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Mount Lyell Remediation
Research and Demonstration Program

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Department *of* Environment and Land Management

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A joint program between the Supervising Scientist and the Department of Environment and Land Management, Tasmania.

This report describes research that is part of the Mt Lyell Remediation Research and Demonstration Program, a joint program between the Supervising Scientist and the Department of Environment and Land Management, Tasmania.

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Executive summary

The lower reaches of the King River contain approximately 100 million tonnes of overbank, river bottom and delta deposits consisting of tailings discharged by the Mount Lyell Mining and Railway Company since early this century. These discharges ceased in December 1994. The tailings deposits create a range of short and long term environmental problems.

The main problems associated with the tailings deposits are:

- the impact on water quality in the lower King River and Macquarie Harbour, and associated potential toxic effects on aquatic life, due to the continuing availability of high concentrations of metals and acid released from the tailings;
- reduced amenity for local residents and visitors due to the limitations placed on surrounding land use and activities in the lower King River and Macquarie Harbour; for example dust storms, and poor navigation through the delta area;
- poor aesthetics resulting from dead rainforest vegetation next to the river, tailings banks bare of vegetation and the large expanse of desert-like delta at the mouth of the King River. This issue is of particular significance considering the area's importance as a tourist destination.

Four possible strategies are available for dealing with the tailings deposits—do nothing, remove the tailings, treat or stabilise them on site, or some combination of removal and in situ treatment/stabilisation. The 'do nothing' option does not address any of the environmental problems created by the presence of the tailings and is not recommended. However, it is noted that other studies have demonstrated that the river bank and delta tailings deposits probably only contribute in the order of 1–5% of the metal loads and that priority should be given to the lease site for water quality objectives.

The other three strategies include a range of different options which are examined on the basis of feasibility, cost and degree of mitigation of environmental problems.

Removal of the tailings from the river banks and delta best addresses the on-going problem of poor water quality resulting from high levels of metals and acid. There are significant problems, however, with relocating the tailings to a secure area, and the sheer volume of material creates unacceptably high costs if all of the tailings are removed. Methods of removal or reducing the surface area of tailings include dredging, dynamic compaction and use of explosives.

Dredging is the most versatile of these methods; removal to a tailings dam or disposal on the floor of Macquarie Harbour are the two associated relocation options. The other methods lower or remove sections of the delta to adjacent deeper water in Macquarie Harbour. For river bank deposits removal strategies involve pushing parts or all of the bank into the river during high flow conditions. This would allow successful revegetation of the remaining bank areas. The problem of the removed tailings would be transferred further downstream where they would be removed or treated by strategies being employed on mitigating problems with the delta.

It is recommended that any dredging of the tailings on the delta remove approximately the top 1.5 metres. This would lower the dredged parts of the delta beneath low water level and greatly reduce the problems associated with oxidation and acid generation in the tailings. This process has a number of environmental risks that need careful management. Appropriate dredging technology, such as use of a cutter suction dredge and silt curtains around the dredged areas, will reduce these risks.

Disposal of dredged tailings to deeper areas in Macquarie Harbour is technically feasible and would be significantly cheaper than disposal to a purpose-built tailings dam. Both of these disposal options require more detailed assessment of the possible environmental impacts, particularly in relation to water quality. For harbour disposal these studies would include grain-size analysis, hydraulic testing, tidal current studies, elutriate testing for metal availability and ecological risk assessments. Additional studies prior to construction of a tailings dam would include environmental assessment of potential dam-sites and access routes, and detailed design investigations to ensure appropriate drainage characteristics of the tailings dam. Following construction and placement of tailings, rehabilitation would be required as well as on-going monitoring and possible treatment of leachate.

A range of options exist for treatment or stabilisation of tailings deposits. The volume and nature of the tailings make a number of these options unrealistic—both from a cost and technical perspective. These include various thermal and physical/chemical treatments such as vitrification, oxidation/reduction and solidification. Mineral reprocessing is a form of physical/chemical treatment that aims to extract any valuable metals from the tailings. On the basis of metal content, and technical and environmental problems associated with extraction, relocation and rehabilitation processes, this option is considered non-viable.

Stabilising the tailings by capping or covering with imported material requires significant engineering works to ensure its success. These and associated transport requirements result in costs of hundreds of millions of dollars and rule it out as a viable option. Likewise stabilising the tailings by diverting the King River away from the delta area is a very costly exercise with significant environmental risks and a high level of uncertainty in relation to mitigation of existing environmental problems. It can also be ruled out as an option.

A series of trials were conducted to investigate a range of revegetation techniques and their utility as a means of stabilising the tailings. These trials indicated that a combination of treatments, appropriate to local site characteristics, are likely to result in successful revegetation and stabilisation. Revegetation will mitigate, to a degree, all three environmental problems presently associated with the tailings. This is particularly the case in regard to aesthetics and amenity.

After consideration of all these options a combination of removal, relocation and revegetation is recommended as the most appropriate strategy for remediation of the tailings. Since there remains considerable uncertainty in the effects on water quality of the tailings as they exist today and as both the improvement of water quality in both the King River and within the harbour is one of the primary objectives of remediation, this information is critical to the final remediation strategy selected. If unacceptable effects on water quality are identified as a consequence of leaving the tailings in situ, there will be little alternative other than removal of tailings above the water table to prevent ongoing oxidation and metal load generation. Revegetation, while it can fulfil most of the remediation objectives considered in the study, is not expected to be effective in achieving marked improvement in water quality.

The recommended approach to remediation of the tailings deposits is to use a combination of the removal and relocation with revegetation of the tailings in situ. This enables the most suitable treatment to be applied to a given area, and takes account of the unique and variable characteristics of the deposits. The remediation can also be staged as funds become available and information from monitoring provides the necessary information on remediation needs and goals. Cost effective revegetation could be implemented quite rapidly and targeted where a high probability of success is likely. As the need is demonstrated, more costly remediation such as dredging and relocation could be considered.

The recommended treatment of river banks varies according to their characteristics. Options range from encouraging natural colonisation by fertiliser application, replanting with local wetland or rainforest species, excavation of tailings to create permanent wetlands, and removal of some tailings followed by capping with original levee bank material and revegetation. In order to encourage revegetation, surface stabilisation and shelter can be improved with short-lived exotic grasses, wind-proof fencing and/or the placement of tree branches and slash.

The delta has been divided into a number of zones according to the likely success of revegetation treatments. Progressive revegetation is recommended for the perimeter and other areas amenable to revegetation. Dredging of the top 1.5 metres is recommended for the rest of the delta area. This is regarded as the best option to improve water quality but will need to be done after further environmental studies, particularly in relation to relocation issues.

Cost estimates for the recommended strategies are approximately \$600,000 for the river banks, \$400,000 to \$1.9 million for various revegetation options for the delta, and \$15 million to \$30 million dollars for dredging and relocation of delta tailings.

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1 Introduction

Approximately 97 million tonnes of mine tailings and 1.4 million tonnes of slag have been dumped in the Queen and King River systems over the past 78 years and formed extensive sediment deposits on the banks of the lower King River and at the mouth of the river in Macquarie Harbour. These sediments give rise to a number of problems and are continuing to create adverse physical, chemical and biological environmental impacts.

The sediments are rich in pyrite, and contribute to acid drainage in the river, which impacts on the whole riverine and harbour ecology. This is discussed in more detail in section 2 of the report. Elevated dissolved metal levels in the waters of Macquarie Harbour have severe implications for the operation of commercial fish farms in the harbour.

The ability of boats to navigate through the delta and up river has been diminished by the deposition of the tailings material. In particular, local Strahan residents report that the navigation channels in the delta are changeable and hazardous.

