = 1, 2, \dots, M$ , where  $N$  is the total number of grain size bins for gravel.

Note that  $\sum_{j=1}^N \sum_{k=1}^M F_{j,k} = 1$ . The notation for grain size distributions used here is different from that in

Wilcock and Crowe (2003) due to the simplification made to treat the entire sand class as one grain size group. This allows more concise presentation of gravel and sand transfer functions (presented briefly later) than the notations of Wilcock and Crowe (2003) (Cui 2007a). The simplification of treating the entire sand class as a single bin is necessary because it significantly reduces computer memory requirements during simulation, thus allowing for more layers of sediment deposit to be stored in memory. Similar to the surface layer, where the fraction of sand and the fractions of different gravel size groups within the gravel class are denoted as  $[F_{s,k}$  and  $F_{j,k}$ ,  $j = 1$  to  $N$ ,  $k=1$  to  $M]$ , the fraction of sand and fractions of different gravel size groups within the gravel class for bedload, subsurface, and interface are denoted as  $[p_{s,k}$  and  $p_{j,k}$ ,  $j = 1$  to  $N$ ,  $k=1$  to  $M]$ ,  $[f_{s,k}$  and  $f_{j,k}$ ,  $j = 1$  to  $N$ ,  $k=1$

to  $M]$ , and  $[f_{Is,k}$  and  $f_{Ij,k}$ ,  $j = 1$  to  $N$ ,  $k=1$  to  $M]$ , respectively, where  $\sum_{j=1}^N \sum_{k=1}^M p_{j,k} = 1$ ,  $\sum_{j=1}^N \sum_{k=1}^M f_{j,k} = 1$ , and

$\sum_{j=1}^N \sum_{k=1}^M f_{ij,k} = 1$ . Procedures for calculating geometric mean grain size and geometric standard

deviation, which will be used frequently in the equations hereafter, can be found in Cui et al. (1996) and are not discussed here.

### 2.3 Adaptations of Governing Equations for Multiple Rock Types

With the notations for grain size distributions presented above in Section 2.2, the surface-based bedload equation of Wilcock and Crowe (2003) is rewritten below:

$$W_{j,k}^* = \begin{cases} 0.002 \left( \tau / \tau_{rj,k} \right)^{7.5}, & \text{for } \tau / \tau_{rj,k} < 1.35 \quad j = 1, 2, \dots, N \text{ or } s \\ 14 \left( 1 - 0.894 / \sqrt{\tau / \tau_{rj,k}} \right)^{4.5}, & \text{for } \tau / \tau_{rj,k} \geq 1.35 \quad k = 1, 2, \dots, M \end{cases} \quad (1)$$

in which subscript  $j$  denotes grain size bin number, and subscript  $k$  denotes rock type number;  $\tau$  denotes bed shear stress,  $\tau_{rs,k}$  denotes the reference shear stress for sand of the  $k$ -th rock type;  $\tau_{rj,k}$  ( $j \neq s$ ) denotes the reference shear stress for the  $j$ -th size group of the gravel class of the  $k$ -th rock type (to be discussed in more detail below), and  $W_{s,k}^*$  denotes dimensionless transport rate for sand of the  $k$ -th rock type;  $W_{j,k}^*$  denotes dimensionless transport rate for the  $j$ -th size group of the gravel class of the  $k$ -th rock type:

$$W_{s,k}^* = \frac{R_k g Q_T P_{s,k}}{B_a u_*^3 F_{s,k}} \quad W_{j,k}^* = \frac{R_k g Q_g P_{j,k}}{B_a u_*^3 (1 - F_s) F_{j,k}} \quad (2a,b)$$

in which

$$F_s = \sum_{k=1}^M F_{s,k} \quad (2c)$$

$R_k$  denotes submerged specific gravity of sediment particles of the  $k$ -th rock type,  $g$  denotes gravitational acceleration,  $B_a$  denotes active channel width,  $u_*$  denotes shear velocity (and  $u_* = \sqrt{\tau / \rho}$ , where  $\rho$  denotes the density of water),  $Q_T$  denotes the volumetric transport rate for combined sand and gravel, and  $Q_g$  denotes the volumetric transport rate for gravel. The reference shear stresses,  $\tau_{rs,k}$  and  $\tau_{rj,k}$ , were defined by Wilcock and Crowe (2003) so the shear stress at which the dimensionless sediment transport rates,  $W_{s,k}^*$  and  $W_{j,k}^*$ , have a low value of 0.002, as indicated in equation (1). The reference shear stresses,  $\tau_{rs,k}$  and  $\tau_{rj,k}$ , are grain size and rock type dependent:

$$\frac{\tau_{rs,k}}{\rho R_k g D_{sg} \tau_{rsg}^*} = \left( \frac{D_{sk}}{D_{sg}} \right)^{b_{sk}}, \quad b_{sk} = \frac{0.67}{1 + \exp(1.5 - D_{sk} / D_{sg})} \quad (3a,b)$$

$$\frac{\tau_{rj,k}}{\rho R_k g D_{sg} \tau_{rsg}^*} = \left( \frac{\bar{D}_j}{D_{sg}} \right)^{b_g}, b_g = \frac{0.67}{1 + \exp(1.5 - \bar{D}_j / D_{sg})} \quad (3c,d)$$

in which  $\tau_{rsg}^*$  denotes a surface geometric mean based reference Shields stress for the k-th rock type,  $D_{sk}$  denotes the geometric mean grain size of the surface sand in the k-th rock type; and  $D_{sg}$  denotes the geometric mean grain size of the surface layer (including both sand and gravel classes). Based on flume experimental data, Wilcock and Crowe (2003) proposed that surface geometric mean based reference Shields stress,  $\tau_{rsg}^*$ , decreases with the increase in surface sand fraction ( $F_s$ ):

$$\tau_{rsg}^* = 0.021 + 0.015 \exp(-20F_s) \quad (4)$$

The above equations allow for the calculation of the total bedload transport rate ( $Q_T$ ), gravel transport rate ( $Q_g$ ) transport rates, and sand transport rate ( $Q_s = Q_T - Q_g$ ). They also allow for the calculation of the fractions of sand in the bedload for different rock types ( $p_{s,k}$ ), and the grain size fractions for different grain size bins and different rock types ( $p_{j,k}$ ).

To link the surface, subsurface and bedload grain sizes, the model adapts the gravel transfer function of Hoey and Ferguson (1994) and Toro-Escobar et al. (1996) and the sand transfer function of Cui (2007a). In the case of degradation, the transfer functions are specified as

$$f_{lj,k} = f_{j,k}; j = s, 1, 2, \dots, N; k = 1, 2, \dots, M \quad (5a)$$

and during aggradation, the transfer functions become as

$$f_{lj,k} = \chi p_{j,k} + (1 - \chi) F_{j,k}; j = 1, 2, \dots, N; k = 1, 2, \dots, M \quad (5b)$$

$$f_{ls,k} = \begin{cases} [0.4 - 0.1\sigma_{gg} + (0.6 + 0.1\sigma_{gg})F_s] F_{s,k} / F_s & \text{for } \sigma_{gg} < 4 \\ F_{s,k} & \text{for } \sigma_{gg} \geq 4 \end{cases}; k = 1, 2, \dots, M \quad (5c)$$

in which  $\chi = 0.7$  was derived based on the St. Anthony Falls Laboratory (SAFL) downstream fining experiment Run 3 by Toro-Escobar et al. (1996); and  $\sigma_{gg}$  denotes geometric standard deviation of the gravel class of the interface sediment.

The Exner equation of sediment continuity is adapted as

$$(1 - \lambda_p) B_s \frac{\partial \eta}{\partial t} + \frac{\partial Q_T}{\partial x} + Q_g \sum_{k=1}^M \left\{ \beta_k \sum_{j=1}^N [p_{j,k} + (1 - F_s) F'_{j,k}] \right\} = 0 \quad (6a)$$

$$\begin{aligned}
& (1-\lambda_p)B_s \left( \frac{\partial[(1-F_s)L_a F_{j,k}]}{\partial t} + (1-f_{Is})f_{1j,k} \frac{\partial \eta}{\partial t} \right) \\
& + \frac{\partial(Q_g p_{j,k})}{\partial x} + \beta_k Q_g [p_{j,k} + (1-F_s)F_{j,k}'] \\
& + \frac{\beta_k Q_g}{3\ln(2)} \left( \frac{p_{j,k} + (1-F_s)F_{j,k}'}{\psi_{j+1} - \psi_j} - \frac{p_{j+1,k} + (1-F_s)F_{j+1,k}'}{\psi_{j+2} - \psi_{j+1}} \right) = 0
\end{aligned} \tag{6b}$$

$$(1-\lambda_p)B_s \left( \frac{\partial(F_{s,k}L_a)}{\partial t} + f_{Is,k} \frac{\partial(\eta - L_a)}{\partial t} \right) + \frac{\partial(Q_T p_{s,k})}{\partial x} - \frac{\beta_k Q_g}{3\ln(2)} \frac{p_{1,k} + (1-F_s)F_{1,k}'}{\psi_2 - \psi_1} = 0 \tag{6c}$$

in which  $\lambda_p$  denotes porosity of the sediment deposit;  $B_s$  denotes width of sediment deposition or erosion;  $\eta$  denotes the thickness of sediment deposit;  $t$  denotes time,  $\beta_k$  denotes volumetric abrasion coefficient (fraction of volume lost per unit distance transported) for the  $k$ -th rock type;  $L_a$  denotes surface layer thickness;  $f_{Is} = \sum_{k=1}^M f_{Is,k}$  is the sand fraction of all the rock types in the interface sediment;  $F_{j,k}'$  is an areal estimate of the fraction of exposure of surface gravel of the  $j$ -th group and  $k$ -th rock type (and  $F_{1,k}'$  is for  $j = 1$ ) given by Parker (1991a,b) below:

$$F_{j,k}' = \frac{F_{j,k} / \sqrt{D_j}}{\sum_{j=1}^N \sum_{k=1}^M (F_{j,k} / \sqrt{D_j})} \tag{7}$$

$\psi_j$  denotes base-2 logarithmic grain size psi-scale associated with grain size  $D_j$ , *i.e.*,

$$\psi_j = \log_2(D_j), \quad j = 1, 2, \dots, N, N+1 \tag{8}$$

Equation (6a) represents the conservation of total sediment load (sand and gravel), and the last term on the left-hand side is a sink term, representing gravel loss to silt as gravel abrades into smaller gravel particles, sand, and silt (Parker 1991a,b). Equation (6b) is the conservation of gravel in the  $j$ -th size group and  $k$ -th rock type, in which the first term involving  $\beta_k$  represents gravel mass lost to silt by abrasion and the second term involving  $\beta_k$  represents gravel mass transfer between adjacent size groups through abrasion. The factor  $(1-F_s)$  in the abrasion term means that only  $(1-F_s)$  of the surface layer is composed of gravel. Equation (6c) represents the conservation of sand, and the last term on the left hand side represents increased sand mass through abrasion of gravel, which is also seen in equation (6b) for the finest gravel size group (*i.e.*, for  $j = 1$ ).

The simulation of the study area is intended for long-term predictions of channel responses to mining activities, and thus, fine sediment infiltration and entrainment functions described in Cui (2007a) can be neglected (*cf.* Cui, 2007a,b).

The governing equations for water flow are identical to those used in *TUGS* model (Cui 2007a) and are provided below:

$$\begin{cases} \frac{dh}{dx} = \frac{S_0 - S_f}{1 - F_r^2}, & F_r \leq F_{rn} \\ S_f = S_0, & F_r > F_{rn} \end{cases} \quad (9)$$

in which  $h$  denotes water depth;  $x$  denotes downstream distance,  $S_0$  denotes local bed slope;  $S_f$  denotes friction slope; and  $F_r$  denotes Froude number, which is calculated by assuming a wide rectangular channel:

$$F_r = \frac{Q_w}{A_w \sqrt{g A_w / B_w}} \quad (10)$$

in which  $Q_w$  denotes water discharge;  $A_w$  denotes wetted area;  $B_w$  denotes the width water surface.  $F_{rn}$  in equation (9) is the critical Froude number that determines whether application of the backwater equation is needed or whether quasi-normal flow may be assumed. Here an arbitrary value of  $F_{rn} = 0.8$  is used in the simulation, and any  $F_{rn}$  value of between 0.75 and 0.9 produces similar results. The friction slope  $S_f$  is calculated with the Keulegan (1938) resistance formulation,

$$\frac{Q_w}{A_w \sqrt{gh S_f}} = 2.5 \ln \left( 11 \frac{h}{k_s} \right) \quad (11a)$$

in which  $k_s$  denotes roughness height and is assumed to be proportional to surface layer geometric mean grain size of combined gravel and sand,

$$k_s = k D_{sg} = k D_{gs}^{F_s} D_{sgg}^{1-F_s} \quad (11b)$$

in which  $D_{sg}$  denotes the geometric mean grain size of the surface layer for combined gravel and sand; and  $D_{sgg}$  denotes the surface gravel geometric mean grain size. Because  $k_s$  is located inside the log function in equation (11a), a specific choice of a  $k$  value is not particularly sensitive to model simulation. In Cui (2007a, b), the  $k$  value was assumed to be 2.5 but here we will use it as a calibration coefficient. As in the *TUGS* model, form friction is assumed to be relatively unimportant and is ignored in the *OKTUGS* model, as it is designed primarily for simulation of gravel-bedded rivers, and also for simplicity.

The Keulegan resistance formulation (Eq. 11a) is valid only for a large water depth ( $h$ ) relative to roughness height ( $k_s$ ). When water depth becomes shallower than roughness height, neither the resistance formulation nor the sediment transport equation are likely to be valid. It is expected, however, that sediment transport under these low depth conditions will be less important. With that, the most likely concern associated with the formulation under the condition of shallow water depth is not the correct prediction of sediment transport, but rather mathematical stability, because  $u/u_*$  value

calculated with Eq. (11a) can become negative. As a precaution and to reduce problems associated with a potential negative  $u/u_*$  value, the Keulegan resistance formulation is modified for the case of  $h/k_s < 1$  to

$$\frac{Q_w}{A_w \sqrt{ghS_f}} = \exp\left(2.635 - \frac{0.834}{\sqrt{h/k_s}}\right), \quad \text{for } \frac{h}{k_s} < 1 \quad (11c)$$

With the application of Eq. (11c) for  $h/k_s < 1$ , Eq. (11a) will be applied under the condition of  $h/k_s \geq 1$ . Eq. (11c) provides a smooth connection with Eq. (11a) at  $h/k_s = 1$  while maintaining positive values for  $u/u_*$  under all conditions (Figure 3). Here we reiterate that the application of Eq. (11c) is not intended to provide a correct prediction of shear velocity under low  $h/k_s$  conditions, which is expected to be relatively unimportant because sediment transport is expected to be small. Instead, Eq. (11c) is applied as a way to overcome some of the potential mathematical difficulties in

modeling, especially when an iteration method (e.g., the bisection or Newton-Raphson method) is used to solve water depth from a known friction slope based on the specified friction formulation.

Combining the backwater equation and quasi-normal flow assumption under different Froude number flow conditions allows for a relatively simple algorithm in simulating sub- and supercritical flow conditions, and the results from this simulation are almost identical to more complicated methods as demonstrated in Cui et al. (2005) and Cui et al. (2006).

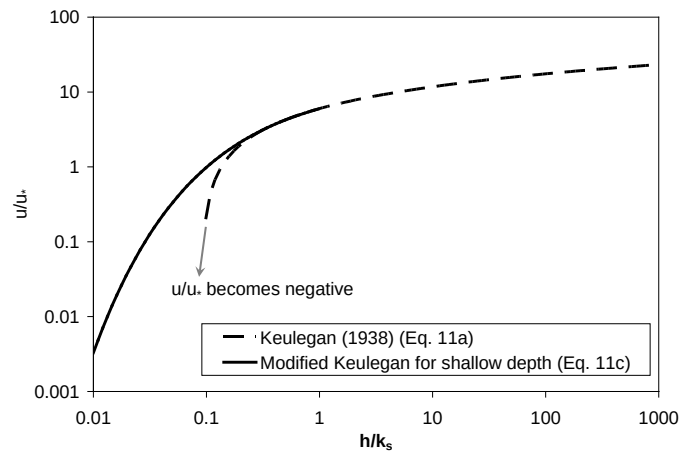


**Figure 3. Keulegan (1938) resistance formulation and its modification for low relative water depth in order to overcome mathematical difficulties in modeling.**

## **2.4 Further Adaptations of Governing Equations for Valley-Wide Aggradation and Subsequent Channel Incision**

A sketch conceptualizing valley-wide aggradation during mining operations and the potential channel incision and formation of terraces once mine waste disposal ceases is provided in Figure 4. Following the procedure in *OKGRAV*, it is assumed that the entire valley will aggrade at the same rate as the active channel during mining operations due to frequent channel avulsion associated with high sediment loads and channel braiding (Figure 4a). Once the sediment disposal ceases following mine closure, channel incision processes will begin (Figure 4b). It is assumed that a) the incision process

will have the same active channel geometry during the period of degradation; and b) the active channel will be able to migrate laterally within the valley, creating an inner valley wider than the active channel itself while cutting through the valley floor deposits. It can be expected that terraces will be left behind following channel incision if the active channel does not migrate enough to reach either side of the valley floor (Figure 4b). This is common behaviour when braided rivers degrade.

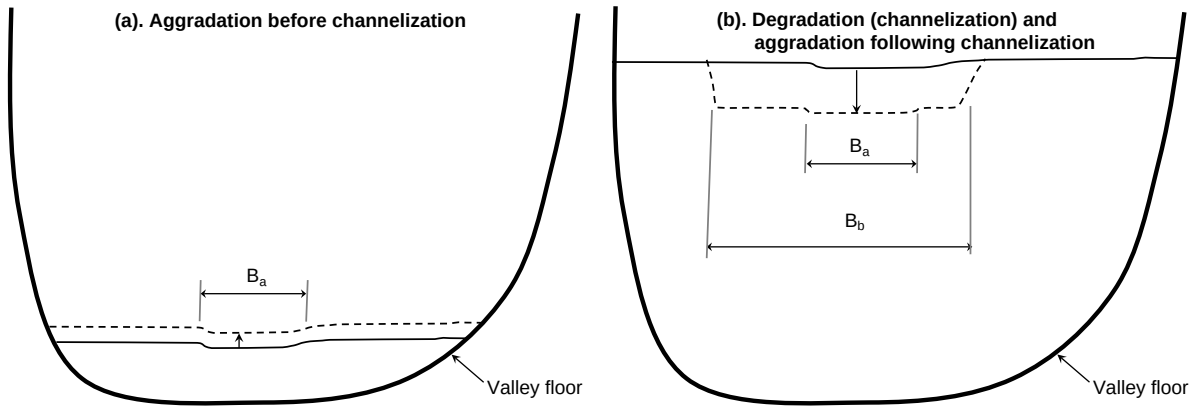


**Figure 4. Sketch showing the conceptualization of the aggradation and degradation processes: (a) aggradation before channel incision, after OKGRAV model of Gary Parker (Cui and Parker 1999); and (b) degradation (channel incision) and aggradation following incision. During degradation in (b), the active channel (denoted with a width  $B_a$ ) migrates back and forth, creating an inner valley (denoted with a width  $B_b$ ) that is wider than the active channel. If  $B_b$  is narrower than the valley width, the degradation will leave terraces behind, storing sediment for a long period.**

For simplicity, both the active channel and the inner valley resulting from lateral migration during channel aggradation are assumed to be rectangular in shape. There may still be occasional channel aggradation during the period of channel incision but this will only occur within the inner valley area instead of the entire valley. With that, the Exner equations of sediment continuity (Equations 6a,b,c) need to be adjusted under different aggradation or degradation scenarios and are briefly described below.

- 1) Aggradation prior to channel incision (Figure 4a): replace parameter  $B_s$  in equations (6a,b,c) with valley width  $B_v$ ; apply equations (6b, c) to calculate interface sediment fraction  $f_{ij,k}$ .
- 2) Aggradation after channel incision (i.e., aggradation within the incised channel, Figure 4b,): replace parameter  $B_s$  in equations (6a, b,c) with  $B_b$  (Figure 4b); apply equations (6b,c) to calculate interface sediment fraction  $f_{ij,k}$ .
- 3) Degradation: replace parameter  $B_s$  in equations (6a,b,c) with  $B_b$  (Figure 4b); apply equation (6a) to calculate interface sediment fraction  $f_{ij,k}$ .

## 2.5 Model Adaptation for Simulation of a Channel Network

The model has been adapted to allow for simulation of channel networks using the approach of Cui and Parker (1999) and can be applied to river systems with an arbitrary number of tributaries. The key to this adaptation is the Exner equations at the confluence of rivers as demonstrated in Figure 5, in which Tributary B joins River A to form a river junction.

In the river junction shown in Figure 5, the Exner equations are constructed to balance the sediment that is transported through cross sections (nodes)  $\alpha$ ,  $\beta$  and  $\chi$ . In more general terms, the mass of sediment particles in a particular size range that enters Nodes  $\beta$  and  $\chi$  minus that which exits Node  $\alpha$  must be identical to the mass increase of the same size range by aggrading the reaches between Nodes  $\alpha$  and  $\beta$  and between Nodes  $\alpha$  and  $\chi$  if there is no particle abrasion. In the case where there is particle abrasion, the mass conservation condition should also include the gain or loss of sediment in the size range. Detailed equations are not discussed here but they can be constructed based on the above description in reference to equations (6a), (6b) and (6c).

Because the *TUGS* model has been examined extensively with experimental and field data (e.g., Cui 2007a, 2007b; Gomez et al. 2009), and the key components of *OKTUGS* model (i.e., sediment transport equations for a single rock type and hydraulics calculations) are identical to that of *TUGS*, only limited model examinations are conducted for *OKTUGS*. These focus on model behavior in channel networks and with multiple rock types, mostly on a qualitative basis. Details of these qualitative examinations are not presented in this report. Model examination and calibration for the study area is presented in a later section.

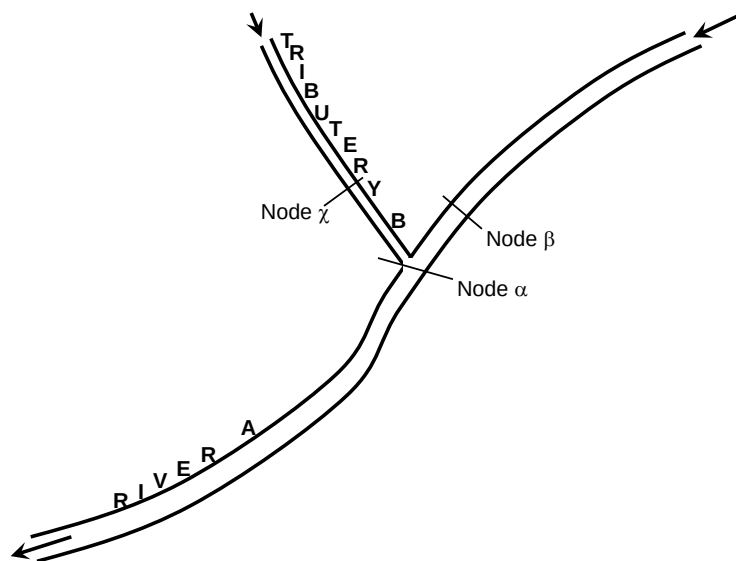


**Figure 5. A sketch of a tributary junction of a river system, demonstrating node locations for the Exner equations of sediment continuity.**

### 3.3 Estimates of Deposition in the Ok Mani and the Ok Tedi

Previous modeling studies carried out by the authors since 2003 have used estimates of deposition in the Ok Mani and Harvey Creek based on high quality photogrammetric mapping reported in Marshall (2001, 2006). These surveys have a baseline of March 1996. Based on figures supplied by OTML, Marshall (2001) reports no waste rock dumping into Harvey Creek before 1990. However, Marshall notes that there are considerable uncertainties about early dumping figures.

As part of the data preparation for the OKTUGS study, a set of 1982 20-m contour maps of the mine area produced by BHP Engineering were scanned and digitized. A digital elevation model was produced from the scanned and tagged contours with interpolated elevations along streamlines at 5-m intervals to give better representation of terrain in the Ok Mani and Harvey Creek. Comparison of this DEM with a second one produced from 1996 elevations suggests that about 80 million m<sup>3</sup> had accumulated in the Ok Mani and Harvey Creek before the 1996 survey. We suspect that this may have been a combination of overburden stripping, landslides and construction waste.

On the Middle Ok Tedi, it is only possible to make a rough estimate of deposition given the data available. This has been done by multiplying the average depth of deposition at each of the measured point elevations by the area of deposition, as determined from classified LANDSAT 7 Thematic Mapper data. In making these calculations, the river was divided into an upper reach, from the Ok Mani junction to a point 75 km downstream, where the deposits are mainly gravel, and a lower reach where sand has been deposited. Table 1 shows the results.

**Table 1: Estimated Volume of Deposition in the Middle Ok Tedi**

|                                              | <b>Upper Reach (Mainly Gravel)</b> |           | <b>Lower Reach (Sand)</b> |           |
|----------------------------------------------|------------------------------------|-----------|---------------------------|-----------|
| <b>Deposition</b>                            | 1982-2008                          | 1992-2008 | 1982-2008                 | 1992-2008 |
| <b>Area (km<sup>2</sup>)</b>                 | 27.06                              | 27.06     | 23.0                      | 23.0      |
| <b>Mean Depth (m)</b>                        | 2.704                              | 2.016     | 2.603                     | 3.876     |
| <b>Volume (10<sup>6</sup> m<sup>3</sup>)</b> | 73.17                              | 62.19     | 89.15                     | 59.88     |

Particle size distribution data for the Middle Ok Tedi are limited. Pile (2001) has data for a series of bars in the system obtained during a major study of sediment geochemistry (Table 2). Combining Pile's data with Table 1 gives estimates of total sand/silt and gravel in the Middle Ok Tedi listed in Table 3.

The deposition volumes assume an equal depth of sediment accumulation across the whole valley width. However, deposits may be shallower towards the valley edges. There are only a few cross sections for the Middle Ok Tedi dating from the early stages of the mine but these show that the

thinning effect could reduce volumes by about 25% in the upper part of the river and about 35% downstream from Ningerum. With a 25% reduction, the amount of gravel deposition (101.6 Mt) is in line with estimates about 97 Mt produced using *OKGRAV* (Pickup and Cui 2003, 2009a).

The volume of stored sand is substantially greater than previously assumed. Using Pile's figures for percent sand in the braided and meandering reaches and the 25% valley edge reduction factor gives a sand storage value of 111 Mt in the Middle Ok Tedi. Taking a more conservative approach and using percent sand values for the Pile's braided reach rather than including the meandering reach gives a value of 100 Mt of stored sand. Previous modeling exercises have assumed zero sand storage (Cui and Parker 1999) and about 30 Mt (Pickup and Cui 2003, 2009a).

**Table 2: Median diameter ( $D_{50}$ ) of grain size, proportion of gravel and sand/silt, on river bars (from Pile, 2001).**

| River Reach   | Sites | Gravel (%) | Sand/Silt (%) | $D_{50}$ (mm) | Dist. from Mine (km) | Gravel/sand Ratio |
|---------------|-------|------------|---------------|---------------|----------------------|-------------------|
| Upper Gorge   | 1     | 84.4       | 15.5          | 35.6          | 28                   | 5.4               |
| Middle Gorge  | 5     | 76.4       | 23.6          | 38.2          | 43                   | 3.2               |
| Lower Gorge   | 12    | 58.8       | 41.2          | 26.5          | 61                   | 1.4               |
| Upper Braided | 15b   | 49.0       | 51.0          | 22.9          | 103                  | 1.0               |
| Lower Braided | 18    | 21.7       | 78.2          | 13.5          | 120                  | 0.3               |
| Upper Meander | 21    | 0.0        | 100.0         | 0.18          | 130                  | 0.0               |

**Table 3: Estimated Volumes of Sand and Gravel Deposition in the Middle Ok Tedi 1982-2008**

|                                 | Upper Reach |           | Lower Reach |           |
|---------------------------------|-------------|-----------|-------------|-----------|
|                                 | 1982-2008   | 1992-2008 | 1982-2008   | 1992-2008 |
| % Gravel                        | 73.2        | 73.2      | 26.8        | 26.8      |
| % sand/Silt                     | 25.3        | 25.3      | 74.7        | 74.7      |
| Volume ( $10^6 \text{ m}^3$ )   | 73.17       | 62.19     | 89.15       | 59.88     |
| Total Tonnage(Mt) <sup>1</sup>  | 128.0       | 108.8     | 156.0       | 104.8     |
| Gravel Tonnage(Mt) <sup>1</sup> | 93.7        | 79.7      | 41.8        | 28.0      |
| Sand Tonnage (Mt) <sup>1</sup>  | 32.4        | 27.5      | 116.0       | 78.2      |

(1) Assumes a bulk density of  $1.75^2$ .

<sup>2</sup> Bulk densities are unknown and have to be estimated. We have used several bulk density values in this report depending on convention and local usage. 1.75 is used for deposited river sediments and landslide material where we have assumed some compaction. Natural sediment is converted using a value of 1.65 (this is the convention). Dredge stockpiles are converted at 1.62 since this is the value used by OTML.

### 3.4 *Sediment Mass Balance, Conversion of Gravel to Sand and Sediment Delivery to Bige During Mining*

The information provided by the 2008 Middle Ok Tedi survey makes it possible to estimate the rate at which gravel is converted to sand and silt during its passage through the system using a mass balance approach. This and the supply of tailings are the critical variables governing sand supply to the Lower Ok Tedi and the Middle Fly. The mass balance calculations for 1985-2004 are presented below.

#### **Sulphide Creek**

|                  |                 |
|------------------|-----------------|
| Waste Rock Input | 186.0 Mt        |
| Landslide Input  | 122.0 Mt        |
| Storage          | 2.4 Mt          |
| <b>OUTPUT</b>    | <b>306.6 Mt</b> |

#### **Ok Mani/Harvey Creek**

|                    |                 |                               |
|--------------------|-----------------|-------------------------------|
| Waste Rock Input   | 466.7 Mt        |                               |
| Landslide Input    | 122.0 Mt        |                               |
| Waste Rock Storage | 319.2 Mt        | Assuming a 49% retention rate |
| <b>OUTPUT</b>      | <b>331.5 Mt</b> |                               |
| <b>TAILINGS</b>    | <b>461.1 Mt</b> |                               |

#### **Middle Ok Tedi**

|                                             |                 |                                         |                           |
|---------------------------------------------|-----------------|-----------------------------------------|---------------------------|
| Inputs                                      |                 |                                         |                           |
| Waste Rock/Landslide                        | 638.1 Mt        | 575 Mt gravel                           | 63.8 Mt sand <sup>3</sup> |
| Tailings                                    | 461.1 Mt        |                                         |                           |
| Gravel Storage                              | 101.6 Mt        | (1982-2008 data pro rata)               |                           |
| Conversion to sand/silt                     | 473.4 Mt        | (82.2% rate from gravel mass balance)   |                           |
| Total sand/silt input                       | 934.5 Mt        | (Tailings + abrasion + waste rock sand) |                           |
| Natural load (sand)                         | 60.0 Mt         |                                         |                           |
| Natural load (silt)                         | 60.0 Mt         |                                         |                           |
| Sand/silt storage                           | 100.0 Mt        | (1982-2008 data pro rata)               |                           |
| <b>Total Sand/Silt Output<br/>(to Bige)</b> | <b>954.5 Mt</b> | <b>(47.7 Mt/year average)</b>           |                           |

---

<sup>3</sup> Based on sampling by Pile (2001)

## 4. OKTUGS Model Setup and Input

The study area is divided into 15 reaches, as depicted in the schematic sketch in Figure 14:

- ◆ Reach 1: Middle Ok Tedi between Konkonda and Ok Birim confluence;
- ◆ Reach 2: Middle Ok Tedi between Ok Birim and Ok Taub confluences;
- ◆ Reach 3: Middle Ok Tedi between Ok Taub and Ok Munga confluences;
- ◆ Reach 4: Middle Ok Tedi between Ok Munga and Ok Menga confluences;
- ◆ Reach 5: Middle Ok Tedi between Ok Menga and Ok Mani confluences;
- ◆ Reach 6: Upper Ok Tedi between Ok Mani and Sulphide Creek confluences;
- ◆ Reach 7: a short reach of the Ok Tedi upstream of Sulphide Creek confluence;
- ◆ Reach 8: Sulphide Creek;
- ◆ Reach 9: Ok Mani downstream of the Harvey Creek confluence;
- ◆ Reach 10: a short reach of Ok Mani upstream of Harvey Creek;
- ◆ Reach 11: Harvey Creek;
- ◆ Reach 12: a short reach of the Ok Birim;
- ◆ Reach 13: a short reach of the Ok Taub;
- ◆ Reach 14: a short reach of the Ok Munga;
- ◆ Reach 15: a short reach of the Ok Menga.

The purpose of including Reaches 7, 10, 12, 13, 14 and 15 is to provide a mechanism to include natural sediment supply from the Upper Ok Tedi, Ok Mani, Ok Birim, Ok Taub, Ok Munga, and Ok Menga.

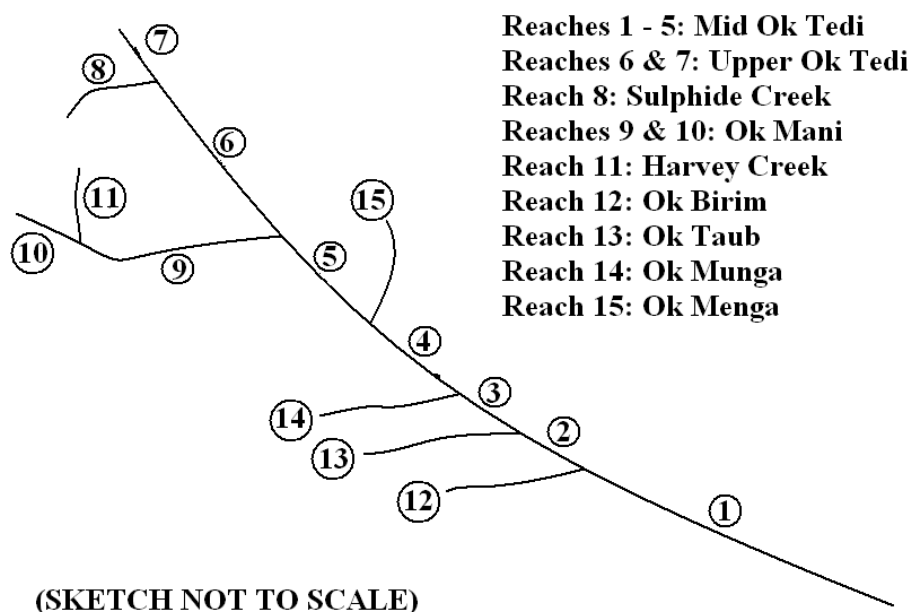


**Figure 14. Schematic sketch of reach delineation of the study area, in which the numbers inside circles indicate reach numbers used in the OKTUGS model simulation.**

## 4.1 Natural sediment supply

There are limited data on natural sediment supply to the Mine Area Creeks and to the Ok Tedi from tributaries. However, a regional denudation rate can be estimated from the limited sediment sampling data that are available. Pre-mine data from Pickup et al. (1981) are listed in Table 4. More recent data for the Ok Ma, Ok Birim and Ok Menga based on OTML suspended sediment sampling are also included. The assumed long-term sediment supply values from different sources used as *OKTUGS* input are also provided in Table 4. The *OKTUGS* sediment supply follows that estimated by Pickup et al. (1981) or uses newer estimates where available. Rough estimates based on the catchment area are provided where data are not available.

**Table 4: Estimated denudation rates and sediment supply for Ok Tedi and Upper Fly Drainage Basins, and the natural sediment input used for *OKTUGS* modeling**

| Station                     | Catchment Area (km <sup>2</sup> ) | Denudation Rate (mm/yr) <sup>a</sup> | Estimated Sediment Supply <sup>a</sup> (Mt/yr) | Assumed Average Bedload Input in <i>OKTUGS</i> (Mt/a) | Percent of Sand in the assumed <i>OKTUGS</i> Input |
|-----------------------------|-----------------------------------|--------------------------------------|------------------------------------------------|-------------------------------------------------------|----------------------------------------------------|
| Ok Ningi                    | 4.56                              | 4.77-6.48                            | 0.036-0.049                                    |                                                       | n/a                                                |
| Ok Menga                    | 240                               | 0.59-0.74                            | 0.23-0.29                                      |                                                       |                                                    |
| Ok Menga (OTML data)        | 240                               | 1.83                                 | 0.72                                           | 0.7                                                   | 30 <sup>c</sup>                                    |
| Upper Ok Tedi               | 420                               | 2.75-4.74                            | 1.91-3.28                                      | 3.2                                                   | 25 <sup>c</sup>                                    |
| Ok Ma (OTML data)           | 65.5                              | 1.89                                 | 0.2                                            |                                                       | n/a                                                |
| Ok Birim (OTML data)        | 977                               | 0.83                                 | 1.34                                           | 1.4                                                   | 50 <sup>c</sup>                                    |
| Upper Fly (OTML data)       | 6,300                             | 0.25                                 | 2.6                                            |                                                       | n/a                                                |
| Ok Mani                     | 23                                | n/a                                  |                                                | 0.1 <sup>c</sup>                                      | 25 <sup>c</sup>                                    |
| Sulphide Creek <sup>b</sup> | 39                                | n/a                                  |                                                | Negligible                                            | 10 <sup>c</sup>                                    |
| Harvey Creek <sup>b</sup>   | 3.4                               | n/a                                  |                                                | Negligible                                            | 10 <sup>c</sup>                                    |
| Ok Munga                    | 312                               | n/a                                  |                                                | 0.7 <sup>c</sup>                                      | 40 <sup>c</sup>                                    |
| Ok Taub                     | 208                               | n/a                                  |                                                | 0.6 <sup>c</sup>                                      | 50 <sup>c</sup>                                    |
| <b>Total</b>                |                                   |                                      |                                                | 6.7                                                   |                                                    |

a. Assuming a 1.65 t/m<sup>3</sup> bulk density.

b. Excluding sediment contributions from dumping related landslides (discussed later);

c. Values are a rough estimate for *OKTUGS* model input and should not be used as a reference for future analysis.

In the absence of field data, we have estimated grain size distributions for gravel and sand input to study area tributaries (Figure 15) to facilitate the modeling. Because the sediment supply from

mining operations will be an order of magnitude greater than the natural sediment supply, estimating the grain size distribution for natural sediment supply should not significantly affect the quality of the modeling.

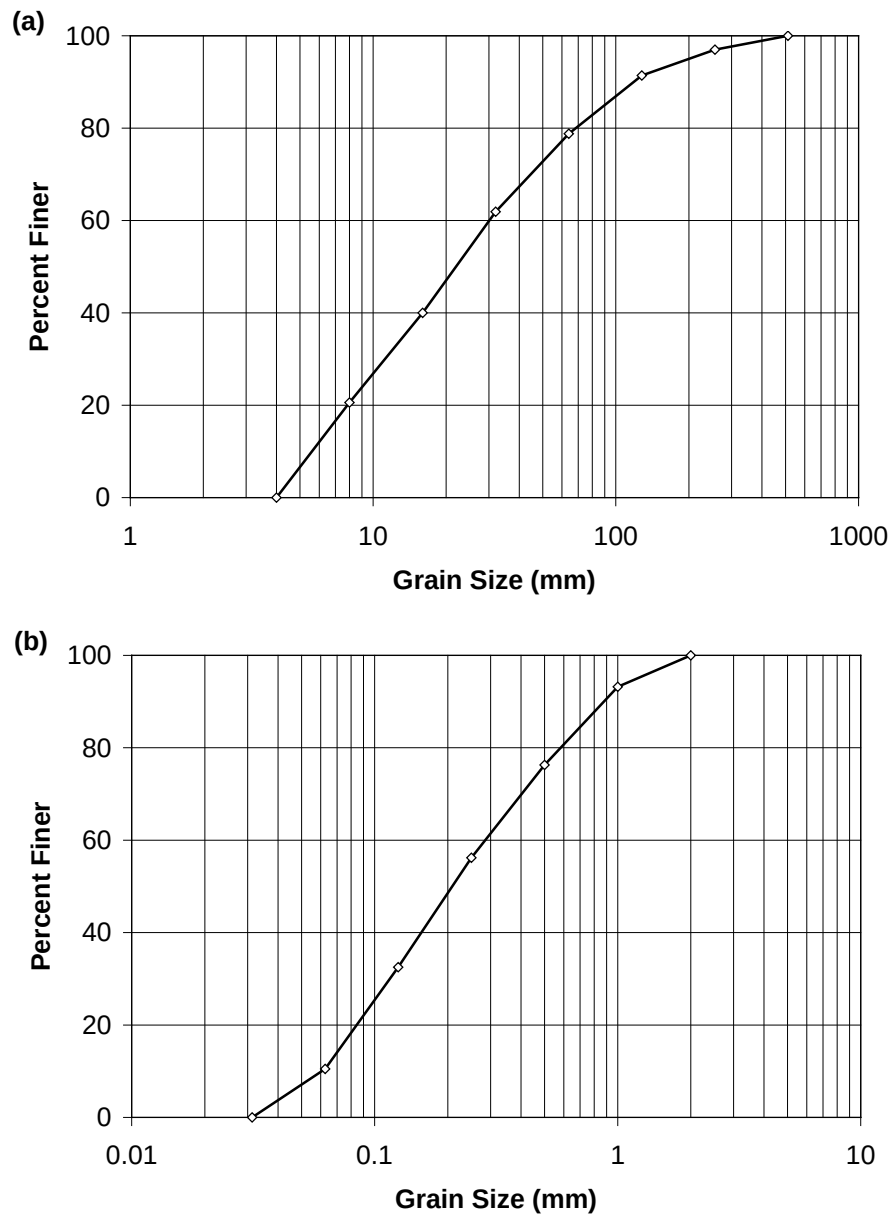


**Figure 15. Assumed grain size distribution for natural sediment supply to the study area. (a) Gravel; and (b) sand. Gravel is truncated at 512 mm, even though gravel as coarser as 1000 mm is observed on channel bed in Tabubil.**

No analysis has been done to quantify the abrasion coefficient of gravel in the study area. The maximum grain size in the study area based on 1978 photographs, maps and field notes of C. Cole and F. C. Pratt (Appendix A) may offer some hints (Figure 16). The estimated volumetric abrasion coefficient is  $0.0245 \text{ km}^{-1}$  (i.e., 2.45% of the gravel volume will be lost for each 1 km distance traveled). It is, however, expected that an abrasion coefficient based on the largest particles is likely to overestimate the true value because some of the large particles may travel very infrequently, and

long term abrasion by other particles in transport, together with physical and chemical weathering, may gradually reduce their size as they are transported slowly downstream. Also, because we have truncated gravel grain size at 512 mm, we have used a smaller volumetric abrasion coefficient of  $0.012 \text{ km}^{-1}$  for the model that would compensate somewhat for the missing coarser particles.

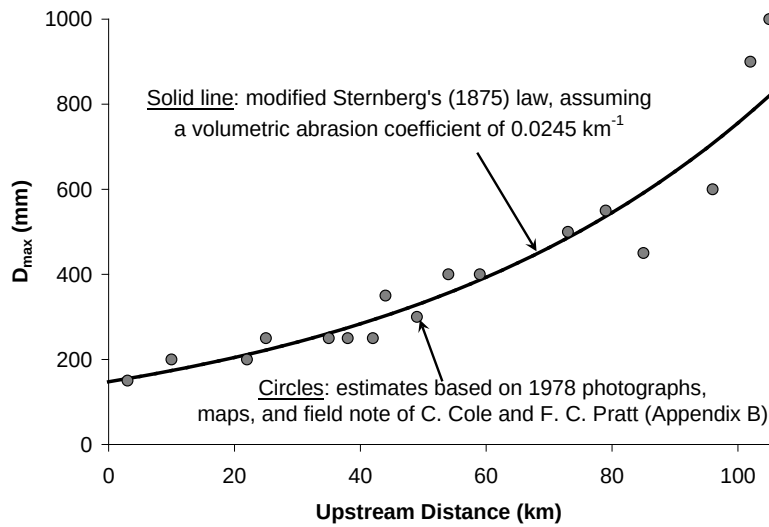


**Figure 16. Maximum particle size estimated based on 1978 photographs, maps and field notes of C. Cole and F.C. Pratt (Appendix A) and regression line for abrasion coefficient.**

## 4.2 Downstream control

An incomplete discharge and water surface elevation data set is available at Konkonda for the period between 1 January 1984 and 29 September 2008. The water surface elevation data shown in Figure 17 indicate that water stage has been influenced by the sediment deposition and erosion, rising until the late 1990s in response to sediment deposition, then falling until about 2005 due to dredging, and then rising again while the dredge was excavating the West Bank Pyrite Concentrate Storage Facility. To derive a water surface elevation series at the downstream end of Middle Ok Tedi as input to OKTUGS model, the water surface at Konkonda ( $\zeta$ ) is broken into two components: one is time dependent to capture the changes during mining operations, while the other is discharge dependent:

$$\zeta = \zeta_t + \zeta_Q \quad (12)$$

in which  $\zeta_t$  is fitted with a sixth order polynomial equation below and shown in Figure 17:

$$\begin{aligned} \zeta_t = & 17.636 - 1.4357 \times 10^{-22} (t - t_0)^6 + 4.5587 \times 10^{-18} (t - t_0)^5 \\ & - 4.5546 \times 10^{-14} (t - t_0)^4 + 1.4368 \times 10^{-10} (t - t_0)^3 \\ & + 4.6530 \times 10^{-8} (t - t_0)^2 + 1.3131 \times 10^{-4} (t - t_0) \end{aligned} \quad (13)$$

and  $\zeta_Q$  is fitted with a power function as

$$\zeta_Q = 0.0757Q_w^{0.6104} - 4.0 \quad (14)$$

in which  $\zeta$  denotes water surface elevation at Konkonda, in meters;  $t$  denotes time, in days;  $t_0$  denotes time for 1 January 1984, and  $Q_w$  is discharge in  $m^3/sec$ .

Details of the fitting of Equations (12) through (14) are not discussed further. Comparison of observed stage and that calculated with Equations (12) through 14 is presented in Figure 18.

To extend the downstream water surface elevation at Konkonda beyond the period of record for an initial simulation, it is assumed that  $\zeta_t$  keeps a constant value of 21.402 m between 30 August 2008 and 31 December 2014 (approximately one year after mine closure). Starting on 1 January 2015,  $\zeta_t$  will decrease exponentially approaching the pre-mining value of 17.636 with the following formulation:

$$\zeta_t = 17.636 + 3.766 \exp[-5 \times 10^{-4}(t - t_1)] \quad (15)$$

in which  $t_1$  denotes time in days for 1 January 2015 (Figure 19).

As a sensitivity test, we also conducted a run assuming that water surface elevation at Konkonda decreases faster than the values assumed in Figure 19 following mine closure. The results indicate that sediment supply to the downstream reach is not significantly affected (discussed in detail later).

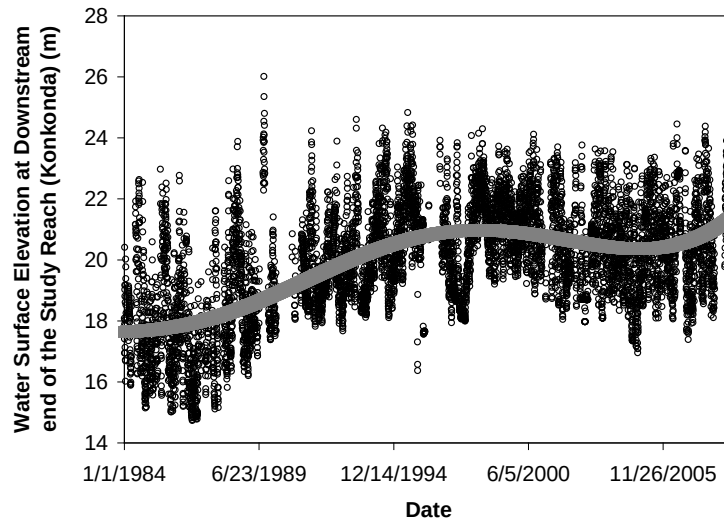


**Figure 17. Recorded water surface elevation at Konkonda and the trend in time due to sediment deposition and erosion. The thick grey line represents the fit for  $\zeta_t$  with Equation (13).**

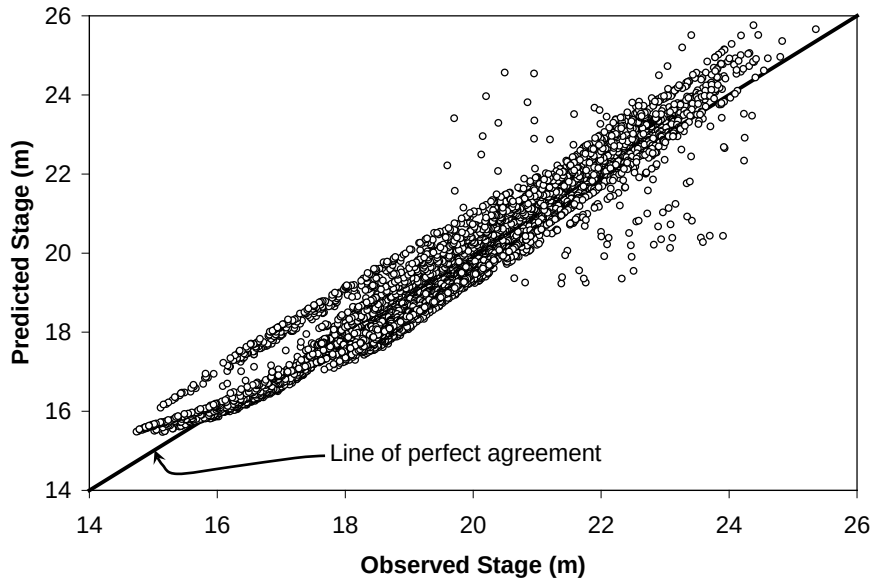


**Figure 18. Comparison of recorded water surface elevation at Konkonda with that calculated using Equations (12) through (14).**

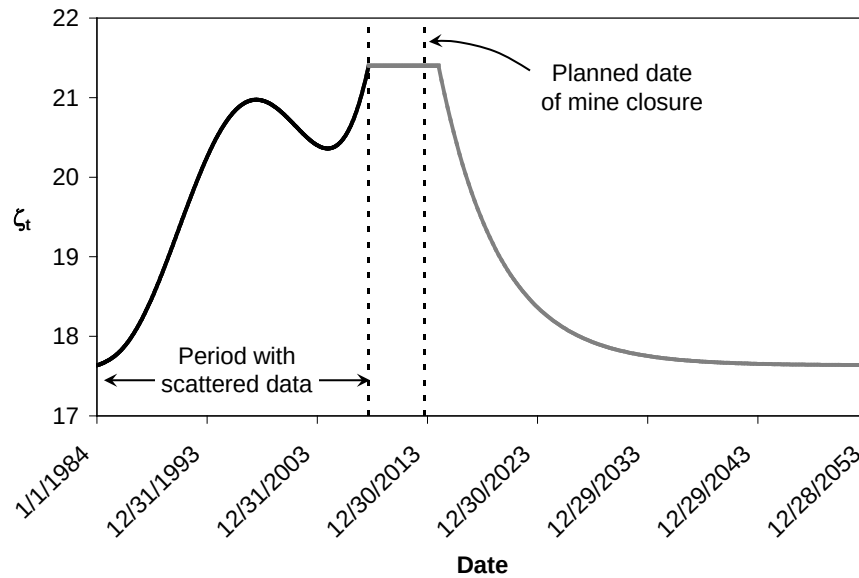


**Figure 19. Formulated  $\zeta_t$  value extending into the future for initial *OKTUGS* simulation.  $\zeta_t$  presented in this diagram is in meters.**

### 4.3 Daily average discharge

The *OKTUGS* model uses a time series of mean daily flows to represent river hydrology. This is a change from the *OKGRAV* model used in previous studies which relied on flow duration curves (Pickup and Cui, 2003) and brings the upper river system model hydrology into line with that of the lower Ok Tedi and Middle Fly *HEC-6* model.