The visual impact of the tailings deposits in the river are clearly severe, with tourists and locals alike being presented with barren banks and crusted stumps of once vigorous rainforest trees along the river banks. The huge, exposed expanse of the delta is known to spawn dust storms in summer months, which pose not only a visual impact, but a health concern as well.

1.1 Approach

The approach to this project was to break it up into three phases. The first phase was to undertake a literature review of world best practice in various treatment options for tailings material of a similar nature to those in the King River.

The second phase of the project was to gather together acknowledged technical experts in various fields, to discuss in detail those possible options most likely to be suitable for the King River tailings, based on the results of other studies being carried out as part of the Mount Lyell Remediation Research and Demonstration Program (MLRRDP). These experts included consultants in fields such as tailings geochemistry, reprocessing, revegetation and tailings dam construction. The related MLRRDP studies included:

Project 4: Tailings and fluvial processes in the Queen and King Rivers (Locher 1995).

Project 5: Characterisation and impact assessment of mine tailings in the King River system and delta, western Tasmania (Taylor et al 1996).

Project 7: The behaviour of copper in sediments and waters of Macquarie Harbour, western Tasmania (Teasdale et al 1996).

The third phase, which was run concurrently with phase 2, was to conduct revegetation trials on the banks and delta of the King River. This phase was designed to provide valuable information about possible revegetation strategies.

Throughout the project there was keen interest from the local community and tourists. The revegetation trials in particular raised considerable interest, as they were a visible, physical sign that things may be about to change for the King River. Public meetings were organised and held to inform interested groups about the project's progress, and to seek input from the public about the issues of concern to them, and their views on the objectives of any remediation program.

1.2 Outline of report

This report summarises the remediation objectives and needs. The characteristics of the tailings, documented in project 5 (Taylor et al 1996), are discussed in light of these objectives. The companion literature review is available as an unpublished paper (Nazarov & Russo 1996); however a summary of the processes and options from this review is presented in section 3. The broad range of options for remediation are briefly described.

The most feasible options for the banks and the delta are then discussed in more detail, in sections 4 and 5. The framework for this detailed examination includes their feasibility, environmental impacts, ability to meet objectives, costs and timing issues.

Finally, a remediation strategy is recommended which draws on a combination of these options. An outline of which options are most suitable in combination and in different locations is given, and timing issues discussed.

1.3 Remediation objectives

The principle objectives for the remediation of the tailings deposits were determined following discussions with Strahan and Queenstown residents, representatives of the Department of Environment and Land Management and the Office of the Supervising Scientist and consultants. These discussions took place over the course of the project at public meetings, field days and working bees.

The objectives can be summarised under the following five headings:

1. **Water quality:** to maintain or improve the existing water quality in the King River and Macquarie Harbour. This objective relates to the adverse impact of raised metal levels on the river and harbour ecology, including the commercial fish farms in Macquarie Harbour.
2. **Aesthetics:** to improve the visual impact of the tailings banks and delta. There is a tourist drive along the King River (Teepookana Forest Drive), and the delta and banks are visible to both tourists and local residents from boats in the harbour and the King River.
3. **Reduction in dust:** local residents complain of the adverse visual and health implications of dust storms which are generated on the delta following periods of dry weather in summer months.
4. **Enhanced amenity:** stabilisation of the channel would improve navigation through the delta which is a major objective for local residents. An improved environment would broaden land use options to include the possible use of the area for new recreation pursuits or other uses.
5. **Community benefits:** including employment opportunities, community ownership and pride issues and public relations aspects of the remediation. There is considerable interest in ongoing community involvement in the remediation works, for example, a nursery to provide plant material, and local people to provide labour for future projects.

2 Description of tailings deposits

This section outlines the nature, volume and distribution of material in the tailings deposits. It summarises briefly and highlights relevant information presented in project 5 (Taylor et al 1996). The location of the King River and the delta are shown in fig 1.

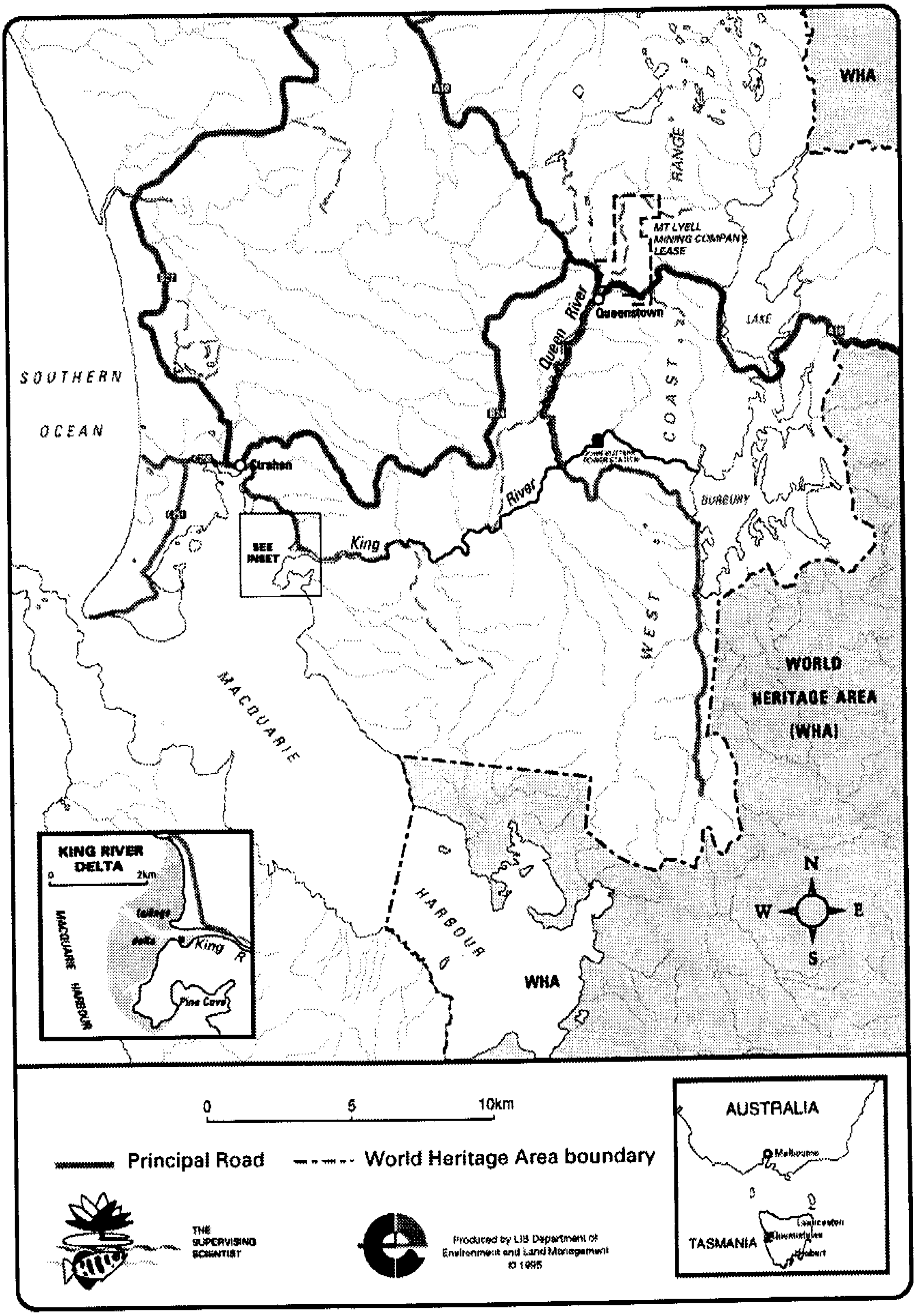


Figure 1 Location of the King River, detail of delta shown in insert

2.1 Geology and morphology

Delta

The surface of the delta consists of a broad expanse of low relief, highly oxidised tailings material with irregularly distributed and partially buried logs and occasional other wastes. The delta displays a maximum relief of approximately 2.0 m above the harbour water during an average low tide, but the majority exhibits relief of less than 1.0 m. The delta was last surveyed by the HEC in 1988. Figure 2 shows the relief of the delta.

Typical tidal variations produce vertical water level rises on the order of 20–40 cm, and under low tide conditions the subaerial surface area of the delta is approximately 2.5 sq km (80% of the time the tides are less than 38 cm) (Koehnken 1996). The maximum tide recorded in Koehnken's study was 1.4 m in May 1994. Rises in water level up to approximately 1.0 m may occur more than once per year during neap tides and under the influence of low pressure systems and during flooding in the Gordon River. During these peak flow events, much of the delta may be inundated. Following the damming of the King River, the flood events in the river have been much reduced with the possibility that the flooding on the delta has also been reduced. Hydrology studies indicate that what was once a 1:2 year flood is now a 1:50 year flood. There have also been major changes in flood behaviour, with the power station operations resulting in much faster river level changes.

The delta is bisected by a narrow channel through which the King River flows (plate 1), and shallow channels traverse the surface of both the north and south lobes. These smaller waterways convey tidal and overflowing river water and incident rainfall off the delta towards the harbour.

The north and south portions of the delta are reported to display broadly different physical and chemical characteristics. The north delta is comprised of finer grained material than the south, and therefore includes a higher proportion of finer grained sand, clay and organic debris. The north delta appears to be significantly more sheltered in terms of lateral transport than the south lobe, and hence finer grained fractions have a greater opportunity to settle out. These gross physical/chemical differences are reflected in the groundwater chemistry (Taylor et al 1996).

Large sections of the delta, in particular the southern lobe, appear to have developed during flood events. 'Megascopic foresets' are visible due to planation during successive flood events and display current directions radiating away from the mouth of the King River. These are established during peak flows and are sporadically filled with finer grained, horizontally stratified components during the waning phase of a flood event.

Successive flood events are believed to have removed portions of the earlier deposits. Consequently, the detailed internal structure of the delta is predicted to be extremely complex and locally highly variable. A widespread distinctive laminated horizon was not identified and coherent horizontal stratification was only evident on the scale of metres (especially on the north lobe).

The likely changes to the delta morphology following the reduction in flood events from the King River and the reduction in sediment load due to the cessation of tailings are uncertain and erosion and channel movement may occur, as well as the possible settlement of the delta surface.

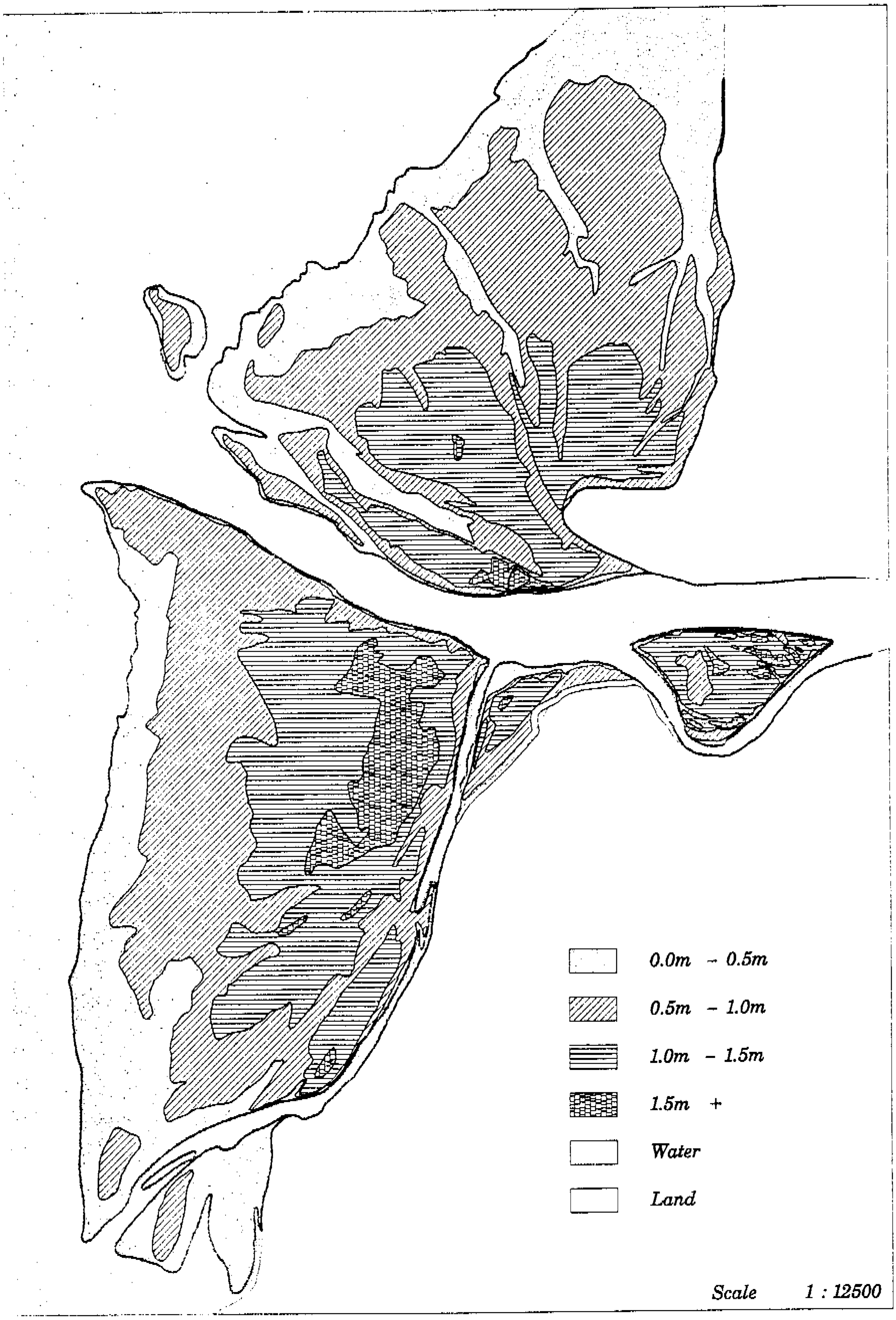


Figure 2 Relief of delta (1988 information)

There is some anecdotal support for this, with the Strahan jet boat driver and other residents reporting that the channel in the delta is now more stable and clear than it was immediately following cessation of tailings going into the river.

In addition to typical silicate- and sulphide-bearing tailings sediment, the delta contains a small but common component of slag, numerous thin layers of leaf-litter dominated organic debris, irregularly distributed buried and exposed logs, and a minor component of miscellaneous refuse (eg tyres, cardboard, cans, bottles).

Wind erosion is reportedly significant during the dry summer months and small dunes at the back of the north delta are evidence of this effect. The dunes indicate that wind-borne tailings transport is predominantly to the east. The position of logs and other water-borne debris at this location indicate that at least some time in the past flooding extended to this level.

River banks

The majority of sediment contained in the King River bank deposits is reported as being unsaturated, extensively oxidised and dominantly comprised of mine tailings. The grainsize of tailings material appears to increase downstream, with the delta hosting the coarsest grained debris. Tailings deposit thickness also decreases downstream, with nearly 95% of bank storages in the lower reaches of the King River (Locher 1995). A naming system for the banks, as devised by Locher, is shown in fig 3.