Existing flow records for the Ok Tedi and the Mine Area Creeks do not cover enough locations to represent the whole upper river system. They also contain too many gaps to be used directly as model inputs. We have therefore chosen to generate a long-term synthetic record using the statistical characteristics of the observed river flow data. This record preserves the observed flow variability including extremes of behaviour such as large floods. It also reproduces medium term fluctuations such as the wet and dry periods which are often attributed to *el Nino* and *la Nina* events although these are not the only sources of flow variability. Another advantage of the synthetic record approach is that it can be expressed in generalised form and adapted to estimate flows at each node of the *OKTUGS* model and to estimate inflows from ungauged tributary systems.

Previous studies have shown that regional flow duration curves can be generated from observed values simply by dividing each flow by catchment area and expressing the result in terms of discharge per unit area (Pickup and Cui 2003). A slightly better result comes from dividing by catchment area raised to the power 1.08. Figure 20 shows the close relationship between discharge and catchment area for a range of flow durations whereas Figure 21 shows the duration curves for available gauging stations in the project area standardized by catchment area. In Figure 21 only the Ok Ma (MAA10) deviates from the general pattern and this is thought to be related to errors in the station discharge rating curve rather than real differences. Importantly, because the regression lines in Figure 20 remain virtually parallel, a range of discharges standardized by catchment area can be used to represent flows throughout the Ok Tedi drainage basin. Translating these standardized flows into a discharge record at any given node in the model merely involves multiplying by Catchment Area<sup>1.08</sup>.

Given the consistency in standardized flows across the drainage basin, the Ok Tedi at Haidauwogam (Station TED15) was used to generate a regional synthetic discharge record. The flow duration curve for this station lies closest to the regional average and records go back to 1991 with only limited periods of missing data. Plots of discharge against time show that the station was either stable or rating curve updates have been done frequently enough to offset rising water levels due to deposition. After 2003, water levels and discharges show an upward trend indicating deposition and an incorrect rating curve so this part of the record was discarded.

Time series analyses of daily discharge values show that a log-normal transform normalizes the data for all stations in the Upper Ok Tedi drainage basin. They also show that a lag one autoregressive model (AR1) is the best fit time series model in all cases. A 100-year synthetic series was generated from TED15 using this model. This gives a reasonably good representation of the range of flows and both short and medium-term variability (Table 5). One difference between the observed and generated datasets is that minimum and maximum values are more extreme in the generated dataset. This is to be expected given that the generated dataset set parameters come from a longer series so there is more chance for extreme values to occur.

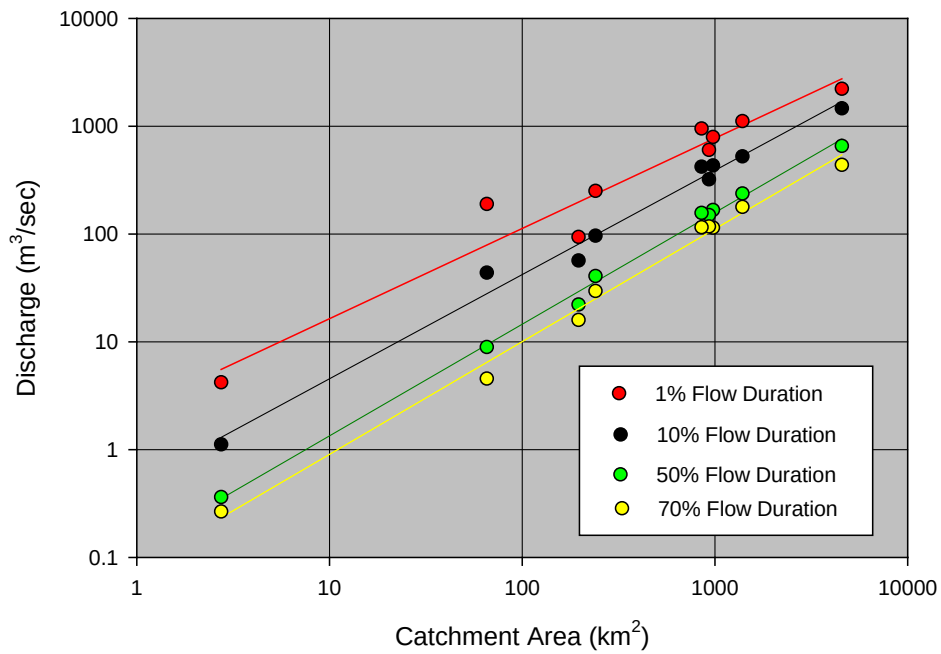


**Figure 20. Discharges at specific flow durations for Ok Tedi drainage basins plotted against catchment area.**

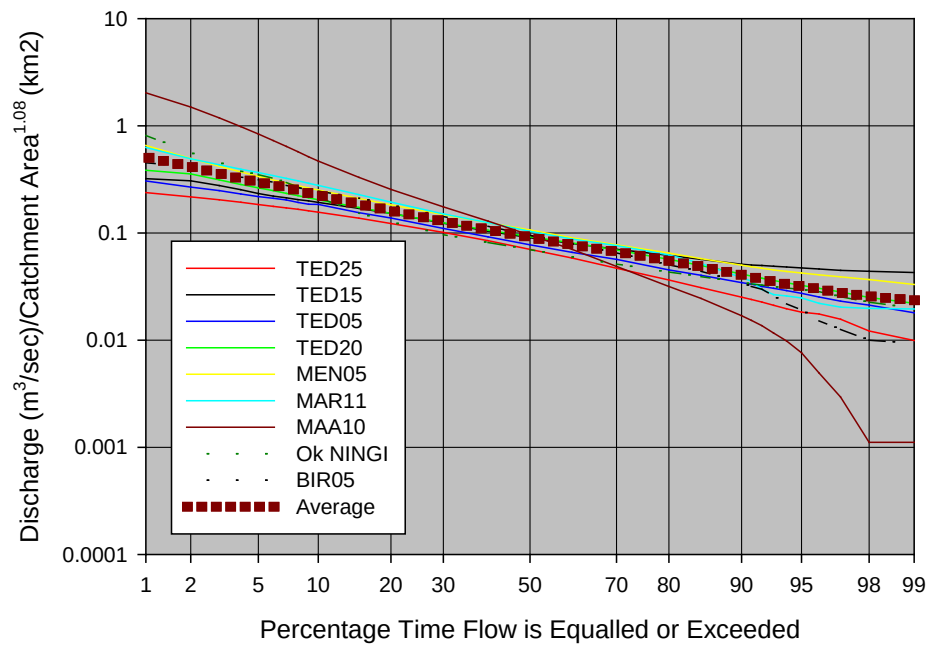


**Figure 21. Flow duration curves for Ok Tedi drainage basins scaled by catchment area.**

A synthetic flow series is needed at each *OKTUGS* model node. This requires information on catchment areas throughout the Ok Tedi drainage basin. These were produced by building a digital elevation model from Shuttle Radar Topography Mission data, generating a drainage net from it, and running a downstream flow accumulation routine. The resultant pattern of catchment areas is shown in Figure 22.

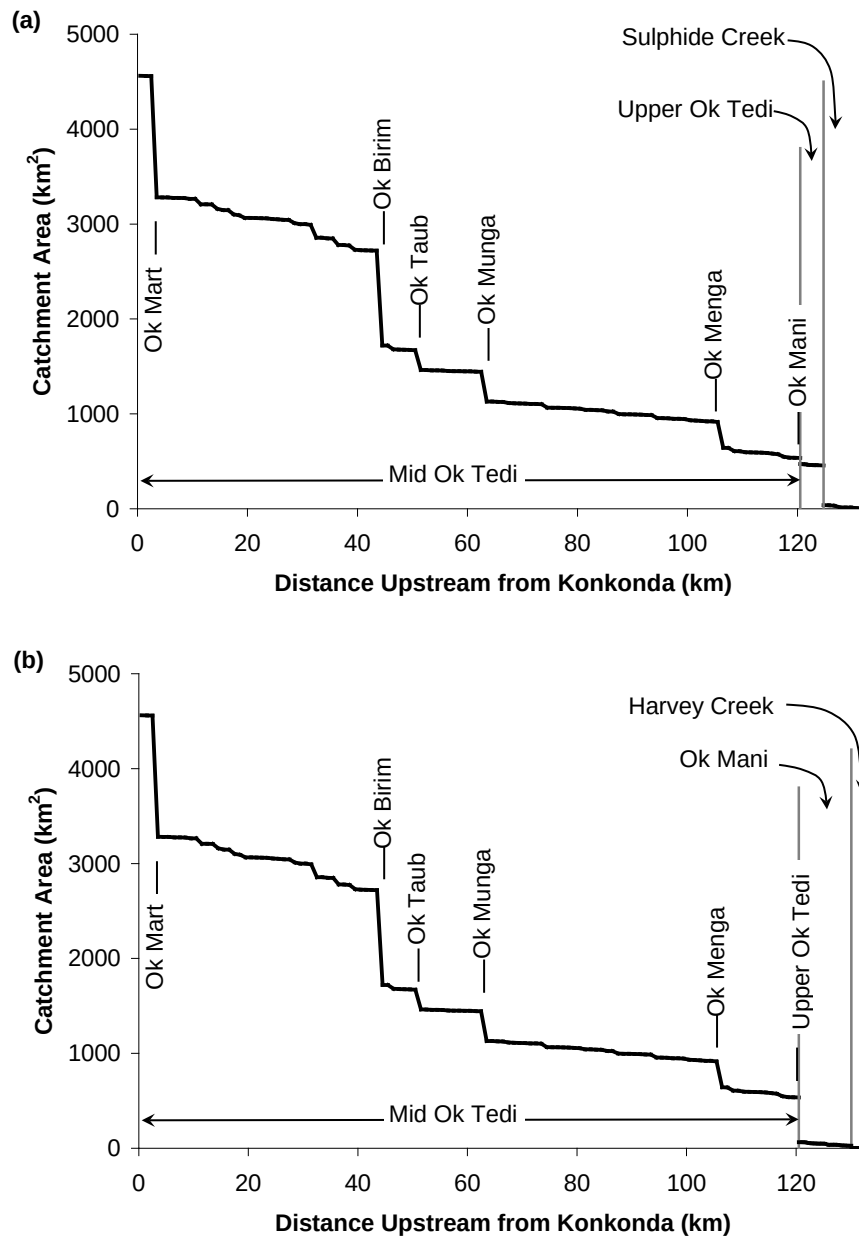


**Figure 22. Downstream variation in catchment area: (a) Middle Ok Tedi, Upper Ok Tedi and Sulphide Creek; and (b) Middle Ok Tedi, Ok Mani and Harvey Creek.**

**Table 5: Observed and Generated Flow Characteristics for TED15**

| Parameter               | Historical | Generated | Parameter | Historical | Generated |
|-------------------------|------------|-----------|-----------|------------|-----------|
| Mean                    | 182.4      | 180.4     | Minimum   | 43.7       | 21.5      |
| Standard Deviation      | 92.8       | 92.15     | Maximum   | 858.3      | 1142      |
| Coefficient of Variance | 0.5075     | 0.5107    | ACF lag 1 | 0.641      | 0.728     |
| Skewness                | 1.488      | 1.632     | ACF lag 2 | 0.483      | 0.533     |

#### 4.4 Channel and Valley Widths

Model calculations of erosion and deposition require information on valley width and channel width. These were obtained from a LANDSAT 7 Thematic Mapper image acquired on 15 Feb., 2008. Image resolution is 30 m but it can be increased using the 15 m resolution panchromatic channel on this instrument. Valley widths were measured after classifying the image using standard techniques in the ENVI image processing package and extracting areas of deposition. Channel widths were obtained by classifying areas of surface water within valleys.

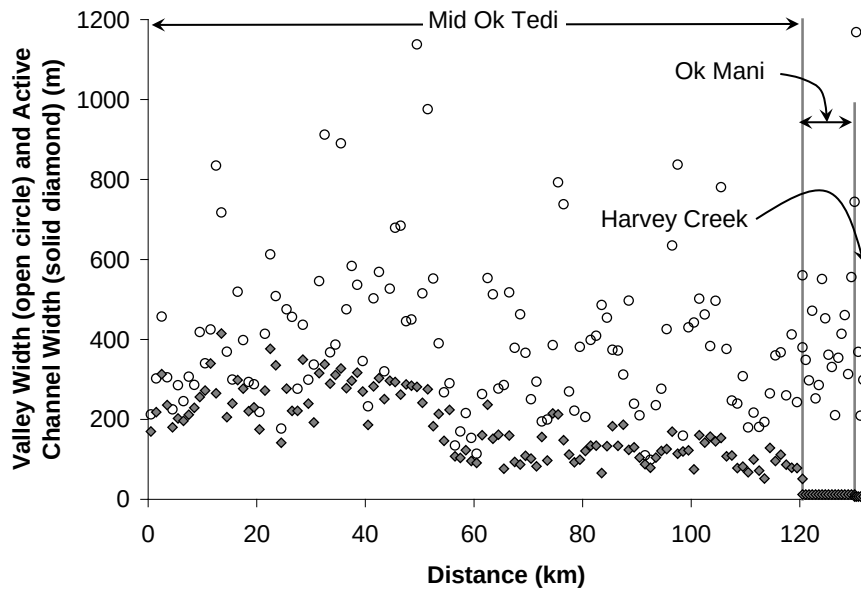


**Figure 23. Channel and valley widths for the Middle Ok Tedi. Open circles are valley width, and solid diamonds are active channel width.**

Other than valley and active channel widths, the *OKTUGS* model also needs input for the width of the incised inner valley ( $B_b$  in Figure 4) following channel incision after mining operation. Apparently  $B_a \leq B_b \leq B_v$ , and a larger  $B_b$  value will allow for more sediment to be eroded downstream

following mine closure, and a smaller  $B_b$  will allow more sediment to remain in the system in the form of terraces. For simplicity, we have assumed

$$B_b = \min(1.5B_a, B_v) \quad (16)$$

To examine if different assumptions will result in different results, we have used the maximum and minimum possible values (i.e.,  $B_b = B_v$  and  $B_b = B_a$ ) in sensitivity tests (to be discussed later).

## 4.5 Mine related sediment supply

As discussed earlier in Section 3, there are three types of mine related sediment: a) fine grained tailings disposed into Ok Mani about half way between its confluences with Ok Tedi and Harvey Creek; b) coarse grained rock waste disposed of into Harvey Creek (the southern dump) and Sulphide Creek (the northern dump); and landslides as a result of rock waste disposal at the two dumps: the Harvey Creek landslide and the Vancouver landslide. Mine related sediment supply values are listed in Table 6, with data for tailings and rock waste provided by OTML from operational records and mine planning projections. The landslide values are based on observed values (Marshall 2000, 2001, 2006) and projections into the future.

Grain size distributions for rock waste are based on sampling by Pile (2001) (Figure 24a). Landslide sediment size distributions are assumed to be identical to that of natural gravel supply provided in Figure 15(a). Grain size distribution for tailings was provided by OTML based on 2002 data as shown in Figure 24b. As a best guess, the average specific gravity of the tailings and rock waste is assumed to be 3.0 for the simulation while the specific gravity for natural sediment and sediment from landslides is assumed to be 2.65.

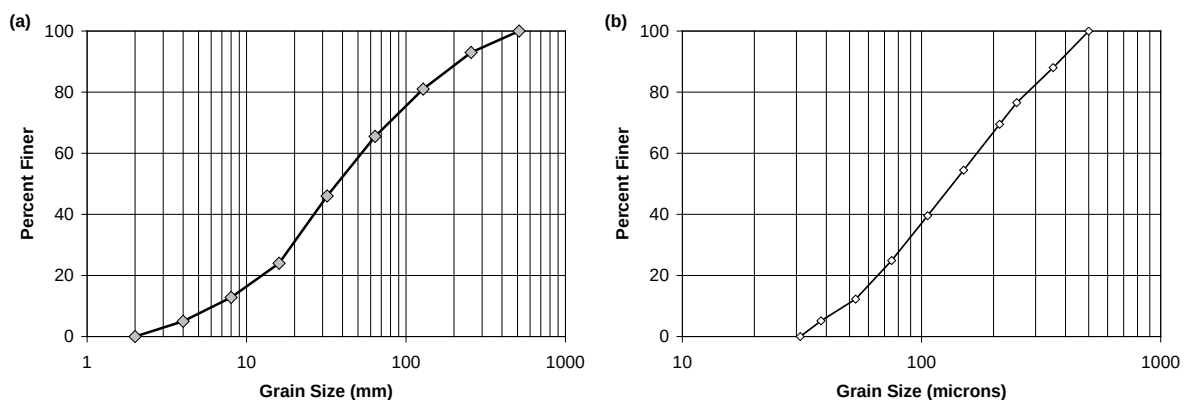


**Figure 24. Assumed grain size distribution for (a) rock waste based on Pile (2001); and (b) tailings, based on OTML analysis in 2002.**

**Table 6. Mine related sediment supply to the river system<sup>a</sup>, in Mt**

| Year | Tailings | Rock Waste - N.<br>Dump | Rock Waste - S.<br>Dump | Vancouver<br>Landslide | Harvey<br>Landslide |
|------|----------|-------------------------|-------------------------|------------------------|---------------------|
| 1985 | 2.38     | 3.800                   |                         | 0                      | 0                   |
| 1986 | 3.1      | 9.500                   |                         | 0                      | 0                   |
| 1987 | 9.72     | 11.800                  |                         | 0                      | 0                   |
| 1988 | 14.93    | 23.400                  |                         | 0                      | 0                   |
| 1989 | 23.6     | 29.700                  |                         | 55.6                   | 0                   |
| 1990 | 27.42    | 26.688                  | 1.112                   | 37.6                   | 1                   |
| 1991 | 27.01    | 14.178                  | 13.622                  | 22.2                   | 19                  |
| 1992 | 26.74    | 6.506                   | 15.454                  | 6.9                    | 24                  |
| 1993 | 28.62    | 3.391                   | 10.639                  | 0                      | 16                  |
| 1994 | 29.71    | 4.292                   | 23.178                  | 0                      | 22                  |
| 1995 | 29.52    | 4.345                   | 36.045                  | 0                      | 28                  |
| 1996 | 28.51    | 2.356                   | 40.054                  | 0                      | 18                  |
| 1997 | 15.47    | 0.356                   | 35.204                  | 0                      | 12                  |
| 1998 | 24.46    | 9.880                   | 34.260                  | 0                      | 8                   |
| 1999 | 30.88    | 15.165                  | 43.047                  | 0                      | 8                   |
| 2000 | 28.59    | 11.465                  | 37.517                  | 0                      | 6                   |
| 2001 | 27.658   | 6.576                   | 43.203                  | 0                      | 5                   |
| 2002 | 29.65    | 1.670                   | 46.469                  | 0                      | 5                   |
| 2003 | 27.55    | 0.534                   | 39.432                  | 0                      | 6.5                 |
| 2004 | 25.60    | 0.473                   | 47.474                  | 0                      | 5.5                 |
| 2005 | 24.68    | 2.332                   | 51.618                  | 0                      | 5                   |
| 2006 | 26.88    | 10.69                   | 33.037                  | 0                      | 5                   |
| 2007 | 25.16    | 0.992                   | 38.67                   | 0                      | 4                   |
| 2008 | 20.84    | 16.90                   | 22.40                   | 0                      | 4                   |
| 2009 | 21.59    | 21.29                   | 34.01                   | 0                      | 3                   |
| 2010 | 20.92    | 7.51                    | 17.52                   | 0                      | 3                   |
| 2011 | 20.78    | 3.41                    | 13.86                   | 0                      | 3                   |
| 2012 | 20.51    | 2.18                    | 12.33                   | 0                      | 2                   |
| 2013 | 10.27    | 0.729                   | 4.13                    | 0                      | 1                   |

a. Assuming a bulk density of 1.75 t/m<sup>3</sup>;

|  |                                                                                                                                                                                            |
|--|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | From original <i>OKGRAV</i> Input Spreadsheets                                                                                                                                             |
|  | Mill Production (2) Sheet of <i>OkARD</i> Input Plan Dec 2008_FP3.xls                                                                                                                      |
|  | Mine Production (2) Sheet of <i>OkARD</i> Input Plan Dec 2008_FP3.xls                                                                                                                      |
|  | No new estimates have been available since 2003. Value of 5 based on discussions with A. Marshall since sliding continues rather than the gradual reduction suggested by Dietrich & Parker |
|  | <i>OkARD_Bige_v2.xls</i>                                                                                                                                                                   |

## 5. OKTUGS Model Examination and Calibration

The *OKTUGS* model was examined with the available field data and calibrated so that a) it does not result in significant sediment deposition under pre-mine conditions with the input data discussed in Section 4; and b) it reproduces the observed patterns of sediment deposition during mining operations to date.

The first adjustment to the sediment transport model is to revise equation (4) to

$$\tau_{\text{rsg}}^* = 0.036 \quad (17)$$

It is important to note that equation (4), which stated that the reference Shields stress decreases with increasing sand content, was developed under laboratory conditions where the ratio between gravel and sand median size was relatively small, whereas in the study area this ratio can be as high as 100. While it has been observed independently that increasing sand content does help the mobilization of gravel particles (e.g., Dietrich 1989; Cui et al. 2008), these observations were all made with relatively small gravel particles due to the constraints of flume experiments, and thus, all with a relatively small median gravel to sand diameter ratio. There has been speculation that the effect of sand content on the reference Shields Stress ( $\tau_{\text{rsg}}^*$ ) value becomes insignificant when the median gravel to sand diameter ratio becomes large. This is confirmed by a series of recently conducted flume experiments (J. Gaffney, *per. comm.*). The adjustment of equation (4) to equation (17) reflects such a finding.

The second adjustment is to increase the gravel and sand transport capacities predicted with the Wilcock and Crowe (2003) equation by a factor of  $k_G$  and  $k_S$ , respectively, defined below and shown in Figure 25:

$$k_G = 4 \exp(400S^2); \quad k_S = 2 \exp(400S^2) \quad (18a,b)$$

in which  $S$  denotes local bed slope. Figure 25 shows that an adjustment factor of 4 is used for gravel and a factor of 2 for sand for slopes below 0.01. Sediment transport models are routinely corrected with factors of 2 to 3, and a factor of 4 is not beyond the range of the scatter contained in many sediment transport data sets (e.g., Brownlie 1982). Indeed, the *HEC-6* model used on the Lower Ok Tedi and Middle Fly required an adjustment factor of 8. The adjustments increase with slope, reflecting the increased gravitational force on sediment particles.

In addition to adjusting Wilcock and Crowe's (2003) equation, an additional restriction is added to the sediment fraction interface during aggradation (equation 5c) so that

$$f_{\text{ls},k} \geq \min(0.3, p_{\text{s},k}) \quad (19)$$

in which  $p_{s,k}$  denotes sand fraction of the  $k$ -th rock type of sediment in transport. This restriction allows the model to trap sand within gravel deposits during aggradation, as it has been estimated that the sand fraction in bed material in the Ok Tedi is approximately 30%.

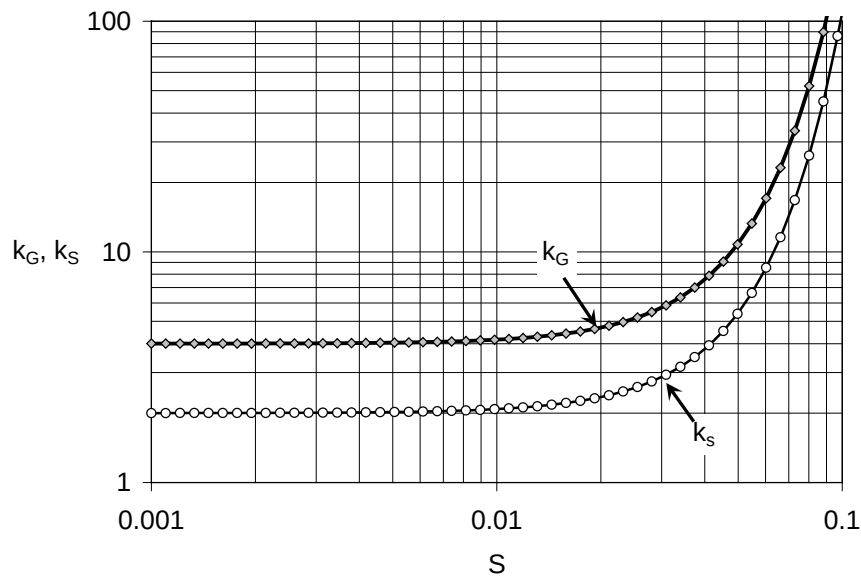


**Figure 25. Coefficient adjusting sediment transport rate calculated with Wilcock and Crowe (2003)**

Simulation results are first examined by comparing the simulated depth of sediment deposits in the Middle Ok Tedi and the Ok Mani with field observations (Figures 26, 27 and 28). In Figure 26, the predicted depth of sediment deposition in the Ok Mani for years 1996, 1997, 1998, 2000, and 2004 are compared with observed data, and show a similar spatial pattern and magnitude of deposition. In Figure 27, the predicted depth of sediment deposition in the Middle Ok Tedi for the year 2008 is compared with observed data, also showing a similar pattern and magnitude of deposition. Figure 28 compares the depth of deposition in the period 1985 to 2001 at four locations in the Middle Ok Tedi: TED44 , TED50, TED54 and TED56 (respectively 4.5, 14, 24 and 29 km downstream of the Ok Mani junction). Results in Figure 28 indicate that the model reproduced the observed general depositional pattern, although the depth of deposition from year to year differs somewhat from observations. This is to be expected because *OKTUGS* models reach- and time-averaged aggradation and degradation rather than behaviour at point locations.

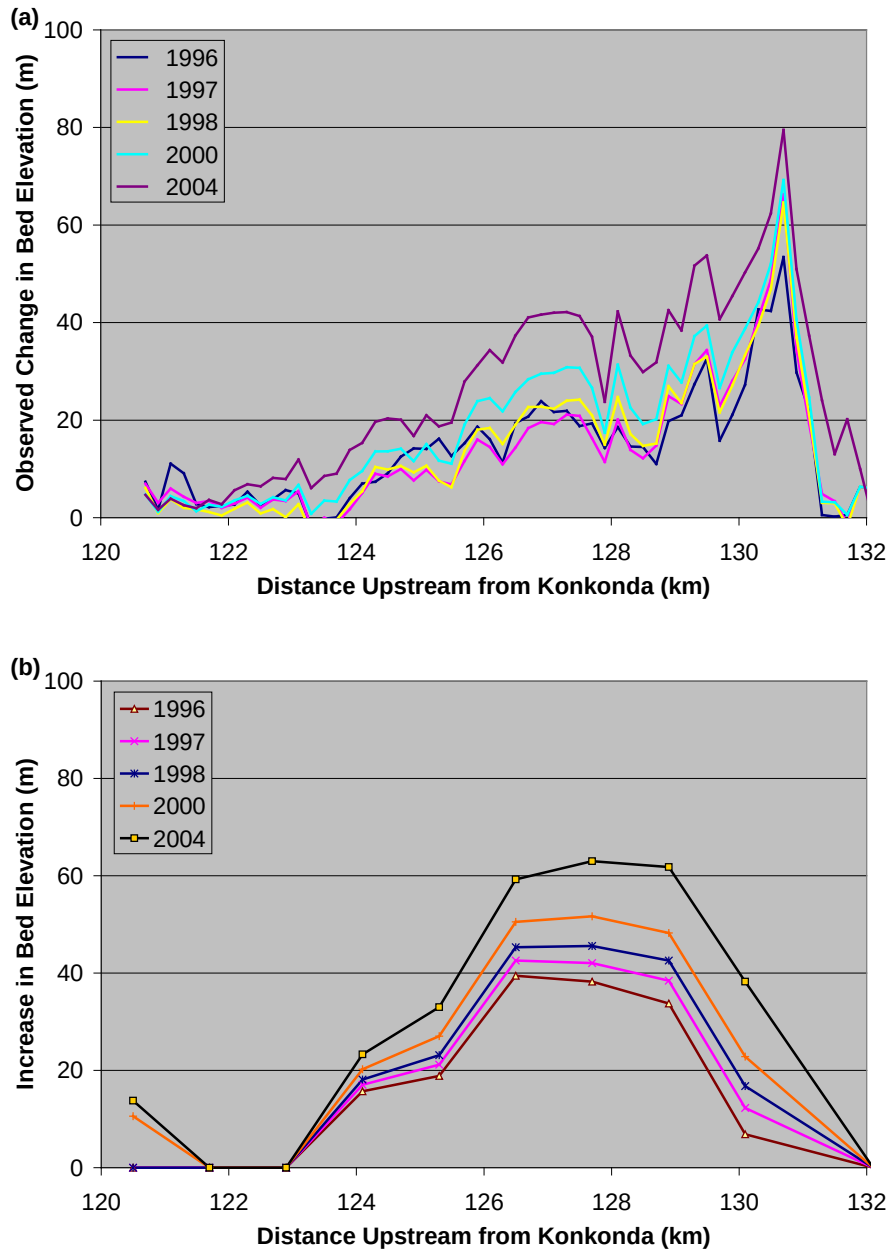


**Figure 26. Comparison of simulated and observed sediment deposition in Ok Mani. (a). Observations; and (b). simulation.**

As well as depositional patterns in the Ok Mani and Middle Ok Tedi, we also examined the amount of sediment deposited in various parts of the river system over time. These include a time series for the Ok Mani and Harvey Creek between 1985 and 2008 (Figure 29a), the amount of sediment deposition in Sulphide Creek in 2003 and 2008 (Figure 29b), and the amount of sediment deposition in other reaches (Table 7).

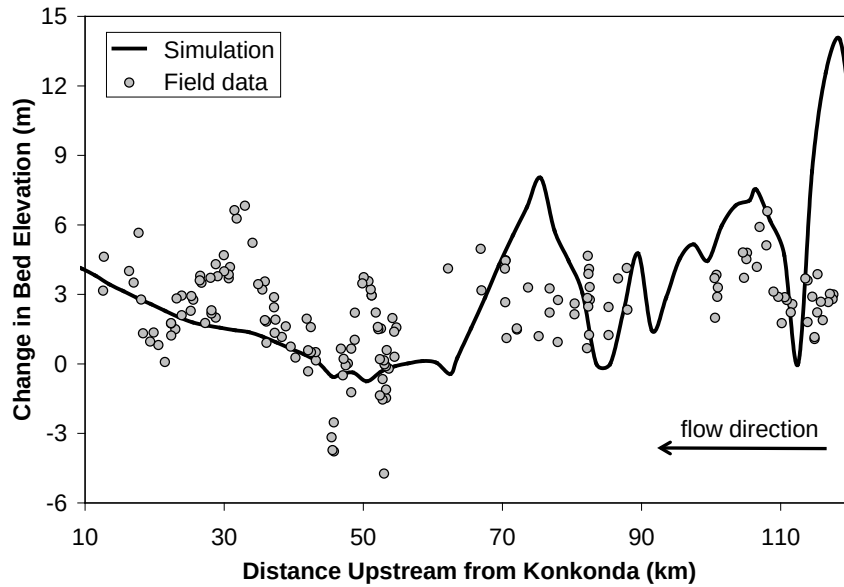


**Figure 27. Comparison of simulated and observed sediment deposition in the Middle Ok Tedi. Simulation is for the period of 1985 to 2008, while the observation is based on spot heights from 1982 air photos and a 2008 GPS survey.**

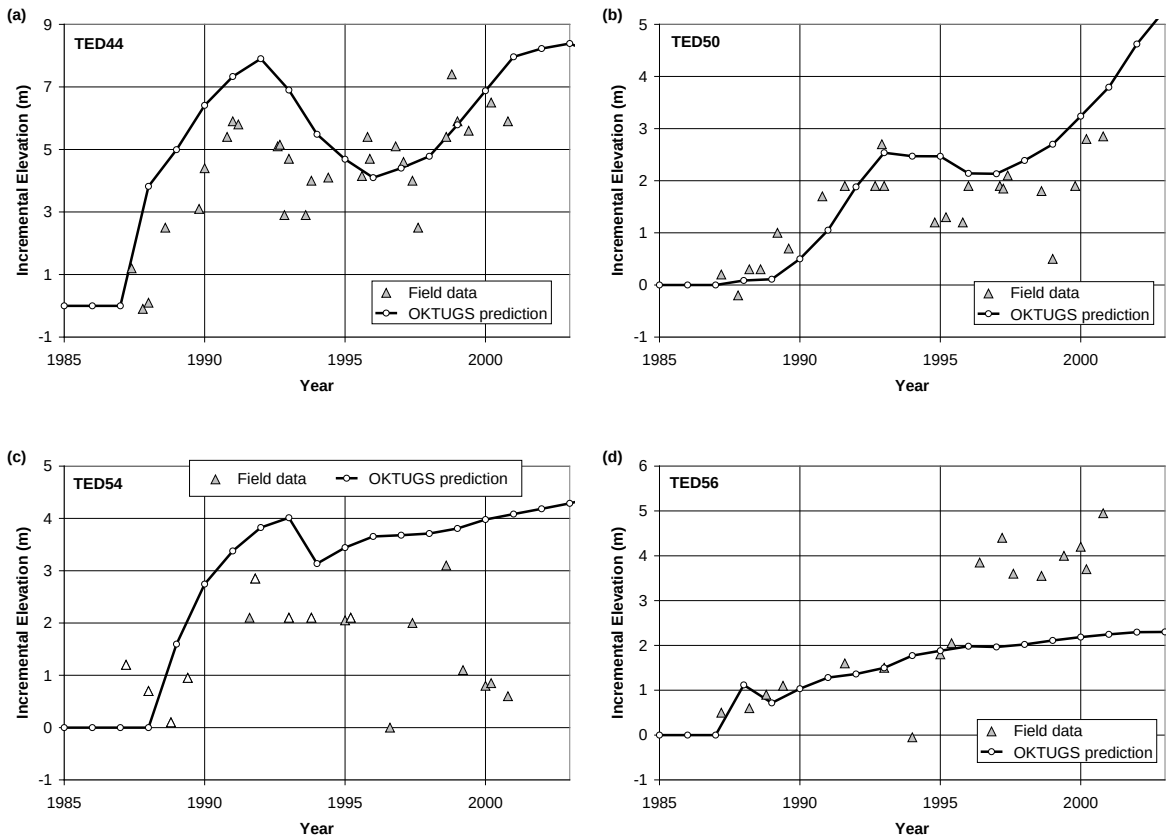


**Figure 28. Predicted and measured change in bed elevation of the Ok Tedi at cross sections TED44, TED50, TED54, and TED 56. The predicted values are for average bed elevation; the field data (Pickup and Cui, 2009a) are for thalweg elevation.**

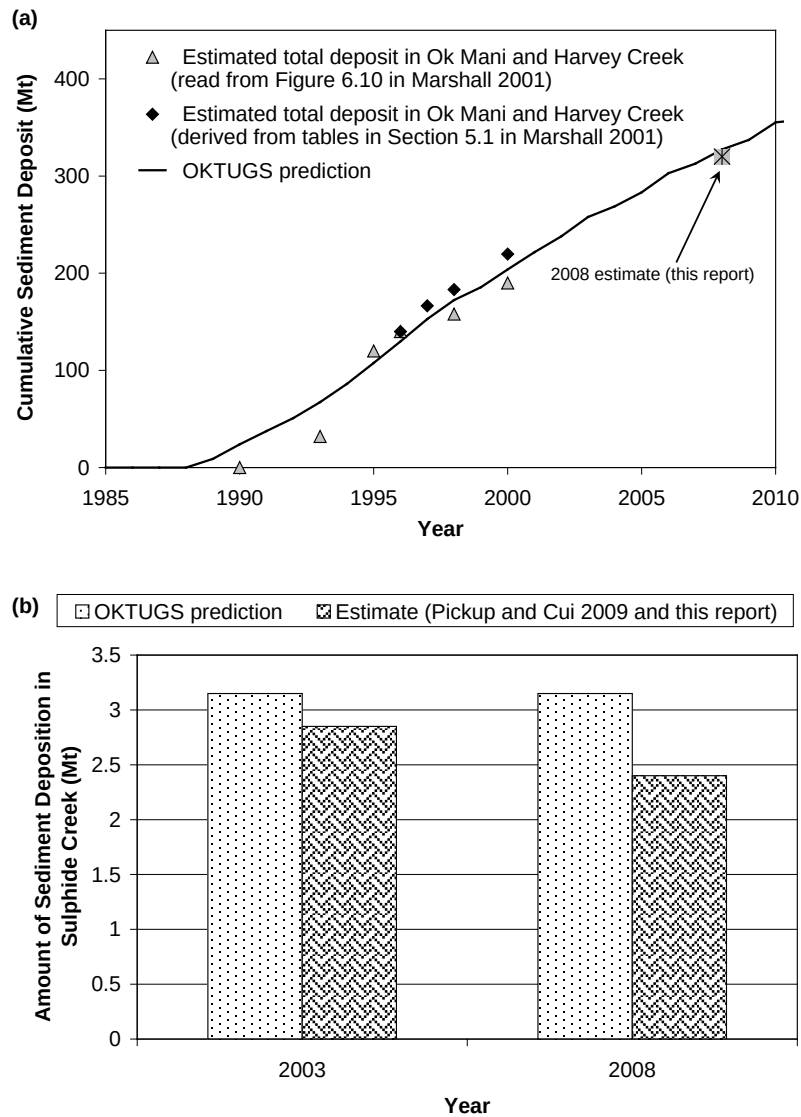


**Figure 29. Simulated sediment storage in (a) Ok Mani and Harvey Creek; and (b) Sulphide Creek, compared to field estimates.**

**Table 7. Predicted and estimated sediment storage in 2008**

| River reach                  | Prediction <sup>a</sup> | Estimate <sup>b</sup> |
|------------------------------|-------------------------|-----------------------|
| Sulphide Creek               | 3.1                     | 2.4                   |
| Ok Mani and Harvey Creek fan | 327                     | 320                   |
| Upper Middle Ok Tedi         | 183                     | 128                   |
| Lower Middle Ok Tedi         | 66                      | 156                   |

a. Assuming a bulk density of 1.75 t/m<sup>3</sup>;

b. Based on 1982 and 2008 DEM.

Comparisons in Figure 29 indicate that the model closely reproduced the amount of sediment deposition in the Ok Mani/Harvey Creek system and in Sulphide Creek. Results in Table 7 indicate that the simulated amounts of sediment deposition in 2008 are very close to those estimated from digital elevation models for two of the four reaches where DEMs are available. The estimated sediment deposition in Ok Mani and Harvey Creek is 320 Mt, while the simulation produced 327 Mt; and both the estimated and simulated deposition in Sulphide Creek are less than 5 Mt.

In the upper Middle Ok Tedi, the simulation produced 183 Mt of deposition compared with an estimated value of 128 Mt. Applying a valley edge deposit thinning factor of 25% reduces the estimated value to 97 Mt. The difference is relatively large but is within a reasonable range, considering the relatively good agreement in predicted and observed depth of sediment deposition shown in Figure 27. The higher predicted depositional volume in the upper Middle Ok Tedi seems to be the result of a greater depth of sediment deposition near the upstream end of the reach where there are no observed data, and near 75 km, where there is a spike in the predicted depth of sediment deposition.

The largest discrepancy in the amount of sediment deposition comes from the lower Middle Ok Tedi (downstream of ~ 45 km in Figure 27). The model produced 66 Mt of sediment deposition while the estimate is 156 Mt. However, applying a valley edge deposit thinning factor of 35% reduces estimated deposition to 101 Mt. Comparison of predicted and observed depth of sediment deposition shown in Figure 27 also indicates that the difference is far less than what is suggested by the comparison of the amount of sediment deposition in Table 7. The predicted depth of sediment deposition fairly closely resembles that observed in the field, except that it is unable to produce the detailed local variations as expected.

While there are differences between estimated and modeled amounts of deposition in the upper and lower Ok Tedi, the totals are very close. After applying valley edge deposit thinning factors, the estimated total deposition is 198 Mt compared with a model result of 249 Mt.

Another way of viewing model output data is to compare modeled average annual sand and silt transport near Bige with values obtained from the field-based sediment budget in Section 3.4. Model results for the period 1985-2008 show an average sediment transport rate of 49 Mt/yr, which is within 3% of the 47.7 Mt/yr estimated from the sediment budget. This is an excellent match.

Based on the above observations, we believe the calibrated model reasonably reproduced the observed data and is suitable for prediction of future conditions. However, we acknowledge that there are considerable uncertainties in both the modeling, as with any sediment transport modeling exercise (e.g. Pickup 2003), and the estimated deposition in the Middle Ok Tedi. We provide sensitivity tests in a later section to highlight possible effects of some of the uncertainties.

## 6.2. Discussions of OKTUGS Modeling

The *OKTUGS* model was developed and calibrated to simulate sediment transport dynamics in the Middle Ok Tedi and mine area creeks. Unlike its predecessor (i.e., *TUGS*), which successfully simulated sediment transport dynamics in two large rivers without model calibration (Cui 2007b; Gomez et al. 2009), the simulation of the study area with *OKTUGS* relied on substantial model calibration. There are several reasons for this:

- a). The slope of the river system in the study area is substantially higher than that used to develop Wilcock and Crowe's (2003) sediment transport equation, which is one of the key pieces of the model;
- b). The grain size for gravel is substantially coarser than that used to develop Wilcock and Crowe's (2003) sediment transport equation and the sand transfer function of Cui (2007a);
- c). There are still large data gaps for this study such as the lack of information on sediment supply from tributaries. Also, water discharge records for the entire study area had to be generated based on statistical characteristics and discharge records at a few locations.
- d). The river system is far more complicated system than that previously modeled with *TUGS* (i.e., Sandy River in Oregon, USA simulated in Cui 2007b and Waipaoa River in New Zealand simulated in Gomez et al. 2009). It is more than twice as long, has many tributaries, and a supply of sediment with a different specific gravity.

With model calibrations, *OKTUGS* was able to closely reproduce the sediment deposition patterns and amount of sediment deposition in several key reaches, and thus, we expect that it should provide useful information on future sediment transport characteristics in the study area.

Inherent to any sediment transport modeling exercise, the simulation still contains substantial uncertainties. Some of the uncertainties have been reduced through model calibration. The parameters affected by model calibration include sediment supply and grain size distribution from tributaries, grain size distribution and specific gravity of the sediment from mining disposal, water discharge, and active channel width.

Two key parameters are not included in the calibration process: the inner valley width following channel incision after mine closure, and water surface at the downstream end of the model after mine closure. Sensitivity tests by varying the inner valley width following channel incision indicate that, although it significantly affected the amount of sediment deposition in the study area, it only marginally affected the sediment transport rate near Bige, which is the key parameter to predict as it provides the upstream boundary condition for the *HEC-6* simulation of the downstream reaches.

Sensitivity tests by varying the water surface elevation at the downstream end of the model following mine closure indicated that this variable had minimal effect on the predicted sediment supply near Bige.

## 8. Potential for Capture of Sediment at Bige

The sediment particle size that forms the cutoff point between bed-material load (which can be captured by the dredge) and washload (which cannot) varies with the flow and sediment characteristics (Parker 2000). Where data on flow characteristics are limited, rules of thumb are usually applied, for example by assuming that the finest 10% of sediment in bed samples is the washload size fraction. Another method, used here, is an equation from Graf (1971) in which the washload cutoff point is set as:

$$v^2/gd = 360 \quad (20)$$

where  $v$  is flow velocity,  $g$  is acceleration of gravity and  $d$  is particle size. This method gives a reasonable fit to Ok Tedi and Fly River data.

The washload cutoff size for the dredge slot has been calculated using a *HEC-RAS* steady flow model for the reach between Konkonda and cross section OK30 upstream of Bige. Cross section data were derived from A. R. Marshall's 2008 survey and a dredge slot CAD file (3534-3123.dwg) provided by *DREDECO*. The model was calibrated to give a close fit to observed data showing the water surface slope between Konkonda and Bige (Figure 38).

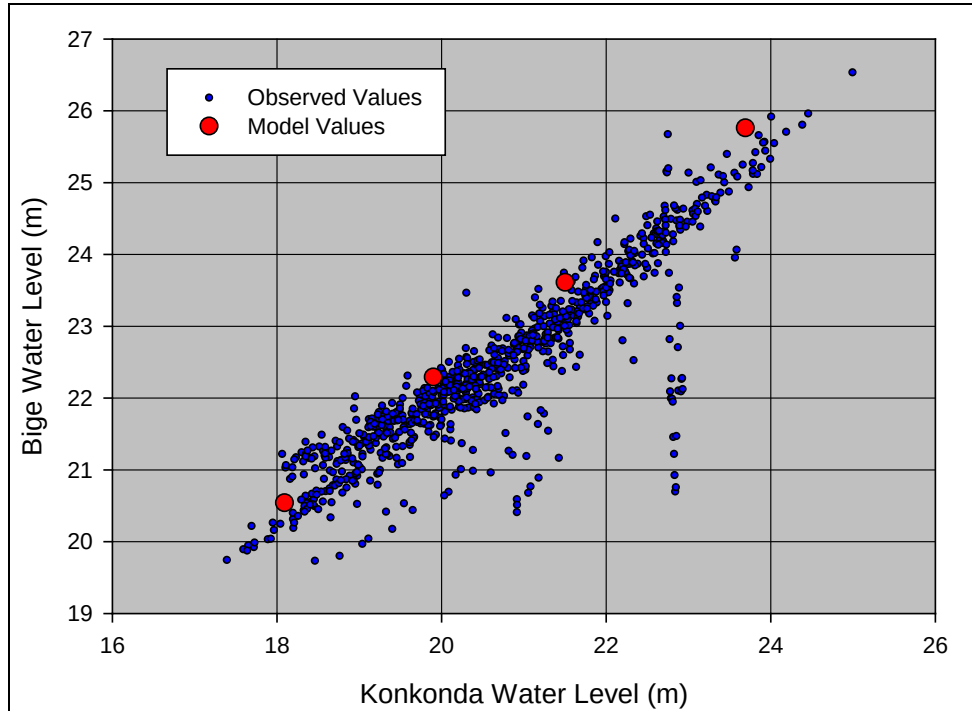


**Figure 38: Observed water levels at Konkonda and Bige compared with *HEC-RAS* model predictions.**

Calculated flow velocities in the dredge slot vary from 0.17 m/sec at a flow of 500 m<sup>3</sup>/sec to 0.46 m/sec at flows of 2,000 m<sup>3</sup>/sec. These values produce washload cutoff particle sizes of 0.008 - 0.046 mm. These compare well with observed values of D<sub>10</sub> for dredge slot bed samples (Figure 39). We have adopted a value of 0.03 mm to represent average conditions. This is effectively the lower particle size boundary for sand in the *OKTUGS* runs. We can therefore assume that only the sand delivered to Bige by *OKTUGS* is available for capture by the dredge.

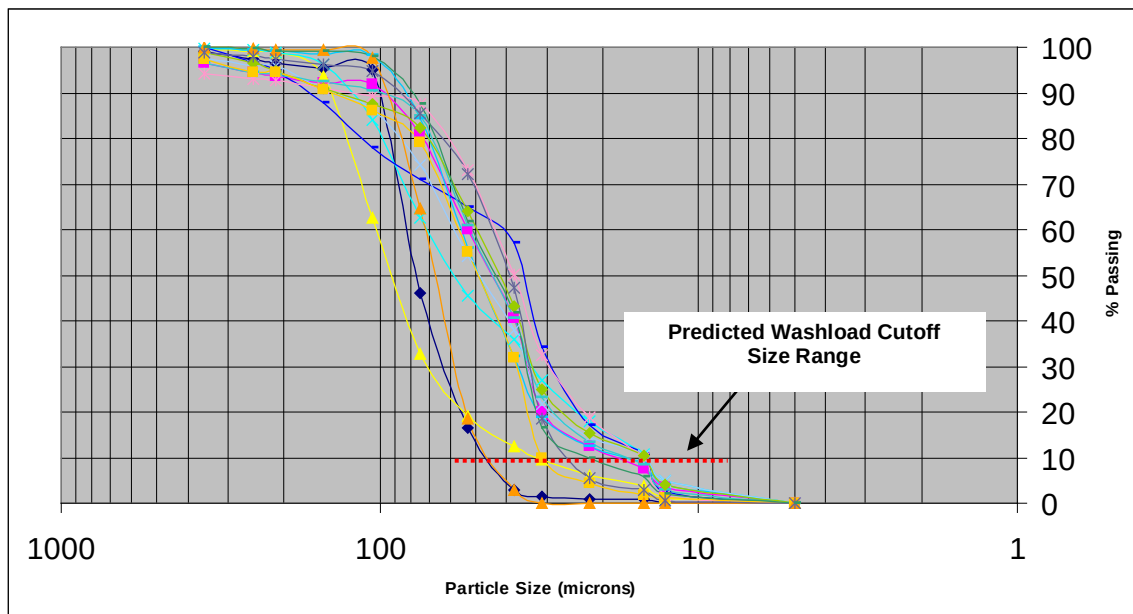


**Figure 39: Bed material particle size distributions for site TED17 (mid-dredge slot) from Enviro\_sample\_sizings.xls (2001 data).**

The actual amount of sand captured depends on many factors such as dredge time out of the river, breakdown time, amount of sand bypassing the dredge intake, etc. These factors can be grouped into a single dredge efficiency value which may be derived by comparing sand delivery with observed dredge output. This gives a value of 88% using sand delivery values from Run 13, 81.9% with Run 13c sand delivery values, and an average of 85%. These values are much higher than the dredge efficiency value of 50% used in our interim *OKTUGS* report (Pickup and Cui, 2009b). However, that report assumed that much of the material treated as washload by *OKTUGS* was available for dredging, hence the discrepancy.

Based on the foregoing analysis, estimates of potential sand and gravel capture at Bige have been made and are presented in Table 8. Also included are the interim estimates made by Pickup and Cui (2009b) using a sediment budget approach. These are remarkably close to the model results. We have assumed that dredging might continue until 2017 but this is purely for the purpose of calculation. We are not aware of any plans to continue dredging after mine closure.