The sediment banks have evolved by progressive draping of sediment onto the surface. Although lateral continuity of layers for more than tens of metres is unlikely, well developed stratification and shallow dips away from the spine of the bank are predicted to be common features. Surface water entrapment has occurred on the landward side of many sediment bank deposits. These areas often develop permanent or intermittent creeks. Semi permanent bodies of water are situated on some of the banks and are direct evidence of (shallow) subsurface aquitards (ie clay dominated layers). Preliminary observations suggest that the internal structure of the banks has significant implications for surface runoff and groundwater discharge with discontinuous aquitards permitting partial infiltration and then facilitate rapid discharge and accumulation of incident rainfall to shallow pools on the banks.

Organic debris comprising buried logs and abundant leaf litter is irregularly distributed throughout the banks.

The sediment banks have stopped growing following the reduction in size and frequency of floods since power station operation and only minor river bank erosion has been identified, except in some areas where the tourist jet boat operates.

King River: Bottom sediments

River bottom sediments include a predominance of slag and coarse grained sulphidic sediments. The relatively high density of this material has restricted its distribution to the river bottom and the upper portion of the delta. Since the disposal of slag only commenced in 1972, much of it resides in the upper part of the river bottom sequence and the upper 2 m of the delta.

2.2 Acid drainage

Observations of sulphidic materials indicates that significant oxidation of pyritic tailings material takes more than 12 months, but virtually complete oxidation has taken less than four years. Most of the river tailings deposits are oxidised with the possible exception of banks C and D, and the upper 1.5 m of the delta is the main source of acid and metal fluxes. Below this level and below the water table the tailings are basically unoxidised.

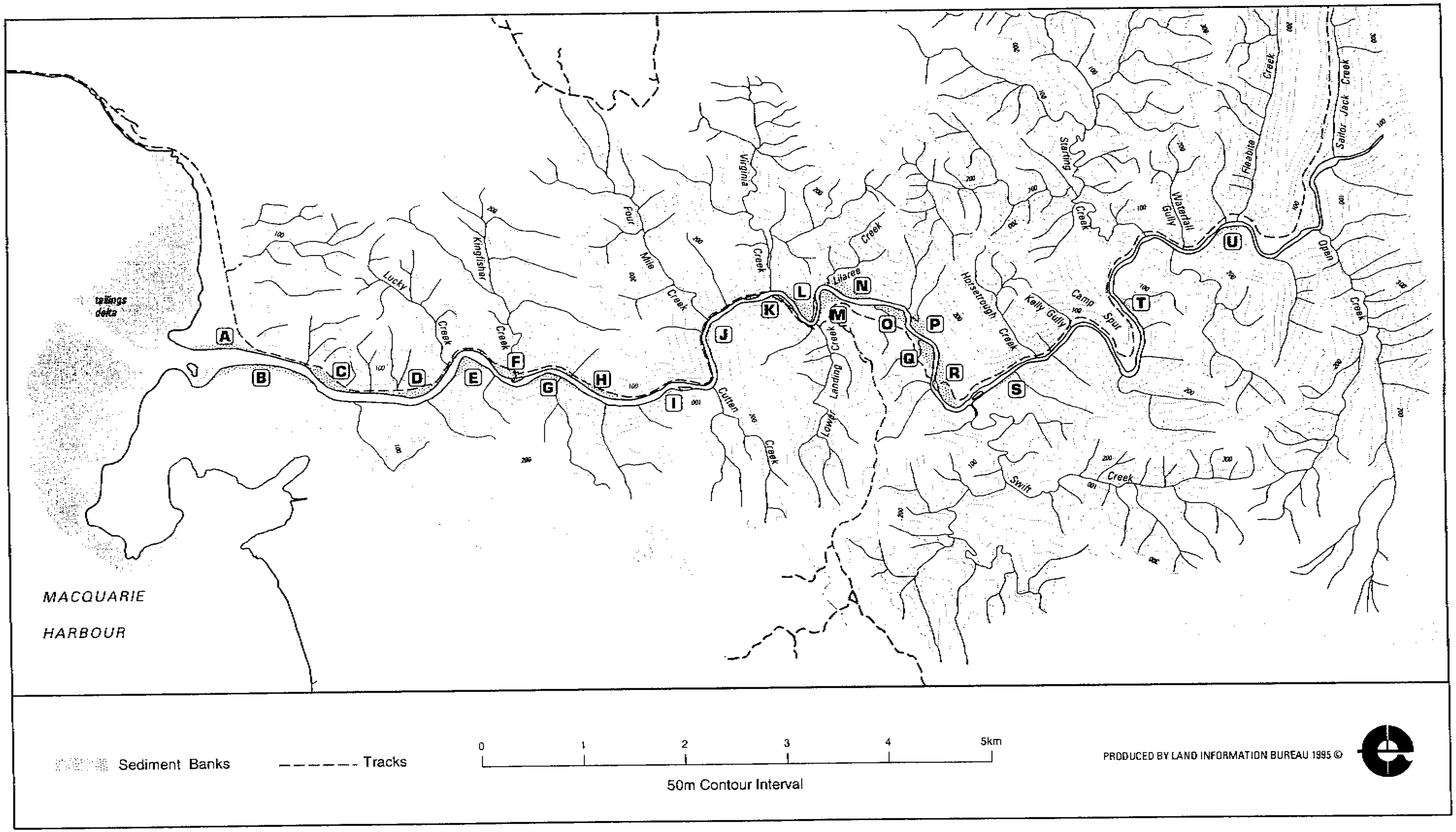


Figure 3 Location and identification of tailings banks in King River (from Locher 1995)

Surface groundwater interactions

Runoff plus infiltration for the banks and delta is predicted to be close to 70–80%, with a recharge estimated at about 20% with evapotranspiration locally as high as 10%. Groundwater in the delta is believed to be derived from on-shore groundwater sources and from surface infiltration by rain, river and harbour water. The majority of the delta exhibits less than 1.5 m of relief relative to the average harbour water level, and depth to groundwater in the delta is usually less than 0.5m. Groundwater levels respond rapidly to rainfall, tidal influences and river level changes caused by operation of the power station.

Groundwater in the sediment banks appears to be derived primarily from infiltration by rainfall and from surface drainage, with lesser contributions from river-margin groundwater sources and local input from the King River.

Metal and acid fluxes

The mass of pollutants contributed from surface runoff from the banks is expected to be equivalent or significantly less than that from groundwater discharge from the banks. The supply of metal and acid from surface runoff from the delta is predicted to be equivalent or significantly higher than that provided by groundwater discharge from the delta.

The total mass of metal and acid generated from groundwater and surface water interacting with the tailings are small compared with those released from the Mount Lyell lease site (estimated at approximately 1–5% of that of the lease site). However, the short-lived episodes of water pollution produced by surface flushing of the banks and delta may be critical to local water quality. These episodes are expected to supply sporadic, large volume pulses of low-strength but highly acid leachate to river and harbour water, and may have a significant impact on aquatic ecosystems. As improvements are made to lease area sources, it is expected that the effects of the these sporadic inputs may become more apparent and may indicate the need to reduce these inputs. Additional studies are required to quantify these inputs.

2.3 Predicted impacts of tailings deposits on water quality

Existing pollution levels are predicted to continue for thousands of years.

The short-term storm/flood runoff events are believed to be producing the most damaging ecological impacts through punctuated release of accumulated/concentrated acid and metals from the surface of the banks and delta.

From observations of the delta and the river banks, the largest contribution to acid neutralisation in groundwater appears to be from bacterial sources. The near-neutral pHs from groundwater in the delta are attributed largely to bacterial sulphate reduction with essentially no free carbonate remaining in unsaturated tailings. It was concluded that natural bioremediation is currently active in both the banks and the delta, and is locally (at least) very effective in lowering the concentrations of acid and metals in groundwater. These processes should be encouraged by continued revegetation. If this biological activity ceases, the copper loads could double.