**Table 8: Estimated sediment delivery and capture at Bige (dredge efficiency of 85%).**

| Year | Sand/Gravel (Mt) |         | Silt/Clay Mt |         | Dredge Sand Capture <sup>1</sup><br>(million m <sup>3</sup> ) |         |                |
|------|------------------|---------|--------------|---------|---------------------------------------------------------------|---------|----------------|
|      | Run 13           | Run 13c | Run 13       | Run 13c | Run 13                                                        | Run 13c | Interim Report |
| 2009 | 15.56            | 13.25   | 36.65        | 35.68   | 8.16                                                          | 6.95    | 8.87           |
| 2010 | 17.82            | 15.38   | 32.38        | 33.98   | 9.35                                                          | 8.07    | 7.17           |
| 2011 | 19.13            | 17.90   | 28.94        | 30.79   | 10.04                                                         | 9.39    | 6.86           |
| 2012 | 18.54            | 16.21   | 27.39        | 29.37   | 9.73                                                          | 8.51    | 6.60           |
| 2013 | 12.97            | 11.50   | 18.25        | 20.16   | 6.81                                                          | 6.03    | 5.82           |
| 2014 | 9.59             | 5.82    | 15.61        | 18.95   | 5.03                                                          | 3.05    | 2.82           |
| 2015 | 8.09             | 3.48    | 11.81        | 19.17   | 4.24                                                          | 1.83    | 2.63           |
| 2016 | 5.68             | 2.87    | 7.23         | 13.53   | 2.98                                                          | 1.51    | 2.27           |
| 2017 | 6.26             | 3.35    | 8.27         | 15.85   | 3.28                                                          | 1.76    | 1.90           |

1. Assumes a bulk density of 1.62

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*2014 SEDIMENT MODELING STUDY*

***THE 2013 OKTUGS MODEL REVISION AND  
CALIBRATION (WITH UPDATED MANDA  
INFORMATION)***

**DR. GEOFF PICKUP, CONSULTING GEOMORPHOLOGIST  
1538 SUTTON RD  
SUTTON, NSW 2620, AUSTRALIA**

**&**

**DR. YANTAO CUI, CONSULTING RIVER ENGINEER  
1841 TANGLEWOOD LANE  
BRENTWOOD, CA 94513, USA**

**REPORT TO ENVIRONMENT DEPARTMENT  
OK TEDI MINING LTD**

***29 MARCH 2014***

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# 1. INTRODUCTION

In 2008 and 2009, *Cui and Pickup (2009)* developed the *OKTUGS* model to simulate the sediment transport and deposition in the Upper and Middle Ok Tedi and the Ok Tedi Mine Area Creeks. The model was calibrated with the field observations then available which included changes in riverbed elevation in the Middle Ok Tedi, and changes in sediment storage in the Ok Mani and Sulphide Creek. The model has been used by OTML to examine the impact of various mine plans ever since with minimal revision. This report describes work carried out in 2013 to revise the current model and to incorporate new data including changes to the mining operation. It also describes model recalibration and compares model results with newly available data. The report supplements the *Cui and Pickup (2009)* technical report so only the model revision and model recalibration results are reported. Full details of the model are available in the 2009 report.

## 2. MODEL REVISIONS

Two changes have been made to the *OKTUGS* model. The first is an attempt to reproduce changes in the catchment area of Harvey Creek, initially as the mine expanded and removed much of the original topography, and subsequently, as the tunnel drainage was introduced to the pit so that most pit drainage no longer exited through the southern slot. The second modification is a revision of the gravel abrasion model, increasing the amount of material broken down to sand rather than silt.

In addition to these changes, we also reviewed the model code and revised some procedures and corrected some minor coding errors. The model is now much more stable under a wider range of conditions.

### 2.1 REVISION TO GRAVEL ABRASION

Previously, it was found that *OKTUGS* underestimated the amount of sand delivered to the Lower Ok Tedi and did not match dredging offtake at Bige and water level increase over time in the Lower Ok Tedi and Upper Middle Fly. *OKTUGS* results had to be corrected to match the observed data by converting part of the silt produced by abrasion to sand, thereby increasing total sand delivery to Bige at the start of the Lower Ok Tedi by

approximately 40% and limestone sand delivery to the same location by 30%. This correction is now built into *OKTUGS* by introducing an adjustment coefficient for each rock type:

$$Q_{adjusted\ silt\ by\ abrasion} = \delta Q_{predicted\ silt\ by\ abrasion} \quad (1)$$

$$Q_{adjusted\ sand\ by\ abrasion} = Q_{predicted\ sand\ by\ abrasion} + (1 - \delta)Q_{predicted\ silt\ by\ abrasion} \quad (2)$$

in which  $Q$  denotes sand or silt flux, and  $\delta$  is a calibration coefficient.

Although the adjustments represented by Equations (1) and (2) are empirical, there are underlining reasons such an adjustment is needed. In the original *OKTUGS* model, *Parker's (1991a, 1991b)* formulation was used in which abrasion gradually grinds down each gravel particle, reducing its size by producing silt until the core becomes a sand-sized particle. This means that a gravel particle, no matter its size and lithological composition, will eventually become a single sand particle while the rest of the particle becomes silt. This formulation underestimates sand production (and thus, overestimates silt production) because gravel particles often break down into their constituent grains or crystals which are often sand-sized. The adjustment presented in Equations (1) and (2) provides a more realistic formulation.

## 2.2 REVISIONs TO INCLUDE CATCHMENT AREA CHANGE IN HARVEY CREEK

There is little information on how the catchment area of Harvey Creek increased as the natural topography was consumed during the early history of the mine. We assumed that the pit reached its current lateral extent by about 1996, and pit drainage was through the southern slot into Harvey Creek. From 2011 pit drainage was to the Ok Ningi via a tunnel, effectively reducing the catchment area of Harvey Creek. Estimates of catchment area of Harvey Creek are shown in Fig. 1 and the model was revised to use all three sets of estimates as described below.

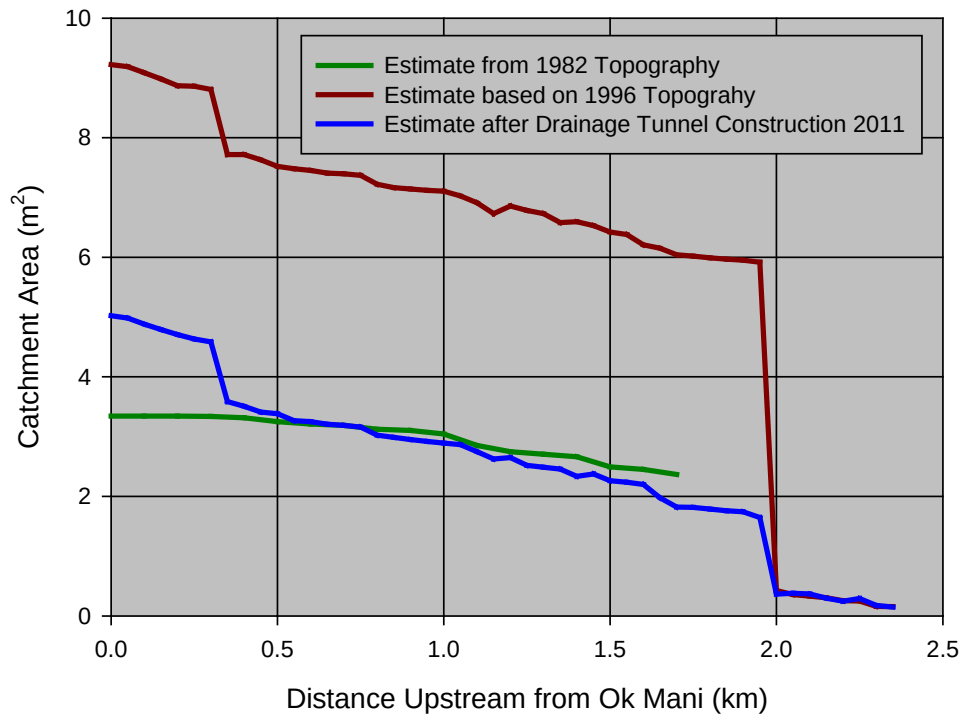


**Figure 1: Estimated catchment area of Harvey Creek.**

- 1985 – 1996: linear increase from the 1982 estimate to the 1996 estimate.
- 1997 – 2010: 1996 estimate.
- 2011 and after: 2011 estimate.

The catchment area in Ok Mani downstream of Harvey Creek confluence includes Harvey Creek, and thus, its catchment area is affected by the change in Harvey Creek. This change is also implemented in the revised model.

## 2.3 MODIFICATIONS TO LANDSLIDE MATERIAL AND WASTE ROCK GRAIN SIZE DISTRIBUTIONS

The *Cui and Pickup (2009) OKTUGS* model assumed that landslides produced gravel particles with a similar particle size distribution to waste rock. Waste rock was also assumed to be composed entirely of gravel. However, some sand and silt is also produced from landslide activities, especially where landslides add weathered material to river. Also, while there is initially very little sand and silt in the waste rock, some of it breaks down to sand and silt during and soon after dumping (*Pickup and Others, 2010*). In the

absence of observed data, we have assumed the following fractions of sand and silt in landslide material and in waste rock:

- Landslide material: 10% of silt, 5% of sand and 85% gravel.
- Non-limestone waste rock: 15% of silt, 5% sand, and 85% gravel.
- Limestone: 15% silt, 1% sand, and 84% gravel.

These values are assigned as part of the calibration process below and can be revisited in the future if new field data becomes available.

### 3. MODEL RECALIBRATION

After the revisions discussed in Section 2 were implemented, the model was calibrated by adjusting the sand/silt fractions in landslide material and in waste rock, and adjusting  $\delta$  values in Equations (1) and (2) by trial-and-error so that:

- Total sand delivery to lower Ok Tedi for the period of 1985 – 2013 increases by approximately 40%.
- Limestone sand delivery to lower Ok Tedi for the period of 2000 – 2013 (limestone prior to 2000 was not simulated) increases by approximately 30%.
- Modelled suspended sediment concentrations at Ningerum reasonably match the observed values;
- Modelled channel aggradation/degradation patterns reasonably match the observations for the Middle Ok Tedi; and
- Modelled cumulative sediment deposits in Ok Mani and Harvey Creek reasonably match the estimated values.
- Modelled cumulative sediment deposits in Sulphide Creek reasonably match the estimated values.

The final calibrated  $\delta$  values are 0.4 for natural sediment (including landslide-generated sediment) and waste rock, and 0.037 for limestone-generated sand. While these values were derived by trial and error for the upper river system, they originate from work on the lower river where the original *OKTUGS* sand delivery estimates were found be less than dredge offtake at times and insufficient to produce enough deposition to raise water levels further downstream by observed amounts. The limestone sand output also seemed

too low to generate observed ANC values in Bige dredge sands and modelled TSS values at Ningerum also seemed high

The recalibrated model produces the following results:

- The average annual sand delivery to the Lower Ok Tedi for the period of 1985-2013 increased from 17.2 Mt/year to 24.0 Mt/year, representing an increase of 39.5%. If sand delivery had remained at 17.2 Mt/year, it would not be sufficient to meet observed dredge sand capture which averages 17 Mt/year but has been as high as 21 Mt/year, even with a dredge efficiency of about 85%.
- The average limestone delivery to lower Ok Tedi for the period of 2000 – 2013 increased from 0.16 Mt/year to 0.21 Mt/year, representing an increase of 27.7%.

A number of tests have been applied to see how well the recalibrated model matches observed river behaviour. On the upper river, these are:

- Ability to reproduce the observed mass of deposition on the Ok Mani and Sulphide Creek systems;
- Ability to match observed changes in riverbed levels on the Middle Ok Tedi;
- Ability to match observed suspended sediment loads at Ningerum.

On the lower river system, the tests of model accuracy were focussed on ability to reproduce observed changes in water level over time at Konkonda on the Lower Ok Tedi, Kiunga on the Upper Fly, and Kuambit, Manda and Obo on the Middle Fly.

### 3.1 MODEL VALIDATION – UPPER RIVER SYSTEM

Modelled cumulative sediment deposition in Ok Mani and Harvey Creek is shown in Fig. 2. The model closely matches the measured values although there is some underestimated in recent years.

Modelled cumulative sediment deposition on Sulphide Creek also matches observed deposition, or rather, the lack of it (Fig. 3). Sulphide Creek has a high transport capacity and holds very little mine sediment. The model results also show that the 120 Mt of sediment contributed by the Vancouver Landslide did not remain in Sulphide Creek for very long. The model was unable to reproduce the 1 Mt or so of erosion shown as negative values in 1996 and 2004. These were the results of side wall erosion which is not built into the model. These values may be too high because the changes in volume over time

have not been corrected for the change from treetop heights to bare sediment that occurs with sidewall erosion.

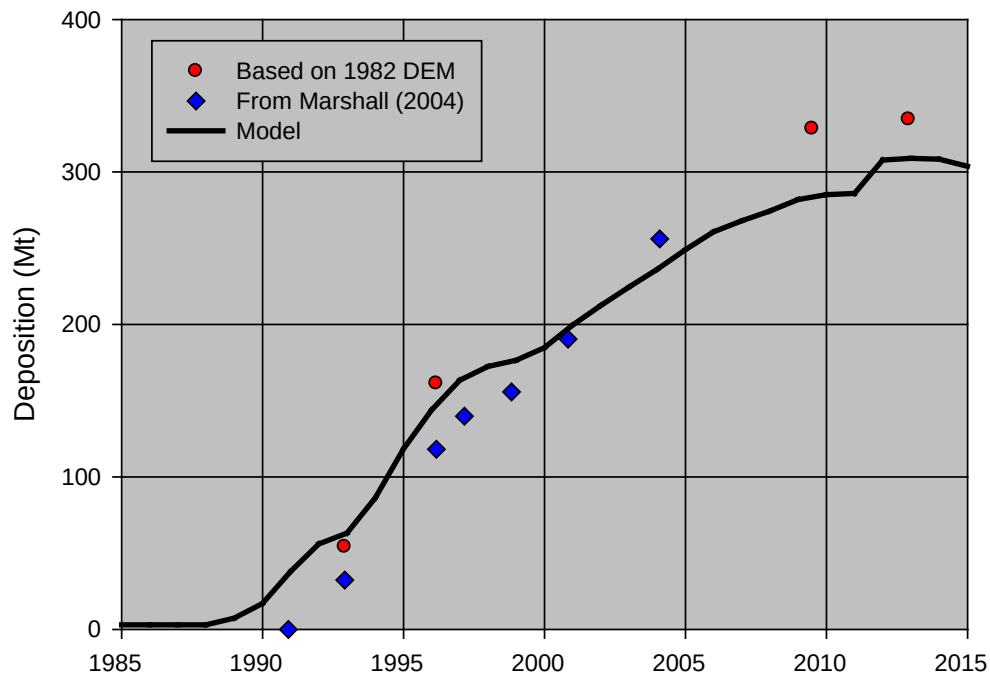


**Figure 2: Comparison of modelled and observed cumulative sediment deposition in Harvey Creek and the Ok Mani.**

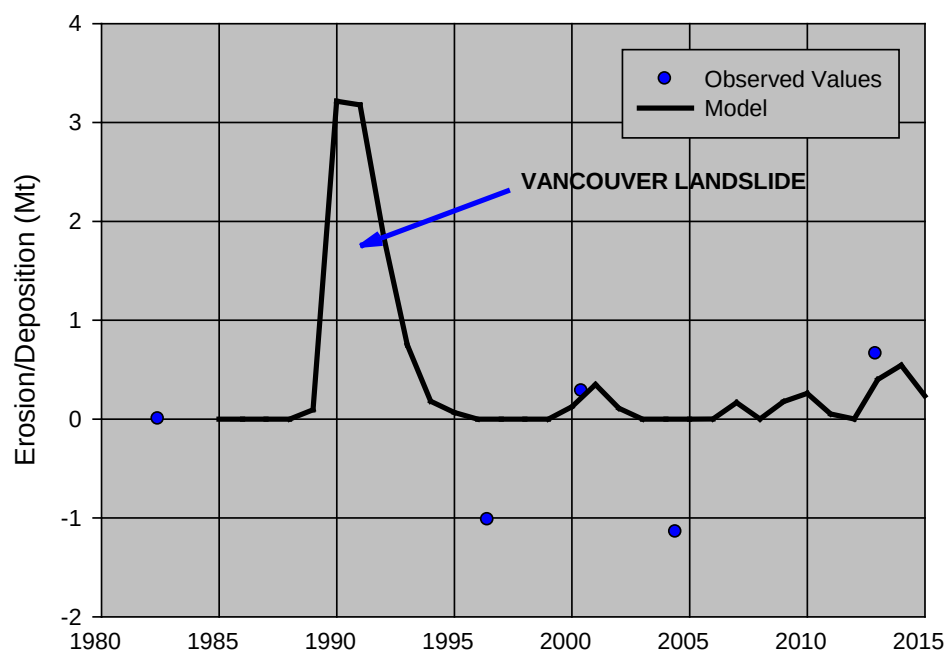


**Figure 3: Comparison of modelled and observed cumulative sediment erosion and deposition in Sulphide Creek.**

Figure 4 shows observed and modelled suspended sediment concentrations at Ningerum, near the end of the gravel reach of the Middle Ok Tedi. The observed values

are from surface gulp samples. Model values are from average annual silt loads and were converted to gulp sample-equivalent sediment concentrations using a mean flow of 300m<sup>3</sup>/sec. A multiplier of 0.845 was converted suspended sediment concentrations to gulp sample-equivalent values (*Pickup, 2013*).

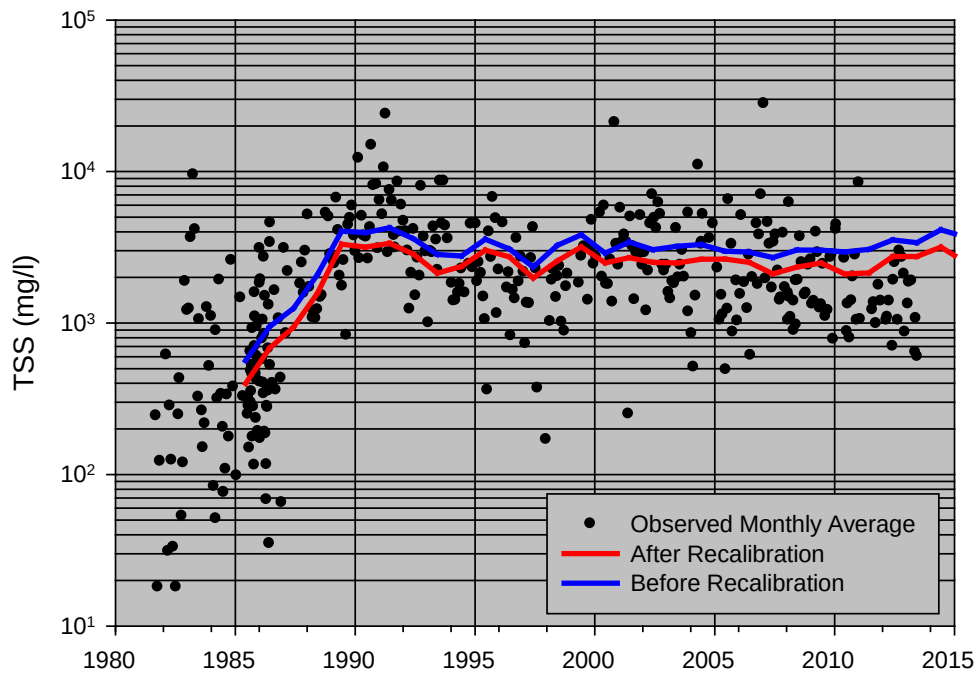


**Figure 4: Observed and modelled suspended sediment concentrations at Ningerum.**

The modelled average suspended sediment concentrations at Ningerum match the observed values reasonably well from the mid-1990s to 2013. Before that, the model underestimates observed values, especially around the time of the Vancouver Landslide (around 1990). The discrepancy probably results from the fact that early landslides contained mainly weathered material which would have large amounts of fines. However, there are no data on early landslide particle size distributions to allow adjustment of model inputs.

Modelled channel aggradation/degradation patterns reasonably match the observations for the Middle Ok Tedi (Fig. 5). The model seems to become more accurate over time (i.e., the predicted aggradation and degradation between 2008 and 2012 match field observation better than the previous two periods). This may be because the 1982 and 1992 elevations were based on photogrammetric analysis of fairly high-altitude air photos. The 2008 data come from differential GPS data acquired during a small boat journey down the river whereas the 2012 data are from airborne lidar with good ground control. The 2008 and 2012 data are more

accurate than the earlier values. These results provide us with reasonable confidence in the model's capability to predict the future conditions in the river system.

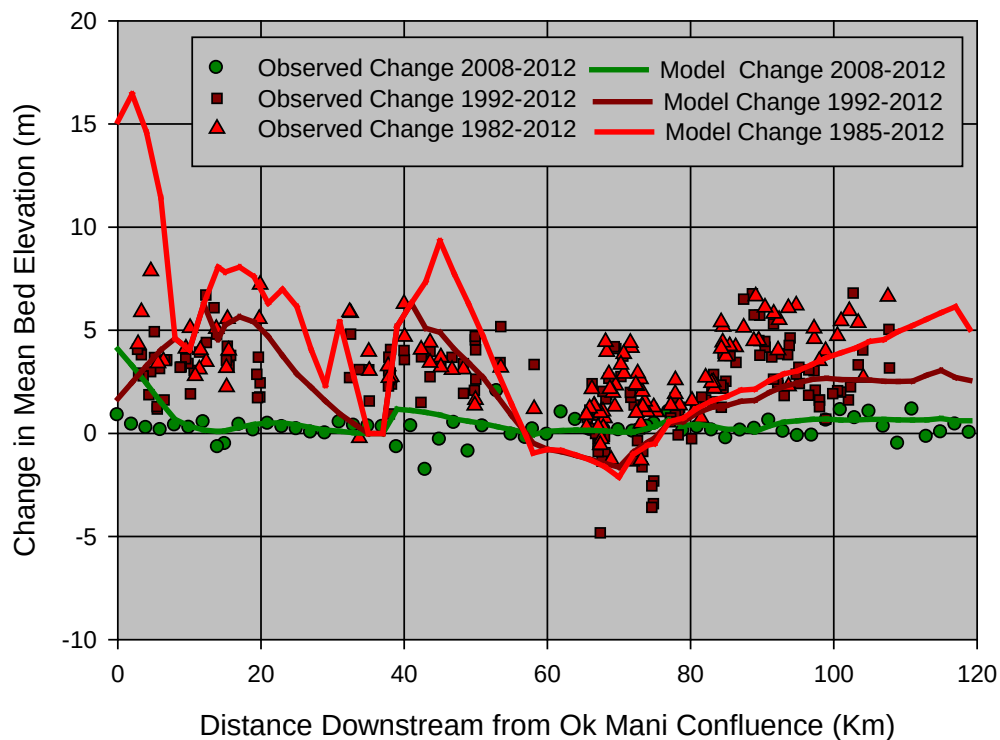


**Figure 5. Comparison of observed and modelled changes in bed elevation in the Middle Ok Tedi.**

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## **APPENDIX TWO**

### **DEVELOPMENT OF REGIONAL RIVER HYDROLOGY RELATIONSHIPS AND THE DEVELOPMENT AND CALIBRATION OF THE LOWER RIVER SEDIMENT TRANSPORT MODEL HEC-6**

*EXTRACTS FROM PICKUP, G. AND CUI, Y. 2003.  
EFFECTS OF MINE LIFE EXTENSIONS AND RATES  
OF DREDGING ON THE OK TEDI AND FLY RIVER -  
A SEDIMENT TRANSPORT MODEL STUDY USING  
OKGRAV6 & HEC-6. REPORT TO ENVIRONMENT  
SECTION, OK TEDI MINING LTD*

FOREWORD

The material in this Appendix describes regional hydrology relationships and HEC-6 model setup and calibration results from a 2003 study using data from the early period of mine life calibration when tailings inputs were substantially higher than the present situation. Waste rock and landslide inputs were also generally higher except in very recent times. There have been several attempts to update both the hydrology and the sediment transport model over the last twenty years but with no improvement on the accuracy of model outputs when compared with observed river system behaviour. We have therefore continued to use the 2003 model for operational predictions.

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## SUMMARY

Two sediment transport models are used in modeling runs. Runs with *OkGrav6* (see Appendix One) cover effects in Mine Area Creeks and the Upper and Middle Ok Tedi. Runs with *HEC-6* examine likely changes in the Lower Ok Tedi and Middle Fly. *OkGrav* was updated in this process and recalibrated using new data on flow durations, sediment characteristics, sidewall erosion and deposition. *HEC-6* was calibrated using observed water levels and patterns of deposition from cross section surveys.

Both *OkGrav6* and *HEC-6* require flow data at various input points. Generating these data required considerable work on the OTML hydrology database to derive both regional relationships and long term flow data. This included flow duration curves for the Mine Area Creeks and Upper and Middle Ok Tedi. On the Lower Ok Tedi and Middle Fly, data gaps were filled in and discharges recalculated to allow for rating curve shifts and backwater effects. A 100-year record containing realistic climatic variations was then generated for modeling.

Both models were calibrated and validated against observed data and produced good results. However, there are many data gaps and questions remain about model accuracy in the lower Middle Fly and parts of the Middle Ok Tedi.

Sand and silt output from *OkGrav6* were fed into *HEC-6* after accounting for dredging.

Results from *HEC-6* show that initially, heavy sediment accumulation occurs in the lower part of the Ok Tedi between Iogi and D'Albertis Junction. This deposition is reduced by dredging and by natural erosion after mine closure. By about 2060 much of this deposition has cleared. The Lower Ok Tedi holds material for longer and deposition persists beyond 2060.

Model results compare well with those obtained by Parker and Cui (1999). Long term deposition in the Lower Ok Tedi is almost identical. Deposition in the sand zone of the Middle Fly is similar but occurs later and persists for longer. This is a consequence of changes to the *OkGrav* model which now holds more sand upstream of the Lower Ok Tedi and releases it over a longer period. During mine life, deposition in the backwater zone of the Middle Fly is similar but more accumulates in the long term. This may result from the delay in sand delivery from the reach upstream.

## 1. INTRODUCTION

### 1.1 Background

Ok Tedi Mining Ltd (OTML) is examining the possibility of extending mine life for additional periods of five and ten years beyond 2010. This study was commissioned to examine the likely impact on deposition and water levels in the Ok Tedi and Middle Fly River systems. A second task was to examine how changes in the current rate of dredging would affect the river system.

This report presents the study results and includes a description of the modeling techniques, and how the various model datasets were obtained.

## 1.2 Objectives

The main aims of the study were to:

- Estimate dumping and tailings disposal scenarios for mine life extensions of 5 and 10 years beyond 2010 using the existing mine plan and future waste rock and tailings disposal rates of 55 Mt/year and 30Mt/year respectively.
- Provide estimates of the amount of deposition in the Mine Area Creeks, Ok Tedi & Middle Fly.
- Estimate changes in water level on the Lower Ok Tedi and Middle Fly in response to deposition.
- Estimate post-mining river behaviour for a period of up to 50 years after cessation of mining.
- Compare results with earlier modeling studies.

## 1.3 Approach

The project was split into two tasks:

- Modeling of sediment transport and storage in Mine Area Creeks & the Upper and Middle Ok Tedi using the *OkGrav* (Cui and Parker, 1999) sediment model by Dr. Yantao Cui (Stillwater Sciences) with advice from Prof. Gary Parker (University of Minnesota).
- Modeling of sediment transport, storage and water level changes on the Lower Ok Tedi and Middle Fly using the *HEC-6* model (Hydrologic Engineering Centre, 1992) and output from *OkGrav* by Dr Geoff Pickup.

The approach was to calibrate and verify models prior to making estimates of future river behaviour. It was also necessary to represent the sand deposition currently occurring between the Lower Ok Tedi gorge and the downstream end of the pre-mining gravel sand transition zone near Konkonda.

Recent data from the *OTML HYDSYS* database, photogrammetric surveys of Mine Area Creeks, and detailed cross section measurement on the Lower Ok Tedi and Middle Fly were used with the models whenever possible. The *OkGrav* model was also updated to reflect patterns of erosion that have emerged since dumping of waste rock largely ceased on Sulphide Creek.

## 2. METHODS

### 2.1 Mine Area Creeks and Upper/Middle Ok Tedi Modeling with *OkGrav6*

The *OkGrav5* model and its predecessors were developed and continuously upgraded by Professor Gary Parker over the period 1986-1999. The model was purpose-built for the Mine Area Creeks and the gravel sections of the Upper and Middle Ok Tedi. It has been used in virtually every study of upper river system sedimentation since the mid 1980s and gives a reasonable reproduction of observed behaviour over most reaches. The model treats the lower section of Harvey Creek and the upper reach of Sulphide Creek as debris flow runout zones. The Ok Mani, lower Sulphide Creek and the Ok Tedi are modeled as fluvial zones. A detailed description of the model is provided in Section 5.

A new version of the model (*OkGrav6*) was developed for this study. It incorporates updated hydrology data, a revised sidewall erosion component for Harvey Creek, and a reformulation of the debris flow runout component for post-dumping situations when erosion occurs. The model was also recalibrated using data from Marshall (2001) and digital elevation models derived from Marshall's survey data.

### 2.2 Lower Ok Tedi and Middle Fly Modeling with *HEC-6*

While there are a number of moveable boundary one, two and three-dimensional sediment transport models available, surveyed cross section spacing does not justify going beyond a one-dimensional model of the river channel. There is also a lack of information on floodplain topography, flow patterns and hydraulic roughness which makes it difficult to justify the two-dimensional modeling needed to represent floodplain behaviour. We have therefore used a one-dimensional channel model to represent the Lower Ok Tedi and Middle Fly.

*HEC-6* (Hydrologic Engineering Centre, 1992) is a one-dimensional moveable boundary open channel flow numerical model designed to predict changes in river profiles resulting from scour and deposition over periods of years. The model was developed by the US Army Corps of Engineers and has been in use for more than 20 years.

*HEC-6* divides the river into a series of reaches whose geometry is described by measured cross sections. A continuous flow record is partitioned into a series of steady flows of variable discharge and duration. A water surface profile is calculated for each flow providing information on water surface elevation, flow velocity, energy slope, width and depth at each cross section. Potential sediment transport rates are calculated at each cross section from these flow parameters and a sediment mass balance obtained for each reach based on sediment inflow and outflow. Each cross section is then changed depending on the amount of scour or deposition. The flow computations proceed to the next flow in the sequence and are repeated with the updated channel geometry. Sediment calculations are performed for each particle size fraction in the load and allow for both sorting and bed armouring.

*HEC-6* was chosen for a number of reasons, the most important being the availability of input and calibration data. It was used previously on the Lower Ok Tedi by GHD (1999).

It allows for variable cross section geometry, making it possible to exploit the detailed cross section survey data that have become available since 1997. It is well used, and while data preparation is complex, model operation is fairly simple. It can be calibrated from measured deposition by a process of trial and error and finally, it may be obtained at little or no cost.

Several models were reviewed prior to choosing *HEC-6*. Comments on these models are presented in Appendix A.

### **2.3 Floodplain Deposition**

While *HEC-6* has a crude capacity to model deposition on floodplains, it was run as a channel model only. All flow and sediment transport is therefore confined within the cross section. Several attempts have been made in the past to build in a floodplain deposition component, e.g. Cui and Parker (1999) with *OkFly* and Hranisavljevic & others (1996) with *RMA*. However, there is so much uncertainty about floodplain topography and hydrologic behaviour that model accuracy remains questionable.

#### 4. HYDROLOGIC DATA UPDATES

##### 4.1 Mine Area Creeks and Upper Ok Tedi Flow Duration Curves

*OkGrav6* uses flow duration data to represent water discharge in Mine Area Creeks and the Upper & Middle Ok Tedi. Two sets of information are needed for modeling:

- Long term flow duration curves for predicting future mine impact.
- Flow duration curves for specific periods between 1996 and 2000 for model calibration/validation.

Given the limited stream gauging data in the mine area, these curves must be derived from regional hydrologic relationships that allow values from measured sites to be extrapolated across the region.

The flow duration data used previously with *OkGrav5* were supplied by former *OTML* hydrologist David Paige and originate from the early 1980s (SMEC, 1979; 1982; 1983). These data came mainly from the Ok Ningi and the Ok Ma with limited reliance on other stations. An update is required if sufficient new data are available.

A review of available flow data shows little that is useable from the Mine Area Creeks. Some stream gauging was carried out on the Ok Ningi prior to mining and that provides the only long run of flow information in that area. There are more data for the Upper Ok Tedi and the Ok Ma. However, many of the station discharge ratings are suspect, particularly at high and low flows. Rainfall data are in better condition and there are long runs of daily data for various locations across the upper Ok Tedi catchment.

##### 4.1.1 Derivation of Long-Term Regional Flow Duration Relationships

We have derived a new regional flow duration curve to provide updated water discharge data for sediment transport modeling. This curve may be applied to steep drainage basins in the Upper Ok Tedi catchment at points where upstream catchment area is known. It makes no allowance for lithology and may be subject to error given the quality of the input data. However, it does seem to give useable results across the upper catchment. The following method was used to derive it:

- Flow duration curves were calculated from Upper Ok Tedi catchment gauging stations in the HYDSYS database using a time interval of one minute.
- A flow duration curve for the Ok Ningi was obtained from Klohn Leonoff (1993) and interpolated to provide information at the same intervals as the HYDSYS curves.
- Regression analysis between gauging station catchment areas and a set of flows of specific durations showed a linear relationship with unit slope over

most of the range (Fig. 2). This means that flows may be standardised by dividing discharge by catchment area.<sup>1</sup>

- Flow duration curves for individual stations were standardized in this way and are plotted in Fig 3. These curves were averaged to produce the regional curve in Table 4.

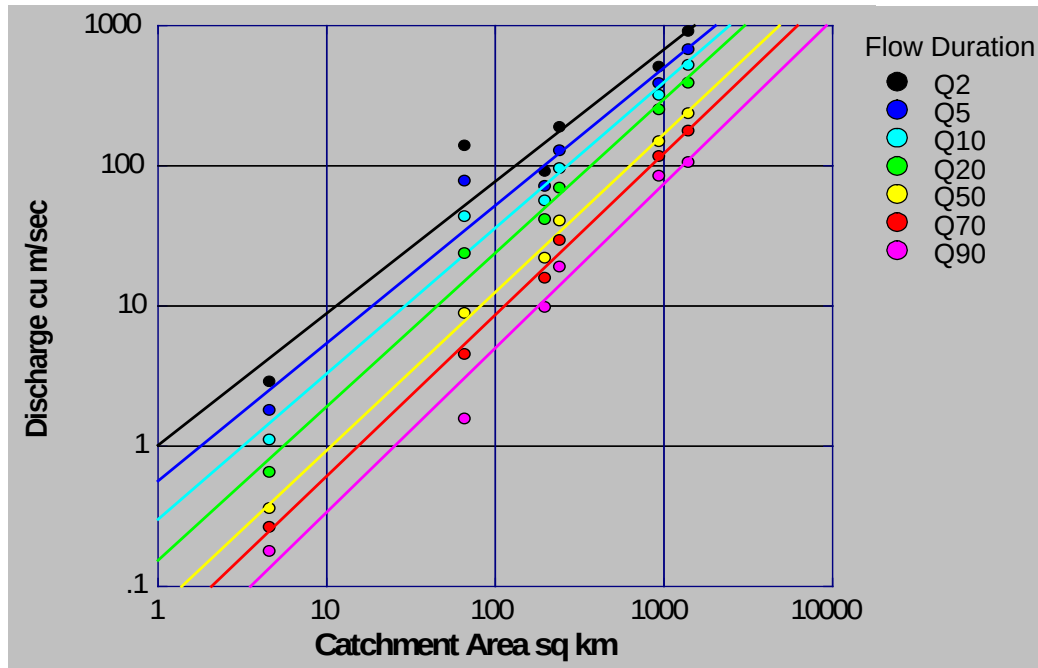


**Figure 2: Variations in discharge of specific durations with catchment area for stations TED05, TED15, TED20, MAA10 and the Ok Ningi.**

The standardised flow duration curves overlay reasonably well except in the case of the Ok Ma where high and low flows deviate from the general trend. We suspect that this may be due to rating curve errors as the Ok Ma rating curve is not well-defined for flows with durations of less than 20%. Accordingly, this station was not used to derive the regional curve.

The regional flow duration curve does not allow for downstream attenuation in discharge. While this effect might be expected over the range of catchment areas considered, the gauging data indicate that this effect is weak and probably within measurement error. SMEC (1979) also found this to be the case and used a single regional curve for catchments in the 20-1500 km<sup>2</sup> range.

<sup>1</sup> An effective catchment area of 2.76 km<sup>2</sup> sq (as opposed to the measured area of 4.56 km<sup>2</sup>) was used for the Ok Ningi because of possible data errors and suspected leakage due to karst features. One or both of these create a discrepancy between rainfall and runoff (SMEC, 1979; 1982; 1983). However, the effect of selecting one value or the other on the flow duration curves for the range of catchment areas modeled in *OkGrav* is very small.

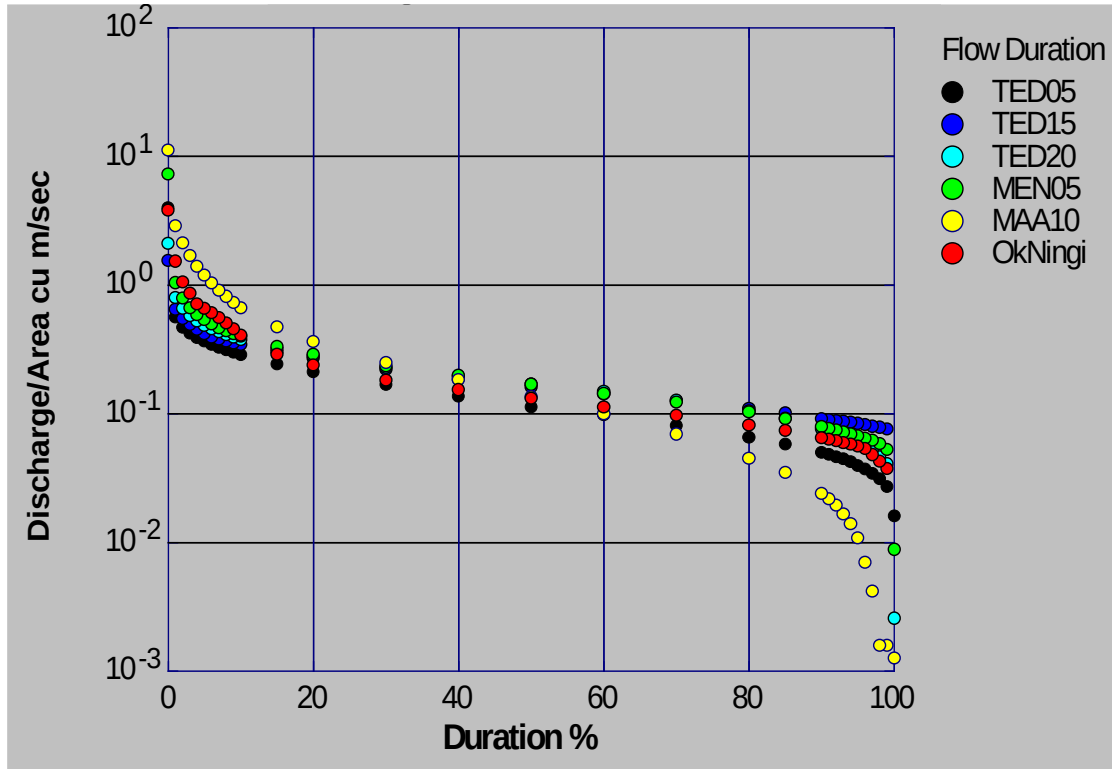


**Figure 3: Standardised flow duration curves for Upper Ok Tedi Catchment drainage basins.**

#### 4.1.2 Extrapolation of Duration Curves for Low Duration/High Flows

Reliable data for flows with durations of less than 1% were not available. We were therefore forced to extrapolate the individual duration curves. While it would have been preferable to use a probability distribution curve as the basis for fitting, insufficient accurate data were available to allow selection of an appropriate distribution. We have therefore used a simple polynomial equation to extrapolate the regional curve for low duration. This equation has the form:

$$Q_D = 0.892 - 0.629 (\log_{10} D) + 0.1064 (\log_{10} D)^2$$

Where:

$Q_D$  is the discharge per unit area ( $\text{m}^3/\text{sec}/\text{km}^2$ ) of duration  $D$   
 $D$  is flow duration in %.

These data are shown in Fig. 4.

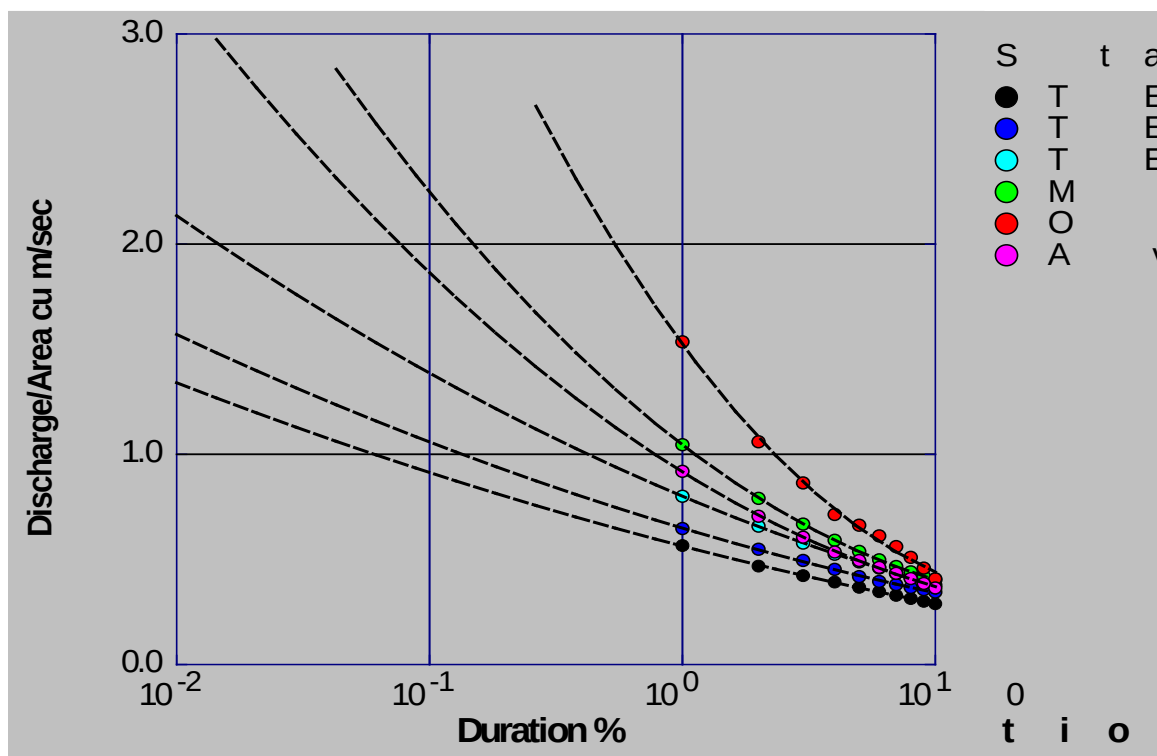


**Figure 4: Extrapolated flow duration curves for high discharges.**

#### 4.1.3 Calibration Period Flow Duration Curves

Flow duration data were needed for the following model calibration/validation periods:

*Ok Mani/Harvey Ck*

March 1996 – March 1997

March 1997 – November 1998

November 1998 – November 2000

*Sulphide Ck*

March 1996 – November 2000

*Upper Ok Tedi*

March 1996 – November 2000.

Not enough flow data are available to construct flow duration curves directly. We have therefore used the regional flow duration curve but adjusted it using rainfalls for the Taranaki and Southern Dumps. The relevant multipliers are listed in Table 3.

| <b>TABLE 3: FLOW DURATION CURVE MULTIPLIERS</b> |               |               |
|-------------------------------------------------|---------------|---------------|
| Rainfall (Annual Equivalent)                    | Southern Dump | Taranaki Dump |
| Mean Annual 1991-2001                           | 8873          | 8868          |
| Mar 1996 – Nov 2001                             |               | 8361 (0.943)  |
| Mar 1996 – Mar 1997                             | 6592 (0.743)  |               |
| Mar 1997 – Nov 1998                             | 6905 (0.778)  |               |
| Nov 1998 – Nov 2000                             | 9029 ( 1.018) |               |

| <b>TABLE 4: REGIONAL FLOW DURATION CURVE DATA</b> |                                                         |                        |                        |                        |                        |
|---------------------------------------------------|---------------------------------------------------------|------------------------|------------------------|------------------------|------------------------|
| Flow Duration<br>Cumulative %                     | Discharge (m <sup>3</sup> /sec)/Area (km <sup>2</sup> ) |                        |                        |                        |                        |
|                                                   | Long Term<br>Average                                    | Mar 1996 -<br>Mar 1997 | Mar 1997 -<br>Nov 1998 | Nov 1998 -<br>Nov 2000 | Mar 1996 -<br>Nov 2000 |
| 100                                               | 0.005                                                   | 0.004                  | 0.004                  | 0.005                  | 0.005                  |
| 99                                                | 0.046                                                   | 0.034                  | 0.036                  | 0.047                  | 0.044                  |
| 98                                                | 0.051                                                   | 0.038                  | 0.040                  | 0.052                  | 0.048                  |
| 97                                                | 0.055                                                   | 0.041                  | 0.043                  | 0.056                  | 0.052                  |
| 96                                                | 0.058                                                   | 0.043                  | 0.045                  | 0.059                  | 0.055                  |
| 95                                                | 0.061                                                   | 0.045                  | 0.047                  | 0.062                  | 0.058                  |
| 94                                                | 0.063                                                   | 0.047                  | 0.049                  | 0.065                  | 0.060                  |
| 93                                                | 0.066                                                   | 0.049                  | 0.051                  | 0.067                  | 0.062                  |
| 92                                                | 0.068                                                   | 0.050                  | 0.053                  | 0.069                  | 0.064                  |
| 91                                                | 0.070                                                   | 0.052                  | 0.054                  | 0.071                  | 0.066                  |
| 90                                                | 0.072                                                   | 0.053                  | 0.056                  | 0.073                  | 0.068                  |
| 85                                                | 0.083                                                   | 0.062                  | 0.065                  | 0.085                  | 0.078                  |
| 80                                                | 0.093                                                   | 0.069                  | 0.072                  | 0.094                  | 0.087                  |
| 70                                                | 0.111                                                   | 0.082                  | 0.086                  | 0.113                  | 0.104                  |
| 60                                                | 0.129                                                   | 0.096                  | 0.100                  | 0.131                  | 0.122                  |
| 50                                                | 0.149                                                   | 0.110                  | 0.116                  | 0.151                  | 0.140                  |
| 40                                                | 0.174                                                   | 0.129                  | 0.135                  | 0.177                  | 0.164                  |
| 30                                                | 0.207                                                   | 0.154                  | 0.161                  | 0.211                  | 0.195                  |
| 20                                                | 0.259                                                   | 0.192                  | 0.201                  | 0.263                  | 0.244                  |
| 15                                                | 0.297                                                   | 0.221                  | 0.231                  | 0.303                  | 0.280                  |
| 10                                                | 0.363                                                   | 0.270                  | 0.283                  | 0.370                  | 0.343                  |
| 9                                                 | 0.385                                                   | 0.286                  | 0.299                  | 0.392                  | 0.363                  |
| 8                                                 | 0.408                                                   | 0.303                  | 0.317                  | 0.415                  | 0.385                  |
| 7                                                 | 0.433                                                   | 0.322                  | 0.337                  | 0.441                  | 0.408                  |
| 6                                                 | 0.461                                                   | 0.343                  | 0.359                  | 0.470                  | 0.435                  |
| 5                                                 | 0.494                                                   | 0.367                  | 0.384                  | 0.503                  | 0.466                  |
| 4                                                 | 0.534                                                   | 0.397                  | 0.416                  | 0.544                  | 0.504                  |
| 3                                                 | 0.605                                                   | 0.449                  | 0.470                  | 0.616                  | 0.570                  |
| 2                                                 | 0.704                                                   | 0.523                  | 0.548                  | 0.717                  | 0.664                  |
| 1                                                 | 0.918                                                   | 0.682                  | 0.714                  | 0.935                  | 0.866                  |
| 0                                                 | 3.762                                                   | 2.795                  | 2.927                  | 3.830                  | 3.548                  |

#### 4.1.4 Derivation of Upstream Catchment Area at OkGrav Cross Sections

The regional flow duration curves require information on upstream catchment area to allow conversion into absolute values of discharge. None of the *OTML* mine area digital elevation models (DEMs) cover the whole catchment area so it proved necessary to build a DEM from the Ok Tedi 1:100,000 mapsheet contours. The contour coverage in the *OTML* ARCINFO database contains many mislabeled or unlabelled contours. These were removed or corrected as far as possible.

The DEM was then created using Delauney triangulation using the TNTmips geographic information system (MicroImages, 2001). A flow accumulation routine was then run to calculate the basin areas which were extracted for specific cross sections.

## 4.2 Lower Ok Tedi and Middle Fly

*HEC-6* requires inflow data at the upstream end of the system and at all significant tributaries. It is also possible to have water off-takes at selected locations. Data may be in the form of flow duration curves or a sequence of flows. In this exercise, a sequence of mean daily discharges has been used to allow for the effects of the droughts and wet periods that are known to have occurred since mining operations began.

The upstream end of the model has been set at Cross Section OKT30 on the Lower Ok Tedi near Iogi Village. Flow data based on the gauging station at Konkonda (TED25) are used for this location after subtracting inflows from the Ok Mart (Station MAR11). There are significant tributary inputs from:

- The Ok Mart near Konkonda.
- The Upper Fly at D'Albertis Junction.
- The Agu (may involve both input and offtake).

There are many other water inputs and off-takes on the Middle Fly associated with tributaries, tie channels, and off-channel lakes, but there is little information on these. We have therefore followed the approach taken in previous modeling exercises and assumed constant discharge down most of the Middle Fly. We have, however, added an inflow/outflow function for the Agu with the discharge rate changing with flow magnitude on the Middle Fly.

### 4.2.1 Data Issues

Daily flow data for modeling runs with *HEC-6* need to cover the following periods:

- A calibration/validation period covering 1985-1997 was used to select model parameters and to ensure that river behaviour under observed waste loads is reproduced accurately.
- A calibration/validation period covering 1997-2002 was used to check that the model can reproduce the effects of dredging.
- A synthetic flow dataset covering the periods 2002-2085 for modeling the new mine plans. While there are many techniques for generating these data, we have chosen to repeat the sequence of 1985-2002 daily flows to create it. We have also used a 13-year lead-in period based on 1985-1997 to allow model “settling in” prior to running the various mine plans and dredging scenarios.

Acquiring a long run of continuous daily flow data of reasonable quality proved challenging. There are data gaps, poorly documented datum shifts, drifting stage-discharge rating curves and other problems throughout the *OTML* hydrology database (e.g. Clews, 2001 and Pickup and Clews, 2001). There are also significant tidal effects

on the lower Middle Fly and a backwater problem on the Upper Fly (FLY05) that has greatly increased in severity since 1995. Creating the daily flow record involved the following steps:

- Production of a set of daily discharges from water level records and rating curves held in the *OTML HYDSYS* database<sup>2</sup>. Correction of rating curves or generation of new ones was required in some situations.
- Inspection of the discharge records and comparison with upstream or downstream stations to remove obvious anomalies.
- Generation of missing data using regressions (with appropriate time lags) with neighbouring gauging stations. Stations affected by backwater were avoided whenever possible in this exercise.
- Generation of flows on the Upper Fly at Kiunga (FLY05) using flow data from the Ok Tedi at Konkonda (TED25) and the Middle Fly at Kuambit (FLY10) to reduce errors due to backwater.
- Estimation of Agu inflows and outflows using flow differences between Kuambit (FLY10) and Obo (FLY15).

Data quality remains poor, even after all these corrections. For example, constant rating curves for specific periods have been used even though ratings may drift continuously. However, gauging data are usually not good enough to derive continuously shifting dynamic rating curves so there was no alternative to the current approach.

#### 4.2.2 Generation of Missing Data by Regression with Adjacent Stations

This was a complex operation since it was rare that data gaps for one station could be filled from the records of only one other since missing records of the additional station(s) sometimes covered the same period. Instead, an order of preference had to be set so that the best correlated stations with data covering missing periods on target stations were used. If this method of infilling proved impossible because of missing data, mean flow for the target station was used. The regression equations and order of preference are listed in Table 5. Data were rarely good enough to justify more than simple linear regression with appropriate time lags although a one curvilinear relationship was used.

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<sup>2</sup> Discharges were supplied by Gary Newton of ECOWISE Environmental Ltd and Patrick Simbina of OTML using the HYDSYS database (version of 13/02/2003). Flows for the Ok Tedi at Konkonda (TED25) were supplied on 01/04/2003 after reworking of station rating data.

| <b>TABLE 5: REGRESSION EQUATIONS AND ORDERS OF PREFERENCE USED FOR INFILLING OF DATA GAPS IN DAILY DISCHARGE RECORDS</b> |                                                                |                 |
|--------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------|-----------------|
| Station                                                                                                                  | Equation                                                       | Correlation (r) |
| Ok Mart<br>(MAR11)                                                                                                       | $Q = 27.12 + (TED20 \times 0.46)$                              | 0.794           |
|                                                                                                                          | $Q = 10.95 + (TED25 \times 0.19)$                              | 0.808           |
|                                                                                                                          | $Q = 206.7$ (Mean discharge)                                   |                 |
| Ok Tedi at<br>Ningerum<br>(TED20)                                                                                        | $Q = 140.63 + (TED15_{t-1} \times 0.64)$                       | 0.666           |
|                                                                                                                          | $Q = 37.79 + (TED15_{t-1} \times 0.72) + (MAR11 \times 0.58)$  | 0.858           |
|                                                                                                                          | $Q = 292.0$ (Mean discharge)                                   |                 |
| Ok Birim<br>(BIR05)                                                                                                      | $Q = 52.21 + (TED20 \times 0.40)$                              | 0.724           |
|                                                                                                                          | $Q = 201.1$ (Mean discharge)                                   |                 |
| Ok Tedi at<br>Konkonda<br>(TED25)                                                                                        | $Q = 131.7 + (TED20 + MAR11 + BIR05) \times 0.89$              | 0.883           |
|                                                                                                                          | $Q = 153.9 + (TED20 \times 1.93)$                              | 0.835           |
|                                                                                                                          | $Q = 286.1 + (FLY10 \times 0.26)$                              | 0.808           |
|                                                                                                                          | $Q = 781.0$ (Mean discharge)                                   |                 |
| Fly at Kuambit<br>(FLY10)                                                                                                | $Q = 319.6 + (TED25 \times 2.726) + (TED25^2 \times 0.000503)$ | 0.828           |

#### 4.2.3 Missing and Inaccurate Records for the Upper Fly at Kiunga (FLY05)

FLY05 has a long record but the ratings are of poor quality and unstable. The station is badly affected by backwater from the Middle Fly, especially after 1993. There is a close correlation with discharge at station FLY10 (Kuambit) on the Middle Fly before 1993 but this may be partly due to backwater. FLY10 also has an unstable rating due to deposition from about 1989 onwards.

Discharges at FLY05 show substantial drift through time, particularly after 1995 (Fig. 6). Discharges at FLY10 show no apparent drift with time (Fig. 5) suggesting that the rating curves are more accurate than those of FLY05. There is a close correlation between discharges on both stations until late 1993 ( $r = 0.92$ ) but after that, the relationship breaks down (Fig. 7).

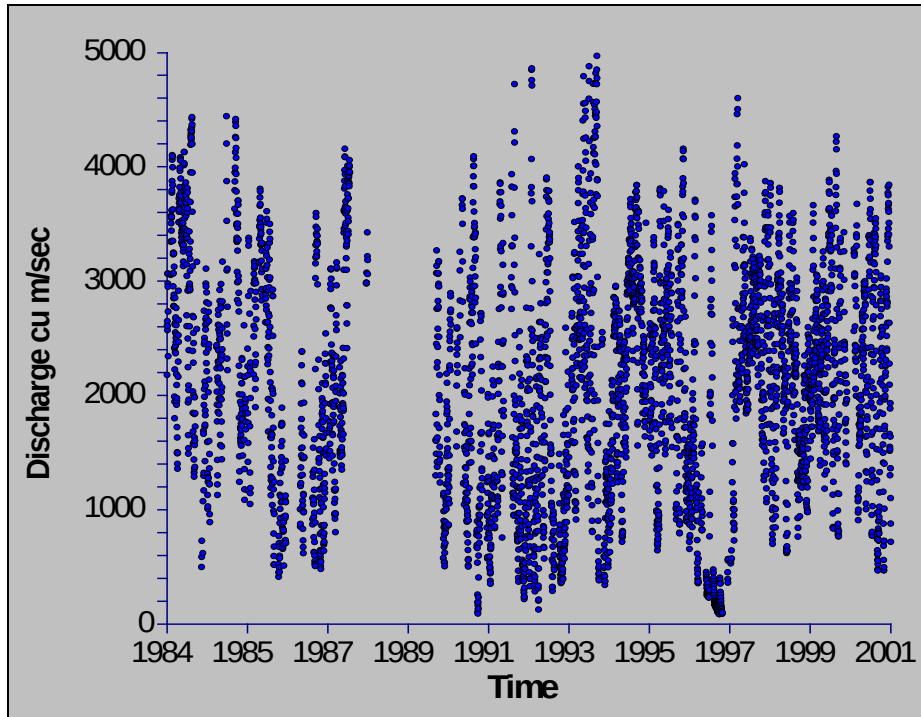


Figure 5: Discharge v Time on the Middle Fly at Kuambit (FLY10).

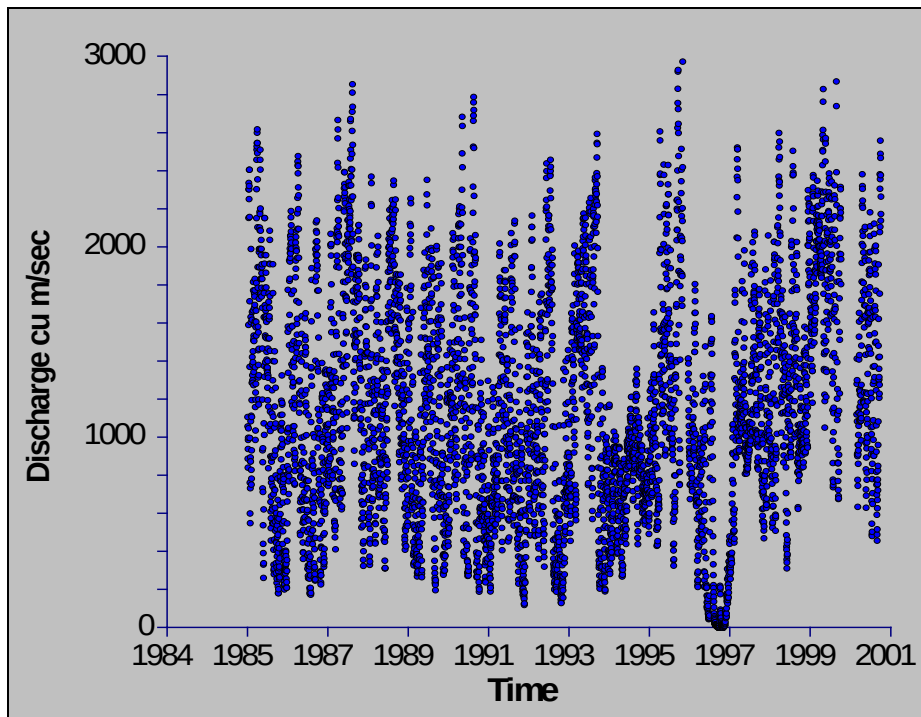


Figure 6: Discharge v Time on the Upper Fly at Kiunga (FLY05). The drift after 1993 may result from backwater effects due to rising bed levels on the Middle Fly.

The problems with FLY05 data present difficulties for modeling. For example, there are many cases where the sum of discharges on the Upper Fly and Lower Ok Tedi exceed flows at Kuambit (Fig. 7), sometimes by more than 1000 m<sup>3</sup>/sec. This is largely due to backwater effects on the Upper Fly but drifting ratings at Konkonda and Kuambit exacerbate the problem.

Attempts to re-rate the FLY05 from flows at Kuambit and Konkonda using statistical and water surface profile models were unsuccessful. The Upper Fly discharge dataset was eventually derived by subtracting TED25 (Konkonda) flows from those at FLY10 (Kuambit). This removes inconsistencies such as negative flows for the Upper Fly.

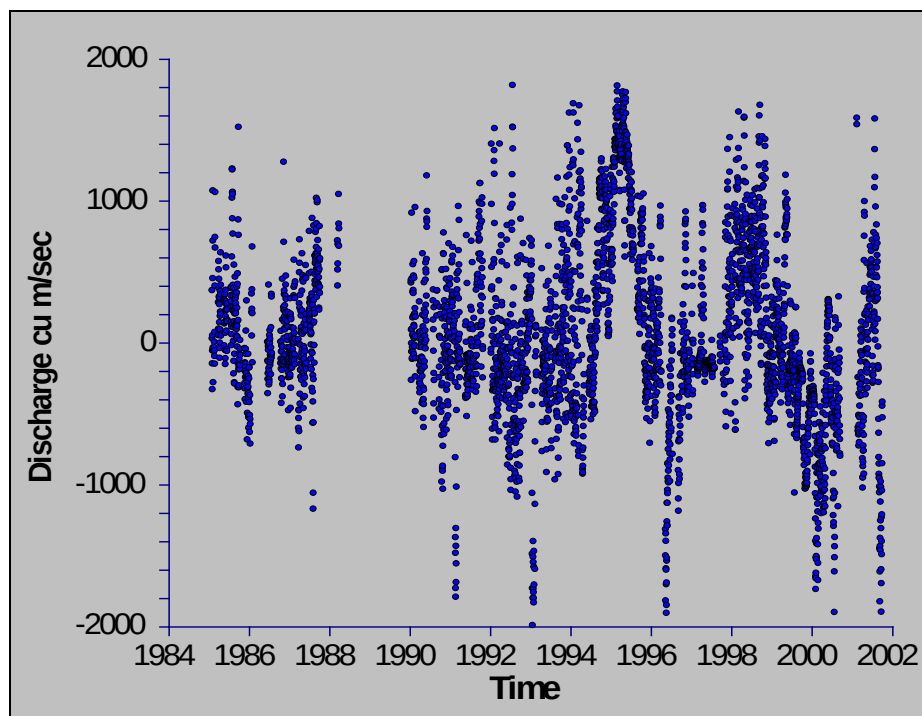


**Figure 7: Deviations from the relationship between discharge on FLY05 and FLY10. The regression equation linking the two sites was fitted for the 1984-1993 period before major drift became apparent. Prior to 1993 the pattern of variation is random as expected. After 1993, systematic variation with time occurs, indicating a complex pattern of rating curve drift, possibly on both stations.**

#### 4.2.4 Flows on the Agu and other Middle Fly Tributaries

Middle Fly tributaries may add or remove water from the main river channel depending on flood height and the amount of water in off channel storages. Insufficient data are available to build these processes into the sediment transport model. On average, flow seems to increase downstream with mean discharges of 2089 m<sup>3</sup>/sec at Kuambit, 2341 m<sup>3</sup>/sec at Manda and 2485 m<sup>3</sup>/sec at Obo. However, the lower river discharge rating curves are of poor quality and Obo is affected by tidal variation. Errors of 20-30% in mean flow would not be surprising.

Comparison of flows between Kuambit and Obo shows that there is little correlation and a lag of about 11 days. A plot of the difference in discharge with lag accounted for shows that it varies with the amount of flow and changes from negative to positive as flow increases. This is consistent with inflow from the floodplain when the Fly is low and outflow to the floodplain from the Fly at higher stages (Fig. 8). The equation describing this behaviour is:

$$(\text{FLY15} - \text{FLY10}) = 1608 - 0.197 \cdot \text{FLY10} + 0.00014 \cdot \text{FLY10}^2$$

where FLY15 and FLY10 refer to discharges for those stations in m<sup>3</sup>/sec. This equation may be used to provide a very rough estimate of lower river inflows and outflows.

In practice, it proved difficult to apply the equation without knowledge of tributary catchment areas and off-channel waterbody volumes. We have only modeled contributions to/from the Agu and have assumed that these are 50% of the calculated value.

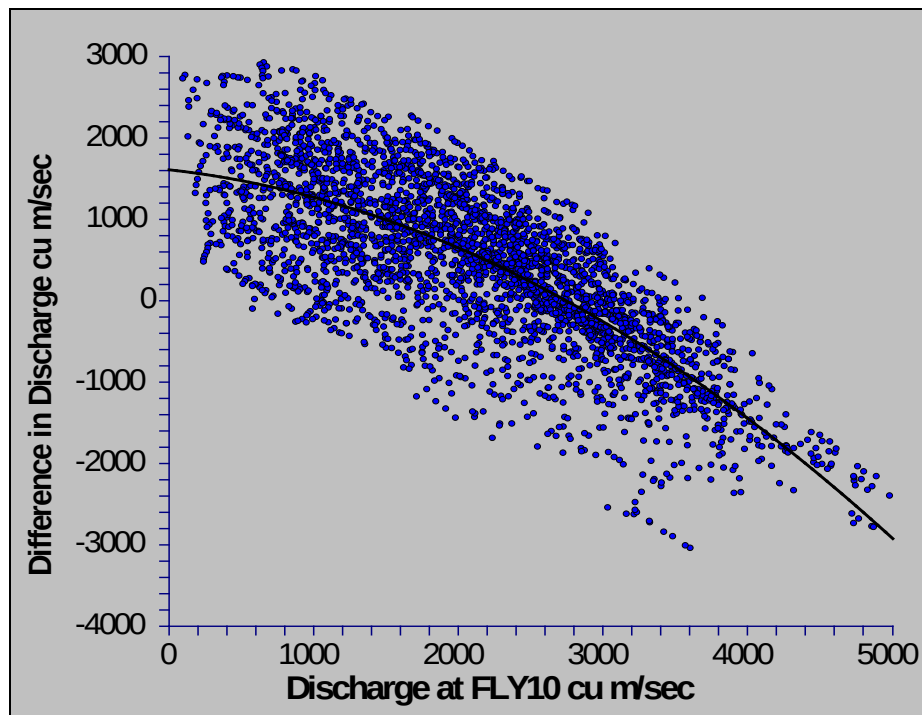


**Figure 8: Difference in discharge between Obo (FLY15) and Kuambit (FLY10) compared with discharge at Kuambit.**

## 7. HEC-6 MODEL CALIBRATION/VALIDATION

### 7.1 Model Setup

*HEC-6* represents a river system by a main stem plus a set of tributaries. Water and sediment flow in at the upper end of the model with outflow at the lower end. Any difference between sediment inflow and outflow is accounted for by erosion or deposition. Inflow and outflow may also occur at tributary junctions. The layout used in this study is shown in Fig. 25

*Inflow of mine waste* at the upper end of the system was calculated using sediment rating curves derived in *OkGrav6*. However, *OkGrav6* does not allow for the sand deposition that has occurred in the Konkonda-Ningerum reach which may include 15-30 Mt of material<sup>3</sup>. This was accounted for by extending *HEC-6* upstream to overlap part of the lowest reach modeled in *OkGrav6*. *HEC-6* then produces about 25 Mt of sand deposition upstream of Konkonda.

*Inflows of natural load* must also be provided for the main stem and the various tributaries.

While various estimates have been made of the natural rate of sediment delivery to the Lower Ok Tedi and from the Upper Fly (Higgins, Pickup and Cloke, 1986), amounts vary substantially (e.g. 2-6 Mt/year). In the absence of anything better, sediment inputs from the Ok Mart and the Upper Fly were taken from GHD (1999). However, a 4 km reach of the Upper Fly was used as a buffer zone between Kuambit and the Upper Fly sediment input point in *HEC-6* to allow for backwater.

The natural load of the Ok Tedi was estimated during model “zeroing” runs (see below) in which natural sediment input was gradually increased to the point where there was little or no net scour in the 1984 reconstructed profile over a 13 year period. Sediment load particle size data came from riverbed samples collected before mine construction began (Pickup, Higgins and Warner, 1979).

*Particle size distributions of river bed material* were obtained from *OTML* sediment sampling programs as summarized in GHD (1999). *Particle size distributions for tributary sediment loads* came from the same source. Particle sizes for bed material load delivered to the upper end of the model were calculated from sampling of dredged material supplied by Barrie Bolton of *OTML*.

*Channel cross sections* for the Lower Ok Tedi and Middle Fly came from survey data provided by A. R. Marshall. The Dec 1997/Mar 1998 survey was used as a baseline while the Mar 2002 provided an endpoint for the model calibration/validation runs. The 1997 survey was also used to reconstruct the pre-mining river geometry.

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<sup>3</sup> This figure is only a crude estimate. It assumes a bulk density of 1.5 and average deposition of 1-2 m spread over a reach 35 km long and 300 m wide. Depth of deposition based on estimates by Barrie Bolton from auguring. Width and reach length estimated from Landsat Thematic Mapper imagery.

Flow data for modeling may be in the form of a flow duration curve or a sequence of discharges. All model runs described in this report used a sequence of observed daily discharges for 1985-2002. Discharges for future periods were generated by repeating this record.

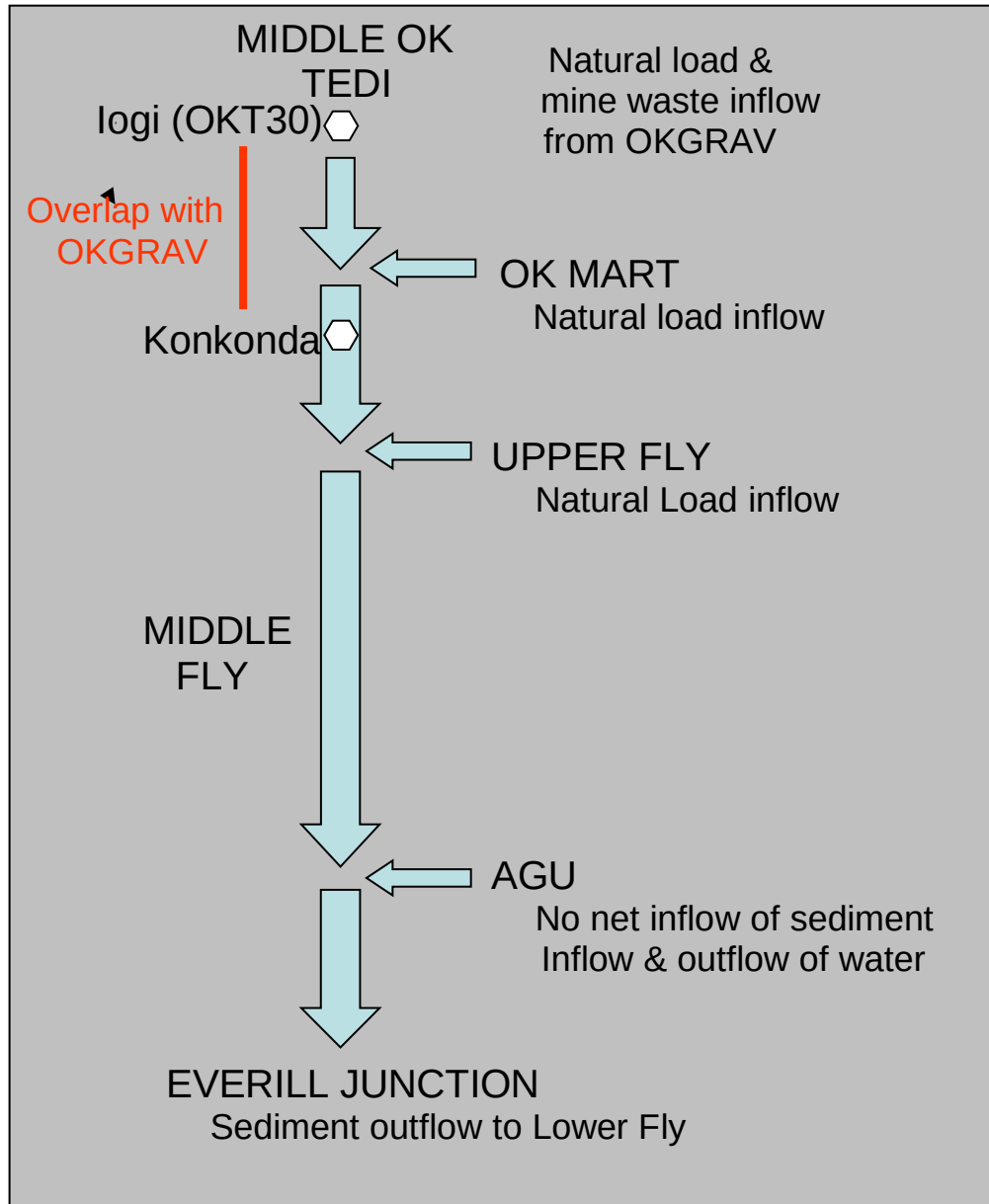


**Figure 25: HEC-6 Model layout showing main inflows and outflows.**

## 7.2 Approach to Model Calibration/Validation

*HEC-6* offers a choice of sediment transport equations for clay, silt, sand and gravel. There are also different methods for dealing with erosion and deposition of material in the silt and clay fractions. Most other parameters can be directly measured or calculated from stream gauging data and bed material samples.

Once transport equations and other parameters have been selected, the model should be validated from observed data where possible. On the Ok Tedi and Middle Fly, there are enough data to allow the following tests of model accuracy:

- A check on whether estimated roughness coefficients and measured channel cross sections reproduce water levels with sufficient accuracy to allow prediction of flood levels. This test was carried out by Pickup (2001) but results are reproduced here for completeness.
- Model “zeroing” using a crude reconstruction of river bed levels at the end of 1984 from a small number of long-term cross sections including Konkonda (TED25), Kuambit (FLY10), Wygerin (FLY11) and Obo (FLY15). The aim of model zeroing is to show that the river does not experience significant erosion or deposition over time with estimated natural sediment loads. It may also be used to estimate natural sediment loads where they are uncertain.
- A test of whether the model can reproduce 1985-1997 deposition on the Lower Ok Tedi and Middle Fly using the reconstruction of 1984 river bed levels. This exercise was undertaken by GHD (1999) using *HEC-6* with Yang’s sand transport equation. We have followed a similar approach but have used slightly different input data.
- A test of whether *HEC-6* can reproduce the complex pattern of erosion and deposition that developed after the introduction of dredging at Bige on the Ok Tedi in 1998. Since then, more than 120 cross sections have been surveyed to a very high standard up to twice a year along the Lower Ok Tedi and Middle Fly. The 1997-2002 period included a drought and a very wet period, both of which affected river behaviour and create a challenging test of the model.

The second and third two tests of model accuracy are not particularly rigorous because only eight cross sections can be used to estimate changes over more than 400 km of river. The fourth test provides a good indication of what level of accuracy the model can achieve but only covers a short period.

## 7.3 Accuracy of Predicted Water Levels

The roughness coefficient is a critical value in determining flow velocity and water surface elevation for a particular discharge. Usually it has to be estimated but it may be derived by comparing calculated water surface profiles with directly measured values. Initial measurements at Kuambit by *Pickup, Higgins and Warner* (1979) produced a value of about 0.035. However, in December, 2000, A. R. Marshall was able to survey a profile down the

Middle Fly during a period of fairly steady flow. Pickup (2001) was able to reproduce this profile very closely using a roughness coefficient of 0.032 (Fig. 26) and this was adopted for the runs with *HEC-6*.

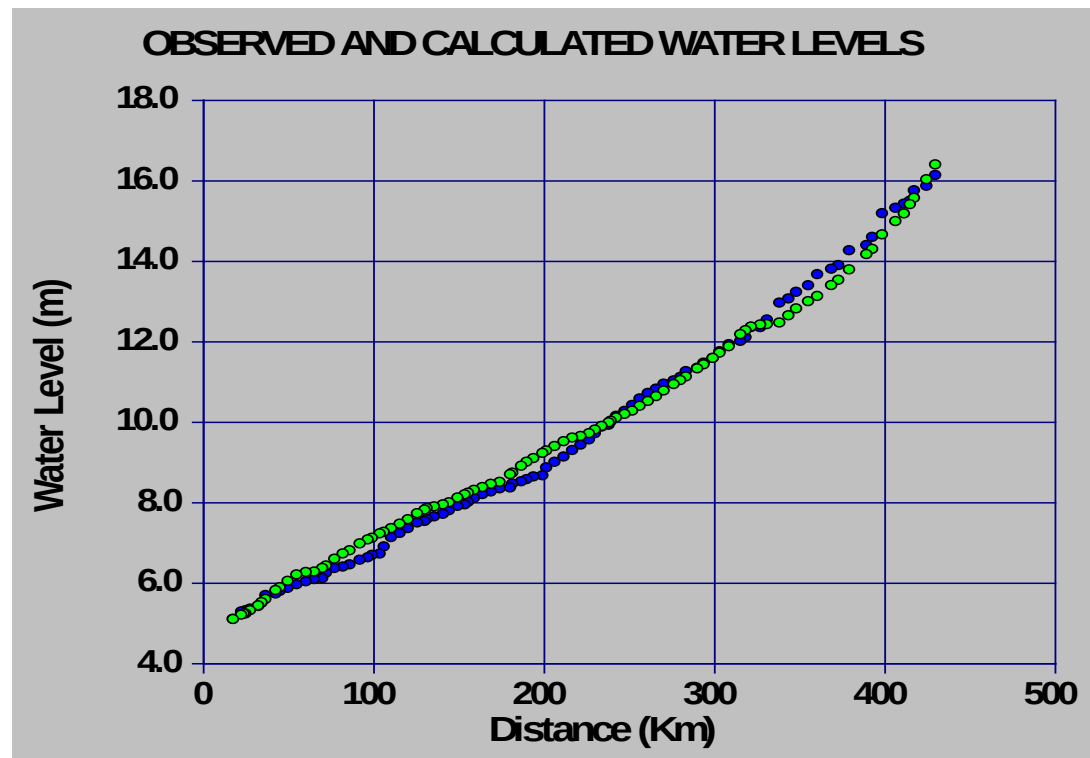


**Figure 26: Observed (blue) and modeled (green) water levels between Everill Junction and D'Albertis Junction, December 2000.**

#### **7.4 Reconstruction of 1984 (Pre-Mining) Riverbed Levels**

While surveys of the Fly for navigation purposes go back as far as 1978, they have little value for reconstruction of the pre-mining channel because soundings do not cover whole cross sections and depths have not been corrected to an absolute datum. This leaves only nine cross sections that have been surveyed either since before mining started or before major deposition began to appear in the river system. Most of these are shown in Figs. 27a and 27b and, together with A. R. Marshall's first detailed cross section survey, form the basis of the riverbed level reconstruction.

The Ok Tedi at Konkonda shows about 7m of deposition at Konkonda. Drilling in the reach upstream near Bige and Iogi indicates sand down to about 8m and 6m respectively (Klohn Crippen, 1996). However, more recent auguring shows sand thickness of 4-6m before hitting gravel (Bolton, pers. comm.). Pickup, Higgins and Warner (1979) report a gravel-sand mix in this area prior to mining so an average depth of deposition of 6m seems reasonable. The amount of deposition probably decreases downstream, declining to about 5m close to D'Albertis Junction.

On the Middle Fly, changes in average bed level over time show about 4m of accumulation between Kuambit and Niukamba and about 3m at Wygerin. Further

downstream, change is less apparent, hence the regression lines on the graphs. The limited data suggest about 0.5m of deposition at Mabaduam and Manda between 1985 and 1997. Further downstream, at Bosset and Obo (not shown), there is no net change in bed level for this period.

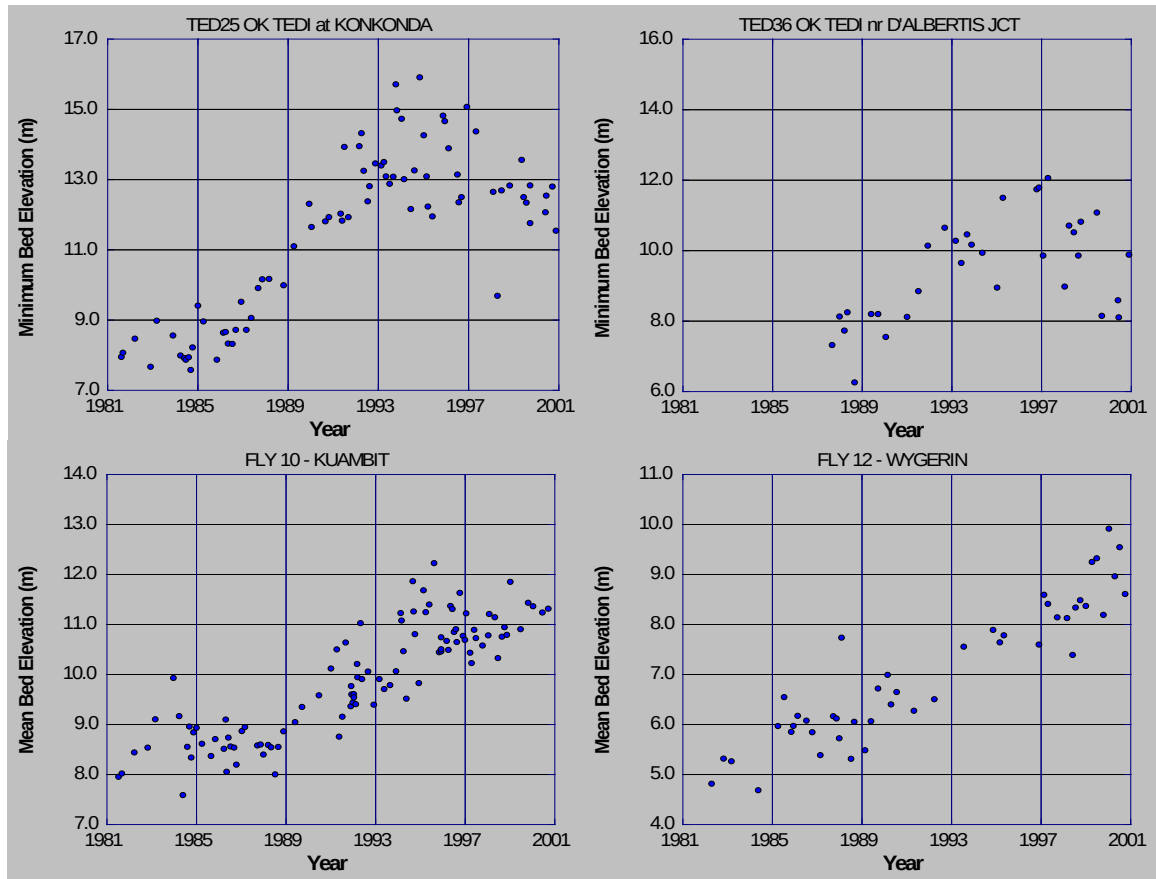


**Figure 27a: Minimum Bed Levels on the Fly & Lower Ok Tedi.**

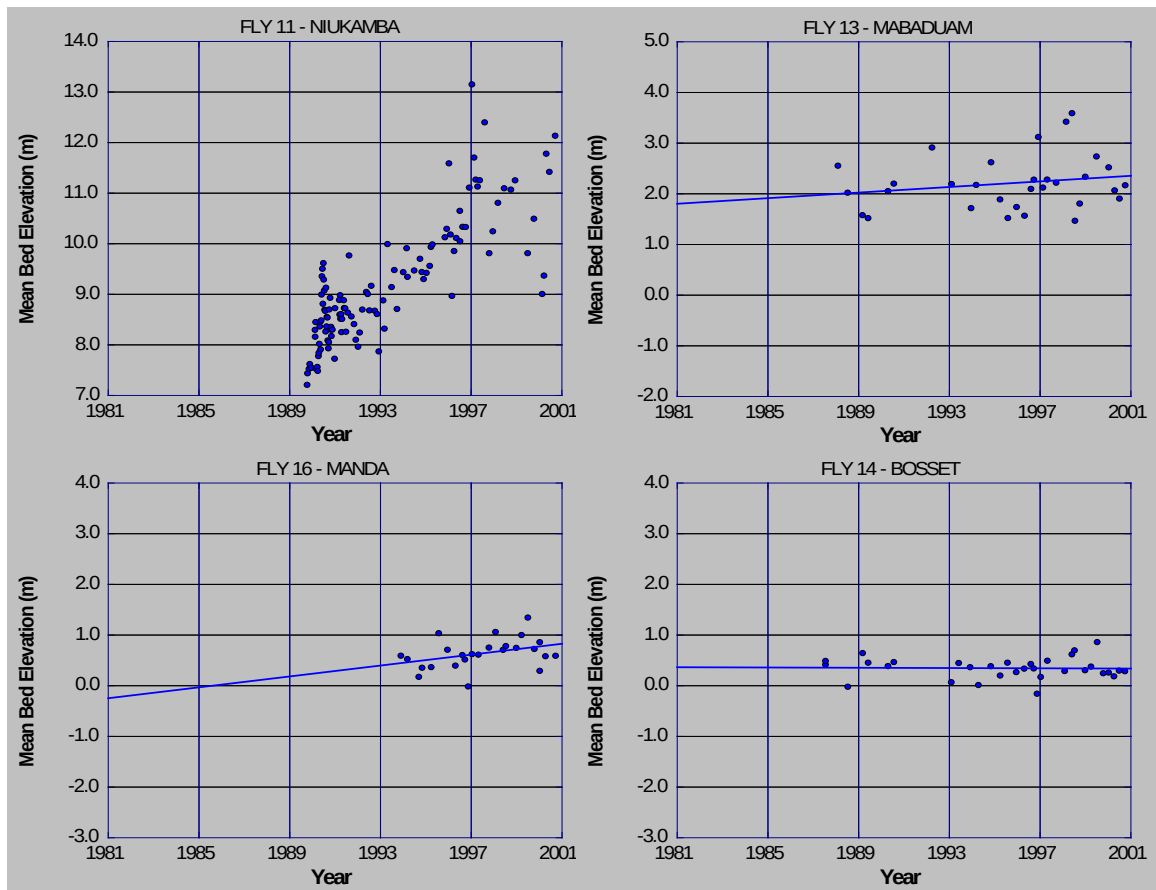


**Figure 27b: Change in mean bed elevation over time for long term Fly River cross sections.**

Based on these data, the late 1984 bed has been reconstructed by subtracting the following values from Marshall's Dec. 1997 Fly River and May 1998 Ok Tedi cross section surveys:

| RIVER REACH                | DISTANCE FROM EVERILL JCT | BED LEVEL CHANGE        |
|----------------------------|---------------------------|-------------------------|
| Iogi to Konkonda           | 479.4 – 510.0 km          | Subtract 6.0m           |
| Konkonda to D'Albertis Jct | 430.5 – 479.4 km          | Subtract wedge 6.0-4.0m |
| D'Albertis Jct to Kuambit  | 424.0 - 430.5 km          | Subtract 4.0m           |
| Kuambit to Wygerin         | 356.0 – 424.0 km          | Subtract 4.0m-3.0m      |
| Wygerin to Mabaduam        | 289.7 – 356.0 km          | Subtract wedge 3.0-0.5m |
| Mabaduam to Manda          | 189.5 – 289.7 km          | Subtract 0.5m           |
| Manda to Bosset            | 137.0 - 189.5 km          | Subtract wedge 0.5-0.0m |

## 7.5 Calibration of Transport Rates

None of the sand transport equations in *HEC-6* produced transport rates great enough to move sand down into the Middle Fly in sufficient quantity to reproduce observed deposition rates. Instead, deposited material built up in the Lower Ok Tedi. The greatest concentration of deposition was at the upper end of the reach between Iogi and Konkonda and produced increases in riverbed and water levels far higher than those observed in the reach. This behaviour can also be seen in GHD's (1999) modeling runs with *HEC-6*.

Underestimation of transport rates is common when using sediment transport equations in heavily laden rivers. For example, Cui (pers. comm.) reports similar problems when attempting to calibrate the *OKFLY* model and was forced to apply a correction factor to calculated rates.

It is possible to calibrate *HEC-6* by adding user-derived sediment discharge rating curves for each particle size range used in the model. However, insufficient data are available to develop suitable empirical curves for the Fly. User-derived rating curves can also generate run-time errors in long simulations which cannot be diagnosed without model source code. An alternative approach to calibrating *HEC-6* is to rescale the time interval used in the model which, in effect, increases the transport rates and moves sediment down the system more quickly. Sediment input rates must also be rescaled so that the model receives the correct volume of sediment over time. This approach proved effective and the model was run using the Yang transport equation with a rescaling factor of 8.

## 7.6 Calibration Results

Model calibration runs show close agreement between modeled and observed river behaviour. Comments and conclusions on changes in maximum bed level and water surface elevation for each calibration/validation run profiles are included in the text boxes below. The relevant bed and water surface elevation graphs follow each text box. Water surface elevations were calculated for discharges of 600 m<sup>3</sup>/sec at Konkonda, 1174 m<sup>3</sup>/sec at Kiunga, and an inflow of 195 m<sup>3</sup>/sec from the Agu.

### **MODEL ZEROING RUNS – BED AND WATER SURFACE ELEVATIONS FIGS. 28 & 29.**

The aim of these runs was to check that the river is close to being stable<sup>4</sup> under estimated natural sediment loads. There should be little change between the 1984 reconstructed bed profile and the 1997 bed after running the model without mine inputs. The water surface profile should also remain unchanged.

The results are very good by river modeling standards. However, there is a small amount of erosion at the upper end of the river system and some infilling of holes. These holes are often associated with meander bends and their behaviour would not be captured by a one-dimensional model such as *HEC-6*. Aggregate or average behaviour is therefore of more interest.

The water surface profile shows very little change between the end of 1984 and 1997 as expected in a successful model zeroing run. In the upper section of the river, it lies well below the water surface profile calculated for the river in 1997 (labeled as “1997 Observed” on the graph) after deposition of tailings and waste rock. The differences between the 1984 and 1997 (no mine) water surface are well within measurement error.

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<sup>4</sup> While, the Lower Ok Tedi and Middle Fly may be treated as a stable system in the short term, there is strong evidence that long term deposition occurs even under natural sediment loads. Estimated natural deposition rates are much less than mine-induced deposition. However natural deposition may become significant in the 75 year model runs described later in this report. A more detailed discussion of this issue, including how we have separated mining-induced effects from natural deposition, is presented in Section 8.1.

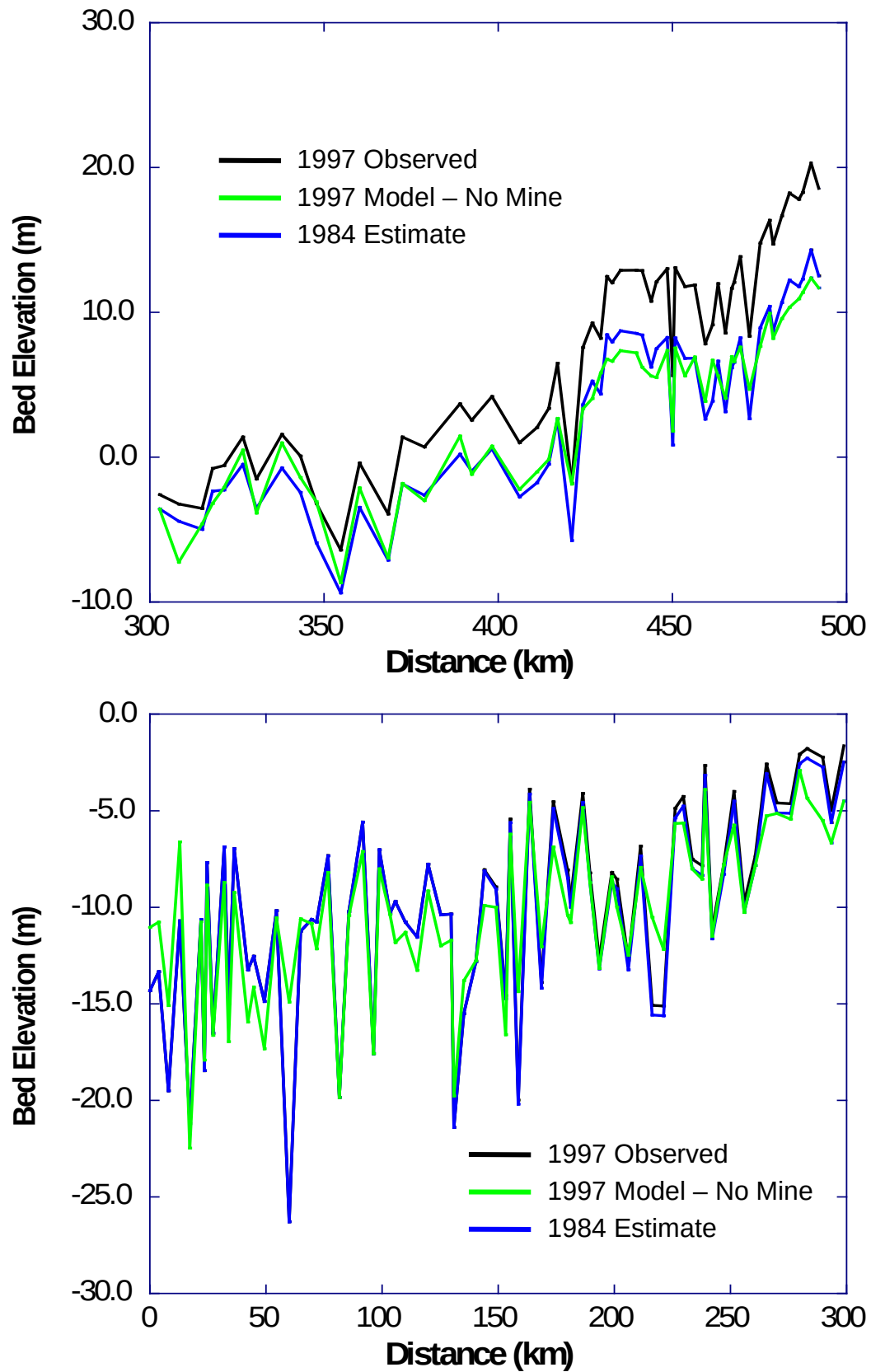


**Figure 28: Bed levels for model zeroing runs. 1997 levels included for comparison.**

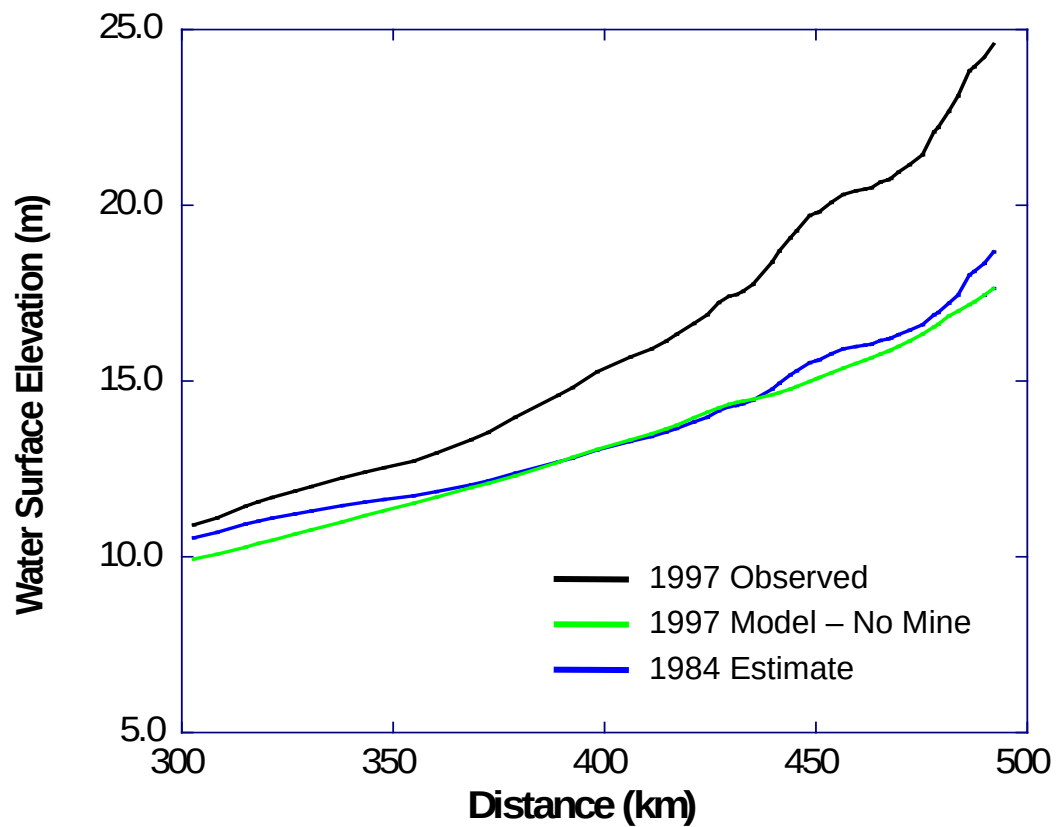
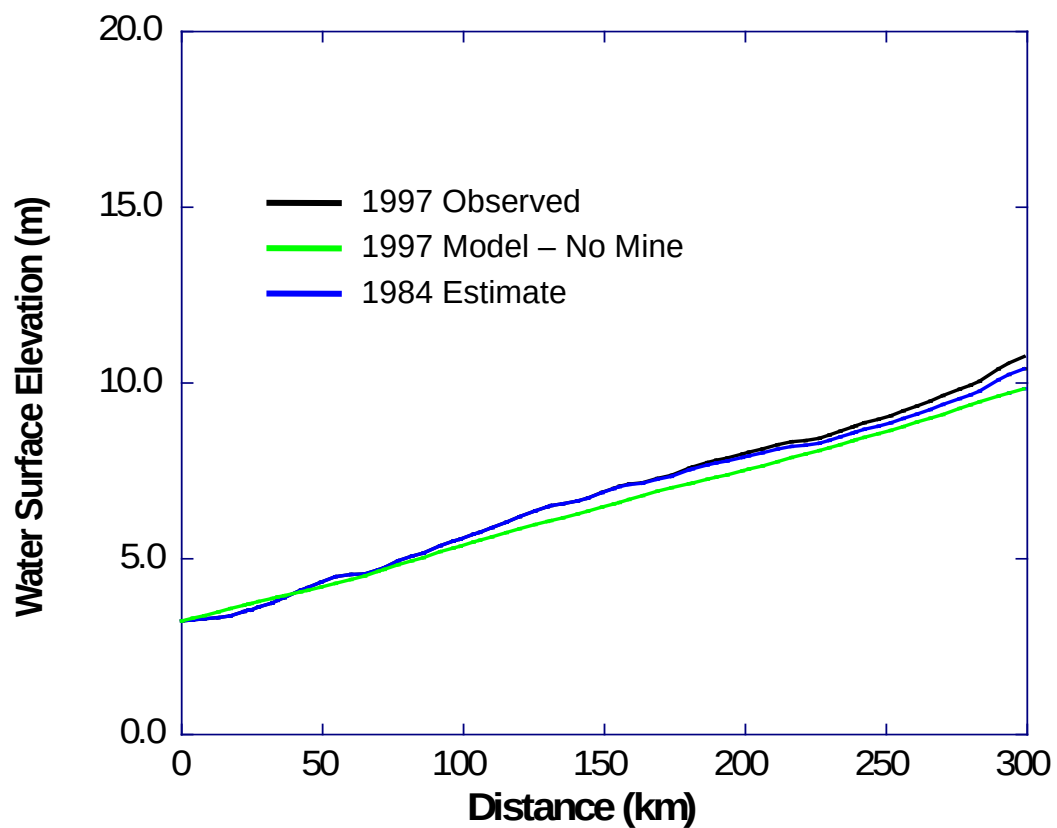


Figure 29: Water levels for model zeroing runs.

**1984-1997 MODEL RUNS WITH NATURAL LOAD, TAILINGS AND WASTE  
ROCK INPUT – BED AND WATER SURFACE ELEVATIONS  
FIGS. 30 & 31.**

These runs were used to calibrate *HEC-6* and to show that it could reproduce river behaviour once mine waste was added to the sediment input stream at the upper end of the model. There are two major sources of uncertainty in these model runs. Firstly, the 1984 bed reconstruction may contain substantial errors. Secondly, output of sand and silt from *OkGrav6* may not always be accurate since there are not enough data to calibrate sand storage and transport at the downstream end of the model. In spite of these uncertainties, *HEC-6* should still reproduce the general pattern of deposition in the river. The water surface profile should also change to reflect rising bed levels.

Once again, the results are very good by river modeling standards. Rising bed levels upstream of the 450 km point are closely reproduced. The model is slightly less successful on the Lower Ok Tedi and 1997 bed levels close to D'Albertis Junction (429 km) are underestimated by about 1 m. There is also a tendency to underestimate 1997 bed levels on the upper part of the Middle Fly between 300 and 410 km but the average is less than 0.5 m. Given uncertainties in the input data and cross section spacing, this is an acceptable degree of discrepancy.

Bed level change in the 0-300 km reach (lower Middle Fly) largely consists of profile smoothing as holes are filled in and some constrictions are reduced by local scour. There is also a build up of material close to the lower end of the model where the backwater effect from the Strickland is greatest. While these results seem reasonable, available data are not good enough for a convincing test of model performance. Little is known about tributary inflows and outflows in this reach and data from only three cross sections were available for the 1984 river reconstruction. Overall, however, results seem reasonable.