2.4 Predicted impact of physical disturbance

Removal/relocation

Any disturbance to tailings which accelerates oxidation is expected to exacerbate metal and acid generation. Physical disturbances which avoid further oxidation, pH decreases and increases in fluid interaction are unlikely to significantly affect metal and acid release from tailings. This means that, under controlled circumstances, it may be possible to mobilise portions of the tailings without increasing short-term metal releases. Removal of sediment from one subaqueous site and immediate deposition into another (at similar pHs) without significant oxidation during transfer is not predicted to cause a significant increase in metal and acid release. Such a process may have other deleterious impacts such as raising turbidity, but increases in metal release are unlikely.

Erosion

Erosion of the river sediment storages is expected to take decades to centuries (Locher 1995). These time scales are general, since erosion will not proceed at a constant rate. Rather it will be discontinuous, and occur mainly during flood events.

Much of the sediment bank erosion and collapse visible on the King River has been an immediate response to the cessation of tailings discharge. While the mine was still discharging tailings, the older orange-colored oxidised tailings banks had their river faces regularly coated with the cohesive fresh grey unoxidised silt. Since mine closure this grey silt has dried out and slumped, pulling out sections of the older bank with it.

There are three reasons why bank retreat is unlikely to continue extensively:

1 There is a hardpan coating of iron oxides which, although discontinuous, provides some stability to the bank faces;

2 As bank retreat makes the stream widen, stream power will diminish and lessen the energy available for erosion; and

3 The original levee banks should form some sort of natural barrier to erosion.

It is predicted that there will be less bank retreat closer to the mouth of the King River.

The impact of erosional processes (eg sediment bank slumping, flood events, wind erosion, surface runoff) on the release of metals and acid from the tailings deposits is difficult to determine, quantify or anticipate. In general, such processes were predicted to have a minor influence on the total mass of sulphidic sediment available for leaching, and water quality.

Flood episodes were expected to be likely to generate the most significant erosion of tailings sediment. Addition of such sediment to surface water will therefore be at a maximum when associated dilution reaches its peak. The overall effect on water quality was expected to be minimal.

2.5 Existing state of tailings revegetation

Delta

The delta is devoid of vegetation over most of its surface, however, effective colonisation has taken place on the northern delta adjacent to the original vegetated shore line. The colonising species are principally composed of rushes (*Restio* and *Juncus* species). Delta colonisation is also occurring from the vegetated perimeters at various locations (north and south) and varies according to the exposure and the chemical nature of the tailings. Figure 4 shows the existing state of revegetation.

River bank deposits

In general the sediment banks are poorly vegetated, with the major evidence of previous growth being numerous tree stumps. The smaller tree stumps, often displaying bases in tailings material, indicate that growth was very commonly initiated within tailings material. The density, diversity and age of living trees on the sediment banks appear to increase up stream.

This was thought to be related to three key factors (Taylor et al 1996):

- new sulphidic tailings are periodically deposited on the lower relief banks, thereby replenishing the supply of acidity and metals,
- typical fluctuations in the water table in the banks are effective in bringing acidity and latent acidity (aqueous $Fe2+$) into the root zone of plants in the lower banks, and
- the higher relief of the upstream banks means that trees have longer to become established before their root zone enters the zone of influence of acid groundwater.

The build-up of wind-blown deposits of tailings can suffocate and kill established plants by reducing oxygen availability. This is particularly true for shallow rooting species such as the Acacia (including Blackwoods). Evidence on banks D and M show wind-blown deposits over remnant dead vegetation.

The control of the water level within the King may reduce the frequency of inundation of the river bank affecting bank chemistry and water table level. This may also contribute to the decline in established bank vegetation.

However, if as hypothesised by project 5, components of the establishing vegetation (taller trees) die after 5–10–15 years of growth, they will have contributed to the accumulation of organic matter on the banks. The surrounding vegetation will continue to shed seed over the banks annually and will be an on-going source of colonising vegetation for the banks. Therefore, vegetation which establishes and then dies will still have contributed to the build-up of organic matter and will be continually replaced from natural seed sources. There is evidence that this is occurring at a number of locations.

3 Overview of options

This study has examined a range of options to achieve the objectives described in section 1.3. All these options are summarised below with expanded treatment of major options in sections 4 and 5.

In general terms, four possible strategies are available:

- do nothing
- removing the tailings
- treating or stabilising the tailings in situ
- some combination of removal and in situ treatment/stabilisation

Table 1 Summary of options

Option	Methods
Do nothing	
Remove tailings	Dredge delta Remove river banks Other methods
Treat or stabilise tailings	Thermal processes Physical/chemical processes Mineral reprocessing Cap tailings Revegetate tailings Divert King River
Some combination of options	*Combination of above methods, discussed in following sections of report*

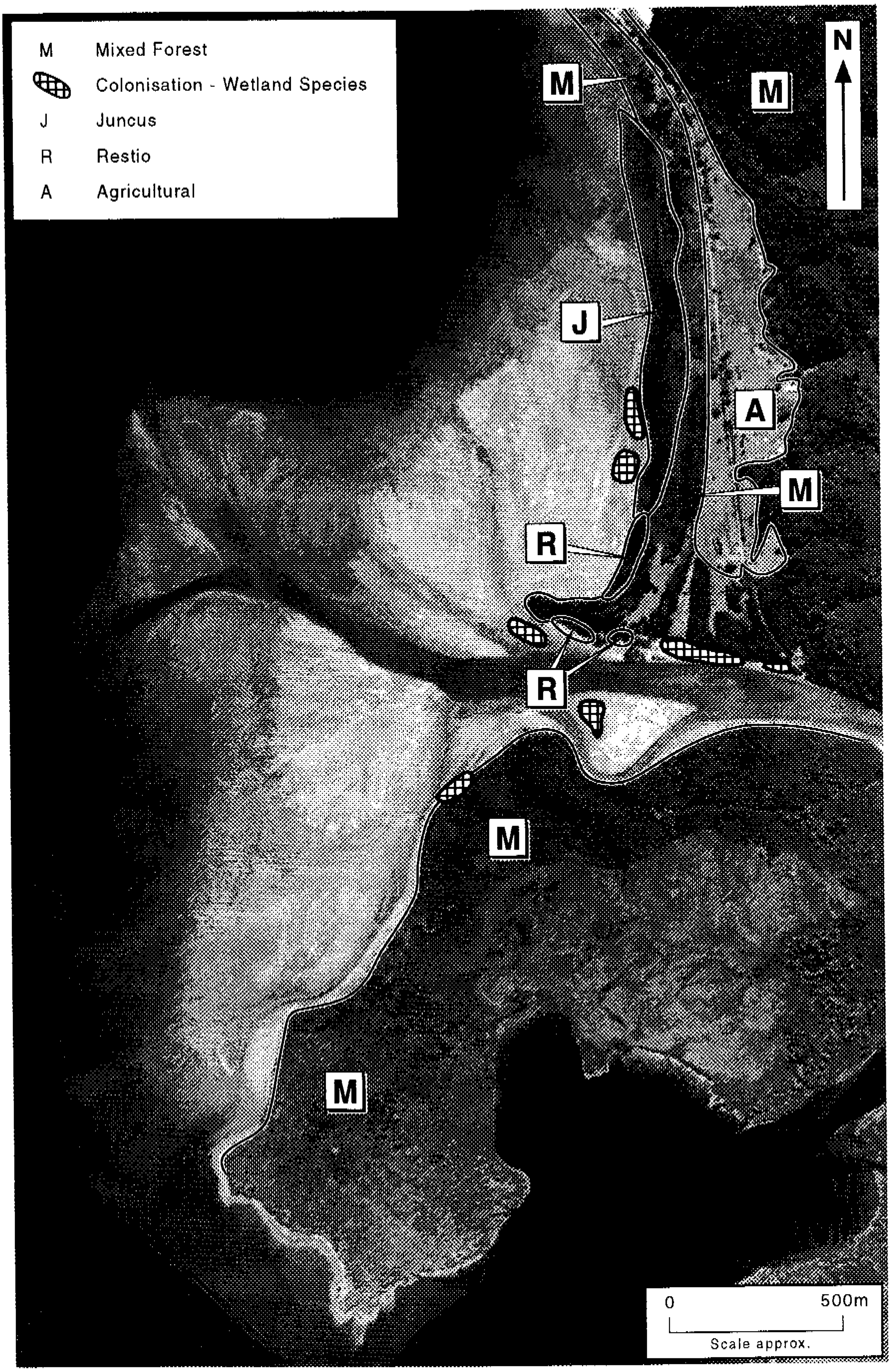


Figure 4 Existing state of revegetation on delta

3.1 Do nothing

This option does not address any of the key objectives of the study. Although the major water quality problems originate from the mining lease, the river banks and the delta will continue to be a significant source of copper to the harbour waters. The 'do nothing' option also fails to address the aesthetics, dust problem, or the low amenity values for the surrounding area.