The pattern of observed and modeled changes in the water surface profile is broadly similar. However, there are some differences in particular reaches. The modeled water surface profile above 450 km is very close to the profile calculated from 1997 cross sections (labeled as 1997 Observed). In the 300-450 km reach, it is about 1 m too low. A difference of this magnitude over 150 km is not great given that bed levels have risen by about 4 m. Below 300 km, the profiles are very similar.

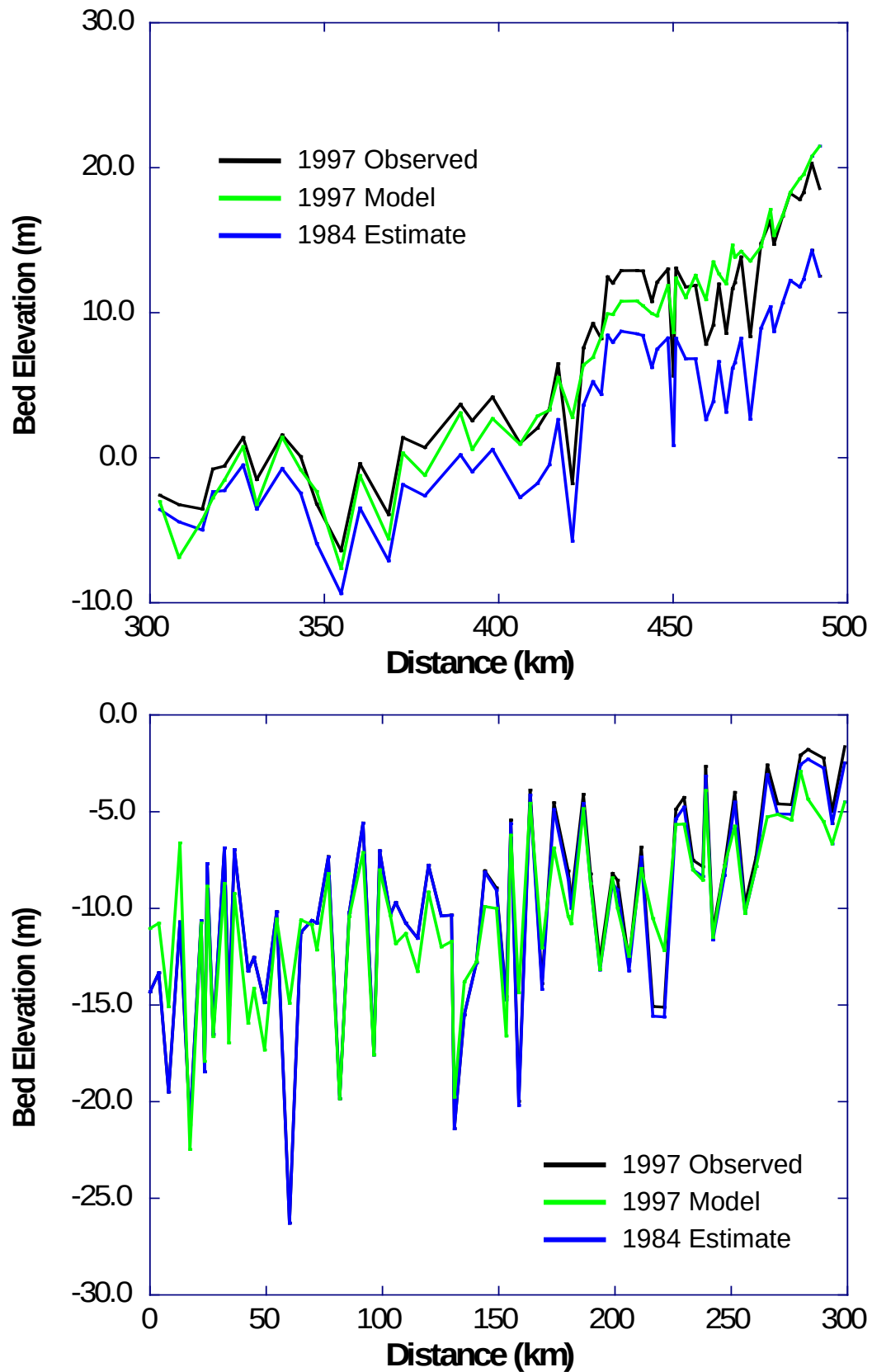


Figure 30: 1984-1997 bed levels with waste rock and tailings input.

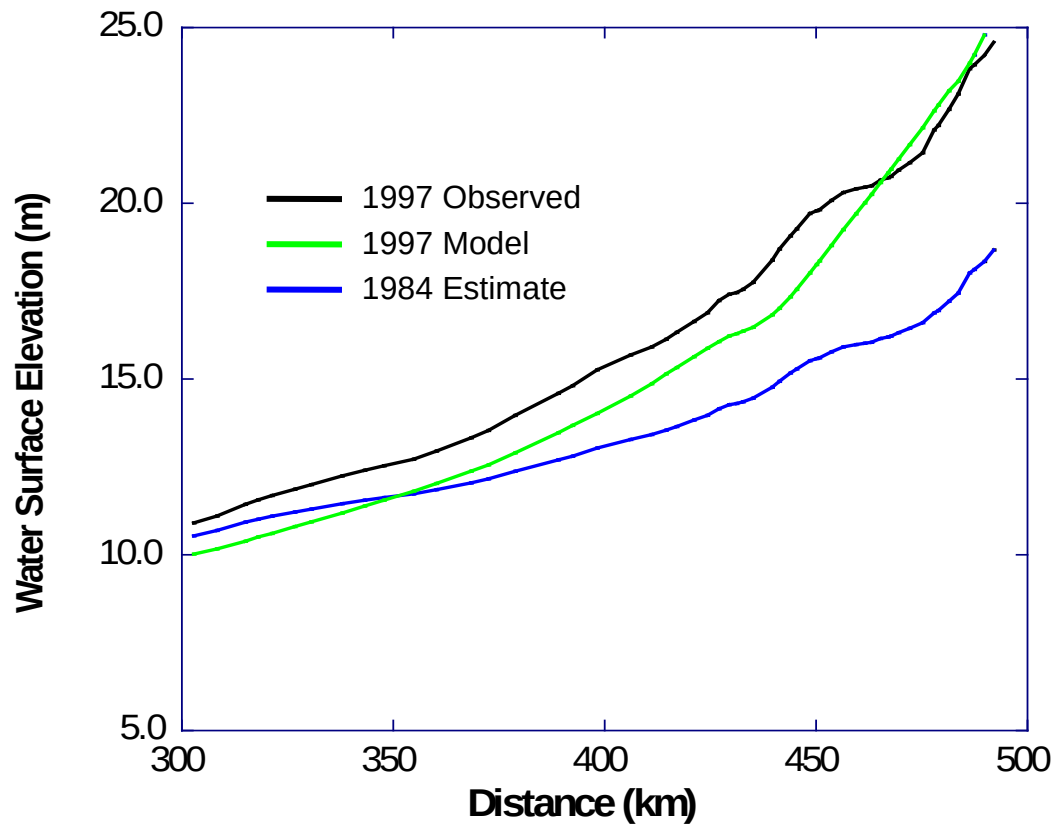
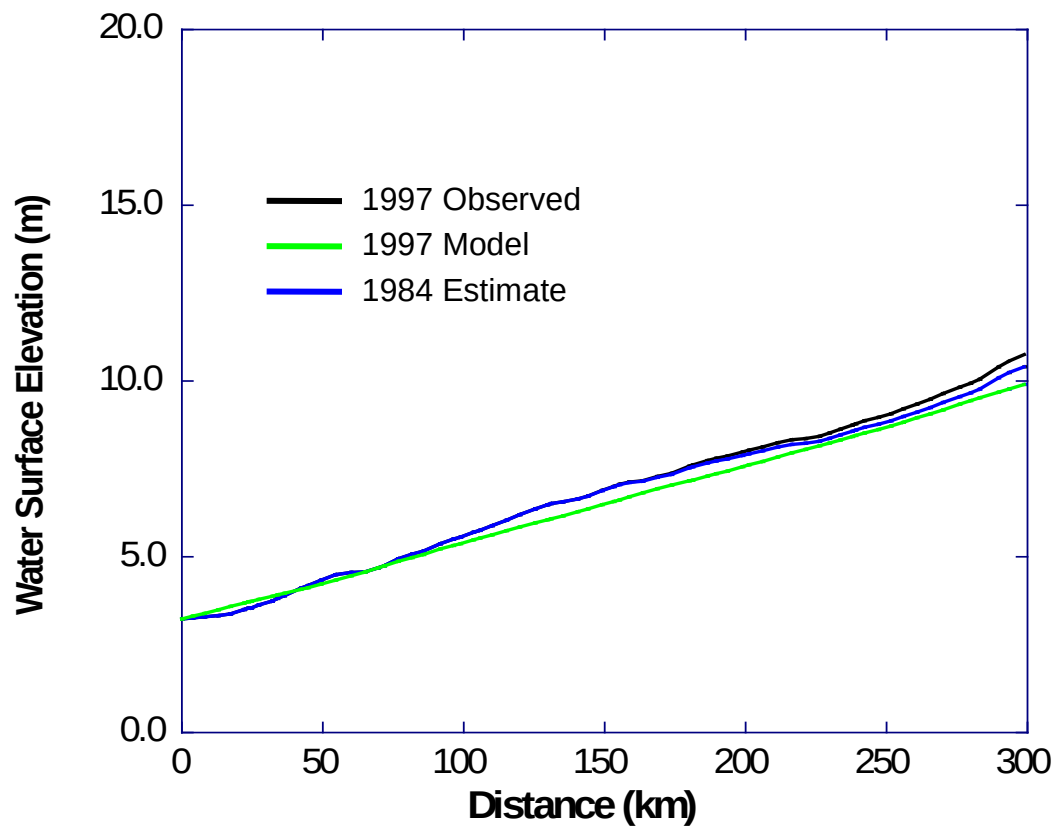


Figure 31: 1984-1997 water levels with waste rock and tailings input.

**MODEL RUNS FOR THE 1998-2002 DREDGING PERIOD – BED AND  
WATER SURFACE ELEVATIONS  
FIGS. 32 & 33.**

These runs were carried out to test how well the model reproduces the effects of dredging. They also show how well the calibrated model works for a different time period and therefore provide a validation of model performance.

The model was run from 1985-2002 rather than starting with the 1997/1998 survey cross sections. This is a better test of long term performance but it does not allow for changes in water surface slope resulting from several meander cutoffs on the Middle Fly. Also, 1998-2002 was a challenging period for modeling as it includes both very wet and dry periods.

The pattern of bed level change in the Lower Ok Tedi and upper reaches of the Middle Fly (300-500 km) is reproduced fairly well but the impact of dredging may be slightly underestimated on the Ok Tedi above 450 km. However, Marshall's survey data for channel centerline bed levels are closer to the model results than the observed minimum bed levels which are plotted here. The differences in the 300-350 km section are probably more due to meander cutoff effects than to sediment load reduction by dredging.

Below the 300 km point, increases in observed minimum bed elevations were greater than increases in modeled values in many reaches. However, most of the differences are less than 2 m. This effect was partly offset by infilling of deeper sections in the modeling results. Most of the changes lie within the range of variability observed in Marshall's cross section surveys between 1997 and 2002.

Water surface elevation results are better than the bed level simulations. The pattern of change between 1998 and 2002 is almost identical and by 2002, the profiles are almost identical over the whole of the river. This is a very good result given that we are attempting to predict changes in elevation of only a few metres over almost 500 km of river.

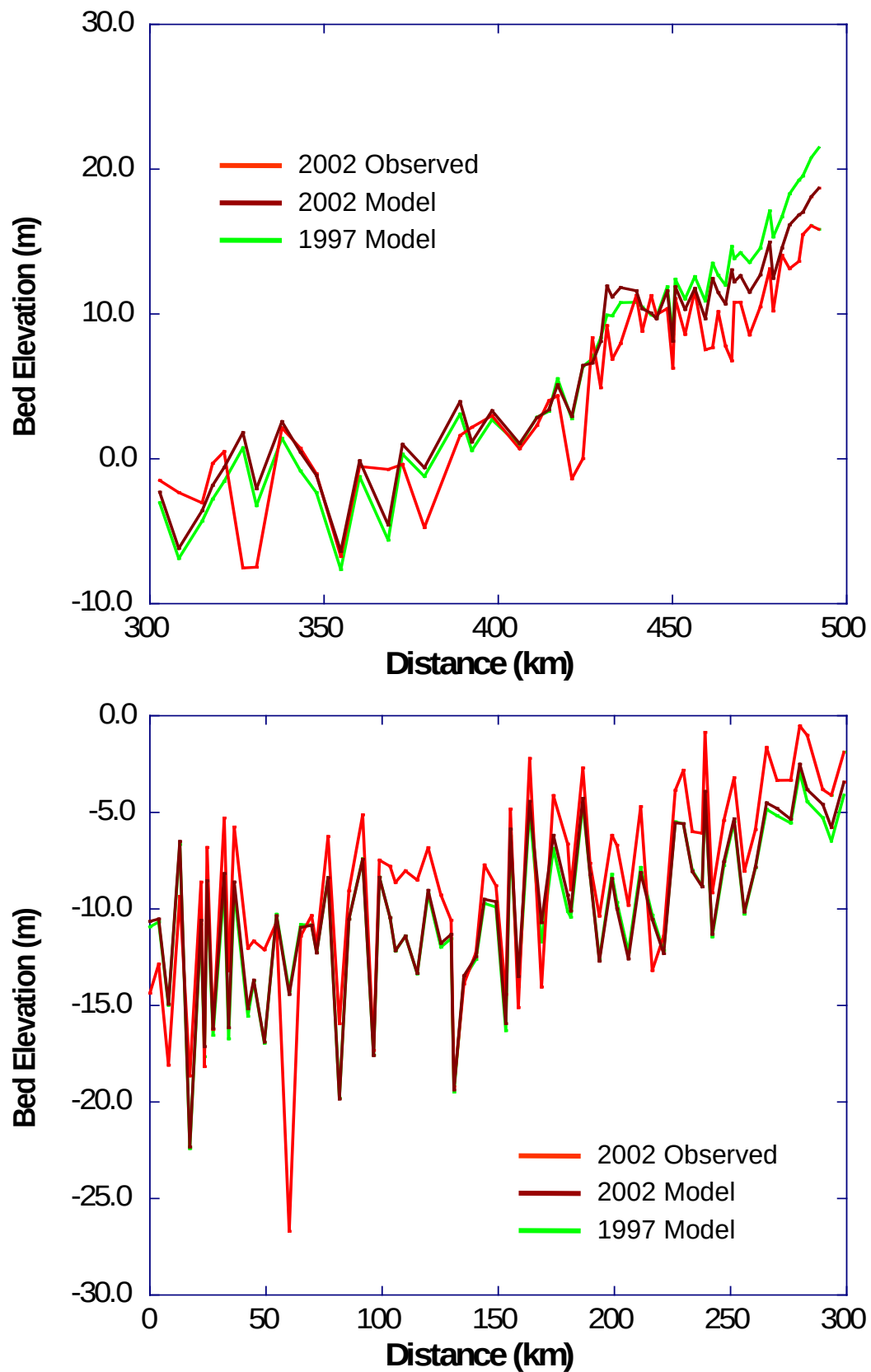


Figure 32: 1997-2002 bed levels with mine inputs and dredging effects included.

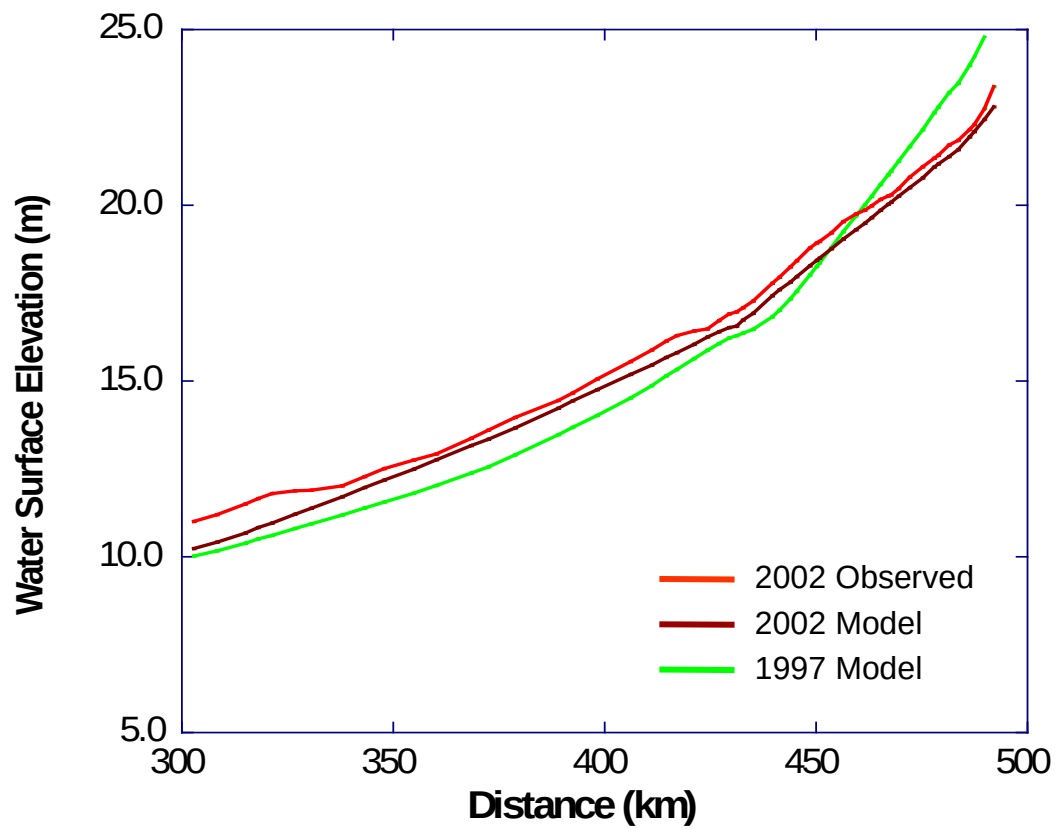
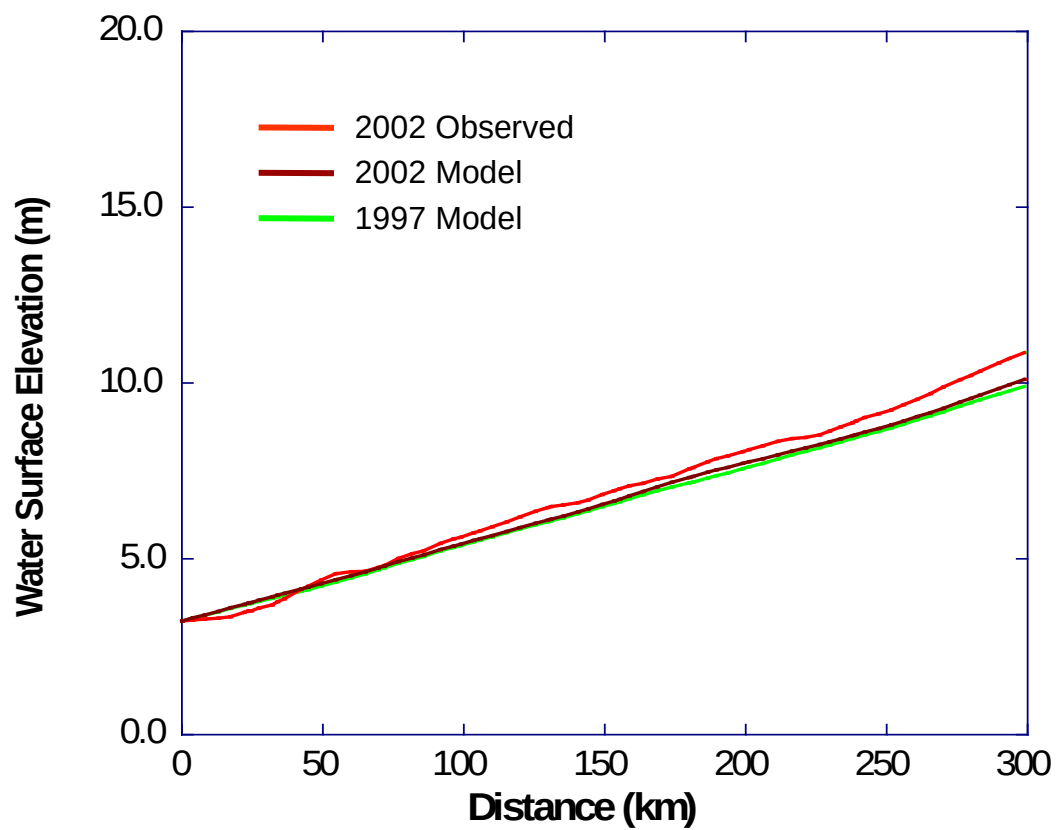


Figure 33: 1997-2002 water surfaces with mine inputs and dredging effects.

## 8. HEC-6 MODEL RESULTS

### 8.1 Introduction

*HEC-6* was run for each mine plan and dredging scenario over a 75 year period from the start of mining. A 13 year lead-in period with natural sediment load only was used to allow the model to “settle-in” and reduce the effect of initial assumptions and boundary conditions. Flows for the lead-in period were taken from the 1984-1997 daily discharge record. The model was also run for the 75 year period with only natural sediment inputs so that these results could be subtracted from the various mine plan and dredging scenarios to estimate the net effect of mining. Results are presented for *natural sediment inputs*, *natural plus mine-derived loads*, and *mine-derived loads only*.

Flows for the mining and post-mining period were generated by using 1985-2002 data and then repeating the 1984-2002 flows to make up a 75-year synthetic flow record. This method ensures that several *El Nino* and *La Nina* events are included and there are both wet periods and droughts. Mine-related sediment inputs were derived from *OkGrav6*. A natural load of 3 Mt/year of sand and 3 Mt/year of silt was assumed for the Ok Tedi while input from the Upper Fly was set at 1.9 Mt/year of sand and 2.4 Mt/year of silt. These values came from model zeroing runs, previous model studies with *OkFly* (Cui, 2000) and with *HEC-6* (GHD, 1999), and yielded no net deposition over the model calibration period.

Model results for each scenario are reported in the sections below.

The first section (8.2) presents model results for natural sediment load alone. It contains a figure showing patterns of deposition along the river and over time and a table showing cumulative deposition by reach. There is also a figure which illustrates water level increase over time at the discharge equaled or exceeded 10% of the time. This value on the flow duration curve is used as a reference level throughout this section. Grey text boxes provide an interpretation of each figure.

Sections 8.3-8.5 use a similar format as Section 8.2 but contain information on the Null (Status Quo) Scenario and mine life extensions to 2015 and 2020. These model runs assume that dredging continues at the current rate. Figures show total deposition, mine-related deposition and associated water level change at the 10% flow duration in all cases. Figures are also presented to show additional deposition and water level change compared with the Null Scenario for the two mine life extension cases. Tables show cumulative deposition in each reach with and without the effects of natural sediment inputs. For mine life extensions, a further table lists additional deposition compared with the Null Scenario

Sections 8.6-8.10 examine a range of dredging options assuming mine closure in 2010. Rates vary from zero to 125% of current rate. Results for changes to dredging rates are in the same format in every case. The first figure in each section shows deposition *additional* to that modeled in the Null Scenario. A second figure shows *additional* changes in water level at the 10% flow duration down the river and over time.

The colours used in the figures to indicate a value are standard throughout this section except in the 125% Dredge Scenario. This permits rapid visual comparison. Grey text boxes containing interpretations of figures are included for each dataset. Data for

*additional deposition and water level changes* describe the net impact of mining and dredging with natural deposition effects removed. Mine-related sediment deposition was calculated subtracting the natural load values from total deposition. In reaches experiencing net erosion, the mine related component was set at zero.

It should be noted when interpreting the results that sediment modeling is a developing technology and errors are possible. The *OTML* datasets used to run the model also contain errors and the surveyed cross sections used to describe the river are too far apart to capture many features. There are also more uncertainties about the behaviour of the lower Middle Fly than other reaches and there is a lack of data in this area. Model accuracy will also decrease with time as inputs from upstream become more uncertain. Sediment modeling results should therefore be seen as reflecting general trends rather than providing detailed information in specific reaches.

## **8.2 75 Year Model Run with Natural Sediment Load Only**

In the 1999 modeling study, the Lower Ok Tedi and Middle Fly were treated as a stable system and the initial long profile was adjusted to achieve zero net deposition (Parker and Cui, 1999). This approach is useful for estimation of mine impact but it does not provide information on natural background rates of sedimentation and of change in water levels. In this study, we have assumed that the natural system is stable during the model calibration period but may experience deposition over the longer term. A model run was carried out to test whether this is the case, to check for possible errors in our estimates of the natural sediment load, and to allow separation of mine impact. It also provides a check on whether the reconstruction of the 1985 river channel is reasonable.

### **8.2.1 Natural Rates of Aggradation**

The case for rising bed levels under natural sediment loading is summarised by Dietrich, Day & Parker (1999). It includes:

- The medium sand fraction present in the river bed material of the upper Middle Fly did not seem to reach the lower Middle Fly prior to mining (Pickup, Higgins & Warner, 1979).
- An apparent rise in the level of the Strickland, backing up the lower Middle Fly and virtually halting meander migration in the lower Middle Fly because of lower bank shear stress values associated with reduced slope.
- Possible subsidence associated with a fault that crosses the Middle Fly floodplain. This may explain why terrace remnant elevations decrease down the Middle Fly but rise again in the Lower Fly (Pickup, 2001)
- The Middle Fly channel levee system may be up to 7 m higher than the surrounding floodplain.

Estimates of the aggradation rate vary but Dietrich, Day & Parker (1999) suggest a rate of 0.1-1 mm/year for the zone away from the channel, 1-10 mm/year for filling of meander cutoff ox-bows, and perhaps 5 mm/year for the channel system. However, the channel system rate aggradation rate may be lower because some sand is transported out of the channel by overbank flow and through tie channels.

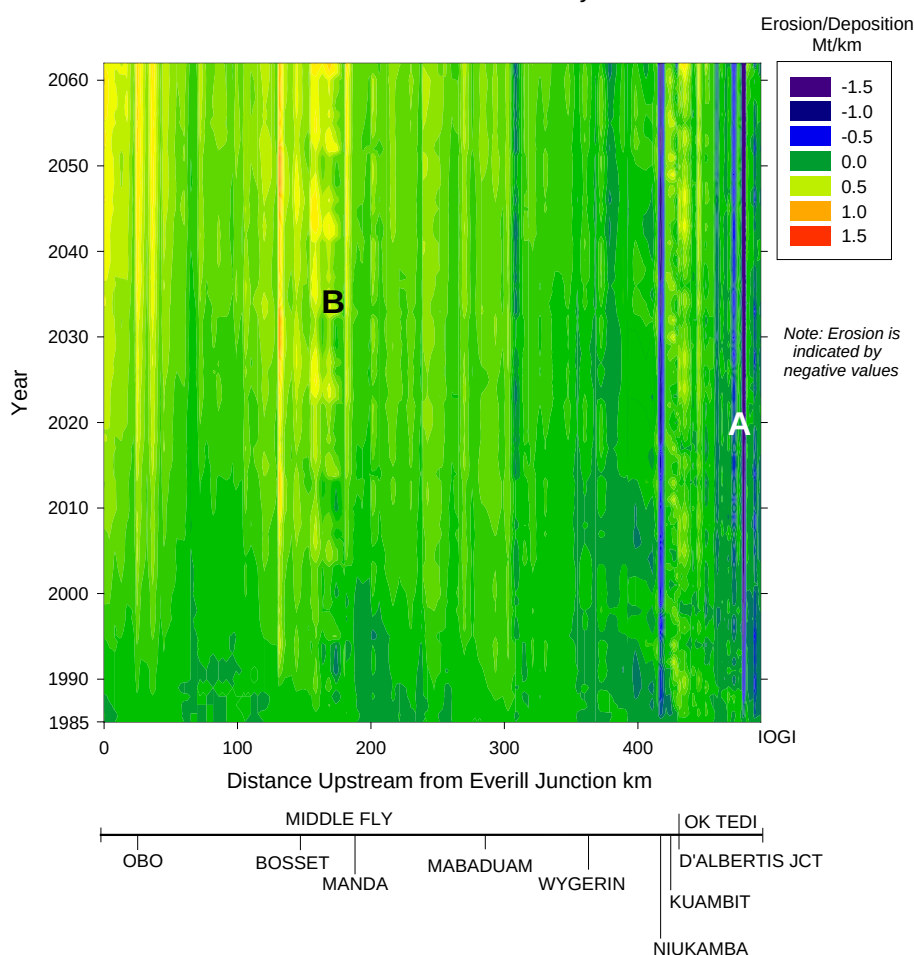
These rates may be conservative. For example, a detailed stratigraphic study of Magela Creek in the Uranium Province of Australia's Northern Territory shows that the whole

floodplain has risen at an average rate of about 4 mm/year since the post-glacial rise in sea level ended 5,000-7,000 years ago (Clarke *et al*, 1992). Magela Creek is much smaller than the Fly but would have a similar history of post-glacial sea level rise. It is also backed up by the much larger East Alligator River so the situation is analogous to the Middle Fly and the Strickland. However, the Magela Creek catchment is much flatter and more geologically stable than that of the Fly, so delivered sediment load would be less. It therefore seems reasonable to expect a higher natural rate in the Middle Fly.

In fact, the 70 year modeling run suggests a natural accumulation of about 10 mm/year (Table 14) if all deposited sediment stays in the channel. If 30% is lost to the floodplain, the rate comes down to 7 mm/year which is close to the Dietrich, Day & Parker (1999) estimate of 5 mm year. This suggests that our estimates of natural sediment load are fairly reasonable and that the reconstructed 1985 river channel does not produce excessive natural erosion or deposition rates.

### 8.2.2 Model Results using Estimated Natural Sediment Loads

Figure 34: Sediment Accumulation by Reach.  
Natural Sediment Load Only.



#### Interpretation of Sediment Accumulation Data under Natural Load

The pattern of deposition shows slight erosion above Bige and slight deposition in the lower Ok Tedi. The upper Middle Fly above Wygerin is close to being stable but downstream, deposition gradually increases with both distance and time with about 60 Mt accumulating in the Manda-Obo reach. This is the Strickland backwater zone and in pre-

mining river bed sediment surveys, showed a marked reduction in the amount of medium sand present. This is consistent with a river experiencing deposition. The deposition in the first 50 km of the Lower Fly is affected by the model boundary condition and should be discounted.

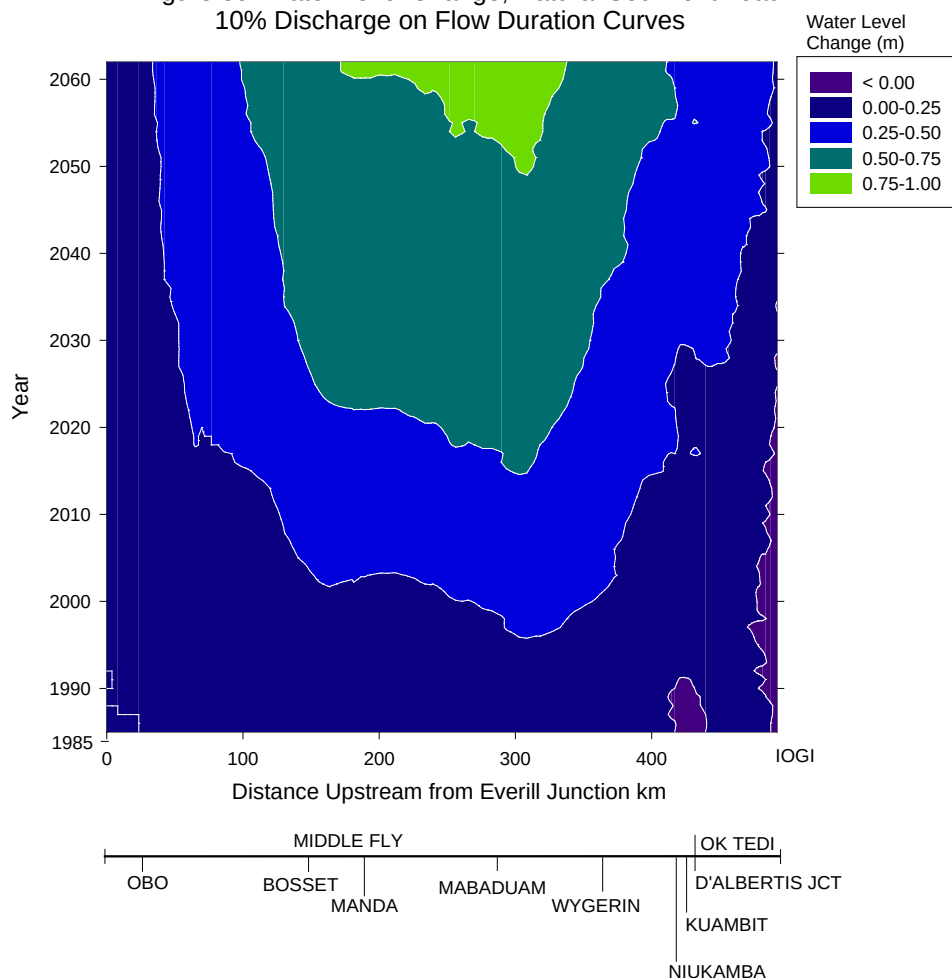
The overall pattern of deposition in the Middle Fly is resembles a deposition sequence suggested by Pickup (1984). In this scheme, downstream edge of Middle Fly sand zone, which extends from D'Albertis Junction to Manda, slowly moves downstream as a front, into the backwater zone. Behind this front, the bed slowly rises to maintain slope, but this effect dissipates upstream,

The vertical striping shows the effect of local variability in the river channel characteristics. This variability takes the form of channel openings, where sediment accumulates, and constrictions, which hold back material in upstream reaches but have limited local deposition. The vertical line marked 'A' shows an extreme example of this behaviour. The openings and constrictions are often associated with outcrops of resistant "red beds" where the pre-Holocene floodplain survives in elevated terrace remnants.

The vertical striping may be broken up into repeating cells of higher and lower deposition (for example the middle part of the vertical line marked 'B'. These result from periods of high and low discharge such as *La Nina* and *El Nino* sequences, several of which were built into the input data.

| YEAR | TABLE 14: CUMULATIVE DEPOSITION (NATURAL LOAD ONLY)<br>BY REACH (Mt) |                  |                    |                  |                |           |
|------|----------------------------------------------------------------------|------------------|--------------------|------------------|----------------|-----------|
|      | Bige-Ieran                                                           | Ieran-D'Albertis | D'Albertis-Wygerin | Wygerin-Mabaduam | Mabaduam-Manda | Manda-Obo |
| 1990 | -2.43                                                                | 3.02             | -3.07              | 4.48             | 1.14           | 8.16      |
| 1995 | -3.03                                                                | 0.65             | -0.11              | 5.26             | 4.10           | 14.35     |
| 2000 | -3.50                                                                | 0.08             | 0.38               | 6.05             | 9.60           | 17.24     |
| 2005 | -3.30                                                                | 3.08             | -4.85              | 6.18             | 12.00          | 26.51     |
| 2010 | -3.47                                                                | 2.13             | -2.21              | 7.41             | 14.59          | 28.16     |
| 2015 | -5.44                                                                | 2.52             | -0.14              | 6.86             | 15.93          | 34.79     |
| 2020 | -4.60                                                                | 2.48             | -0.13              | 8.10             | 18.22          | 37.72     |
| 2025 | -4.13                                                                | 3.76             | -2.02              | 8.61             | 17.96          | 45.52     |
| 2030 | -5.57                                                                | 2.57             | 2.85               | 9.72             | 20.25          | 45.20     |
| 2035 | -5.95                                                                | 3.26             | 2.94               | 9.31             | 21.25          | 50.66     |
| 2040 | -5.32                                                                | 3.80             | 2.53               | 10.97            | 22.79          | 52.13     |
| 2045 | -5.41                                                                | 5.80             | 0.95               | 11.77            | 22.95          | 56.56     |
| 2050 | -5.87                                                                | 4.65             | 4.75               | 12.71            | 24.71          | 55.78     |
| 2055 | -6.20                                                                | 3.03             | 7.95               | 12.35            | 25.57          | 59.40     |
| 2060 | -7.24                                                                | 5.95             | 4.98               | 13.93            | 27.18          | 60.82     |

Figure 35: Water Level Change, Natural Sediment Load.  
10% Discharge on Flow Duration Curves



### Interpretation of Water Level Rise under Natural Load

*Note that scaling and colour scheme on the figure differs from other water level change figures presented later in this section.*

Water level increases with time but the greatest change is centered on the reach immediately upstream of the junction between the backwater zone and the sand zone near Manda. The maximum water level increase is about 0.8 m and occurs at the end of the modeling period.

Downstream from the backwater zone-sand zone boundary, the effect of rising water levels decreases as the amount of deposition is reduced. Upstream, water level rise dissipates more slowly with distance because the system is backed up. This effect eventually extends upstream into the Lower Ok Tedi towards the end of the modeling period. However, water level increase is slight compared with mining impacts shown in later figures.

Predicted water level changes may be slightly overestimated, reflecting errors in the 1985 river channel reconstruction but the effect is limited.

### 8.3 Null Scenario (Current Mine Plan, Current Dredging Rate)

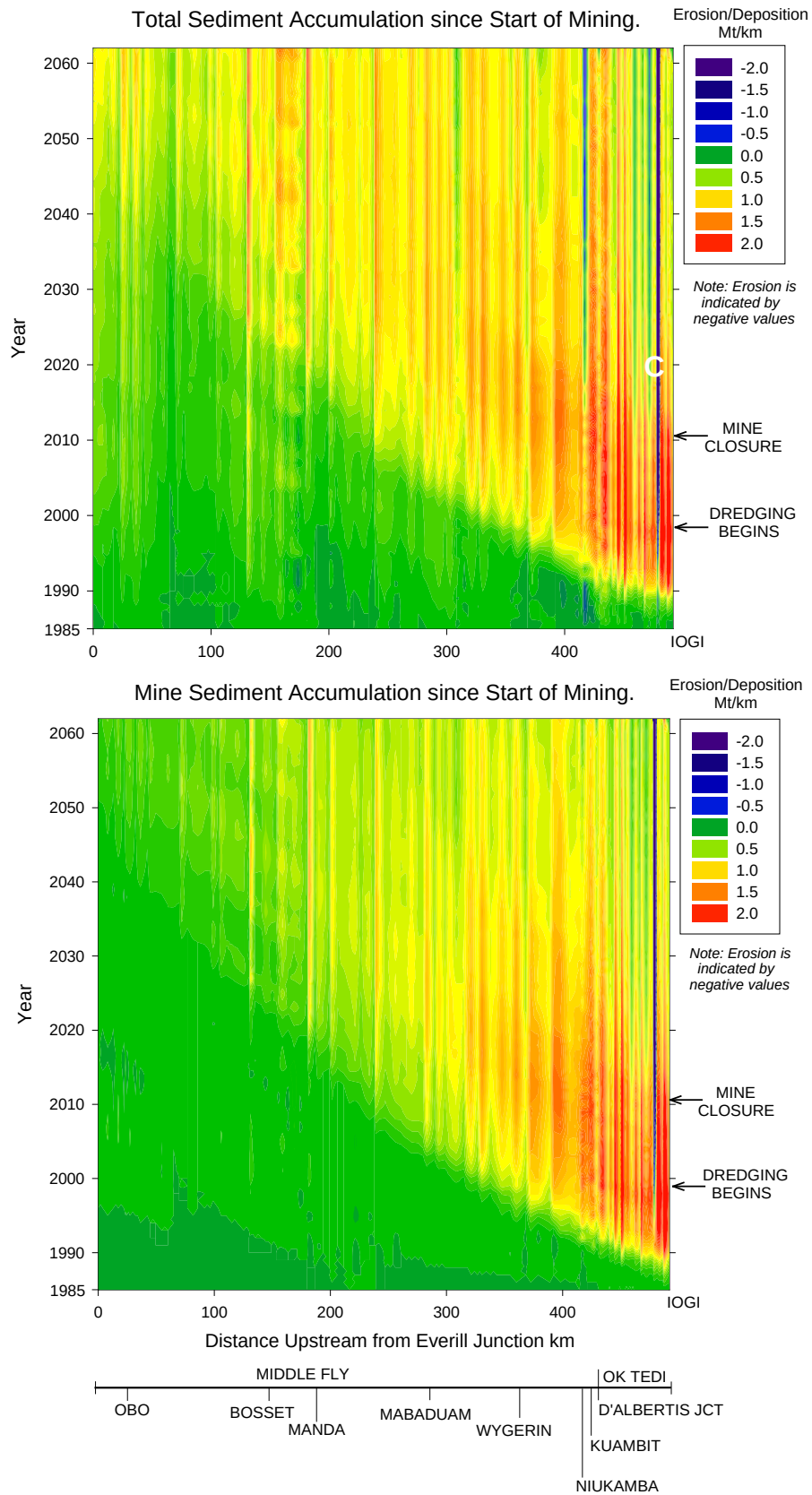


**Figure 36: Total and mine-related deposition – Null Scenario**

### **Interpretation of Modeled Sediment Accumulation Data – Null Scenario**

At its simplest, the pattern of deposition may be seen as a flow of material with a wave-front that gradually moves down the system over time. This behaviour shows as a prominent diagonal break between the green (little or no deposition) feature in the lower left of the image and the red and yellow (greater deposition) zone. The flow attenuates with distance and with time once mining ceases. It also breaks up into separate cells in the lower part of the Middle Fly but leaves behind long term deposits in many reaches.

Initially, heavy sediment accumulation occurs in the upper part of the Ok Tedi between Iogi and D'Albertis Junction. This deposition is reduced by dredging and by natural erosion after mine closure. By about 2060 much of this deposition has cleared and some of the irregularities in the bed that were filled during the lead-in period to stabilize the model begin to reappear. The Lower Ok Tedi holds material for longer and deposition persists in some reaches to at least 2060.

The bulk of deposition initially occurs on the Middle Fly in the 240-420 km reach. Some, but not all of this material, shifts downstream after mine closure. There is some clearing of deposited material from the upper 70-100 km after about 2040 but deposition increases further downstream and shows little sign of clearing by 2060.

There are local build-ups of sediment in the lower part of the Middle Fly after about 2020. These show as short vertical red stripes in the top left hand part of the figure. There is also a prominent scour zone marked 'C' where a scour hole buried during the pre-mining lead-in period reappears after 2020.

While modeled behaviour in the lower reaches of the Middle Fly appears logical, little is known about water inflows and outflows in this reach so questions of accuracy remain. The downstream end of the system is also affected by the assumption of a stable rating curve at Obo as a boundary condition. There is no evidence of rating shift between 1987 and 2001 (Pickup, 2001) but data quality is poor.

| YEAR | <b>TABLE 15: CUMULATIVE DEPOSITION (TOTAL SEDIMENT LOAD)<br/>BY REACH (Mt)</b> |                  |                    |                  |                |           |
|------|--------------------------------------------------------------------------------|------------------|--------------------|------------------|----------------|-----------|
|      | Bige-Ieran                                                                     | Ieran-D'Albertis | D'Albertis-Wygerin | Wygerin-Mabaduam | Mabaduam-Manda | Manda-Obo |
| 1990 | 13.51                                                                          | 17.05            | -1.43              | 5.14             | 1.22           | 8.16      |
| 1995 | 24.69                                                                          | 47.47            | 37.47              | 8.75             | 5.91           | 15.18     |
| 2000 | 22.74                                                                          | 54.69            | 78.32              | 21.09            | 14.17          | 21.90     |
| 2005 | 18.71                                                                          | 55.02            | 82.27              | 43.79            | 20.97          | 33.97     |
| 2010 | 16.31                                                                          | 51.39            | 92.75              | 52.11            | 38.22          | 33.19     |
| 2015 | 7.26                                                                           | 45.94            | 91.39              | 58.37            | 52.53          | 40.50     |
| 2020 | 5.13                                                                           | 39.92            | 82.88              | 62.09            | 65.78          | 46.87     |
| 2025 | 3.12                                                                           | 35.86            | 72.96              | 60.65            | 72.54          | 63.68     |
| 2030 | 0.61                                                                           | 31.16            | 74.18              | 58.50            | 78.50          | 70.23     |
| 2035 | -0.57                                                                          | 30.27            | 68.46              | 57.27            | 79.17          | 84.14     |
| 2040 | -0.44                                                                          | 29.48            | 63.62              | 57.17            | 79.62          | 94.31     |
| 2045 | -1.13                                                                          | 29.94            | 57.98              | 54.33            | 79.92          | 105.86    |
| 2050 | -1.86                                                                          | 27.93            | 60.13              | 52.73            | 80.97          | 109.08    |
| 2055 | -2.43                                                                          | 25.45            | 60.88              | 52.15            | 79.39          | 114.85    |
| 2060 | -3.85                                                                          | 27.51            | 54.69              | 53.00            | 78.53          | 119.20    |

| YEAR | <b>TABLE 16: CUMULATIVE DEPOSITION (MINE SEDIMENT)<br/>BY REACH (Mt)</b> |                  |                    |                  |                |           |
|------|--------------------------------------------------------------------------|------------------|--------------------|------------------|----------------|-----------|
|      | Bige-Ieran                                                               | Ieran-D'Albertis | D'Albertis-Wygerin | Wygerin-Mabaduam | Mabaduam-Manda | Manda-Obo |
| 1990 | 13.51                                                                    | 14.03            | 0.00               | 0.65             | 0.08           | 0.00      |
| 1995 | 24.69                                                                    | 46.81            | 37.47              | 3.49             | 1.81           | 0.83      |
| 2000 | 22.74                                                                    | 54.61            | 77.93              | 15.04            | 4.56           | 4.66      |
| 2005 | 18.71                                                                    | 51.94            | 82.27              | 37.61            | 8.97           | 7.46      |
| 2010 | 16.31                                                                    | 49.26            | 92.75              | 44.70            | 23.62          | 5.03      |
| 2015 | 7.26                                                                     | 43.41            | 91.39              | 51.51            | 36.60          | 5.71      |
| 2020 | 5.13                                                                     | 37.44            | 82.88              | 53.98            | 47.56          | 9.14      |
| 2025 | 3.12                                                                     | 32.10            | 72.96              | 52.04            | 54.58          | 18.15     |
| 2030 | 0.61                                                                     | 28.59            | 71.33              | 48.78            | 58.25          | 25.02     |
| 2035 | 0.00                                                                     | 27.01            | 65.51              | 47.95            | 57.91          | 33.47     |
| 2040 | 0.00                                                                     | 25.67            | 61.09              | 46.20            | 56.83          | 42.17     |
| 2045 | 0.00                                                                     | 24.13            | 57.03              | 42.55            | 56.96          | 49.29     |
| 2050 | 0.00                                                                     | 23.28            | 55.37              | 40.02            | 56.25          | 53.29     |
| 2055 | 0.00                                                                     | 22.41            | 52.92              | 39.79            | 53.82          | 55.45     |
| 2060 | 0.00                                                                     | 21.55            | 49.70              | 39.07            | 51.35          | 58.37     |

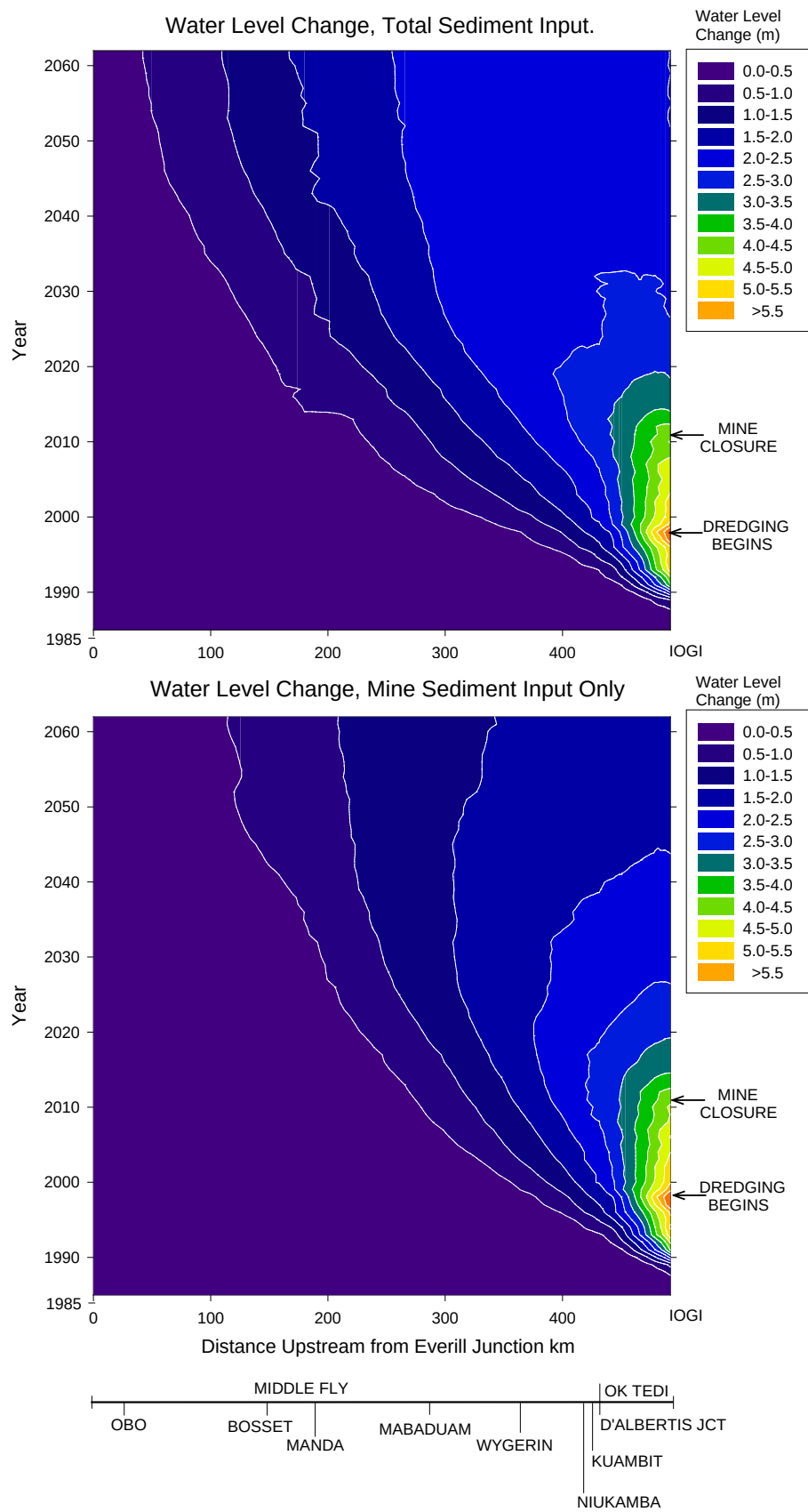


**Figure 37: Total and mine-related water level increase – Null Scenario**

### Interpretation of Modeled Water Level Change Data

Water level changes tend to be more regular than raw deposition data because rises in water level affect upstream reaches and smooth out local increases in bed level. Water level increase is greatest at the upstream end of the system but decreases rapidly after dredging and mine closure. Further downstream, water levels continue to rise until about 2060 when the system stabilizes. Water level changes decrease with distance downstream. However, by 2060, they are still significantly higher than the pre-mining situation over most of the Middle Fly and all of the Lower Ok Tedi.

## 9. COMPARISON WITH 1999 MODEL RESULTS<sup>5</sup>

### 9.1 Background

The 1999 sediment modeling study used *OkGrav5* and *OkFly* to estimate channel deposition, floodplain deposition and overbank flooding in the river system (Parker and Cui, 1999). Two sets of model runs were carried out: a pessimistic scenario in January 1999 and a more optimistic scenario in May, 1999. The optimistic scenario was judged to be the more accurate of the two.

There are many differences between the approach taken in this study and that of Parker and Cui (1999). Some of these differences for the Lower Ok Tedi and the Middle Fly are summarised in the Table 41. Model results should therefore be expected to differ to some degree. However, if there are similarities, this increases confidence in both sets of modeling. In this section we examine the extent to which model results are comparable using the DL and Null (Mine Load only) Scenarios. These have similar dredging rates of about 15 Mt/year and exclude natural deposition.

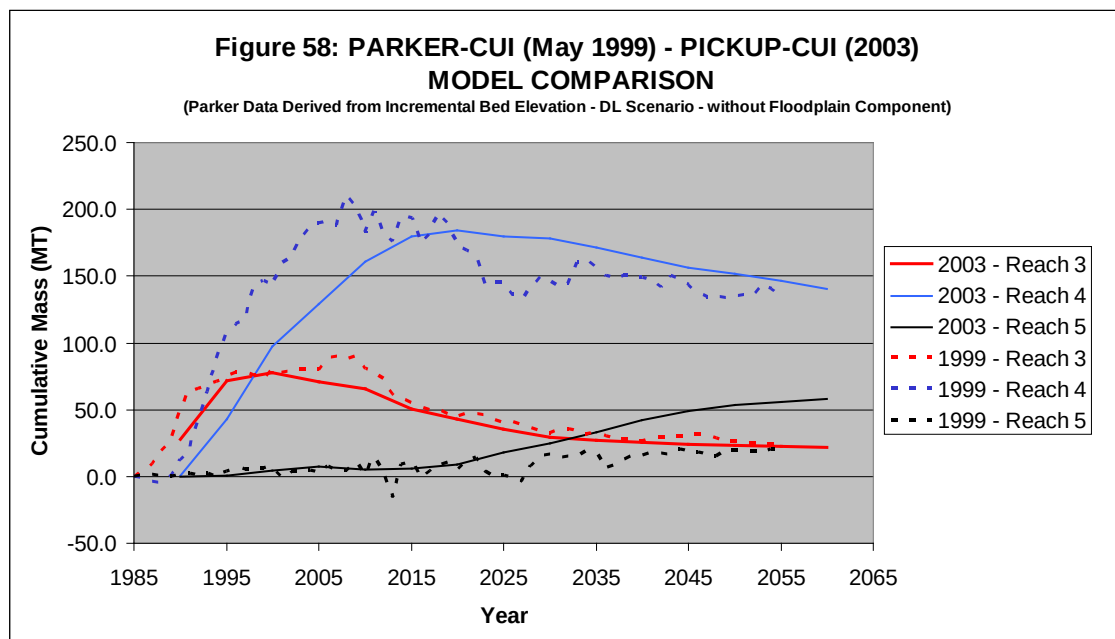
**TABLE 41: SOME DIFFERENCES BETWEEN MODEL STUDIES**

| FEATURE            | 1999 STUDY                                                                                | 2003 STUDY                                                                                                                          |
|--------------------|-------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| Model              | <i>OkGrav5</i> & <i>OkFly</i>                                                             | <i>OkGrav6</i> & <i>HEC-6</i>                                                                                                       |
| Hydrology          | Sequence of representative wet, dry and average years                                     | Daily flow series made up by repeating the 1984-2002 corrected discharge record                                                     |
| Channel Geometry   | Uniform rectangular channel with a rectangular floodplain used as a representative system | Reconstructed 1985 channel system based on 1997 cross section surveys used as a starting point                                      |
| Transport Equation | Brownlie equation, washload cutoff point 43μ                                              | Yang equation but model time step was rescaled to increase the transport rate during model calibration, washload cutoff point 62.5μ |
| Model Zeroing      | System slope adjusted to achieve zero deposition under estimated natural load             | Natural deposition subtracted from total deposition                                                                                 |
| Sediment Particle  | Separate sand fractions handled                                                           | 5 separate sand fractions                                                                                                           |

<sup>5</sup> We are grateful to Andrew Marshall for extracting channel deposition values from the 1999 modeling study and for providing a spreadsheet to allow comparison of model results.

| Sizes                                | via a hiding function                                                                |                                                                                                                          |
|--------------------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Calibration                          | Model calibrated for floodplain roughness coefficient and flood inundation frequency | Model calibrated using observed water surface profile and observed bed deposition before and after the start of dredging |
| Waste input at mine 1985-2010        | 615 Mt tailings, 818 Mt waste rock                                                   | 615 Mt tailings, 876 Mt waste rock                                                                                       |
| <i>OkGrav</i> Input to lower Ok Tedi | DL Scenario, 1985-2010<br>454 Mt sand (>43 $\mu$ ), 758 Mt silt                      | Null Scenario, 1985-2010<br>322 Mt sand (>65 $\mu$ ), 650 Mt silt                                                        |

## 9.2 Comparison of Model Results



### Interpretation of Model Comparisons

The two model studies produce remarkably similar results in spite of major differences of approach. Results for Reach 3 (Lower Ok Tedi) are very close throughout the modeling period. Reach 4 (D'Albertis Junction-Manda, Middle Fly Sand Zone) shows a similar amount of deposition over the long term but in the 2003 modeling run, some of the sediment arrives later and passes down the system more slowly. This occurs because the new version of *OkGrav* allows more deposition of sand upstream of Konkonda during mean life. In Reach 5 (Manda-Obo, Middle Fly Backwater Zone), there is more deposition of sand over the long term, reflecting slower movement of sediment through Reach 4. The lack of deposition in Reach 5 was a cause for concern in the 1999 modeling (Cui and Parker, 1999). The 2003 results may be closer to expected behaviour.

## 11. FUTURE ACTIVITIES TO IMPROVE MODEL PERFORMANCE

Sediment transport modeling at Ok Tedi has a history of experimentation and continuous improvement. While some of this improvement has come from collection of additional data, each round of modeling has added to the body of experience and made it possible to improve precision in the future.

This study has benefited from additional sources of data, especially the mine area sediment storage and river cross section survey programs carried out by A. R. Marshall. *Further data collection* under these programs will allow better model results through greater opportunities for model calibration and validation. Suggestions on how these programs might be developed further were made by Pickup (2002).

Two new programs should allow significant improvement:

- The bed sampling and coring studies along the Middle and Lower Ok Tedi and the Fly now being carried out within the ARD Program. Results from this activity will greatly increase knowledge of river sedimentary behaviour. They may also allow a better reconstruction of the pre-mining river bed level. This would provide a better baseline for future modeling of channel deposition than the reconstruction used in this study.
- The use of satellite based synthetic aperture radar remote sensing to monitor floodplain waterbody behaviour. A trial of this approach is in the early stages of development. If successful, it may allow characterization of floodplain waterbody behaviour, interaction between the river and off-channel water-bodies. It may also allow construction of a floodplain digital elevation model. This information could permit introduction of two-dimensional hydraulic and sediment modeling techniques. It could also improve capacity for estimating floodplain deposition when used in association with the empirical models foreshadowed by Dietrich (2000).

There are also areas where models or model applications can be improved:

- *OkGrav6* focuses on deposition yet the post-mining phase will involve extensive erosion of deposited material in Mine Area Creeks. This process will ultimately govern sediment supply to the Lower Ok Tedi and Middle Fly. While we were able to undertake some calibration of *OkGrav6* under conditions of erosion, fluvial zones in both the Ok Mani and the Sulphide Creek/Ok Gilor systems were still experiencing deposition at the time of the last survey. The Upper Ok Tedi had experienced some erosion with declining use of the Northern Dumps but its characteristics are very different from the Mine Area Creeks so the *OkGrav6* calibration needs further checking as erosion begins in the fluvial zone below the Northern Dumps.
- Another possibility for improving *OkGrav6* calibration under conditions of erosion might be to try to obtain data for the Kawerong River below the Panguna Mine on Bougainville. This system had a regularly monitored network of cross sections during mining and has now had more than a

decade of post-mining adjustment. It is almost identical to the Ok Mani in many ways.

- Representation of the river system by a set of nodes and reaches is “hard-coded” into *OkGrav6* and is therefore fixed. Changing this structure would require significant re-writing of the model although the algorithms would remain the same. More nodes are needed to represent the northern creeks and Upper Ok Tedi and this is recommended if the model is to be used in future. It could also improve representation of the Ok Mani.
- The body of sand accumulating in the former armoured zone and gravel-sand transition zone of Ok Tedi between Ieran and Ningerum may need more monitoring. Also, although it falls within the area covered by *OkGrav6*, it is not part of that model which focuses on gravel transport and deposition. In this study, we allowed the top few cross-sections of the *HEC-6* formulation to control sand delivery to downstream reaches but this distorts behaviour in the uppermost 2-3 km. This should be regarded as an interim solution.
- *HEC-6* was calibrated using flow and cross section survey data for 1984-2002. Much of the impact on the Middle Fly has yet to be felt so uncertainties remain about the downstream travel time of sediment currently accumulated in the upper part of the Middle Fly and the Lower Ok Tedi. At present, cross section surveys for the Middle Fly suggest that the post-1998 pattern of change is dominated by the effects of *El Nino* and *La Nina* events on flow variability rather than mine-related deposition (Marshall, 2002). This limits their usefulness for model calibration. However, as data accumulate, it may become possible to improve calibration of *HEC-6* or any other model used on the Middle Fly. The picture is clearer on the Lower Ok Tedi where post-dredging impacts may be identified.
- *HEC-6* does not provide a satisfactory representation of floodplain deposition. Earlier attempts to represent this process with the *RMA* and *OkFly* models were limited by lack of calibration data and inadequate representation of floodplain topography and behaviour. The use of *HEC-6* water surface profiles and surveyed levee elevations to estimate flooding are only a first approximation. Currently available data do not yet justify two-dimensional models that reproduce flow and sedimentation patterns on floodplains but this may become possible in the next 1-3 years.
- More information is needed on floodplain deposition rates. The most likely way in which modeling of floodplain deposition can be improved is by empirical studies of observed deposition. While Dietrich (2000) describes considerable progress in this area through sampling of copper in floodplain sediments, more needs to be done. One possible approach is to project observed levee deposition rates outwards across the floodplain and to compare results with depth of floodplain deposition.



## ACKNOWLEDGEMENTS

We are grateful to the following individuals for assistance with this project:

Jim Veness who commissioned the study and made the resources and staff of the *OTML* Environment Dept available to us.

Barrie Bolton for assistance in scoping the project and provision of data on mine waste characteristics, dredging, river deposition patterns and river sediment properties.

Patrick Simbina, *OTML* and Gary Newton, *ECOWISE Environmental* for assistance in tracking down and extracting rainfall and runoff data.

Henry Kundapen and Jesse Pile for collection and supply of sediment data for Mine Area Creeks.

Andrew Marshall for: supply of 1992 contour data, contour data for Mine Area Creeks, sidewall erosion survey data for Harvey Creek, and Ok Tedi/Fly River cross section survey data. This study could not have been carried out without this information.

Alan Marks for assistance in construction of high resolution digital elevation models for *OkGrav* calibration data.

Professor Gary Parker of the University of Minnesota for advice, review and assistance in the modification, rewriting and calibration/validation of *OkGrav*.

Elizabeth Pickup for assistance with data extraction and report editing.

Andy Markham for help in identifying sources and locations of early hydrologic data.

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## APPENDIX A: COMMENTS ON MODEL SELECTION

### Mine Area Creeks, Upper & Middle Ok Tedi

The mine area creeks & steep sections of the Ok Tedi pose major problems for sediment modeling. The lower section of the Harvey Creek dump behaves as a debris flow runout zone which is not handled by any of the standard sediment models. The Ok Mani & the Ok Tedi are fluvial zones but contain heavily braided channel systems which conventional channel sediment transport models do not handle very well. Also, softer components of the waste stream break down into smaller particle sizes during transport & tailings travel in suspension at concentrations well above the range handled by virtually all sediment transport equations. These processes are not handled very well by commonly available sediment models.

Several models were developed to describe sediment transport under similar conditions below the Panguna Mine at Bougainville (*BRAID* & *JABA*). These were used in pre-mining studies at Ok Tedi. However, neither model can handle the debris flow runout component. Also, the Ok Tedi did not develop the large tailings deposition basins that built up on the Jaba (which is a much smaller river - see images at the end of this document).

The *OkGrav* model was developed specifically for conditions at Ok Tedi by Gary Parker over a ten year period and has been calibrated from observed river system behaviour. It was used in the 2003 study but was updated & recalibrated with data that had accumulated in recent years.

### Lower Ok Tedi & Middle Fly

The lower Ok Tedi and Middle Fly are single channel river systems with floodplains. They transport sand (mainly as bed material load), silt & clay. *OkGrav* (being a braided river gravel transport model) was not designed to handle these conditions so an alternative model must be used.

There are three sediment transport models that are commonly used: *HEC-6*, *MIKE11*, and *SED2D*. There are many other river sediment transport models, but most modeling efforts are performed with these three.

*HEC-6* is a U.S. Army Corps model, and as such, is in the public domain. It is probably the most used sediment transport model available. It is also widely accepted and by US Federal and State Government Agencies as the model of choice giving it a measure of “official” status (e.g. listed as a best management practice by US EPA in its proposed alkaline coal mining sedimentation strategy guidelines).

*HEC-6* is a 1D model initially developed by William A. Thomas at the Little Rock District of the US Army Corps of Engineers. That program evolved into Version 2.7 in 1976 while Mr. Thomas was at the Corps of Engineers Hydrologic Engineering Center (HEC). Since then, program development by the Waterways Experiment Station (WES) has continued. Version 3.2 was released by HEC in 1986 and replaced by Version 4.0 in 1991. Mr. Thomas added stream network capability, additional transport functions, a more complete computation of cohesive sediment re-suspension, and modified the

movable bed width computation. In 1993, further modifications were made and Version 4.1 computes sediment transport of grain sizes up to 2048 mm.

*MIKE11* is a model developed by DHI (Danish Hydraulic Institute). It has wide acceptability and is well tested and supported. The sediment transport module in *MIKE11* is just one module of many. However, since *MIKE11* is a proprietary model, it is quite expensive. It is not used as often as *HEC-6* and *SED2D*, both of which are public domain models developed. *MIKE11* can model hydrodynamic events, and very complex river networks.

*SED2D* is a 2D hydrodynamic sediment transport model that works with *RMA2* as the flow model. *RMA2* is used to compute the flow field, and then *SED2D* is used to model the sediment transport that then occurs. *SED2D* and *RMA2* are public domain models, both being developed by the U.S. Army Corps of Engineers. However, due to the input and output data complexities, a pre and post processor is necessary to run these two models. Commercial software provides an interface to *SED2D* and *RMA2*. *SED2D* is not often used, unless budgets warrant it, due to the increase in the model complexity of a 2D hydrodynamic model over that of *HEC-6*, which is a steady state 1D model. *The data available at Ok Tedi are insufficient to allow confident use of a 2D model.*

In 1999, the *OKFLY* model was developed specifically for sediment transport studies in the Fly River by Parker & Cui. It has some similarities to *HEC-6* but includes a floodplain deposition component which is still in the experimental stage. The model uses a single sediment transport equation and represents the channel as a rectangular feature with constant width. It also uses a single representative sediment particle size to describe bed material load unlike *HEC-6* which uses up to five sand size components and a range of transport equations.

*HEC-6* was used rather than *OKFLY* for a number of reasons:

- *HEC-6* uses observed channel cross sections. It therefore allows variations in channel width and depth to be specified which can be important in modeling transport & deposition.
- *HEC-6* has a well-tested capacity for modeling water surface profiles which may be verified against observed water levels down the river. Water surface profile modeling is best carried out with measured cross sections rather than the idealised channel representation used in *OKFLY*.
- Given the difficulties and uncertainties in modeling the river system, it was thought desirable to use a different approach from the 1999 study. If the 1999 & 2003 modeling exercises yield similar results, this increases confidence in both.
- *HEC-6* was calibrated in a very different way to *OKFLY* and uses different transport functions. This provides a diversity of approaches which, if they produce similar results, increases confidence.
- One of the modeling team had extensive experience with *HEC-6* on tropical rivers.

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*OCTOBER 2014 SEDIMENT MODELING STUDY*

***GEOCHEMISTRY MASS BALANCE MODEL  
VALIDATION AND LONG TERM PREDICTIONS  
FOR THE UNRESTRICTED WASTE ROCK  
DUMPING CASE.***

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**DR. GEOFF PICKUP<sup>1</sup>, CONSULTING GEOMORPHOLOGIST**

**11 METCALFE ST,**

**NICHOLLS, ACT 2913, AUSTRALIA**

**18 Feb. 15**

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<sup>1</sup> Email: [Pickup01@westnet.com.au](mailto:Pickup01@westnet.com.au), Phone +(61) 2 6262 2034

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## SUMMARY

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This report describes changes to the geochemistry mass balance model that adds a capability for long term prediction out to the 2060. Previously, the model could only predict to the end of mine life. The main change was to add an erosional component that allows excavation of material from accumulated deposits as mine inputs reduce or cease altogether. This requires new calculations to allow mixing between current inputs and eroded material from deposits. It also requires addition of a term to reflect dilution by natural sediment load. Otherwise many of the model equations and calculations remain as in the previous version. The erosional component is derived from the *OKTUGS* sediment model which predicts addition to and removal of material from deposits in the Mine Area creeks and the Ok Tedi.

Several other model components were simplified and the number of model parameters was reduced with more now being estimated from observed data. Model structure was also modified to include the Vancouver Dump and increased use of a Warama Creek Dump.

The model was validated using Sulphur and ANC data from Harvey Creek, the Ok Mani, the upper Middle Ok Tedi and the lower Middle Ok Tedi covering the period 2000-2014. Model predictions gave acceptable matches to observed data in all river reaches.

Long term model predictions of Sulphur and ANC were then made for all model reaches using the Unrestricted mine plan (Appendix 1). This allows for continued use of waste rock disposal in failing dumps rather than a constructed dump on Harvey Creek from 2014 as in previous model runs. A constructed dump scenario was also run using the new mass balance model but is not reported here given that such a dump is now unlikely.

The long term model runs generally show improving ANC:MPA ratios at Bige except for a short period around 2020.

## 1. INTRODUCTION

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Until 2010, predictions of mine waste geochemistry and ARD risk were based on the *OKARD* model developed by *Environmental Geochemistry International Ltd.* During 2010, several studies examined the large body of sediment geochemistry data accumulated by OTML (e.g. *Pile, 2001; OTML Environment Dept., 2006*) with a view to improving understanding of Sulphur and acid neutralising capacity (ANC) in the river system (*Pickup and Others, 2010a; 2010b*). It was also intended to link *OKARD* more closely with the considerable body of sediment transport and deposition modelling carried out by OTML since 2003. This work led to the development of a Sulphur and ANC mass balance model for the river system which provide the inputs to an improved version of the *OKARD* model now known as *OkBalARD* (*EGI and Pickup, 2012*).

The mass balance model (*Pickup and Others, 2010*) was originally developed to predict Sulphur content and ANC of dredge sands at Bige during mine life. As part of that process, mass balance calculations were carried out in various reaches of the river for the period 2001 to 2025. The model assumed a continuous supply of tailings and waste rock and a river system that was largely depositional. It did not allow for erosion and release of material already held in sediment deposits in the various river reaches as this did not occur to any extent during mine life under the scenarios run. Model inputs were derived from observed tailings and delivery rates to the waste dumps and from future mine plans. Deposition and sediment loss rates in the various river reaches came from observed values calculated from sequential topographic surveys. The mass balance model was subsequently enhanced by simplification, recalibration using newly accumulated field data and the addition of a noise model component (*Pickup, 2013*).

The *OkBalARD* and ARD mass balance models perform reasonably well during mine life when the river system is largely depositional. However, they are not suitable for long term predictions covering the period after mine closure when sediment is gradually removed from upper river depositional areas and is redeposited or transported to the lower river. During this period, when sediment transport capacity exceeds delivered load in the upper reaches of the river, there is considerable mixing with and re-excavation of previously accumulated material. ARD risk predictions then require a mass balance model with an erosional component.

Adding an erosional component requires substantial changes to model structure. Most mine-derived inputs will cease and accumulated deposits will begin to erode once mining ends. Reproducing the effects of erosion requires more detailed modelling of the mass, Sulphur content and ANC of the various sediment deposits along the river. The model also needs to represent rates of release of material from the deposits and the process of mixing with material coming from upstream. Additionally, it needs to include the breakdown of gravel to finer material.

The erosional component is too complex for inclusion in the *EXCEL* spread sheet-based mass balance model so it must be sourced from outside. The *OKTUGS* sediment transport model of the upper river system calculates both erosion and deposition over time and on a reach by reach basis and these data may be incorporated within the mass balance model. However, this did not prove simple and required a major restructure of the mass balance spread sheets. It also proved necessary to add some new processes to the spread sheet to allow for mixing of mine derived sediments with the natural load of the river, etc. These processes become increasingly important after mine closure and as mine-derived inputs from the various riverbed deposits are reduced.

Several other changes to model structure are necessary. Besides the rapidly failing Taranaki Dump at the head of Sulphide Creek, there is now a slowly failing waste rock dump on the northern side of Sulphide Creek (the Vancouver Dump) which is releasing material to the river at a much slower rate than other dumps. The model has therefore been modified to reproduce the behaviour of one or more slowly failing dumps. There is also likely to be a substantial increase in material added to Warama Creek to the west of Harvey Creek which contributes material to the Harvey Creek fan at the Ok Mani junction. Previously, Warama Creek inputs were small enough to be ignored. There is also the possibility of a tailings dam which will greatly reduce inputs to the river from 2017 which could be added to the new mass balance model more easily than to previous versions.

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## CHANGES TO MODEL STRUCTURE

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Model inputs, outputs and storages remain essentially the same as in the previous version of the mass balance model (Fig. 1) (*EGI and Pickup, 2012; Pickup and Pile, 2013*) and the basic equations are listed in the associated reports. However, there are changes in processes and the addition of the new waste rock dump on the north side of the mine. New processes include a more detailed representation of gravel breakdown to sand, dilution by the natural sand load of the river in the lower Middle Ok Tedi, and the use of upper and lower sediment storages in each reach.

While many of the remaining process representations in the new mass balance model are inherited from the previous model, there are major changes to some of the calculations. The most significant change is to replace the deposition rate calculations (which only cover the period of mine life) with long term erosion and deposition rates. Previously, deposition rates were determined empirically from measures of deposit volumes derived from ground, aerial and lidar surveys. This is no longer possible as current rates cannot be extrapolated far into the future. Instead, they are now obtained from the recently recalibrated *OKTUGS* sediment model (*Pickup and Cui, 2014*). This model calculates sediment storage volumes and volume changes for individual reaches in the model out to 2060.

The mass balance model uses quarterly inputs of the mass, Sulphur content and ANC values of waste rock and tailings derived from observed values and the mine plan (for future inputs). Waste rock from the southern side of the mine rock and tailings pass through a series of storages consisting of Harvey Creek, the Ok Mani, the upper Middle Ok Tedi and the lower Middle Ok Tedi. Tailings are added at the upper end of the Ok Mani. Waste rock from the northern side of the mine passes through Sulphide Creek and the Upper Ok Tedi into the upper Middle Ok Tedi without any significant deposition in these reaches. There is also a fast path whereby some of the waste rock either consists of sand or breaks down very quickly to sand and passes straight through the gravel reaches of the system as washload before potentially being deposited on the bed of the lower Middle Ok Tedi.

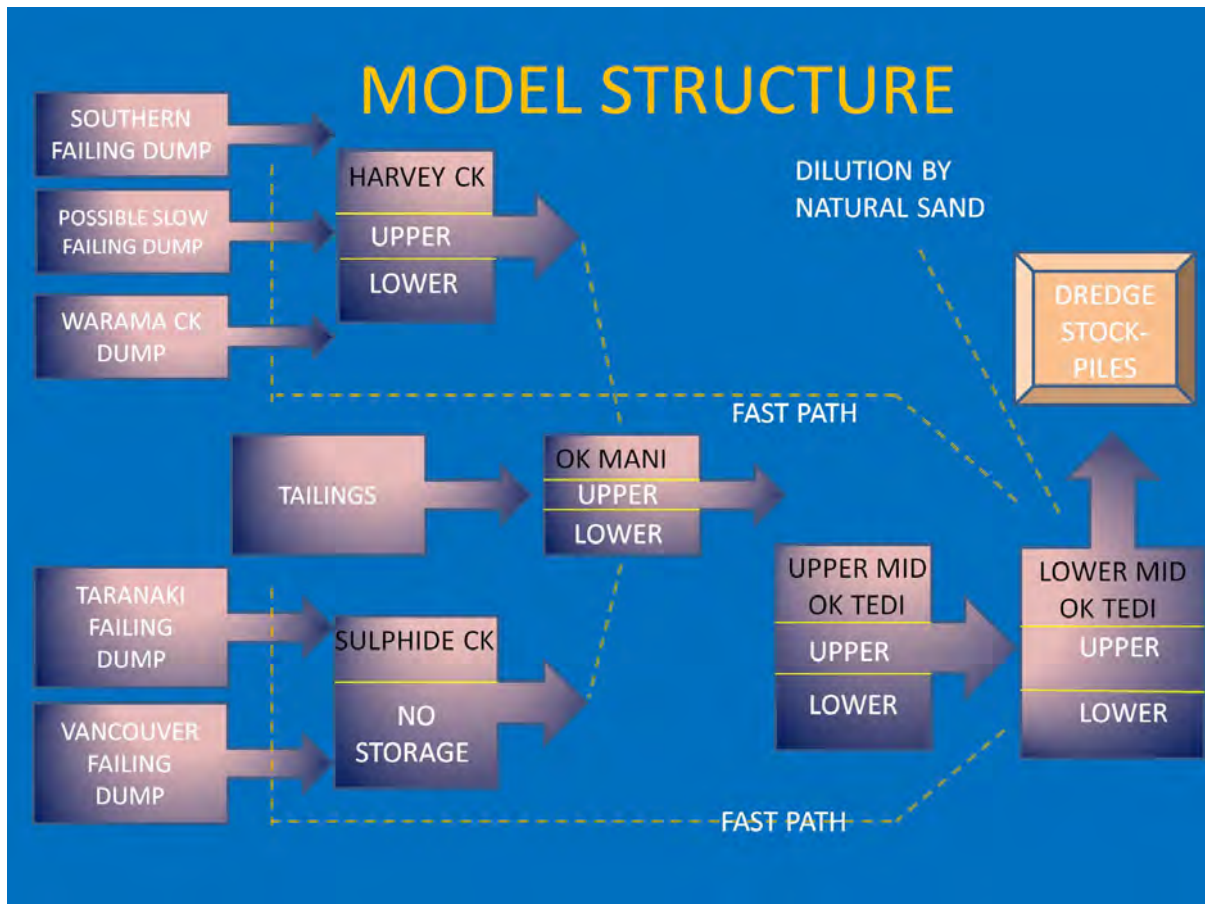


**Figure 1: Long term mass balance model structure. The slowly failing dump feeding into Harvey Creek is a model option unused in the current run.**

Mass balance calculations are simpler than in the previous version of the model. Calculations for each model reach consist of a simple mass balance in which output is derived as:

$$\text{Output} = \text{Input} - \text{Change in Storage (from OKTUGS)}$$

There is significant breakdown of gravel to sand and silt as waste rock passes through the river system to the lower Middle Ok Tedi. The amount of breakdown to sand is calculated using a simple coefficient,  $k$ :

$$\text{Sand} = k * (\text{Gravel Delivered to Reach})$$

The  $k$  values for limestone and the rest of the waste rock are different and become model parameters. Limestone ( $k=0.1$ ) is expected to provide less sand than other material ( $k=0.3$ ). Silt is ignored as it passes straight through the upper river system as washload. Material entering Sulphide Creek passes through a much steeper and more turbulent section of river before entering the upper Middle Ok Tedi. It is assumed to break down to silt more rapidly and has an additional  $k$  value of 0.1. The origin of these constants is discussed in Section 4.

Most sediment transport models use an upper storage and one or more lower storages to represent the behaviour of deposits on the bed. The upper storage holds a mixture of the current input material and the material in the lower storage and allows for limited interchange between the two.

Most of the lower storage remains in situ until excavated by erosion. No depletion of Sulphur and ANC is assumed which is reasonable given that most of the lower storages remain saturated. However, there may be depletion in Harvey Creek where the water table within the deposited waste rock is deep and there is a considerable mass of unsaturated material. Once again, in the absence of any data, depletion has to be ignored or guessed at. In this case, it was ignored.

The mass balance model uses a single upper storage and a single lower storage. Material in both types of storage is assumed to be fully mixed. This may not be the case with the lower storages where some of the material may be quite old. However, in the absence of observed data, there is no choice other than to assume full mixing.

Mixing is controlled by a single parameter (*m*) whereby the Sulphur content and ANC of the upper storage are simple functions of input from upstream and the lower storage:

$$\text{Upper Storage} = (\text{Input} * m) + \{(\text{Lower Storage} * (1 - m))\}$$

While Sulphur mass balance calculations are mostly identical those for ANC, there is one important difference in the lower Middle Ok Tedi where sand begins to be deposited in quantity. Here, an enrichment ratio is applied to the Sulphur sand component to allow for differential rates of transport and deposition of the heavier Sulphur component by the time it reaches Bige. The ratio is a model parameter and increases with the Sulphur concentration in delivered sand

Natural sand load makes up a minor part of total load during mine life, but once tailings disposal ceases and as waste rock deposits are gradually depleted, it becomes more important in diluting both Sulphur and ANC of mine sediments. *OKTUGS* produces separate values for natural sand and mine-derived sand delivered to Bige. This allows weighting of total Sulphur and ANC according to the relative amounts of mine-derived and natural sand load. There are no values of Sulphur and ANC for the natural sand load of the Ok Tedi so Upper Fly data have been used.

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### 3. WASTE ROCK DUMP BEHAVIOUR

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The failing dumps on Harvey Creek and Sulphide Creek (Figs 2 and 3) are assumed to lose all delivered material by the end of each model time step. The Vancouver Dump loses a constant 2% of total dump content in each year.<sup>2</sup> This is an estimate and requires verification from ground survey. However, model results further down the system are not greatly sensitive to small variations in this loss rate.

The Vancouver waste rock dump on the north side of the mine occupies the southern side of a small tributary of Sulphide Creek and has a minimal catchment area contributing runoff to the dump surface (Figs. 2 and 3). The tributary valley itself also has a small catchment area so there is limited potential for erosion of material by streamflow across the dump toe. This means that, even though it is a failing dump, material remains at angle of rest until it reaches the valley floor and losses are much less than those from the Southern Dump (Fig. 2). Losses from this dump are

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<sup>2</sup> Some previous mine plans also assumed a constructed dump on Harvey Ck which is no longer the case. Optionally, the mass balance model could include this. If so, the constructed dump was expected to have very high losses initially but these would decline to 5% of total dump content in a given year by 2020. However, these rates are model parameters and may be varied.

treated in the same way as those from the constructed dump (see footnote 2) with the loss rate set by a model parameter.



**Figure 2: The new Northern Dump (left) showing a limited catchment area and limited toe losses. The Southern Dump (right) continues to have a high loss rate. Photos: January, 2014.**



**Figure 3: The original (left) and new (right) Northern Dumps. Note the much more active original dump. Photo: January, 2014.**

#### 4. ESTABLISHING MODEL PARAMETER VALUES

The model has fifteen parameters but many of these are derived from observed values or are calculated from other parameters. Only six are used to calibrate the model and many of these are initially calculated from observed riverbed sampling data or observed river behaviour.

The parameters are listed in Tables 1-3 with comments on their function and how they are derived. In effect, there are three groups. The first group of parameters governs sediment input amounts and geochemical characteristics. A second group determines sediment behaviour during transfer downstream. These include abrasion of limestone and other rock types to sand and enrichment of the Sulphur content of deposited in the lower Middle Ok Tedi due to preferential deposition of heavier material. A third group controls storage behaviour and mixing between storages and also sets the amount of tailings deposited in storages within gravel bed reaches.

Once parameter values are set, the model may be run and a range of values may be compared with observed data from the river bed and from dredge outputs at Bige. Results from this comparison are described in a later section.

| TABLE 1: MASS BALANCE MODEL PARAMETERS<br>SEDIMENT INPUTS                                                   |                                                                                                          |                                                                                                                           |
|-------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| PARAMETER                                                                                                   | FUNCTION                                                                                                 | DERIVATION                                                                                                                |
| <b>Tailings Sand Fraction</b>                                                                               | Sets proportion of sand in tailings based on PSD of material captured by dredge                          | Observed                                                                                                                  |
| <b>Dump annual loss proportion for Rapidly Failing Dumps</b><br>Harvey Ck, Warama Ck & Taranaki Dumps       | Sets proportion of input material lost to river within model time step                                   | Observed                                                                                                                  |
| <b>Dump annual loss proportion for Slowly Failing Dumps</b><br>Harvey Ck Constructed Dump<br>Vancouver Dump | Sets proportion of total dump content material lost to river within model time step                      | Parameter controls input rate from failing dumps. Set as a model run design parameter rather than a calibration parameter |
| <b>Fast Path Coefficient</b>                                                                                | Sets proportion of total waste rock that is sand and is transported straight to the lower Middle Ok Tedi | Calibration parameter initially set from observed particle size distribution of waste                                     |

|                                          |                                                                                     |                                                                                          |
|------------------------------------------|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| <b>Natural Sand Load Characteristics</b> | Mass, ANC and Sulphur. Used to determine dilution rates in the lower Middle OK Tedi | Derived from pre-mine Ok Tedi sediment load observations and Upper Fly geochemistry data |
|------------------------------------------|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|

| TABLE 2: MASS BALANCE MODEL PARAMETERS<br>SEDIMENT BEHAVIOUR             |                                                                                                                                                                  |                                                                                                                                                                       |
|--------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| PARAMETER                                                                | FUNCTION                                                                                                                                                         | DERIVATION                                                                                                                                                            |
| <b>Fraction of Gravel Output to Lower Middle Ok Tedi Abraded to Sand</b> | Sand load derived from coarse waste rock                                                                                                                         | Estimated from waste rock inputs & studies of total mass in the upper river system deposits                                                                           |
| <b>Fraction of total limestone that breaks down to sand</b>              | Influences ANC in dredge sediments - derived from waste rock and additional run of quarry limestone                                                              | Initially estimated from comparison of ANC in dredge sediments and waste rock and additional limestone inputs. Then a calibration parameter is set by trial and error |
| <b>Sulphur Enrichment Rate</b>                                           | Allows for preferential deposition of relatively heavy Sulphur-bearing material in the lower Middle Ok Tedi sand bed reach. Increases with Sulphur concentration | Calibration parameter with value set by trial and error                                                                                                               |

| TABLE 3: MASS BALANCE MODEL PARAMETERS<br>STORAGE AND MIXING                                                       |                                                                                                                                                     |                                                                                                                             |
|--------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|
| PARAMETER                                                                                                          | FUNCTION                                                                                                                                            | DERIVATION                                                                                                                  |
| <b>Fraction of Gravel Reach Riverbed Material made up of Tailings</b>                                              | Used when comparing observed bed samples with model results and also in calculating Sulphur content and ANC of sediment outflow from gravel reaches | Estimated from geochemistry of input material and observed riverbed samples from Ok Mani and Ok Tedi bars                   |
| <b>Upper/Lower Storage weighting Factor</b>                                                                        | Sets amount of mixing between upper and lower sediment storages in gravel reaches                                                                   | Calibration parameter with value set by trial and error                                                                     |
| <b>Relative proportion of sand delivered to Bige from upper and lower bed storages in the lower Middle Ok Tedi</b> | Controls the degree of mixing in the sand bed reach of the lower Middle Ok Tedi                                                                     | Calibration parameter with value set by trial and error but initially set from observations of Bige bed and dredge material |

## 5. MODEL INPUTS

Inputs of waste rock, expressed as mass, total Sulphur and total ANC are plotted in Figs 4-6. These data come from historical information and from the Unrestricted case mine plan for future inputs (see Appendix 1). They show that, over time, both tailings and waste rock inputs have generally decreased up to around 2010 (Fig. 4). After that, tailings inputs are maintained but the rate of waste rock dumping is more variable with much greater use of the Sulphide Creek dumps.

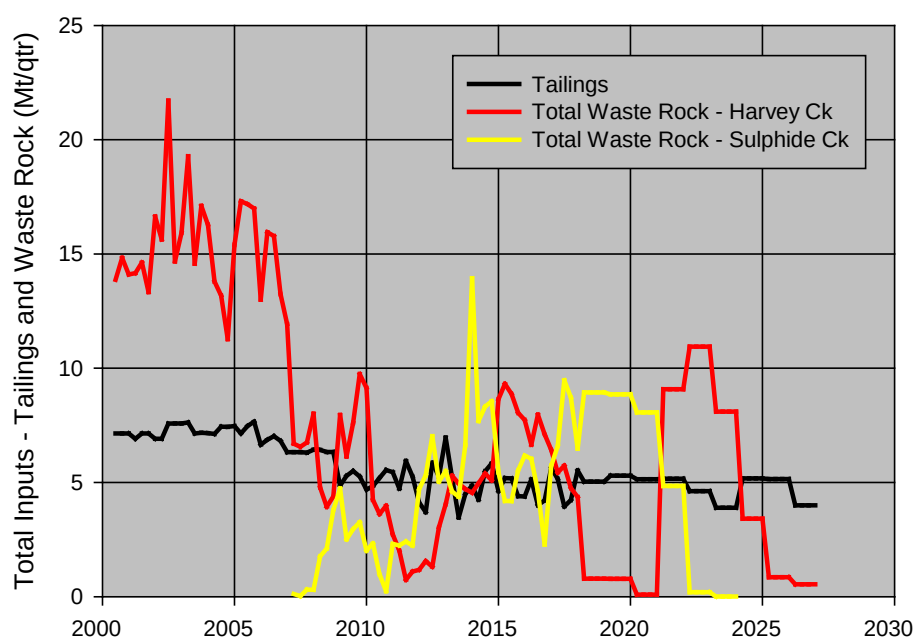


**Figure 4: Total Inputs for the Unrestricted case.**

Total Sulphur inputs also decreased over time to around 2010 (Fig. 5). After that, they become somewhat variable. Even so, Sulphur inputs remain well below those in the period from 2001 to 2008. Sulphur derived from tailings, which, overall, accounts for much of the Sulphur delivery to the lower river, fell to around 2010 but remains more or less constant after that due to the continued operation of the TPP which started to remove Sulphur from tailings in 2009.

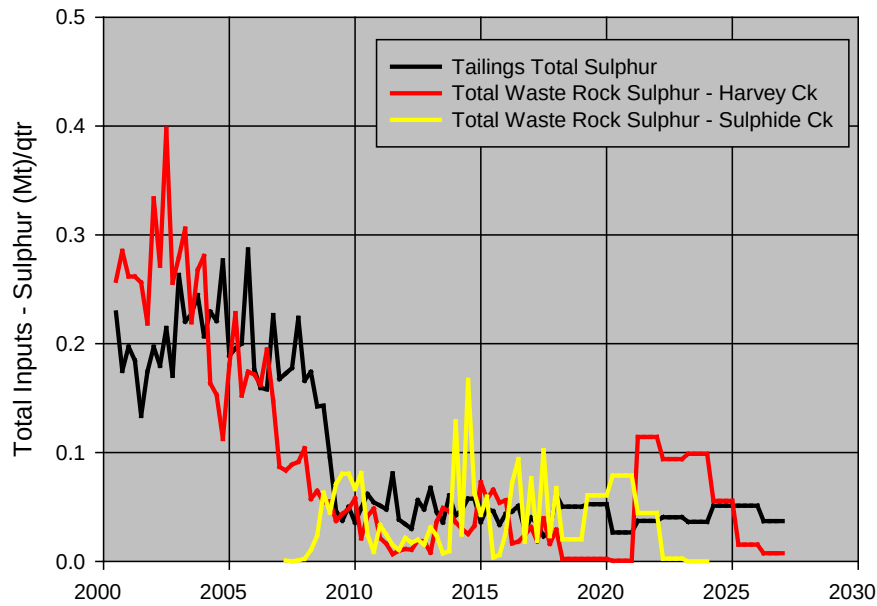


**Figure 5: Total Sulphur Inputs for the Unrestricted case.**

Total ANC inputs are highly variable but fall to a low point around 2012 and then gradually increase until the final years of mine life Fig. 6). The ANC input from tailings increases slightly from 2010 to a peak around 2017 but then falls slightly until mine closure when there is an increase.

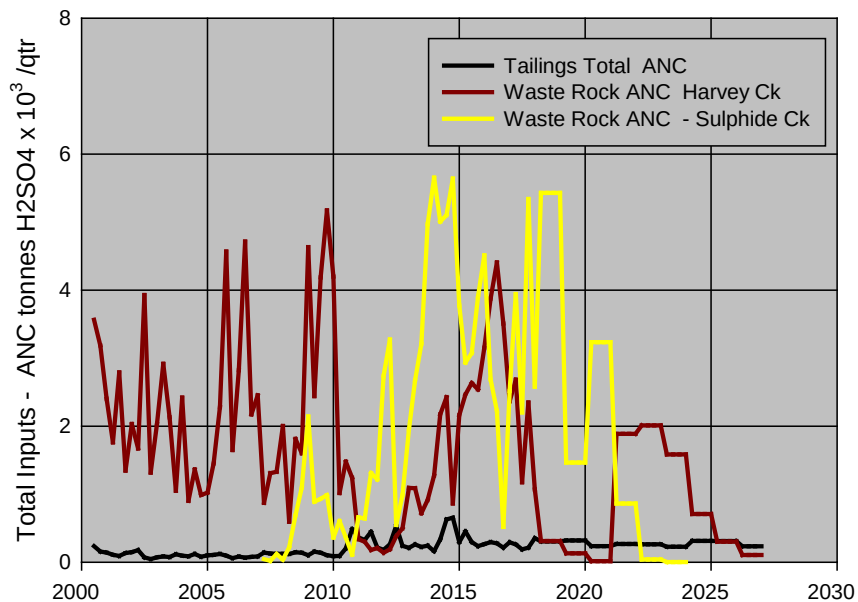


**Figure 6: Total ANC Inputs for the Unrestricted case.**

*OKTUGS* produces annual estimates of total deposition at 2 km intervals down the upper river system. Many of these estimates are approximate given the very basic DEM that had to be used to determine the pre-mine topography. The 2 km data can be easily combined to match the reaches used in the mass balance model. The *OKTUGS* time step does not match the quarterly unit used in the mass balance model so the annual values need to be interpolated to the smaller

time unit. This can produce a stepped effect in mass balance model outputs so the interpolated *OKTUGS* data are smoothed.

## 6. TESTS OF SEDIMENT TRANSPORT MODEL ACCURACY

Model performance depends on:

- Accuracy of mine input data;
- Accuracy of *OKTUGS* predictions of deposition in the various river reaches; and
- The quality of the model calibration (dealt with in the next section).

Mine input geochemistry data is largely derived from a geological block model. While this is thought to be reasonably accurate, there was a period in the mid-2000s when samples of river bed and levee Sulphur content from multiple sources were well below what might have been expected from waste rock Sulphur data. This may reflect errors in the waste rock data.

*OKTUGS* predictions of deposition are reasonably good and are considered in detail in *Pickup and Cui (2014)*. Figures 7 and 8 come from that report and show that Harvey creek and the Ok Mani are modelled very well apart from some underestimation of deposition in recent years. Results for the Ok Tedi are less certain but the observed data (partly derived from relatively low resolution aerial photography from 1982 and 1992) may contain inaccuracies. Recent data from lidar shows much better model performance.

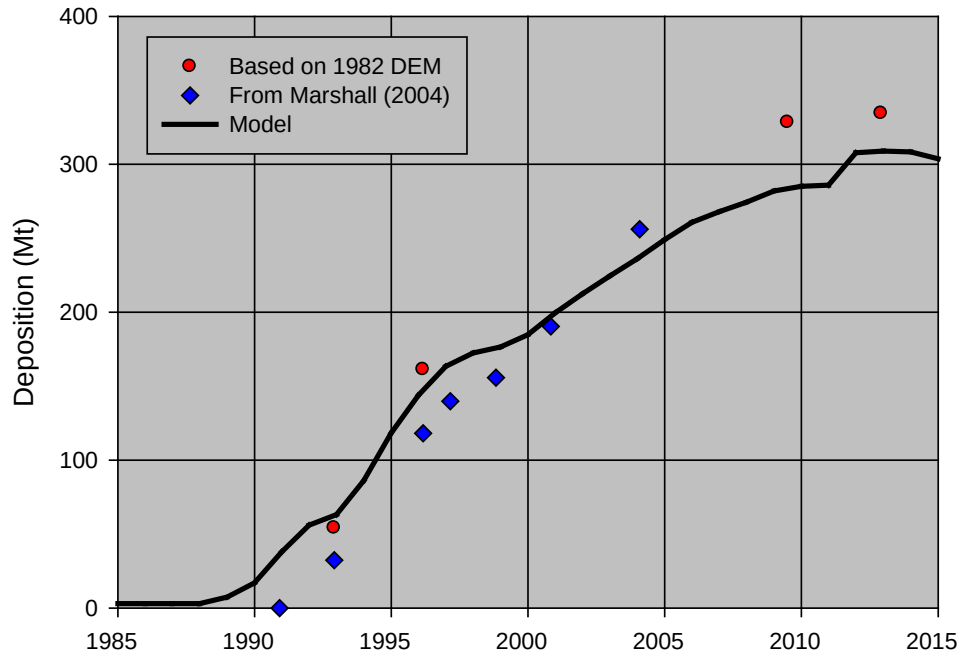


**Figure 7: Comparison of modelled and observed cumulative sediment deposition in Harvey Creek and the Ok Mani (from *Pickup and Cui, 2014*).**

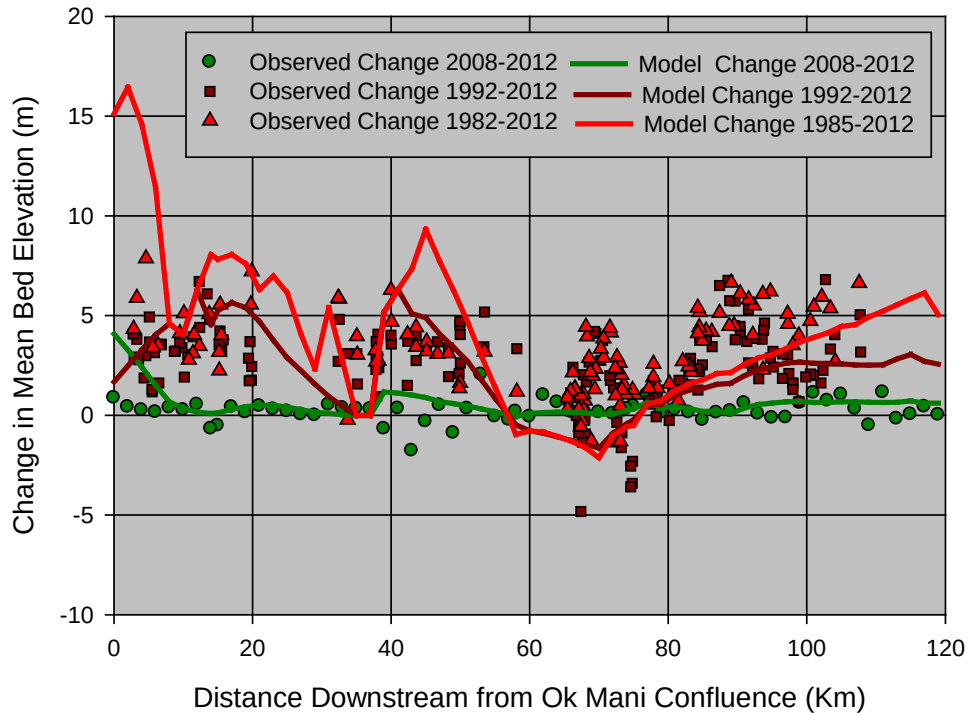


**Figure 8. Comparison of observed and modelled changes in bed elevation in the Middle Ok Tedi (from Pickup and Cui, 2014).**

## 6. MODEL RESULTS FOR THE CALIBRATION/VALIDATION PERIOD

The Sulphur content and ANC of surface material in river deposits is known from a series of samples acquired at regular intervals throughout the upper river system as part of OTML's schedule I and II activities as described in their Annual Environmental Reports. In Harvey Creek and the Ok Mani, sampling is usually carried out on a grid and material comes from the top 30 cm of the accumulated deposits. On the Middle Ok Tedi, where access is more difficult and there is high velocity flow, samples come from channel bars.

Most of the Middle Ok Tedi samples come from gravel reaches and cover more than 100 km of river so they are unlikely to be fully representative. However, they do give a broad indication of how well the mass balance model is performing. The sand bed reach in the lower Middle OK Tedi is sampled intensively by dredging. However, the dredge is at the lower end of the reach and Sulphur content of river deposits is known to increase toward the upstream end.

Model predictions of upper bed storage Sulphur content in Harvey Creek are compared with observed data in Fig. 9. Harvey Creek is a difficult location to sample and there is likely to be wide variability between braided channels and older fan surfaces. It is now even more difficult due to development of a deep central erosion gully. The fan also contains some very large particles (up to 1 m in diameter) which would not have been sampled). There is wide scatter in the observed Sulphur data but the mean value from 2004 to 2013 is 0.67%. The model also predicts substantial

variability but shows a mean of 0.97% which is slightly high. It is suspected that there may be preferential mechanical breakdown of Sulphur-bearing rock by abrasion during dumping and transport down Harvey Creek (*Pickup and Others, 2010a*). This process is not built into the model.