The present environment is changing due to new hydrological and sediment load conditions for the King River since the cessation of previous mine tailings disposal practices and the commissioning of the John Butters Power Station. The only tailings now making their way to the delta are those derived from slumping and other erosion of the tailings along the river bank. Wave action, combined with settling and slumping of tailings, is slowly reducing the size of the delta. This process can be expected to continue for some time, until a situation more in balance with the present regime is achieved. However, it is not known how much these processes will reduce the present size and shape of the delta.

There is varying anecdotal evidence about the changes to navigability in the delta channels. It has been noted that the depth of the channels may have increased, but deposition immediately upstream of the delta has increased the size of an existing sediment bar.

The 'do nothing' option does not satisfy any of the significant concerns associated with this situation. It could be argued that some remediation strategies should not be implemented until the pollution problem exiting the mine lease is corrected. Some options for corrective action on the delta and river banks would also need to take account of likely ongoing erosion. These considerations aside, there can be little justification for delaying or abandoning any effective program to remediate what is one of Australia's most contaminated sites, providing funds are available.

3.2 Removal

Dredging and river bank removal

Various strategies involving the removal of tailings from the delta or river banks have been examined. A number of these appear to address many of the objectives of the study in a cost effective and feasible manner. By removal of the tailings and the disposal to another secure area, the pollutant source would be removed.

The options of dredging and off-site disposal to a tailings dam or locations in the bottom of Macquarie Harbour are discussed in detail in section 5. Various treatments for the river banks are also discussed in section 4.

Other methods

Other methods have also been suggested for removing tailings or lowering the delta so that the tailings are fully saturated and the oxidation processes reduced. These consist of some form of densification of the tailings material. The tailings consist of cohesionless sand and silt deposited in a loose state with the constituent particles in a metastable condition. If the condition is disturbed, the particles may rearrange themselves in a denser more stable condition. The process usually involves some energy input to initiate the rearrangement of particles. The densification involves expulsion of water from in between the particles. This can be amply illustrated on the delta by working the tailings material with the feet until it liquefies and water comes to the surface.

The energy input could be by:

- Dynamic compaction (dropping a large weight repeatedly on a rock working platform on top of the tailings)
- Explosives within the tailings (this involves repeated insertion of explosives into the tailings until the material densifies)
- Square impact rollers operating on a working platform
- Earthquakes

The excess pore pressures generated by such methods can be allowed to dissipate naturally or they can be assisted by the installation of vertical wick drains or gravel drains. Wick drains will not cause settlement unless there are excess pore pressures present. No significant excess pore pressure can be expected in a delta consisting of granular material deposited over many years.

The basic problem with such schemes is that the delta needs to be lowered by at least 1.0 m and preferably more than 2.0 m. The tailings are deposited in the form of the delta overlying a natural delta. The depth of tailings is relatively shallow for about half way out from the shore, then it increases to perhaps 20 m deep. The tailings material is essentially granular and 5.0% reduction in volume is probably a realistic goal with 10% being optimistic. Thus, the tailings would have to be over 10 m deep before the minimum required surface settlement could be optimistically achieved.

Thus, insufficient surface settlement could be achieved over half the delta area, particularly around the mouth of the King River where the most oxidised tailings occur.

Further problems with such schemes are associated with the necessity of providing access or a working platform over the delta surface. Suitable material for such a platform is not readily available.

Due to these fundamental problems, further consideration of these options is not warranted.

Reduction of the area of the delta may be possible by initiating underwater slides with the material flowing out into deeper areas of the harbour. Slides in such material are possible and have been documented in other areas of the world in particular Canada and Sweden. Investigations have been carried out in such areas on the use of explosives to densify loose deposits with questions of initiating submarine slides. Thus, after further testing, it may be possible to initiate underwater slides at the edge of the delta.

Optimistic appraisal is that the slide may regress back to a slope of say 10% and, since the maximum depth is 20 m, the maximum area affected would only be the outer zone of the delta.

This is a relatively minor area and is also the area that is already underwater and contributing only a small proportion of the acid and dissolved metals to the harbour. This option has therefore also not been considered further.

3.3 Treating or stabilising tailings

Thermal treatment

These technologies are discussed in detail in the companion literature review (Nazarov & Russo 1996). Processes such as vitrification involve applying electricity to melt the constituents of the contaminated material, thus producing a chemically stable glass with very low leaching characteristics. These methods involve very high costs and high energy inputs. They are inappropriate for the King River delta tailings.

Physical/chemical treatments

Various strategies can be employed to physically or chemically treat contaminated materials. A number of these, including oxidation/reduction and solidification options, are addressed in the companion literature review (Nazarov & Russo 1996). In general terms, the quantity and nature of the King River delta tailings rule these out as high cost and inappropriate options.

Mineral reprocessing

Mineral reprocessing is a form of physical/chemical treatment that aims to extract any valuable metals from the tailings. It may have the potential of reducing the amount of chemical degradation of the tailings which, in turn, may lead to a decrease in the soluble concentrations of a number of metallic species in the waters that make up the harbour. It may also reduce the negative visual impact of the tailings delta.

Apart from the potential for reduced environmental degradation of the harbour, there have been some views put forward that the reprocessing of the tailings could also provide a positive cash flow. That is, the market value of recovered components could be greater than the total capital and operating costs of the reprocessing complex. If this were the case, then the reprocessing of the tailings would be readily justified on economic and environmental grounds.

Following a summary of the chemical and mineralogical characteristics of the tailings and the mechanism(s) of their degradation, this section briefly considers some of the critical factors that must be taken into account. This is followed by a brief discussion of the current tailings retreatment projects. An outline of some of the more recent reprocessing proposals for Macquarie Harbour tailings is then presented. These are considered in terms of the practicality of the proposed treatment flowsheets, taking into account metallurgical, engineering and financial factors. It is very important to note that the conclusions drawn from this examination are necessarily subjective. This particularly applies to the cost/benefit analysis, which is strictly at the order-of-magnitude level.