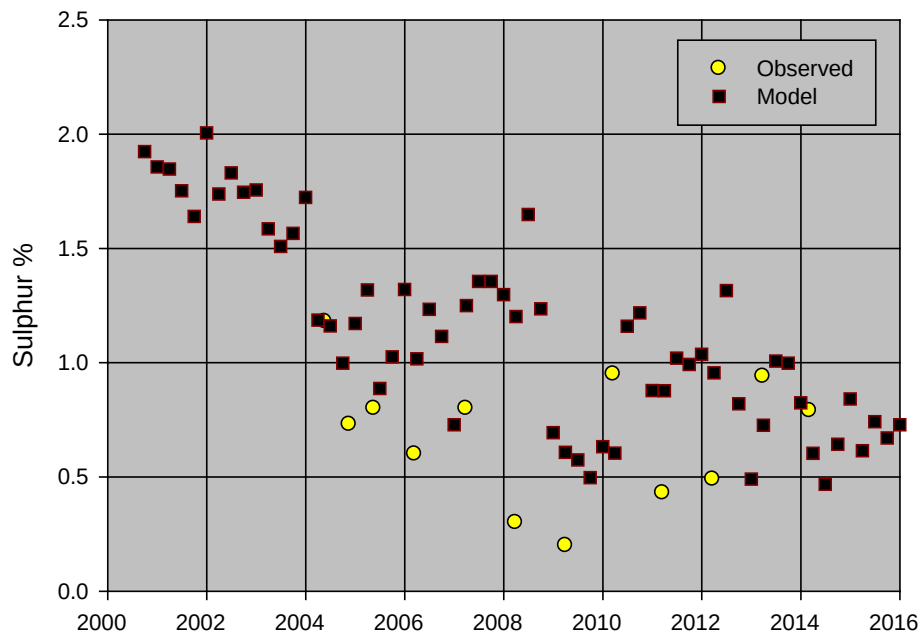


**Figure 9: Observed and modelled surface sediment Sulphur content in Harvey Creek for the model validation period.**

The ANC values of Harvey Creek sediments are shown in Fig. 10. While there is still considerable scatter in both observed data and model predictions, both show a rising trend. Both have similar average values from 2004 to 2014 with the model predicting 192 kg H<sub>2</sub>SO<sub>4</sub>/tonne while the observed data have an average value of 201 kg H<sub>2</sub>SO<sub>4</sub>/tonne.

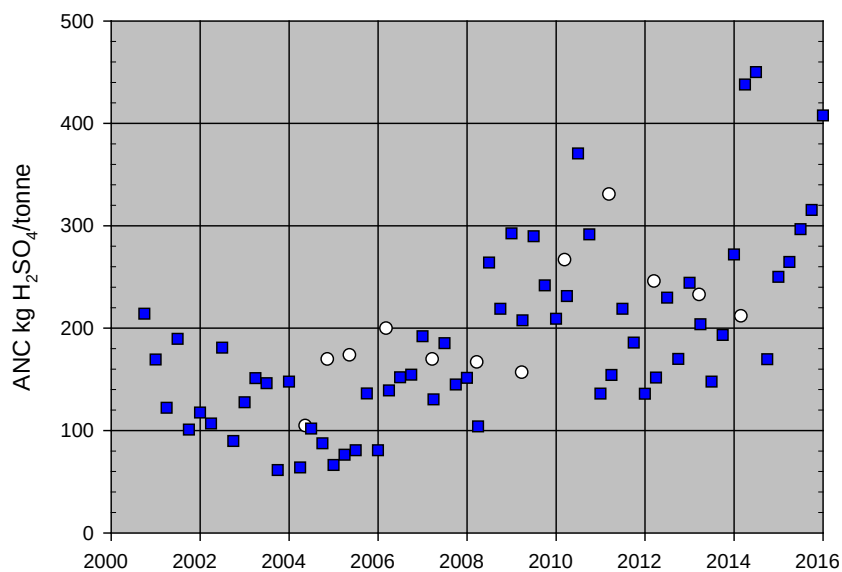


**Figure 10: Observed and modelled surface sediment ANC in Harvey Creek for the model validation period.**

Sulphur content and ANC values for the Ok Mani are shown in Figs. 11 and 12. Once again there is considerable scatter in both observed data and model predictions over time. However, both Sulphur datasets show a downward trend and reasonable correspondence between observed and predicted data. The observed and predicted ANC values both show an upward trend and correspond more closely than the Sulphur values.

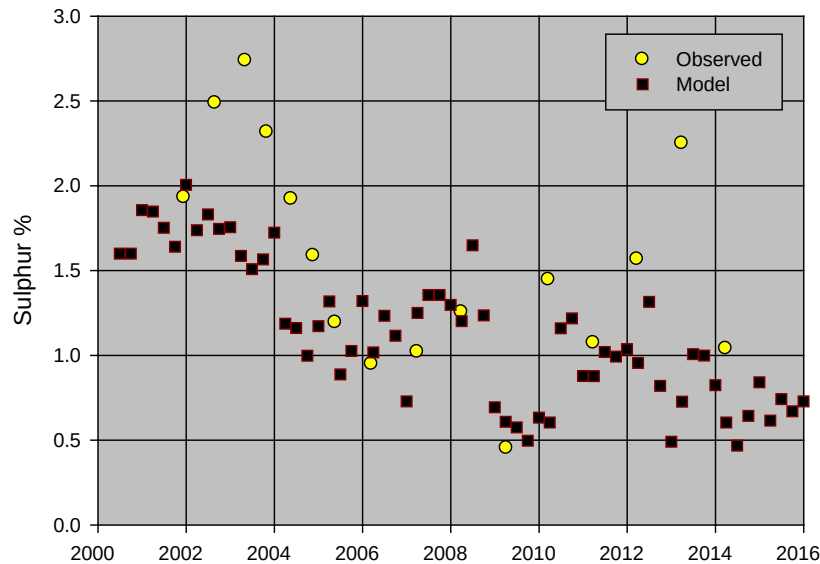


**Figure 11: Observed and modelled surface sediment Sulphur content in the Ok Mani for the model validation period.**

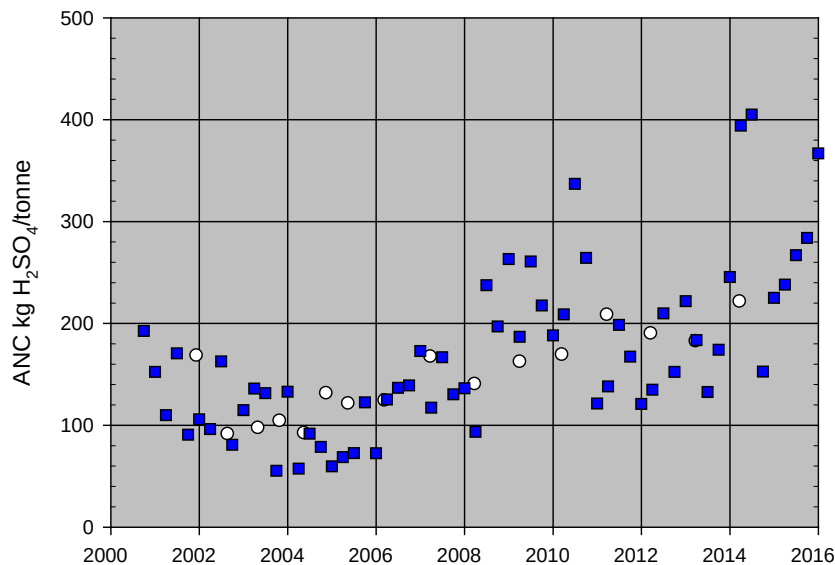


**Figure 12: Observed and modelled surface sediment ANC in the Ok Mani for the model validation period.**

The upper Middle Ok Tedi results are shown in Figs. 13 and 14. The observed values (GSB1-GSB18) come from a series of bars, mostly located in areas of channel widening. Deposited sediments here are likely to be finer than average which slightly favours non-limestone material so the observed %S values may be elevated. Observed ANC values may be biased slightly low. Given

these sampling issues, model predictions of both %S and ANC are good and reproduce observed trends over time.

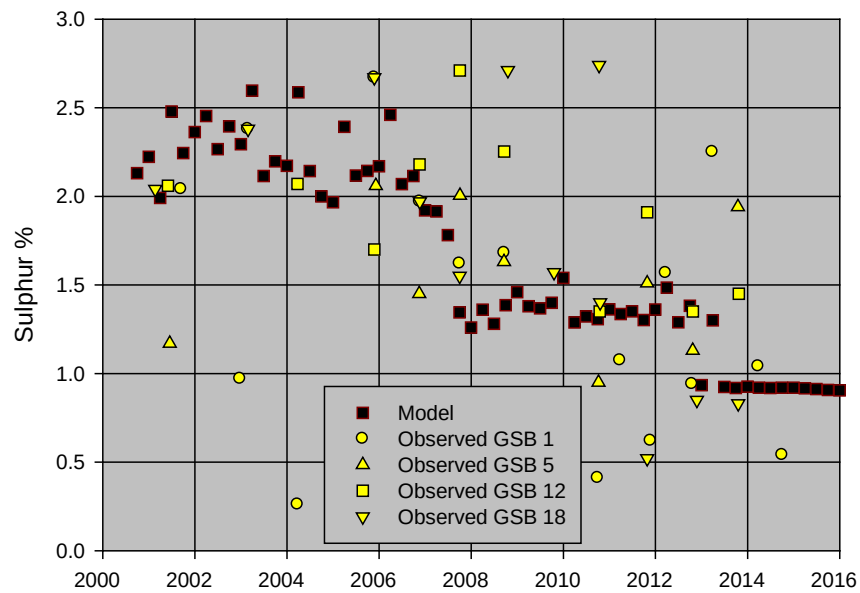


**Figure 13: Observed and modelled surface sediment Sulphur content in the upper Middle Ok Tedi for the model validation period.**

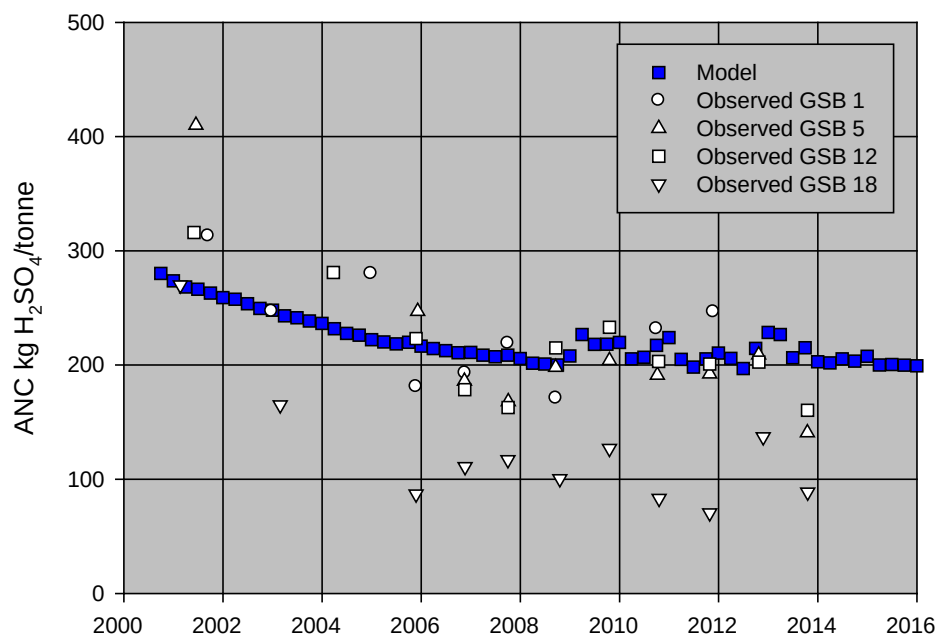


**Figure 14: Observed and modelled surface sediment ANC in the upper Middle Ok Tedi for the model validation period.**

The lower Middle Ok marks a transition from a gravel bed river to a sand bed. Sand deposition in this transition zone favours the heavier material so %S values in river sediments should be

higher than in upstream reaches. The lower Middle Ok Tedi is also the first reach where there is substantial long-term deposition of tailings. The main dataset for comparison with model results is the dredge material geochemistry but there are also data from river channel bars (labelled GSB on the graphs below).

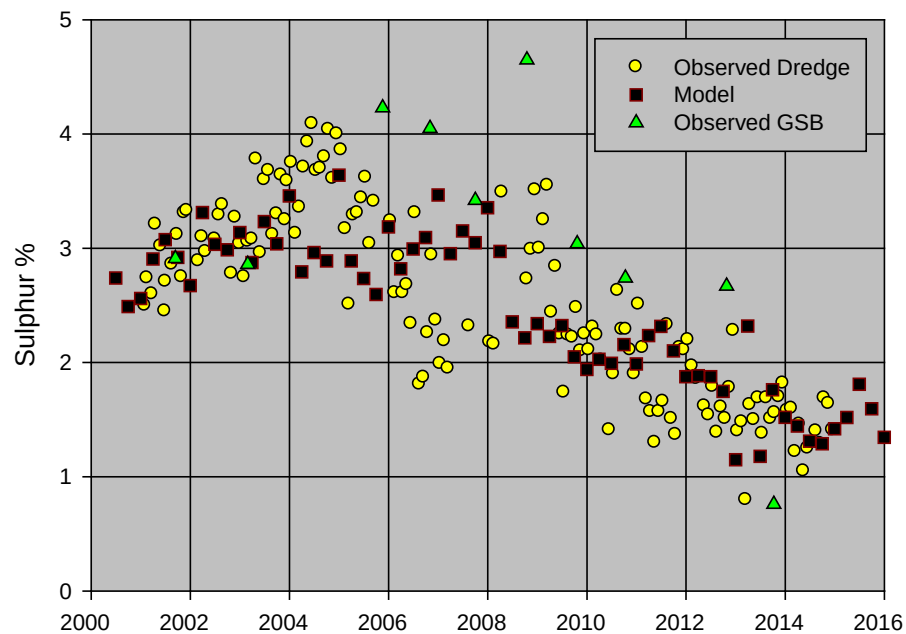


**Figure 15: Observed and modelled surface sediment Sulphur content at Bige for the model validation period.**

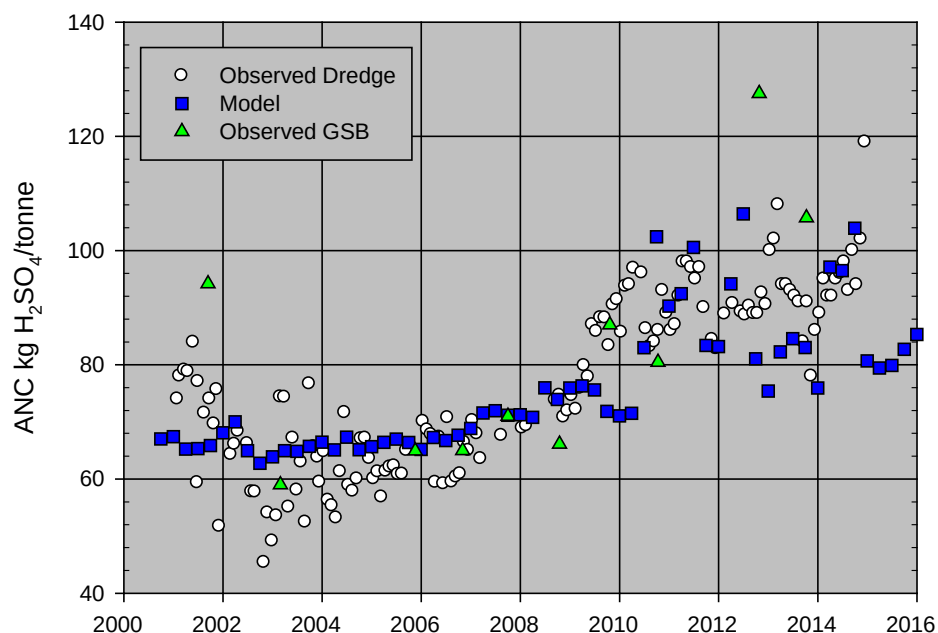


**Figure 16: Observed and modelled surface sediment ANC at Bige for the model validation period.**  
Observed GSB refers to bed samples from channel bars.

Model Sulphur results (Fig 15) correspond with observed dredge data apart from a period between 2006 and 2008 when waste rock input data are thought to be incorrect. The GSB sample data show higher %S content than both the model and the dredge sediments because they come from locations further upstream where greater accumulation of heavier material can be expected. Lower Middle Ok Tedi ANC results also matched the observed data closely.

## 7. MODEL RESULTS FOR THE CALIBRATION/VALIDATION PERIOD

Model predictions for %S, ANC and the ANC:MPA ratio have been made for each of Harvey Creek, the Ok Mani, the upper Middle Ok Tedi and the lower Middle Ok Tedi. These are shown in the graphs below.

In Harvey Creek (Figs 17-19), Sulphur content of surface material continues to fall until 2020 when it begins to rise again until mine closure although there is a slight fall in the last two years of mine life. After that it remains constant. However this is because the river is eroding existing deposits where the Sulphur content is largely unknown for material deposited before 2000. The constant value after mine closure reflects the estimated Sulphur content of pre-2000 deposits at the start of the model run. This was determined from the earliest known sample values in Harvey Creek.

Predicted ANC values (Fig. 18) continue to rise until 2020 when there is a reduction in ANC inputs (Fig.6). ANC: MPA values rise until about 2020 and then fall, eventually reaching the constant value set by initial assumptions about pre-2020 material stored in deposits. All post-2010 ANC: MPA values exceed 4.0.

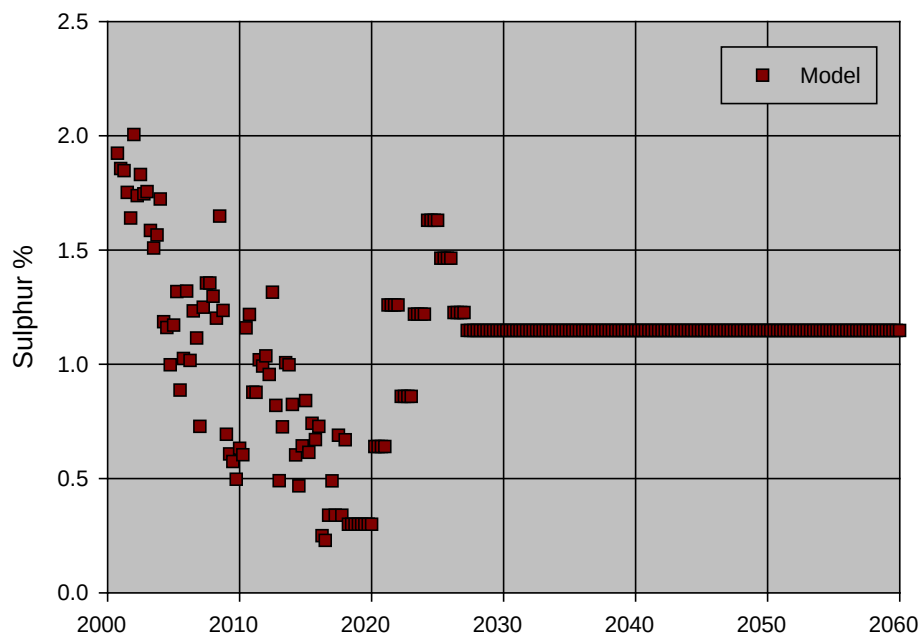


Figure 17: Long term model predictions for surface sediment Sulphur content in Harvey Creek.

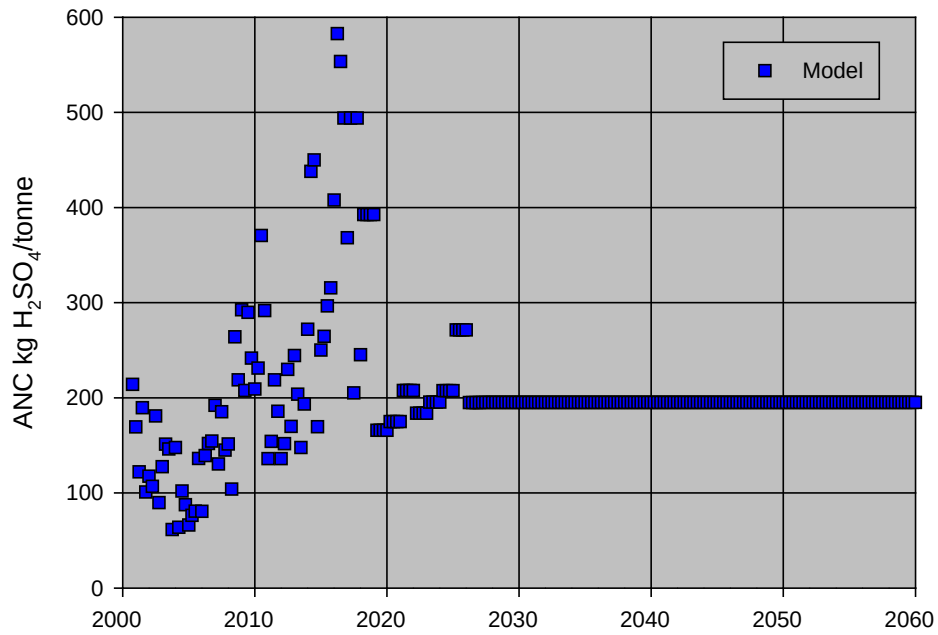


**Figure 18: Long term model predictions for surface sediment ANC in Harvey Creek.**

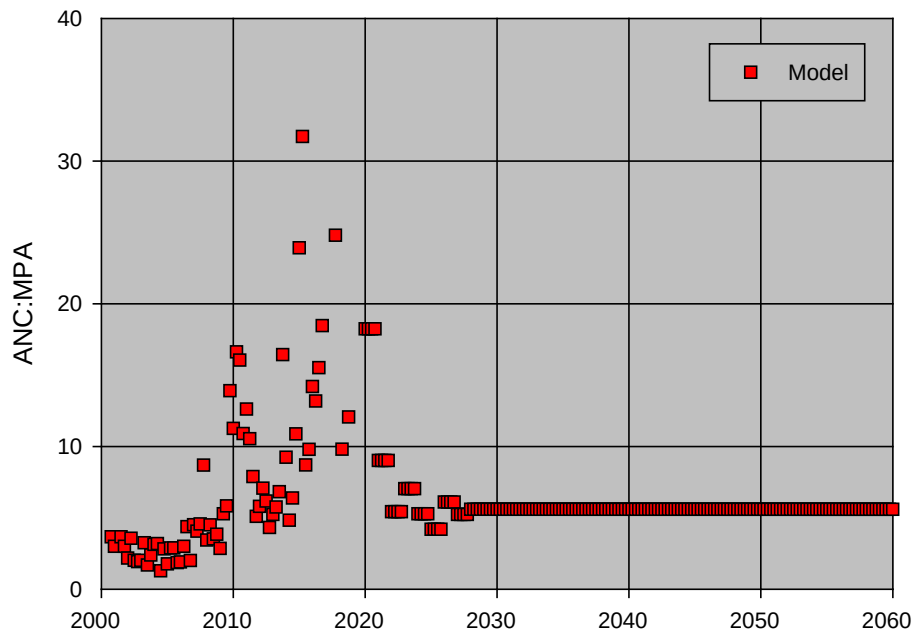


**Figure 19: Long term model predictions of ANC: MPA for surface sediment in Harvey Creek.**

Predictions for the Ok Mani (Figs 20-22) show falling %S values until 2020, followed by a rise. Then there is a gradual fall to the end of mine life marking the end of tailings inputs. Thereafter, %S gradually rises from about 1% to 1.5% by 2060. ANC values continually rise to the end of mine life when they drop abruptly; again reflecting the end of fast path inputs from newly dumped waste rock and tailings disposal. After mine closure, there is a continual increase in ANC up to around 450 kg H<sub>2</sub>SO<sub>4</sub>/tonne by 2060. ANC: MPA ratios gradually increase after 2010 and are always above 3.5.

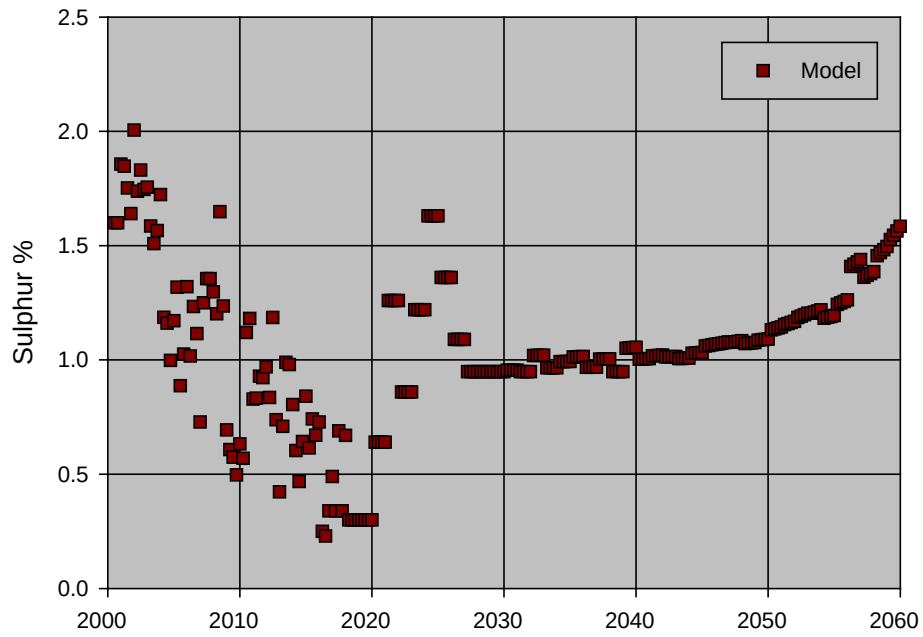


**Figure 20: Long term model predictions for surface sediment Sulphur content in the Ok Mani.**

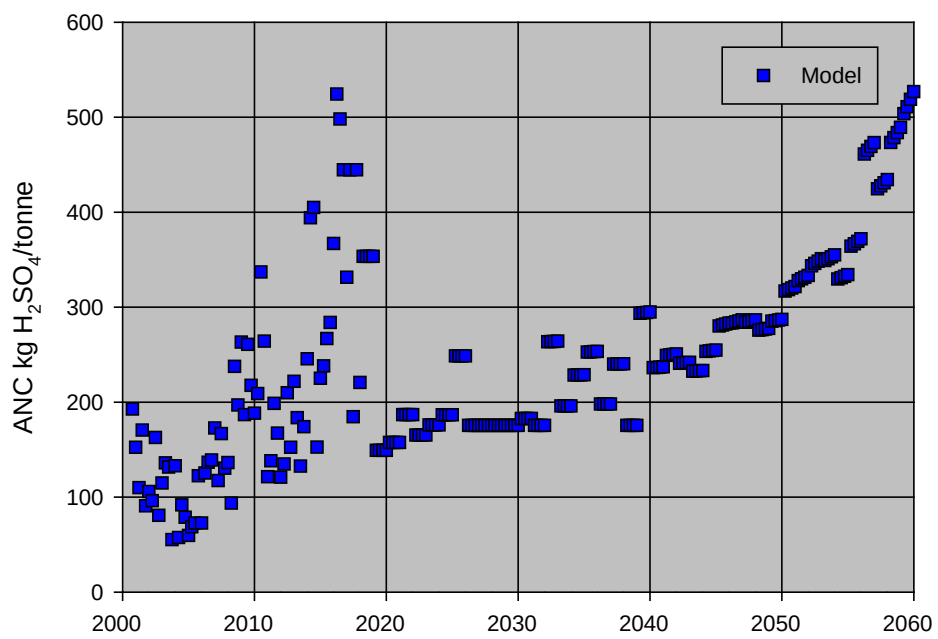


**Figure 21: Long term model predictions for surface sediment ANC in the Ok Mani.**

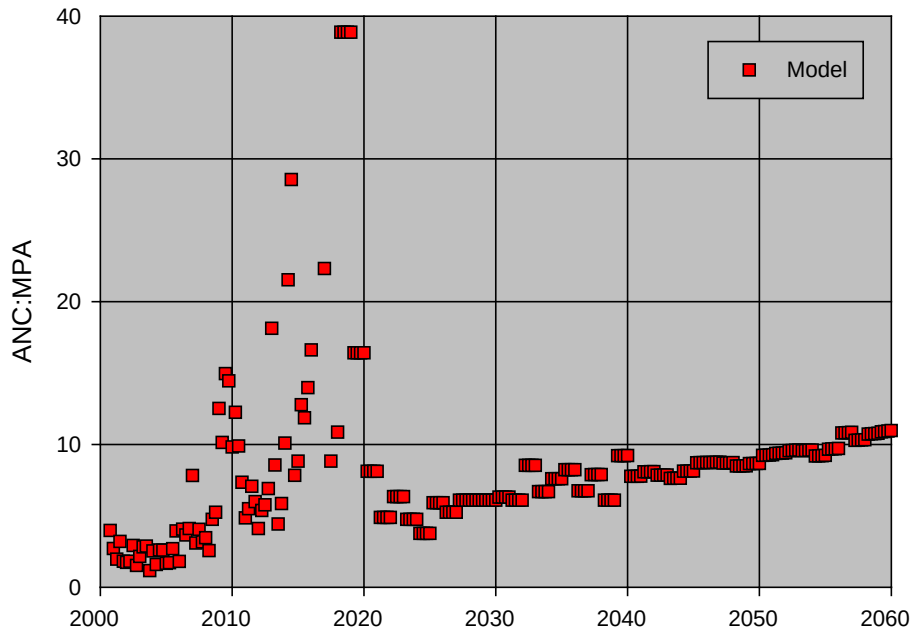


**Figure 22: Long term model predictions of ANC: MPA for surface sediment in the Ok Mani.**

In the upper Middle Ok Tedi, much of the upstream variability is damped out as mine inputs mix with deposited sediment (Figs 23-25). Sulphur content falls until the end of mine life and then remains fairly constant around 0.75%. ANC falls from 200 to 2010, fluctuates during the mine continuation and then remain fairly constant at around 180 kg  $\text{H}_2\text{SO}_4$ /tonne until 2050 when there is a gradual rise. ANC: MPA values rise until about 2015, fall slightly and then remain fairly constant at about 7.5.

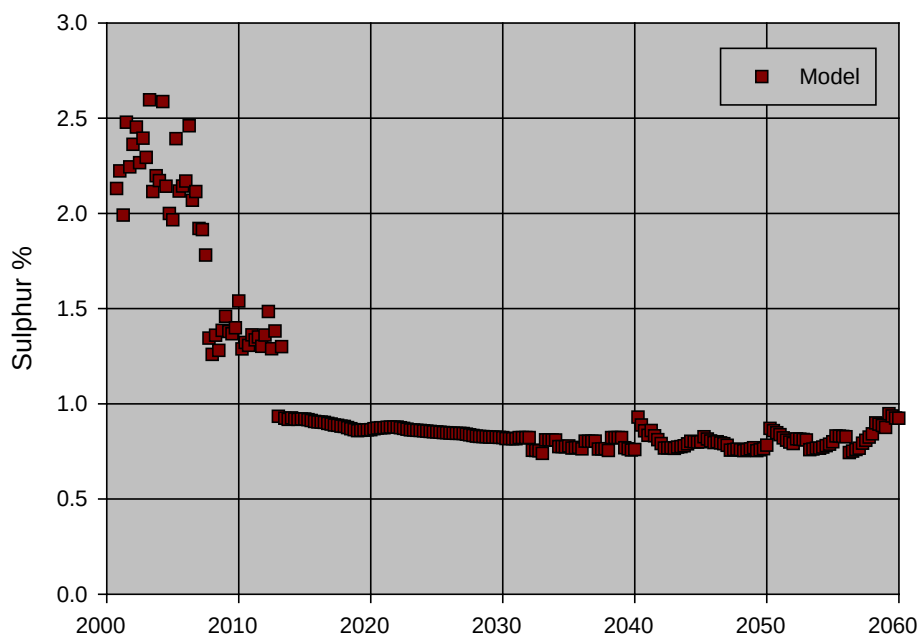


**Figure 23: Long term model predictions for surface sediment Sulphur content in the upper Middle Ok Tedi.**

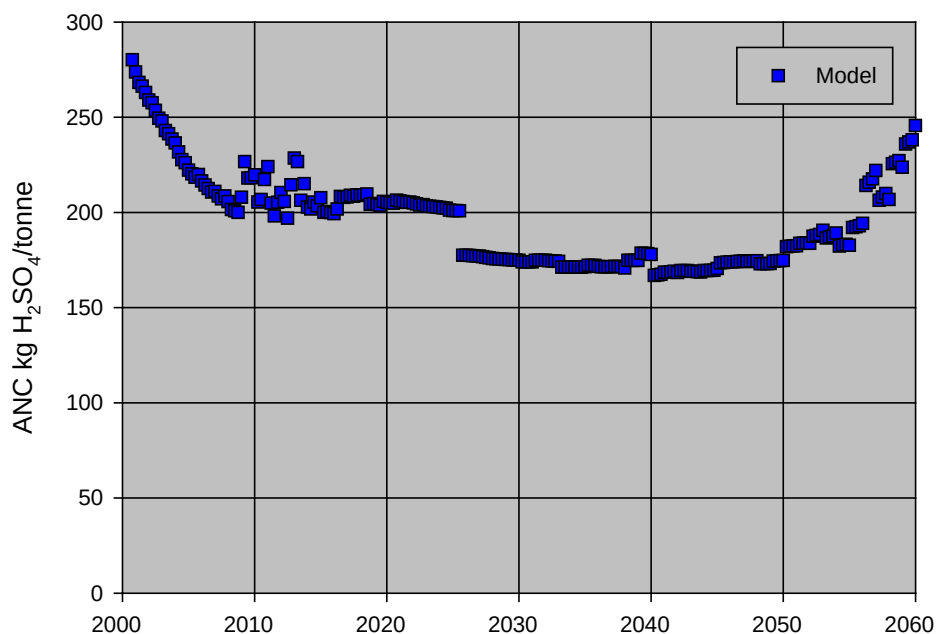


**Figure 24: Long term model predictions for surface sediment ANC in the upper Middle Ok Tedi.**

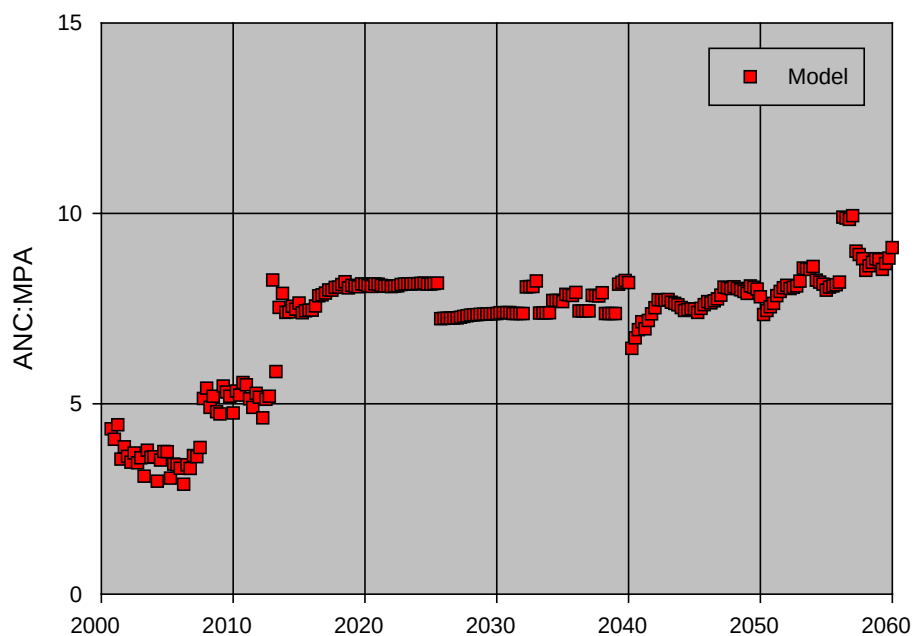


**Figure 25: Long term model predictions of ANC: MPA for surface sediment in the upper Middle Ok Tedi.**

Long term predictions for the lower Middle Ok Tedi at Bige show a generally falling trend in Sulphur until mine closure after which values stabilise at around 1%. ANC is more variable

reflecting waste rock inputs. It rises until about 2020 when there is a steep fall followed by a rise at the end of mine life. Values then fall until about 2030 when they stabilise at around 60 kg  $\text{H}_2\text{SO}_4/\text{tonne}$ . ANC: MPA values rise, fall steeply around 2020 then rise again until the end of mine life. Thereafter, they fluctuate, eventually stabilising at around 1.8 after 2040. Most of the time ANC: MPA values are satisfactory apart from a brief period around 2020 when they fall to around 1.3.

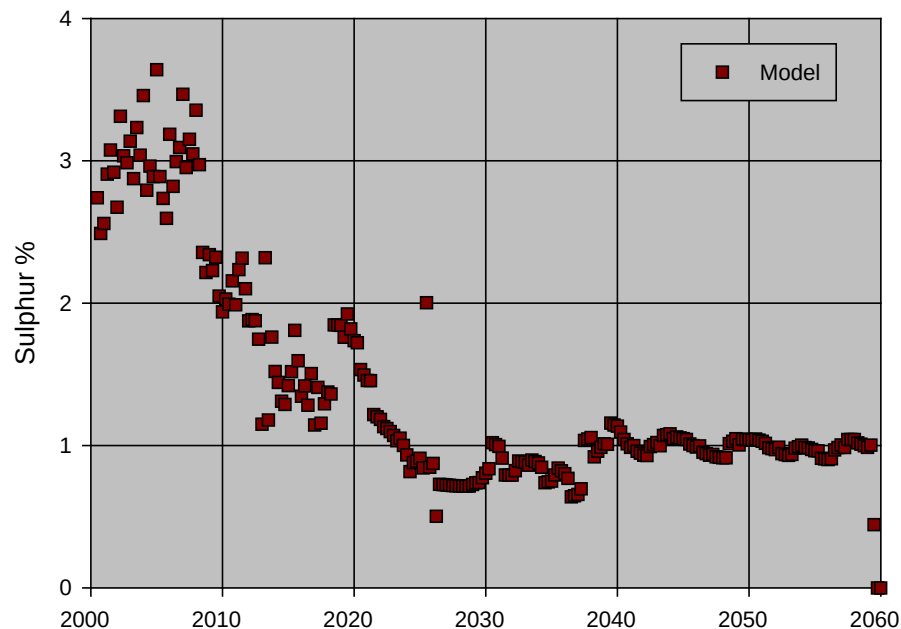


**Figure 26: Long term model predictions for surface sediment Sulphur content at Bige.**

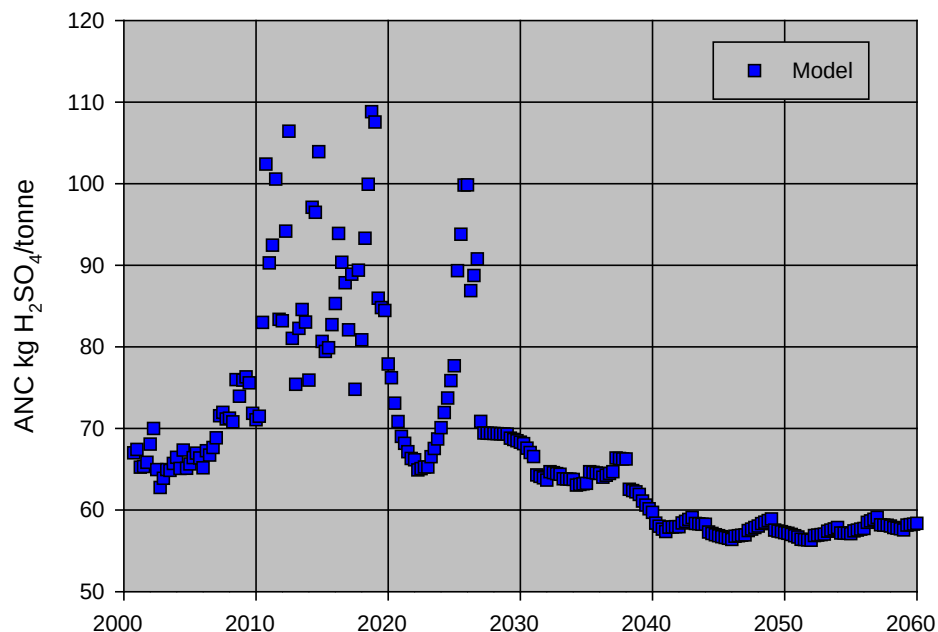


**Figure 27: Long term model predictions for surface sediment ANC at Bige.**

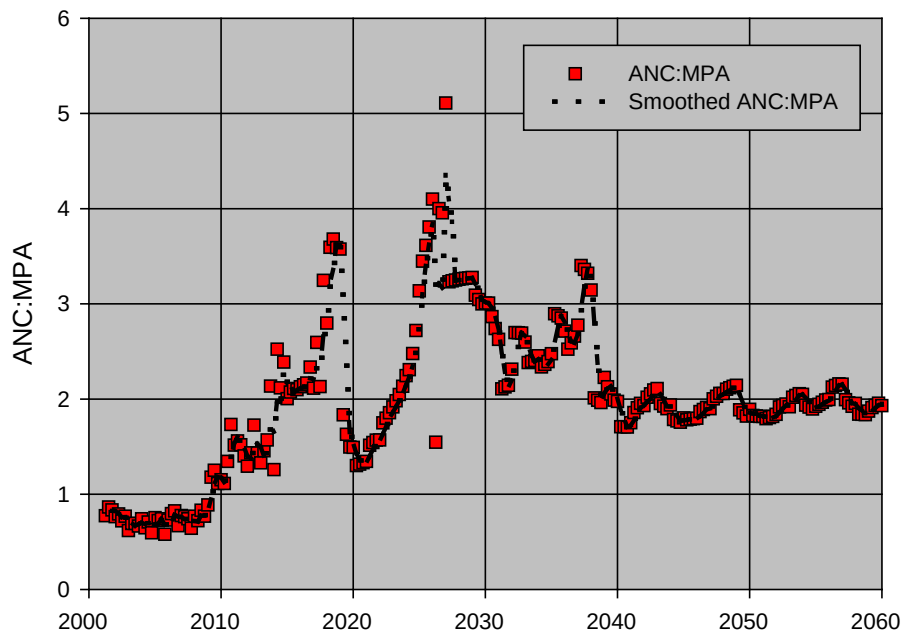


**Figure 28: Long term model predictions of ANC: MPA for surface sediment at Bige.**

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## APPENDIX 1: UNRESTRICTED MINE PLAN

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# THE COPPER MASS BALANCE MODEL FOR SEDIMENT DEPOSITS, DISSOLVED AND PARTICULATE COPPER LOADS

## Report for Ok Tedi Mining Ltd

*Dr Geoff Pickup, Consulting Geomorphologist,*

*Dr Michael Ridd, Environment and Mine Planning  
Consultant*

*Jesse Pile and Erizo Kepe,*

*Environment Department, Ok Tedi Mining Ltd*

9 September, 2018

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## INTRODUCTION – GEOCHEMICAL MASS BALANCE MODEL STRUCTURE

The original upper river system mass balance model (*MBM*) (Fig.1) is described in detail by *Pickup and Pile (2013)* and *Pickup (2014)*. These reports cover the various sediment storages in the river, their inflows and outflows, and the governing equations and calculation methods that drive the model. These are implemented as a multi-worksheet *EXCEL* file which provides estimates of sulphur, ANC and ANC:MPA ratios in river bed deposits at various locations in the upper river system. It also predicts these values in Bige dredge offtake material. This report describes how the model has been extended to include copper in upper river system sediment deposits and also, to estimate dissolved and particulate copper concentration in the lower river system flow and suspended sediment load..

Very little silt is deposited in the upper river system because the river is too fast-flowing. This makes it necessary to use separate models for gravel/sand geochemistry and silt geochemistry.

The original *MBM* focuses on gravel and sand behaviour in the upper river system and includes calculations for individual sections of the river and covers inflow and outflow of sediment, including both sands and gravels, together with the associated sulphur load and ANC. Model accounting also covers the amount and geochemistry of material held in storage in each river section.

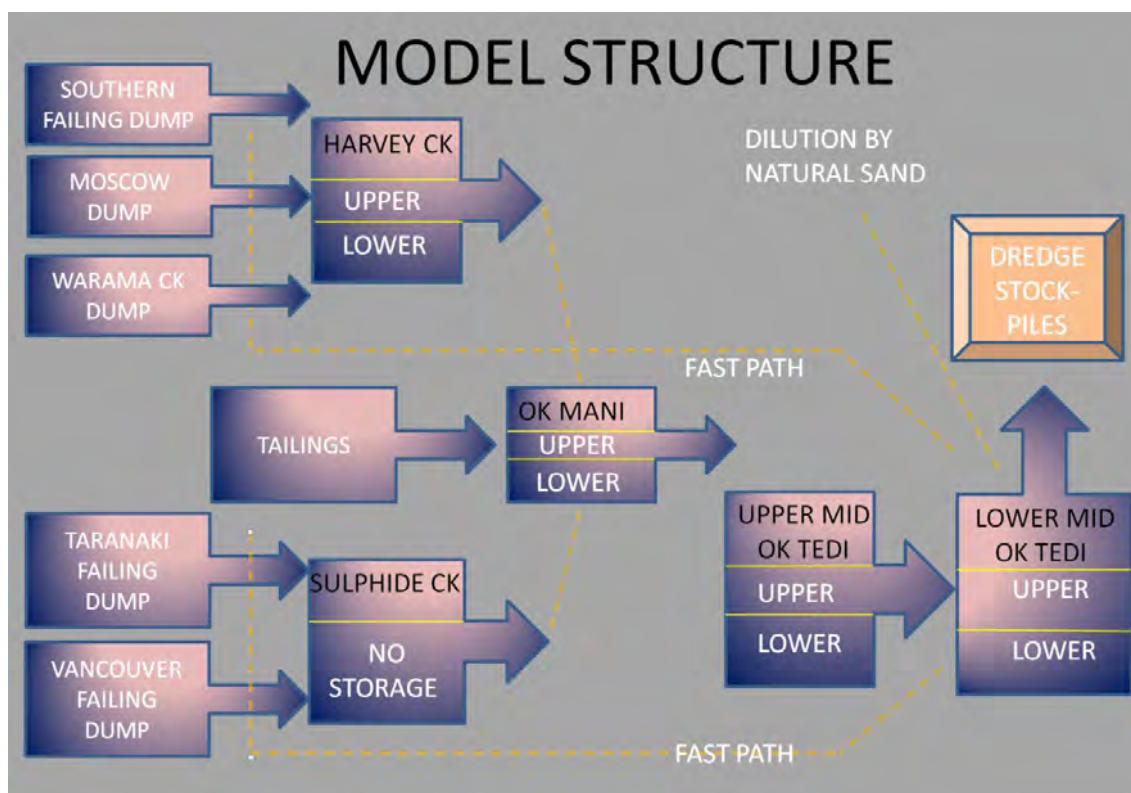


**Figure 1: Geochemistry model structure (sand) – upper River System.**

In the lower river system, copper is delivered within the sandy bedload, as part of the suspended load (consisting mainly of silt), and in dissolved form. The lower river model uses outputs from the upper river mass balance model together with information on silt loads derived from the *OKTUGS* sediment transport model to estimate copper concentration in the suspended sediment load. A set of station-specific empirical regression equations are then used to extend this information to estimation of dissolved copper in river flow.

The upper river system mass balance model (*MBM*) operates in the following manner:

- The sand/gravel *MBM* model consists of inputs from tailings and the waste rock dumps, together with inflows, storages and outflows from the Mine Area Creeks (MACs – Harvey Creek, Sulphide Creek and the Ok Mani), and the upper and Lower Middle Ok Tedi.
- Tailings on entry to the system are divided into sand and silt components with the silt being routed straight through the model to the lower river system.
- The upper Ok Tedi between the Sulphide Creek junction and the Ok Mani is treated as a transit zone with minimal deposition and input material passing through with no alteration.
- The Southern Dumps are treated as rapidly failing and lose their total contents to Harvey Creek within each model 3-month time step. The Taranaki Dump on the north side of the mine is also treated as rapidly failing. The Vancouver Dump is treated as slowly failing and loses 20%<sup>1</sup> of total contents within each 3-month period.
- Sand output at the lower end of the system is delivered to the lower Middle Ok Tedi and the Bige Dredge with both components assumed to have the same geochemistry.
- Some additional silt is generated by particle abrasion during transport down the 120 km of river prior to reaching the dredge site. This is routed straight through to the lower river system.

Each element of the river system has the following processes or elements:

- A fast path from the dumps to the lower Middle Ok Tedi to allow for the finer components of waste rock which pass through the system with minimal deposition (usually 10-15% of input).
- For slower and intermittently moving material, the model assumes input from upstream, storage in riverbed deposits (which may change over time with either erosion or deposition), and output. These values are

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<sup>1</sup> This value was derived from two high resolution surveys of dump volume in the early stages of dump operation. It may need to be reduced once more recent data become available.

determined from the deposition calculations in the *OKTUGS* sediment transport model (*Cui and Pickup, 2009*)

- Use of the *OKTUGS* allowing calculations after mine closure whereas earlier versions of the *MBM* model only operated during mine life.
- Within each section of the river, deposition is held in and upper and lower sediment storage. The upper storage is active and holds material actively moving through the system. The lower storage holds material that is mainly buried but may be exposed at times.
- A proportion of tailings may be held within the interstices of gravel deposits.
- A mixing component which allows material from upper and lower storages to be added to the sediment output.
- An abrasion factor to allow for gravel breakdown to finer material.

### **ADDING A COPPER (SAND & GRAVEL) *MBM* COMPONENT**

The copper model uses the same structure as the Sulphur component of the existing model with changes to two parameters to allow for the differences in particle density. In the sulphur model, expected %S content at Bige is increased by 30% to allow for a higher rate of deposition by sulphur rich material which is heavier than other delivered load. This correction is not applied to copper which does not show fractionation along the dredge slot. . More mixing with the lower bed store in the lower Middle Ok Tedi is also allowed as copper is likely to be more generally distributed throughout the reach than the heavier sulphur-rich material. This seems to be verified by sampling along the 0.8 km length of the Bige dredge slot.

## COPPER (SAND & GRAVEL) MODEL RESULTS

This section compares model results with observed deposition in various reaches of the upper river system. A series of dot points below each graph summarises the main points.

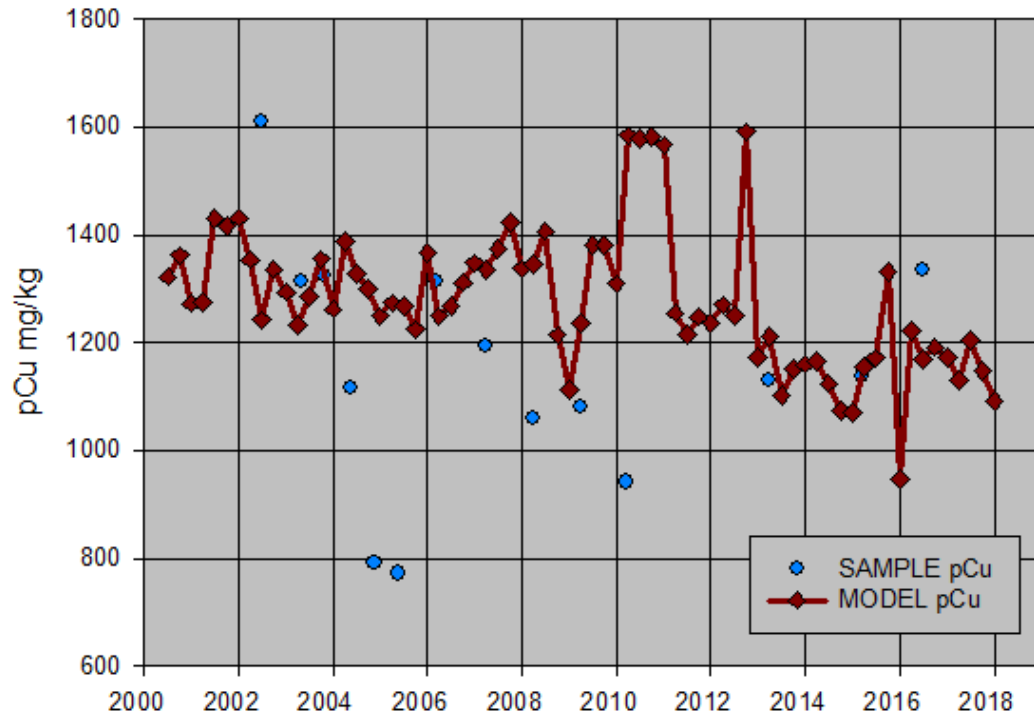


**Figure 2: Harvey Creek – bed particulate copper concentration (pCu).**

- Harvey Creek (Fig. 2) is a very difficult area to sample accurately with fast flowing watercourses and very coarse material including boulders so considerable scatter in the observed data should be expected.
- Model results lie well within the range of observed data.

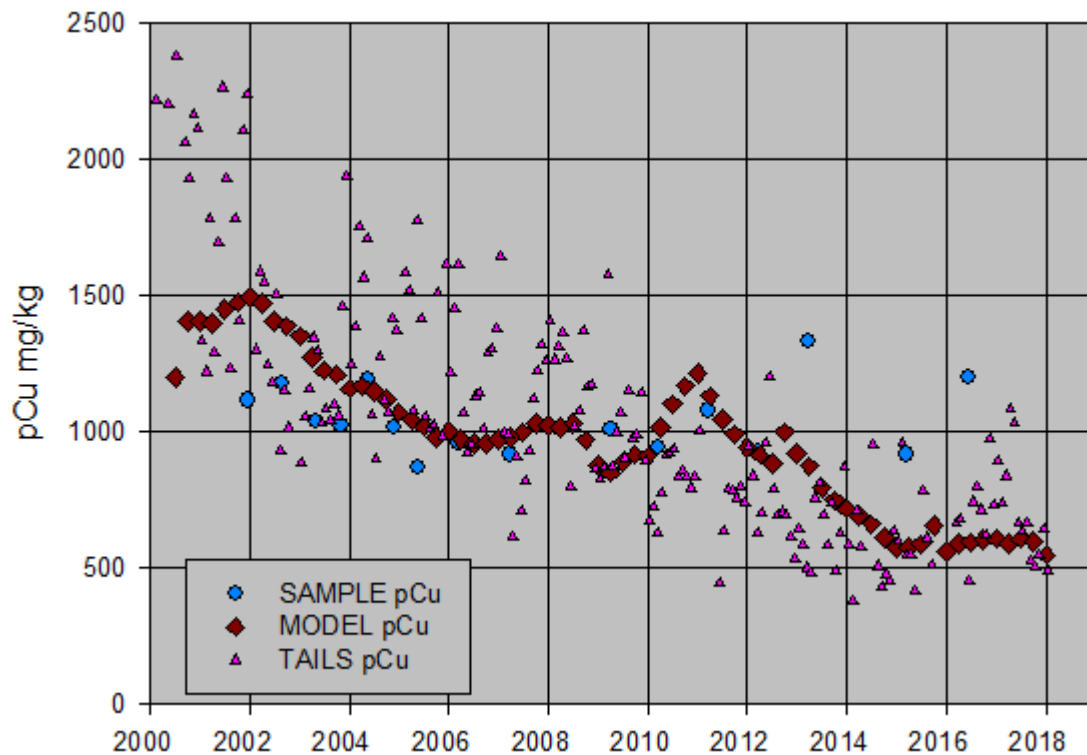


**Figure 3: Ok Mani – bed and tailings particulate copper concentration (pCu).**

- Like Harvey Creek, the Ok Mani is a difficult area to sample as the surface material is coarse gravel but contains a proportion of tailings so again, considerable scatter due to sampling error may be expected in observed data.
- The model performs reasonably well until 2012 when it begins to underestimate the observed data. However, it does reflect the tails values more closely in this period.
- A single model parameter of 0.3 is used to estimate the proportion of tails in gravel so it is possible that this is too high for the Ok Mani. However, it does give reasonable results for the upper Middle Ok Tedi (Fig. 4) and resembles observed values in the gravel bars of that system.
- During the period around 2013, the rate of waste rock dumping into the Harvey Creek system was greatly reduced and there was widespread erosion in its upper reaches including a 50m deep gully. Harvey Creek would then have delivered old waste rock deposits to the Ok Mani with an unknown but almost certainly higher copper content than in subsequent years.

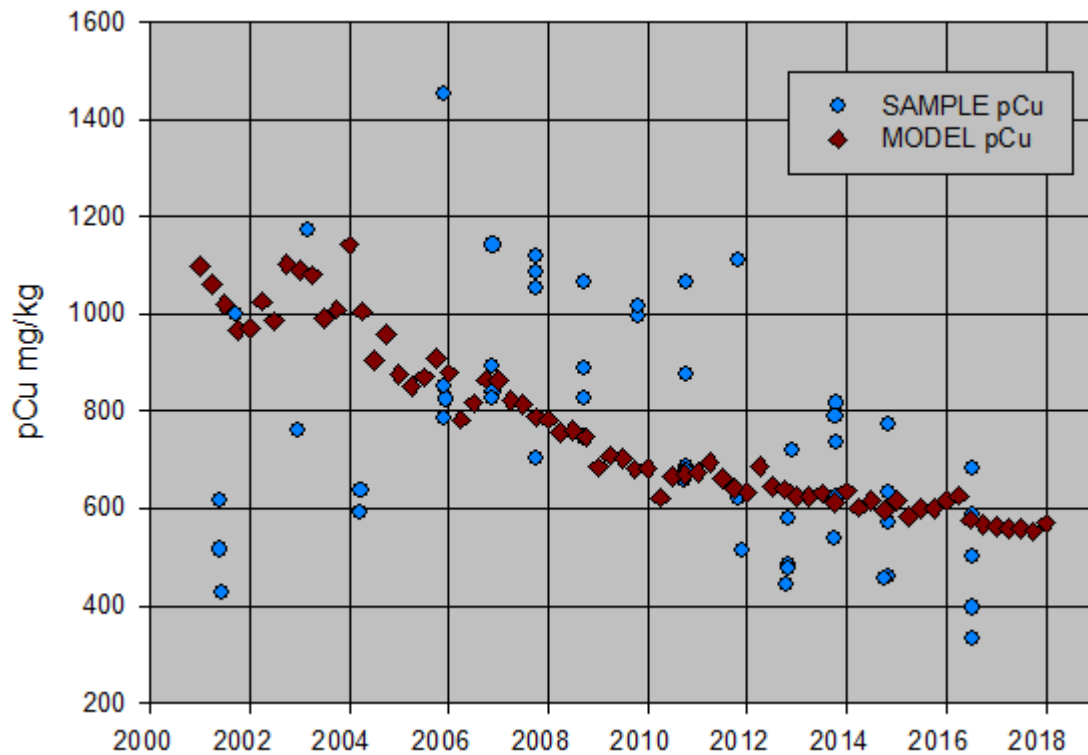


**Figure 4: Upper Middle Ok Tedi – bed particulate copper concentration (pCu).**

- The Upper Middle Ok Tedi observed values come from samples taken from gravel bars. Sampling error would be significant given the 90 km length of the reach.
- The model performs reasonably except during the 2000-2004 period. Initial copper concentration values for older material stored in the reach had to be assumed to start the model run and these may have been too low.
- The decreasing trend in copper values is reproduced reasonably well after 2004.

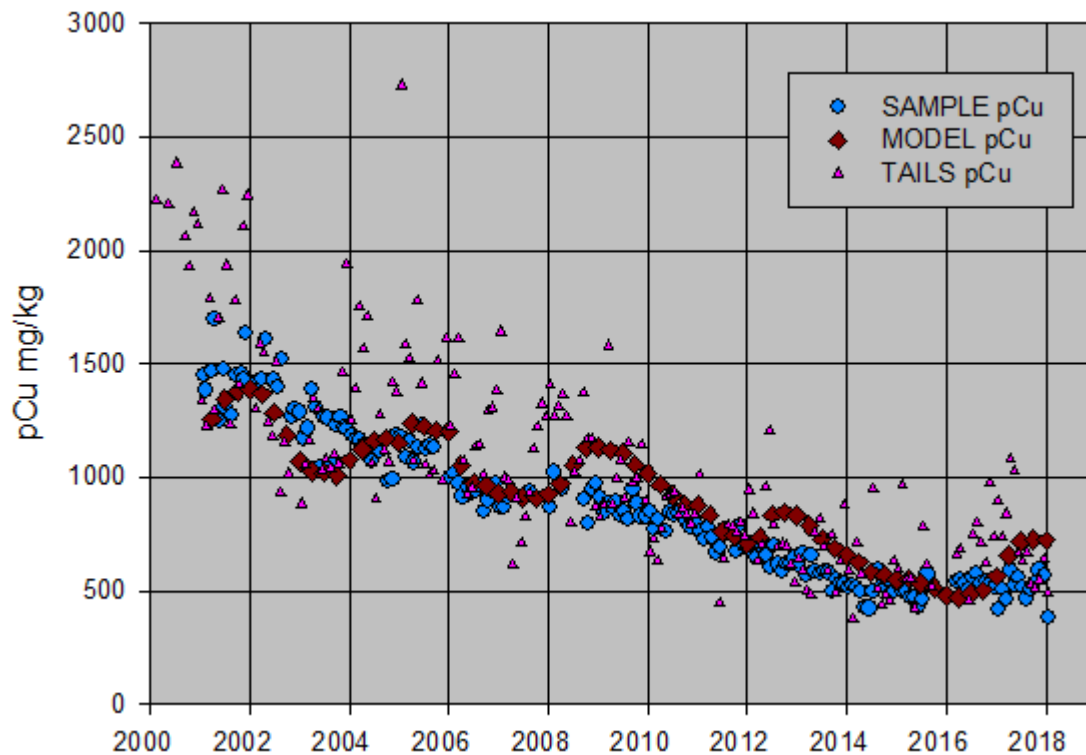


**Figure 5: Lower Middle Ok Tedi and Bige dredge material particulate copper concentration (pCu).**

- Much of the Lower Middle Ok Tedi riverbed material is captured by the dredge so dredge output copper concentrations gives a good measure of copper in sediments delivered from upstream as sand (very little gravel passes through this reach).
- Model behaviour closely reproduces Cu content in Bige dredge material for most of the time, even when tailings Cu content is substantially higher than dredge material. The main deviations are in the early years before 2004. At this time, some low grade materials previously disposed into to the river system were stockpiled for blending purposes. At other times, there were changes to dredging practices. These include periods when the dredge slot was deepened and when the dredge slot was full as main- river dredging was reduced while the Bige West Bank pCon storage was being excavated. At other times, the dredge slot would have been full after mine reopening in 2016 after the 2015 drought and also, the dredge did not operate at full capacity from late 2017.

## PARTICULATE COPPER LOAD

The particulate copper suspended load model assumes that material entering the lower river system is made up of the sand load at Bige and the silt and some of the very fine sand component of tailings. Fine material derived from gravel breakdown is also included. Added to this will be a dilution effect of the natural sediment load from lower Ok Tedi tributaries and the North Fly.

The ability of the river to transport the larger sand sizes as suspended sediment load also diminishes downstream, so the copper concentration in suspended load will be heavily weighted towards the silt component of tailings. These processes may be captured in a simple model with the form:

$$pCu(\text{Lower River}) = k_1 * pCu(\text{Tails}) + k_2 * pCu(\text{Bige model}) \text{ (during tailings input)}$$

$$pCu(\text{Lower River}) = (k_1 + k_2) * pCu(\text{Bige model}) \text{ (after mine closure)}$$

Values for  $k_1$  and  $k_2$  (derived iteratively in a trial and error fitting process) are:

Ningerum: 0.6 and 0.6; Nukumba: 0.6 and 0.4;

Obo: 0.54 and 0.4.

The sum of the Ningerum values exceeds 1 because the suspended load is made up of more sand and less tailings than at Bige and there is no natural load dilution effect. The Obo values sum to less than 1 to allow for dilution and minimal sand in the load.

Comparisons with observed suspended load particulate copper concentration are shown in Figs 6-8. Trends over time in both observed and modeled datasets are very similar at all locations. Goodness of fit measures between date and particulate copper concentration for the various datasets are listed in Table 1.

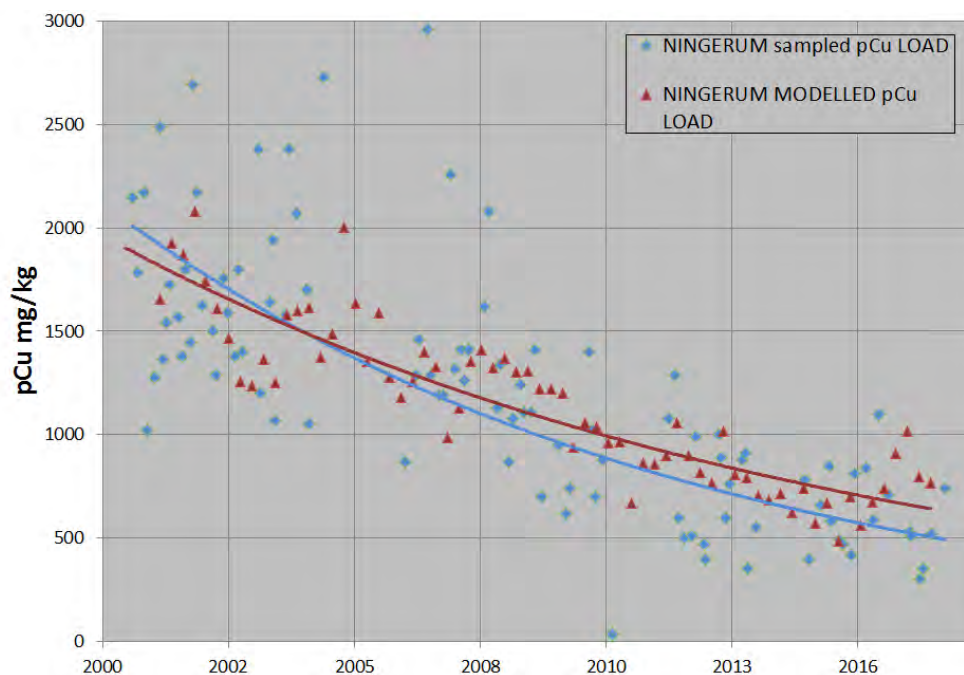


**Figure 6: Observed and modelled suspended load particulate copper concentration (pCu) at Ningerum.**

| TABLE 1: MEASURES OF FIT BETWEEN PARTICULATE COPPER<br>CONCENTRATION AND TIME |                |                   |                |                   |
|-------------------------------------------------------------------------------|----------------|-------------------|----------------|-------------------|
| STATION                                                                       | MODEL          |                   | OBSERVED       |                   |
|                                                                               | R <sup>2</sup> | STANDARD<br>ERROR | R <sup>2</sup> | STANDARD<br>ERROR |
| NINGERUM                                                                      | 0.803          | 287               | 0.457          | 83                |
| NUKUMBA                                                                       | 0.813          | 288               | 0.442          | 854               |
| OBO                                                                           | 0.812          | 284               | 0.668          | 198               |

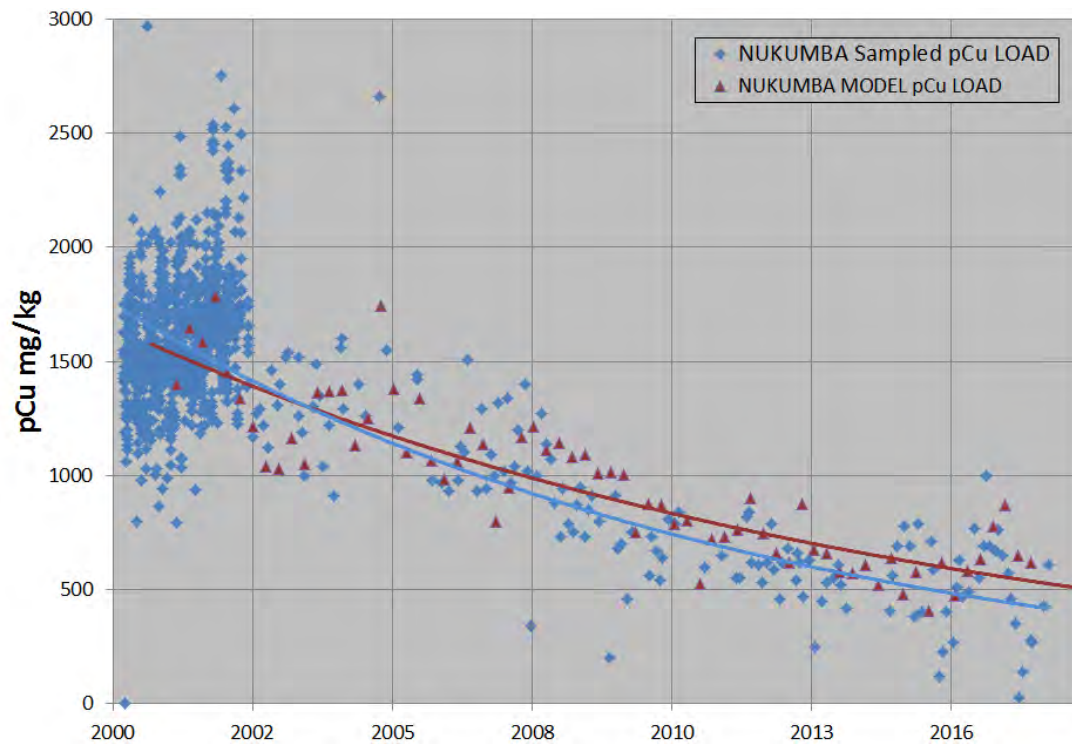


**Figure 7: Observed and modeled suspended load particulate copper concentration (pCu) at Nukumba.**

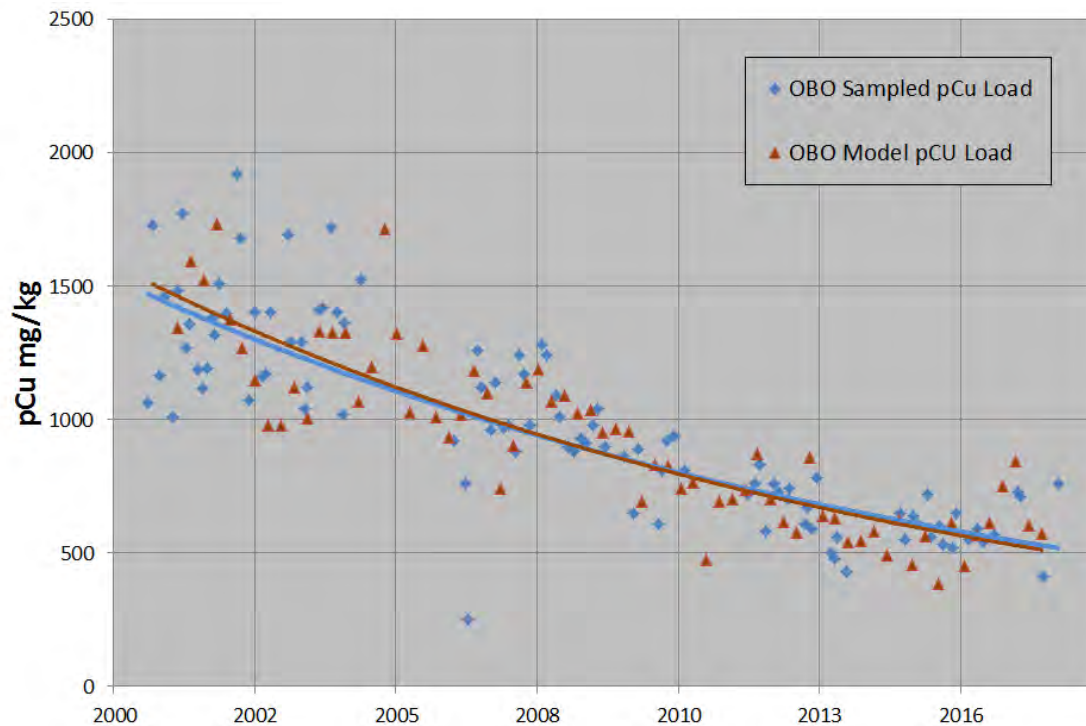


***Figure 8: Observed and modelled suspended load particulate copper concentration (pCu) at Obo.***

- Observed and modeled particulate copper at all locations show a downward trend with time. In all cases, an exponential model fits the data well.
- Model fit to observed and predicted particulate copper concentration data is good throughout and reproduces long term trends. Observed and modeled data produce almost identical regression lines at each station.
- Model scatter is less than observed data which is to be expected since the input data are quarterly (model and waste rock) and monthly (tailings) compared with instantaneous gulp samples.

## MEDIUM AND LONG TERM PARTICULATE COPPER PREDICTIONS

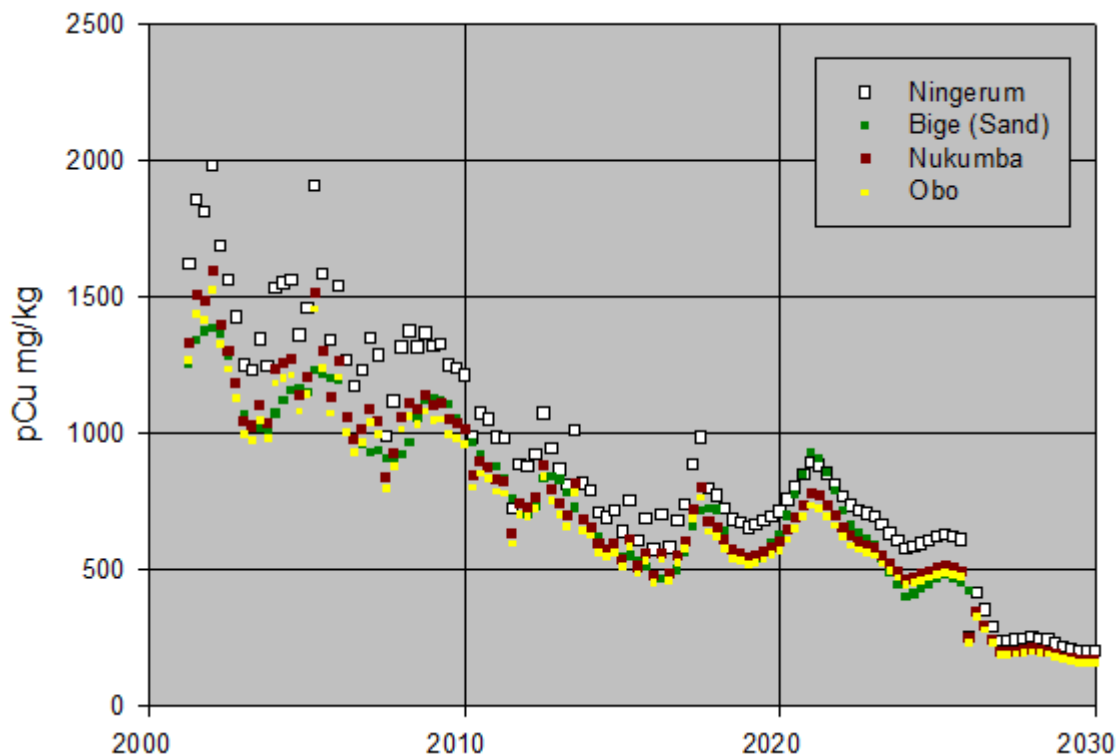


**Figure 9: Medium term particulate copper concentration (pCu) in the Lower Ok Tedi and Middle Fly for recent mine operations and Base Case predictions.**

Figure 9 above shows the pattern of particulate copper concentration in suspended sediment load during current mine operation with a forecast to 2030 for a mine plan currently under consideration.

- The medium term pattern has been for particulate copper concentration content to decline until around 2015. Since then it has levelled out or slightly increased.
- There is then about a 50% increase in particulate copper concentration until the early 2020s. It then declines sharply on closure as tailings input ceases and the natural sediment load of the river substantially dilutes mine inflow from stored upstream deposits.
- The long term pattern (Fig. 10) shows a gradually rising particulate copper concentration value at all locations after mine closure. This occurs because fast path losses from the failing dumps cease and there is no longer any tailings input. Instead, mine-related particulate copper concentration is gradually released from stored deposits upstream. This process takes time as the Upper Middle Ok Tedi deposits continue to grow and accumulate material from Harvey Creek, the Ok Mani and the Vancouver Dump.

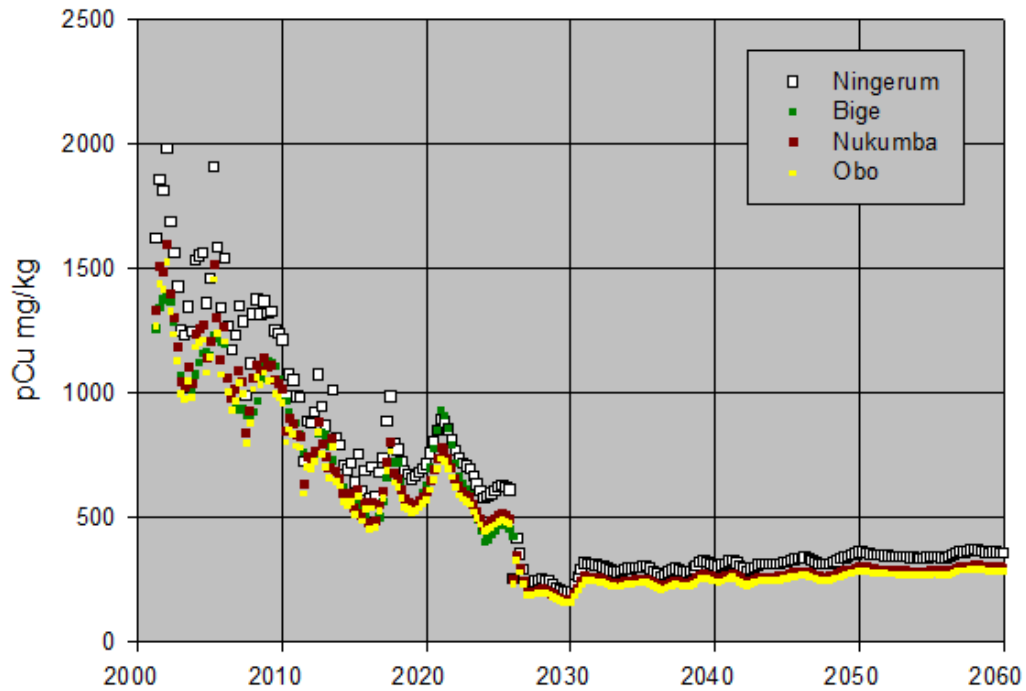


**Figure 9: Long term particulate copper concentration (pCu) in the Lower Ok Tedi and Middle Fly for recent mine operations and Base Case predictions.**

#### COMPARISON BETWEEN BASE AND TARGET CASE PARTICULATE COPPER CONCENTRATION AT NUKUMBA

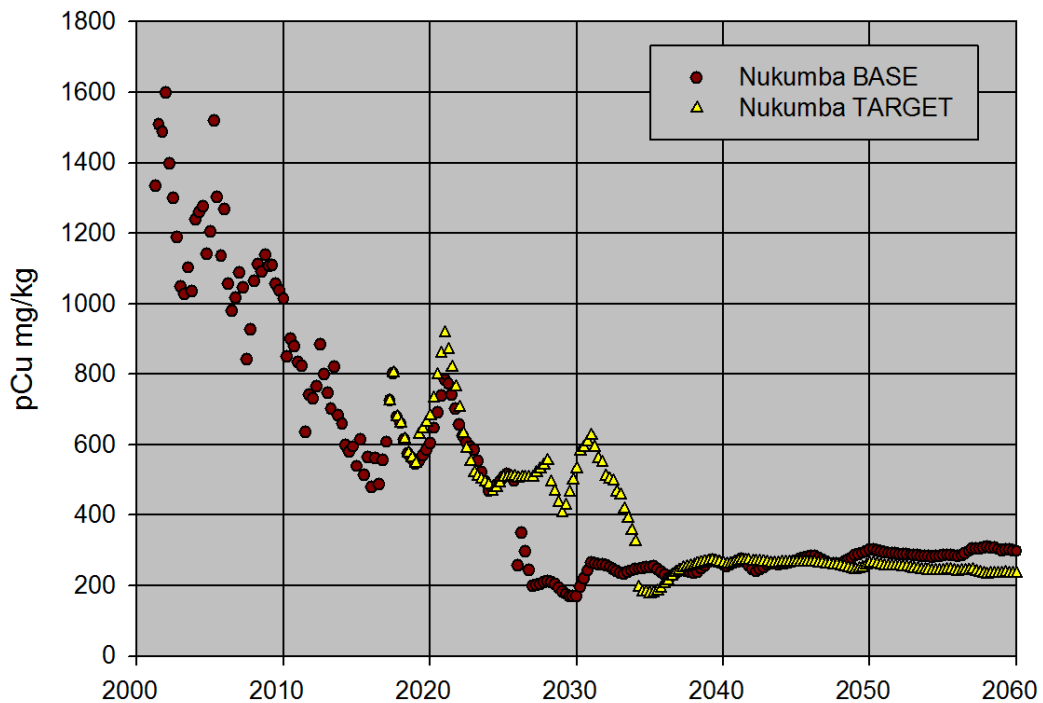


**Figure 10: Long term predictions of particulate copper concentration (pCu) in suspended sediment load at Nukumba.**

The Base and Target Cases are two potential mine plans modeled as part of the 2018 strategic planning exercise. The Base case involves closure in 2025 while the Target Case closes the mine in 2032. The Target Case attempts to exploit the remaining resources as much as possible but it is not a target in the sense of what is being aimed for as it has substantial negative environmental effects. The 2018 Base Case was recently accepted by OTML's Board as the 2018 Life of Mine Plan making it the current operational plan.

- The Target Case involves a substantial increase in deposition and silt delivery to the Lower River system with consequent further development of levee deposition (reported on in Pickup, 2018).
- In terms of particulate copper concentration in suspended load, both cases are almost identical until Base Case closure in 2025. After that, the Target Case maintains a particulate copper concentration roughly double that of the Base Case until closure.
- While the concentration of copper in the suspended load is only substantially different between cases for about eight years, the very large increase in silt load reported in Pickup (2018) (695 Mt compared with 416 Mt between 2025 and 2060), means that there is a substantial increase in total Cu delivered to the river system under the Target Case.
- The slow rise in particulate copper concentration that occurs towards 2060 under the Base Case does not occur under the Target Case but can be expected after 2060.

## CORRESPONDANCE WITH LEVEE DEPOSITS

The period of sampling of levee of deposits is shorter than the other records. However, results closely correspond with observed and modelled particulate copper concentration values in sediment load at both Nukumba and Obo (Figs 11 and 12). Goodness of fit measures are listed in Table 2.

| TABLE 2: GOODNESS OF FIT MEASURES FOR REGRESSIONS<br>BETWEEN COPPER CONCENTRATION IN FLY RIVER LEVEE<br>SURFACE DEPOSITS AND MODELED PARTICULATE LOAD |                   |                |                   |
|-------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|----------------|-------------------|
| NUKUMBA                                                                                                                                               |                   | OBO            |                   |
| R <sup>2</sup>                                                                                                                                        | STANDARD<br>ERROR | R <sup>2</sup> | STANDARD<br>ERROR |
| 0.784                                                                                                                                                 | 36.4              | 0.780          | 35.4              |

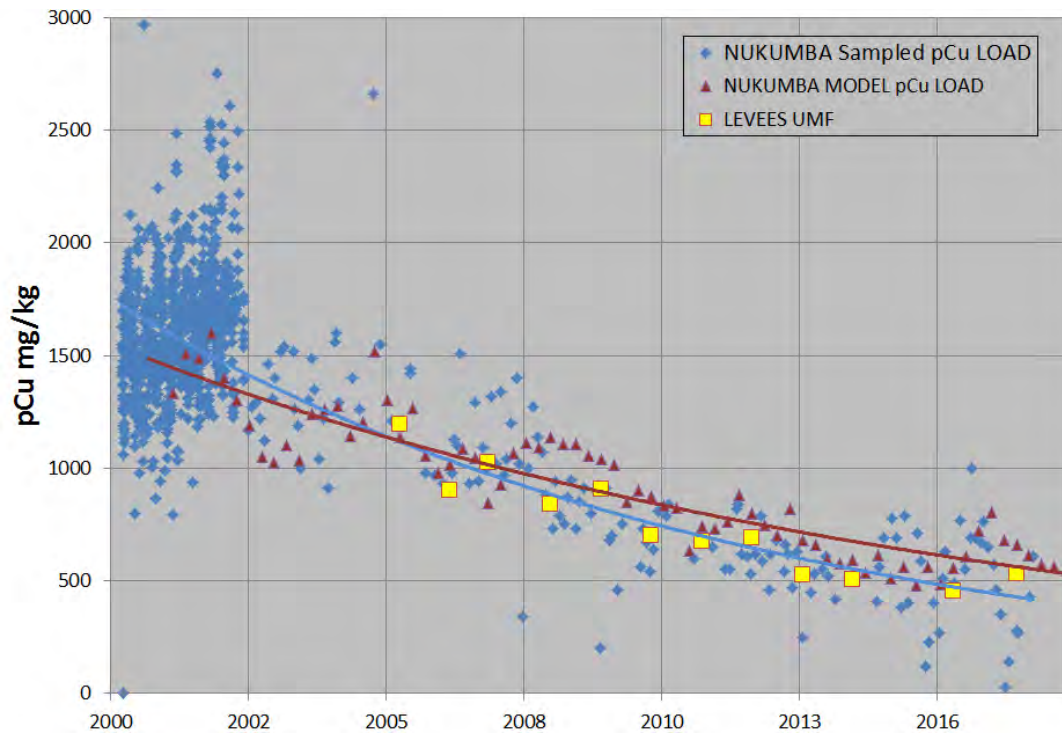


**Figure 11: Observed and predicted copper (pCu) in suspended load compared with average particulate copper concentration values in levee deposits on the Upper Middle Fly (UMF).**

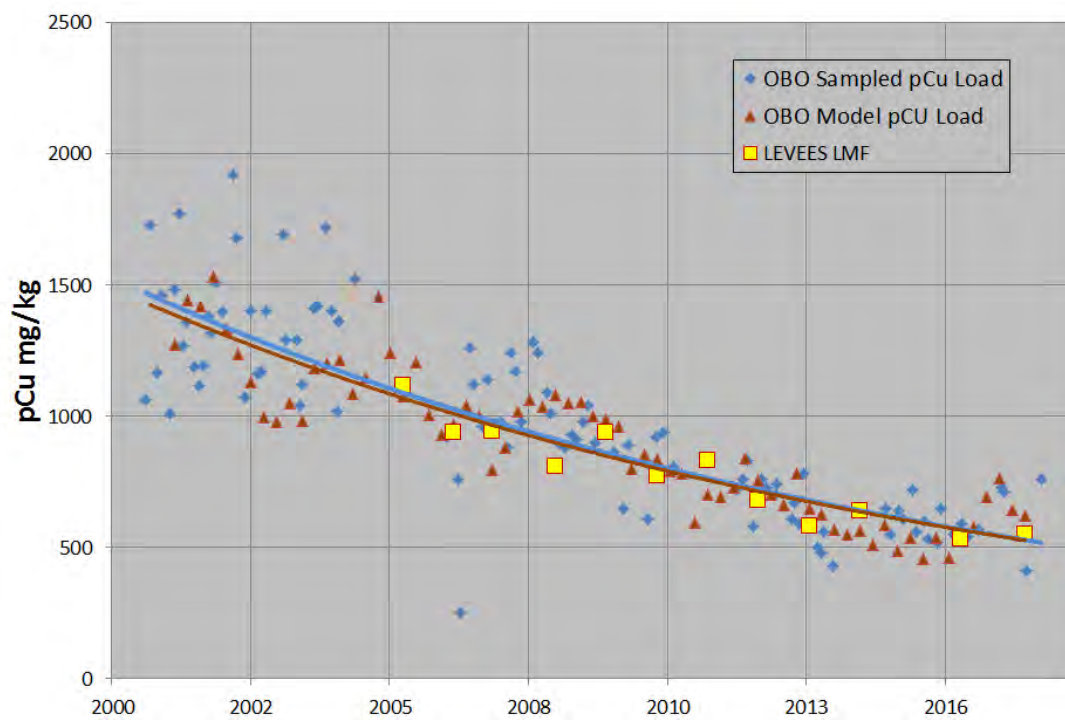


**Figure 12: Observed and predicted copper (pCu) in suspended load compared with average particulate copper concentration values in levee deposits on the Lower Middle Fly (LMF).**

## DISSOLVED COPPER

The biogeochemistry of copper in the Fly River system is described in considerable detail by *Apte (2009)*. In that study, it was found that the partitioning of inorganic copper between solution and solid phases can be described by a simple distribution coefficient,  $K_d$ . However, the value of this coefficient varies downstream as, among other things, particulate copper reactivity increases due to oxidation processes and reductions in mean particle size (with consequent increases in surface area to volume ratios).

Using a similar approach, we have compared observed dissolved copper concentration in water samples with particulate copper concentration in suspended sediment samples at Ningerum, Nukumba and Obo (Fig. 13). There is considerable scatter, even after converting data to annual averages, not only because the data may come from different days within the year but also because the number of samples is small. However, the trends of increasing dissolved copper concentration with higher particulate copper concentrations and higher dissolved copper concentration per unit of particulate copper concentration downriver as more copper is dissolved are apparent although there is little difference between Ningerum and Nukumba.

The slopes of the line of best fit in Figure 13 are 0.042, 0.0050 and 0.0095 for Ningerum, Nukumba and Obo respectively. From these slopes an estimate of the average distribution coefficient ( $K_d$ ) can be made – these are 23,800 L/kg, 20,000 L/kg and 10,500 L/kg for Ningerum, Nukumba and Obo respectively. These values are in the range of  $K_d$  values reported by *Apte (2009)* in zero salinity water at the head of the estuary. The increase in the slopes of the regression lines (and the corresponding decrease in  $K_d$ ) is consistent with a gradual increase in particle reactivity downstream as reported previously by *Apte (2009)*.

Clearer trends emerge when dissolved copper concentration is plotted against model predictions of particulate copper concentration (Fig. 14) rather than observed values. Overall, the standard of prediction is similar to that observed in Fig. 13 with observed particulate copper concentration (Table 3). However, the downstream trend is clearer. This may be because the model particulate copper concentration data have been averaged over four three month time periods whereas the observed particulate copper concentration data come from a few instantaneous gulp samples. This suggests that the model may be used to give a broad indication of dissolved copper concentration down the river system for a given set of waste rock and tailing inputs. The predictive equations for a simple linear model are listed in Table 4.

| TABLE 3: MEASURES OF FIT BETWEEN PARTICULATE COPPER CONCENTRATION AND DISSOLVED COPPER CONCENTRATION (ANNUAL AVERAGES) |                |                                         |                |                |
|------------------------------------------------------------------------------------------------------------------------|----------------|-----------------------------------------|----------------|----------------|
| STATION                                                                                                                | MODEL          |                                         | OBSERVED       |                |
|                                                                                                                        | R <sup>2</sup> | STANDARD ERROR OF ESTIMATE <sup>2</sup> | R <sup>2</sup> | STANDARD ERROR |
| NINGERUM                                                                                                               | 0.436          | 2.74                                    | 0.359          | 3.129          |
| NUKUMBA                                                                                                                | 0.739          | 1.822                                   | 0.755          | 1.582          |
| OBO                                                                                                                    | 0.566          | 3.246                                   | 0.743          | 2.498          |

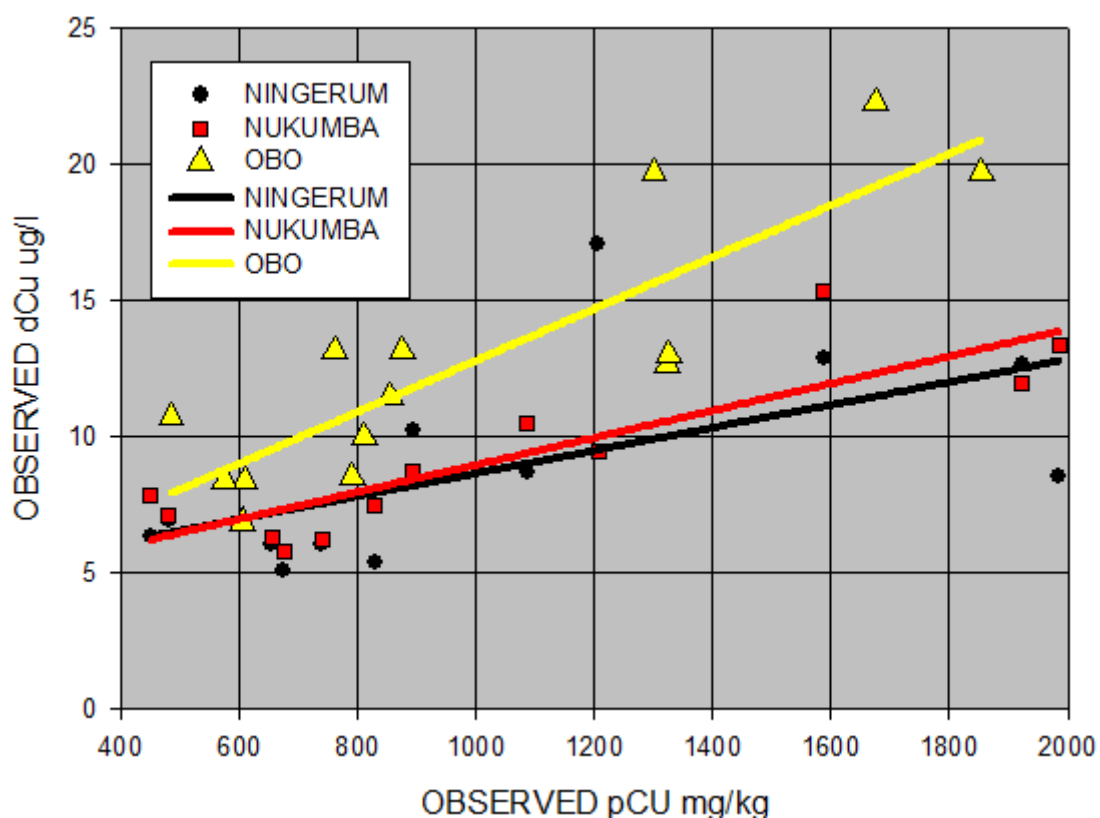


**Figure 13: Observed particulate copper concentration (pCu) and dissolved copper concentration (dCu) in Lower Ok Tedi and Middle Fly water samples.**

<sup>2</sup> This measure includes uncertainty in both slope and intercept of the estimating equation.

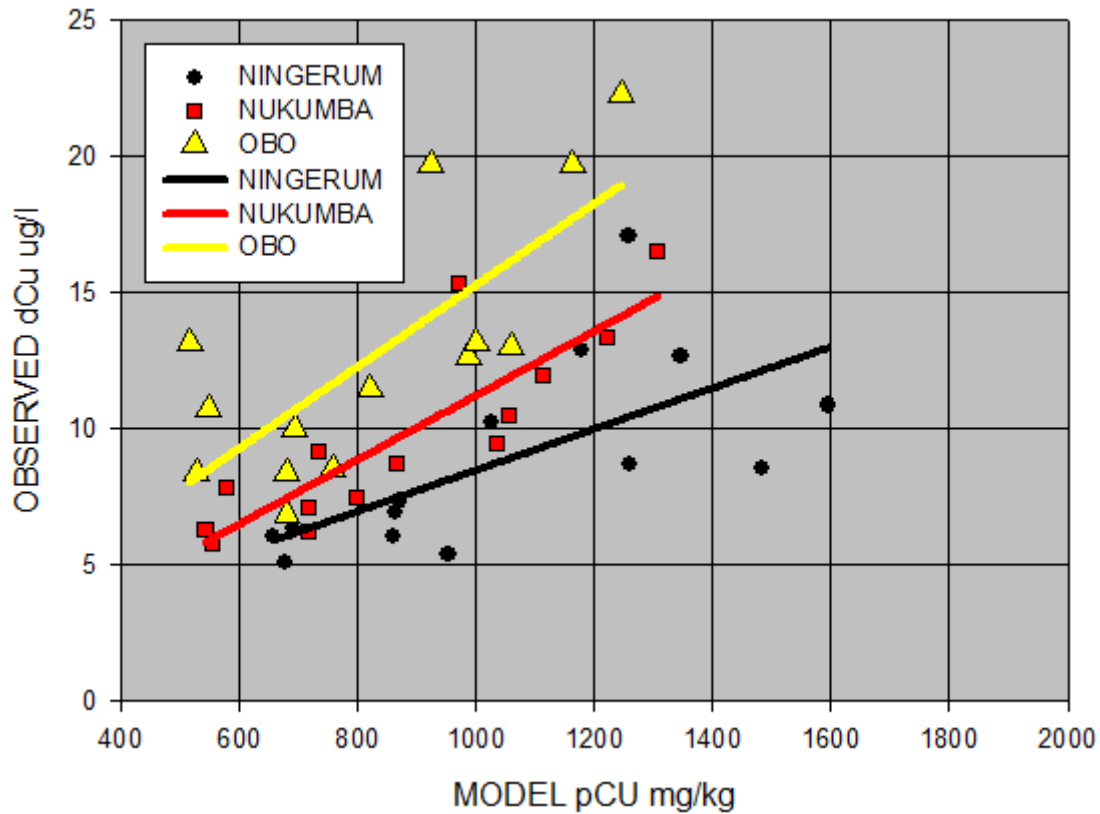


**Figure 14: Model particulate copper concentration (pCu) and dissolved copper concentration (dCu) in the Lower Ok Tedi and Middle Fly.**

| TABLE 4: REGRESSION MODEL COEFFICIENTS FOR A LINEAR MODEL FOR PREDICTING DISSOLVED COPPER CONCENTRATION FROM PARTICULATE COPPER WITH THE FORM: $dCu = a + b \cdot pCu$ |        |        |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|--------|
| LOCATION                                                                                                                                                               | a      | b      |
| NINGERUM                                                                                                                                                               | 0.922  | 0.0076 |
| NUKUMBA                                                                                                                                                                | -0.594 | 0.0118 |
| OBO                                                                                                                                                                    | 0.2926 | 0.0150 |

### COMPARISON BETWEEN BASE AND TARGET CASE DISSOLVED COPPER CONCENTRATION AT NUKUMBA

Long term predictions of dissolved copper concentrations at Nukumba using the regression coefficients in Table 4 for the Base and Target cases are provided in Fig. 15. Unsurprisingly, they mimic the pattern of change in particulate copper over time shown in Fig. 10, notably, that the downward trend in copper concentration reverses from 2018. However, the highest values are no greater than those prior to 2010.

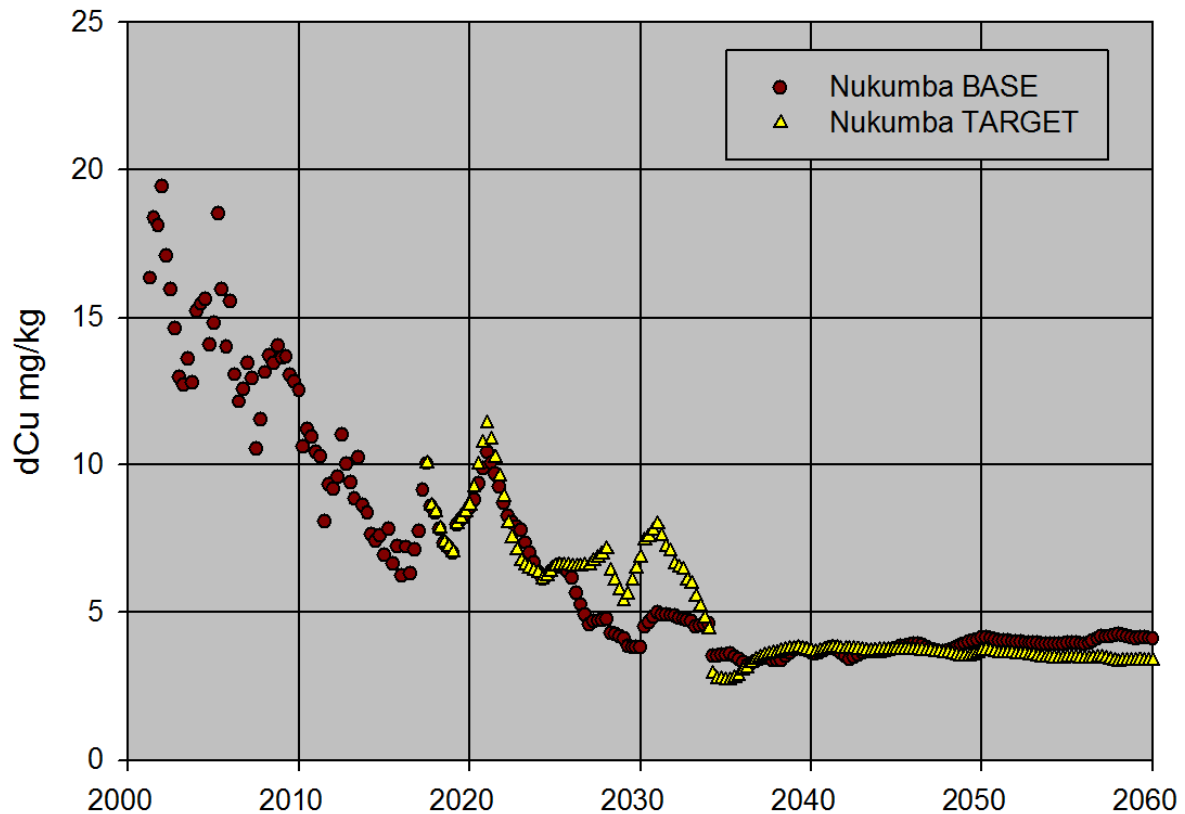


**Figure 15: Long term predictions of dissolved copper concentration (dCu) in suspended sediment load at Nukumba.**

In making predictions using the equations in Table 4, two important assumptions have been made. These are:

- That the reactivity of the suspended sediment does not change over time. For example, if tailings reactivity increased or decreased as a result of a major shift in ore type or processing approach, then the coefficients in table 4 would change and the predictions would be in error. Perhaps more significantly, if oxidation processes occur to a significant extent in deposited material, sediment that was resuspended after mine closure may be more reactive and result in higher dissolved copper concentrations than the predictions;
- It is implicitly assumed that the pH of the river does not change from the levels observed during the model calibration period. If the pH were to decrease, the solubility of copper would increase and marked increases in dCu would occur. The assumption of pH stability is based on the assumption that existing ARD control measures are both implemented and effective.

It should also be noted that the predictions are for annual average copper concentrations – observed concentrations will vary both above and below the annual predictions.

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