The Macquarie Harbour tailings

The tailings that make up the delta within the Macquarie Harbour have been subjected to numerous investigations. Some of the more important conclusions are noted below:

- The delta consists of approximately 85 million tonnes of sediments, made up predominantly of tailings (20–500 micron) from the Mount Lyell crushing/flotation circuit with a lesser amount of relatively coarser slag particles from the original smelting operations.
- The most recent data suggest that the tailings contain 5–7% pyrite with minor amounts of non-ferrous metal sulphides, principally chalcopyrite, $CuFeS_2$, the major copper carrier in the Mount Lyell orebody. The average copper content of the tailings is reported to be 0.16%.
- Sulphide minerals undergo natural oxidation, leading to the formation of acidic, metal-containing solutions. For the Macquarie Harbour tailings, the main minerals of concern are pyrite and chalcopyrite. Some of the more important dissolution reactions, in a simplified form, can be represented as follows:

$$4CuFeS_2 + 17O_2 + 4H^+ = 4Cu^{2+} + 8SO_4^{2-} + 4Fe^{3+} + 2H_2O$$

$$CuFeS_2 + 4Fe^{3+} = Cu^{2+} + 2S + 5Fe^{2+}$$

$$20Fe^{2+} + 5O_2 + 20H^+ = 20Fe^{3+} + 10H_2O$$

$$2S + 3O_2 + 2H_2O = 2H2SO_4$$

$$4FeS_2 + 15O_2 + 2H_2O = 4Fe^{3+} + 8SO_4^{2-} + 4H^+$$

$$FeS_2 + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$

- The importance of both dissolved oxygen and ferric iron in these reactions is to be noted. The generation of soluble copper and iron species, as well as hydrogen irons (acidity), should also be noted. While the oxidation of sulphide minerals is catalysed by bacterial activity (especially *Thiobacillus ferrooxidans*), this will not be significant within the Macquarie Harbour delta as such bacteria have a low tolerance to high salinities. However, direct chemical oxidation will continue to occur, and may even be accelerated, in the saline environment provided the soluble oxygen concentration is maintained.
- No further discharge of tailings from current and future operations at Mount Lyell will occur.
- The vertical and horizontal profile of the delta is dynamic rather than static as a result of variations in flow down the King River, tidal effects, etc.
- Sampling programs indicate that there are significant vertical and horizontal variations in the physical and chemical properties of the tailings. These variations include particle size and mineralogy/chemistry.
- Much of the tailings in the delta is below low tide level and as such is fully saturated. In the saturated state, there is little evidence that there is significant on-going chemical degradation of the sulphidic components of the tailings. This is consistent with the oxidative nature of the dissolution/degradation reactions. Above the 'water table' there is evidence of sulphide mineral oxidation with the generation of metal-containing, acidic pore water that will ultimately seep into the surrounding environment.
- Based on a very simplistic 'in situ' basis, it has been suggested that the Macquarie Harbour tailings could represent a substantial mineral resource, especially in terms of the total sulphur, cobalt, copper and gold contents.

Reprocessing criteria

To be environmentally acceptable, any reprocessing option must ensure that no further short or long-term problems will arise from the treated tailings. This would require complete removal of the components that lead to the generation of the acidic, metal-containing solutions, that is the sulphide minerals. In practical terms this is impossible to achieve. Thus this criterion cannot be achieved unless the treated tailings are subsequently stored in a secure environment in which any further chemical degradation is prevented and/or contained. The complexity of any tailings reprocessing option is perhaps best illustrated by the fact that more than 90% of the original tailings will have to be stored in this secure environment.

For the Macquarie Harbour tailings, reprocessing will involve the physical handling and subsequent disposal of at least 80 million tonnes of retreated tailings. Land disposal would be impractical, the only other alternative being discharge back into the harbour.

Apart from the disposal of the retreated tailings, recovery of any valuable components within the original tailings will, of necessity, generate a range of solid, liquid and gaseous wastes. All of these must be disposed of in an environmentally acceptable manner and add substantially to the overall processing costs.

From a technical and economic point of view, the reprocessing of tailings is dictated by numerous factors, especially the range and potential market value of the recovered products. Since the operators of the Mount Lyell mine have always attempted to maximise metal recoveries in their processing plants, any retreatment processes for the tailings will necessarily be complex. Moreover, the natural degradation of some of the tailings in the delta will increase this complexity. For example, the surface oxidation of the sulphide minerals will alter their recovery (flotation) characteristics. The substantial variations in particle size distribution as well as horizontal and vertical distribution within the delta would make control of an efficient recovery circuit almost impossible. The big risk with such a circuit is that overall recoveries would almost certainly be less than 50% so that the retreated material would not meet the discharge requirements noted previously.

To be economically viable, any tailing reprocessing option would have to compete with plants treating conventional sources of recoverable metals. As discussed later in this report, the claimed major economic components of the Macquarie Harbour tailings are copper, gold and sulphur. In each case, there are numerous other resources that would be economically and technically easier to treat. The grades of the Macquarie Harbour tailings are less than adequate, while factors such as available infrastructure and distance to the market are non-existent and excessive, respectively.

Tailings valuations and reprocessing case histories

Prior to discussing possible reprocessing options for the Macquarie Harbour tailings, it is appropriate to briefly comment upon existing operations and how they compare with the Macquarie Harbour proposals.

The most important point to note is that all base-metal mining operations produce waste of one form or another. Waste rock and/or overburden is dumped in an appropriate manner. Ore, that is material with a grade higher than the predetermined cut-off level, is subjected to a combination of crushing and grinding followed by 'selective' recovery of the minerals of interest by physical methods such as gravity and flotation. The non-ore minerals, plus that portion of the ore minerals that are not recovered, become the tailings. While it is normal practice to recover as much of the ore minerals as possible, reality (technical and economic) dictates that perhaps, at best, only 80% of the desired mineral(s) report to the final product (concentrate). Various factors such as grain size, liberation, solid-solution, etc., determine the overall recoveries into the concentrates. Since pyrite is a significant assessory mineral with most base-metal sulphide ore deposits, the mineral processing operation is usually designed to reject as much of the pyrite as possible. This pyrite reports to the tailing. As noted previously, it is the oxidation of this pyrite that causes the 'problems' with the Macquarie Harbour tailings, and indeed virtually all other base-metal tailings.

On a very simplistic 'in situ' basis, most base-metal tailings deposits can be regarded as a resource for the future. Taking the Macquarie Harbour tailings as an example and based on the data noted below:

Tonnage:	80 000 000 t
Cu Grade:	0.15%
Copper:	$3000/t

one might conclude that the delta contains copper valued at $340 million. Such a calculation, often espoused for tailings reprocessing projects by their promoters, is nonsense in the extreme. Despite very significant improvements in the efficiency of mineral and downstream processing technologies, it is considered that the value of the copper recovered would be no greater than about 10% of the above and would not be sufficient to cover capital and operating costs.

On the basis of the above, it is not surprising to note that there are very few economically viable base-metal sulphide tailing reprocessing plants, even when taking into account the fact that mining costs are nominal. Many attempts have been made, but success has been very limited. The few exceptions are where the grade of the original tailings is relatively high and where appropriate infrastructure and processing facilities are already in place. In Australia the best example of a viable tailings retreatment plant is that operated by Woodlawn Mines. Even here only 20% of the copper and 55% of the zinc in the original tailing are recovered into the concentrate. Since the final tailing contains 0.4% Cu and 1.7% Zn, this material requires careful disposal to avoid oxidation and generation of acidic copper/zinc solutions within the disposal areas. The tailings retreatment operation is only viable because it has been integrated with that for processing fresh run-of-mine ore. It would not be viable on its own accord.

As noted previously, it has been claimed that the gold content of the Macquarie Harbour tailings would add substantially to the economic value of the tailings. Successful gold tailings retreatment processing plants generally have a head grade of at least 0.7 g/t and a recoverable grade of 0.5 g/t (worth about A$10/t tailing). The head grade of the Macquarie Harbour tailings is about 0.1 g/t (about A$2/t tailing).

It is believed that there has yet to be a commercially viable project involving tailings reprocessing in which the tailings were in the form of a delta or similar, that is, partly submerged in an estuarine environment. This makes direct evaluation of the proposed reprocessing of the Macquarie Harbour tailings somewhat arbitrary. However, based on the limited known potential of other tailings deposits in a more ideal environment, it would appear that the reprocessing of Macquarie Harbour tailings could not be expected to be commercially viable.

It would therefore seem that the reprocessing of tailings from the Macquarie Harbour could only be undertaken on the basis that the taxpayer would meet any shortfall in total capital and operating costs. This would only be possible if it was considered that the long-term environmental benefits of the reprocessing would outweigh this shortfall. As noted below, it is considered that this is highly unlikely.

Previously proposed Macquarie Harbour processing options

In this section various proposed processing options are briefly reviewed. The purpose of the review is to clearly identify the metallurgical and engineering complexities of the proposals and to ascertain if reprocessing would in fact generate the purported benefits claimed by the promoters of such a project.

In 1987 Cottesloe Corporation of New Jersey (USA), represented locally by Launceston-based Elisna Pty Ltd, applied for and in 1989 obtained a retention licence (8804) for approximately 60% of Exploration Licence 2/74 that covered the entire delta of tailings within Macquarie Harbour. In 1995 the Tasmanian Government withdrew Cottesloe's retention licence.

Between 1987 and 1994 Cottesloe reviewed existing data held by the Tasmanian Department of Mines and companies that had previously evaluated the delta tailings and undertook further sampling of the tailings in the delta. Various samples were subjected to a limited amount chemical and mineralogical characterisation. In addition, some simplistic gravity separation tests were carried out in order to produce an upgraded product (concentrate).

On the basis of the very limited test work, a conceptual processing flowsheet was formulated by Cottesloe. This consisted of a barge-mounted preconcentrator followed by shore-based processing units using additional mineral processing, pyrometallurgical and hydrometallurgical unit stages. The major treatment steps included the use of screening, hydrocyclones, spirals, flotation, magnetic and electrostatic separators, high temperature roasting under a reducing atmosphere, leaching under both acidic and alkaline conditions, solvent extraction, electrowinning and selective precipitation.

Although not considered by Cottesloe, it should be noted that, in theory, it would be possible to limit reprocessing to the production of concentrates via mineral processing techniques. However, on the basis of the limited information available, such concentrates would be difficult to market because of their relatively low grade.

It is not possible nor appropriate to comment on the flowsheet in detail except to note that many of the proposed unit stages are best described as alchemy. There is no foundation whatsoever for the metallurgical veracity of the proposed flowsheet. Cottesloe conceded that recovery of the 'valuable' components into saleable products would generally be 20–40%. It was also noted that it would be necessary to return the reprocessed tailings back into appropriate areas of the harbour.

The major products of 'commercial value' are claimed to be sulphur, gold, copper and cobalt. Moreover, the proposed flowsheet incorporates the recovery of such minerals as barite, monazite and zircon. These minerals constitute less than 1% of the total tailings and are at concentrations several orders of magnitude lower than those of the mineral sand deposits of Western Australia, Victoria, New South Wales and Queensland.

The purported economic evaluation of the proposed reprocessing flowsheet prepared by Cottesloe is simplistic in the extreme and is based upon a number of unwarranted and erroneous assumptions. These cover both capital and operating costs as well as market prices and opportunities. For example, Cottesloe claimed that a substantial market for elemental sulphur existed. They proposed incorporation of a pyrometallurgical unit in which approximately 50% of the sulphur component of pyrite could be recovered in the elemental state. The process proposed by Cottesloe was far from state-of-the-art, while the purported capital and operating costs of this unit did not include many readily identifiable factors. In the present context, a critique of the valuation prepared by Cottesloe is inappropriate.

It is not possible or practical to prepare an updated financial analysis of a realistic reprocessing flowsheet. However, it could be expected that gross processing costs would exceed actual income by a factor of at least 20.

Cottesloe attempted to identify a number of national and international joint venture partners, without success. This lack of success is not surprising once a preliminary technical and commercial due diligence was carried out by the prospective partners.

Apart from Cottesloe, there does not appear to have been any other recent, concerted effort to establish a viable flowsheet for reprocessing the tailings within the Macquarie Harbour delta. However, a number of individuals and technology developers have made suggestions that retreatment might be possible and should be considered. At this stage it does not appear that any formal proposals have been properly documented. Most of the proposals appear to have been based on an imperfect understanding of metallurgical and engineering principles. Most of the proposed treatment strategies involve dredging of the tailings, as was the case in the Cottesloe flowsheet. At least one proposal involved in situ treatment by 'vitrification'.

Conclusions and recommendations

In summary, reprocessing of the tailings can be regarded as lacking any technical, commercial or environmental credibility. The metallurgical challenges are substantial, as are the financial costs, while the potential income would be limited. Even over a 20 year life-of-operation, considerable disruption to the local region would almost certainly occur. It would not be possible to remove and recover all of those components in the tailings that undergo reactions to yield acidic solutions containing unacceptably high metal solutions. Thus redeposition of the residues from the retreated tailings would have to be carefully planned and executed. Deep water disposal would be the only viable alternative.

It might be possible to recover a limited amount of marketable products from the tailings using only physical methods (screening, hydrocylones, spirals, flotation), although the value of such products would be minimal at best. Moreover, this concept would not alleviate the problems associated with disposal of the retreated tailings.

Stabilisation by capping

The companion literature review (Nazarov & Russo 1996) discusses in detail a range of strategies used overseas and in Australia to cover contaminated materials. The situation with regard to the King River delta presents a number of unique problems if capping or covering is to be a major remediation strategy.

Given the topography, tidal influences and highly acid nature of the upper part of the delta tailings, minimising infiltration and interaction between surface runoff and tailings from the delta were seen as impractical by project 5 (Taylor et al 1996). However various options are considered below.

Importing fill to cover tailings

This would involve opening up a borrow area and/or a quarry nearby and placing fill over the top of the delta to above extreme high tide level. The filling would allow re-vegetation of the surface and reduce the surface area exposed to tidal flushing. The river channel would need to be dredged and lined by a rip rap protected bank.

The external batter would also require to be protected by rip rap to 2.0 m above high water and 2.0 m below low water as detailed in section 5. The rip rap would need to be high quality rockfill from a hard rock quarry. The fill could consist of any uncontaminated material such as sand, clay or rock.

The quantity of fill required to cover the entire delta would be 2.5 million cubic metres per metre depth. Two (2) to three (3) metres depths of material would be required making the total quantity between five (5) and eight (8) million cubic metres or ten (10) to twenty (20) million tonnes.

Additional studies/monitoring

Any detailed design would need to consider:

- Effect of filling on adjacent land. This land is poorly drained at present and some form of stormwater control to conduct it through the delta would be required.
- Settlement of delta materials due to fill placement. Any settlement will require additional fill to be placed to maintain site levels and surface drainage.
- Stability of the delta edge under weight of fill.
- Feasibility of placing rock rip rap toe.
- Continued leaching of metals from tailings.

- Flooding problems for river and areas adjacent to delta.
- Extent of bank raising up the King River.
- Site for a suitable borrow and quarry area.
- Construction of suitable haulage road/railway.

Feasibility

Though there may be a solution to each of these concerns, the magnitude of the work and anticipated cost of hundreds of millions of dollars does not warrant further consideration.

Revegetation

Project 5 (Taylor et al 1996) identified a number of potential remedial measures for reducing acid and metal fluxes involving revegetation of the tailings deposits. The upper 1.5 m of the tailings delta and the sediment banks are the problematic sediments which are contributing metal and acid.

The mass transfer of metal and acid to surface water was identified as depending on several key issues:

- sulphide (pyrite) + slag oxidation rates,
- groundwater fluxes, which are in turn related to hydraulic conductivities and hydraulic gradients, the volume, composition and rate of release of surface runoff, the rate of groundwater level fluctuations (wetting/drying episodes), and the acid neutralising capacity of tailings.

The physical configuration and hydrogeological regime of problematic sediments in the delta (upper 1.5 m) and those in the banks is quite different, and potential remedial techniques have been identified to address these differences. These are discussed below.

Delta

Project 5 (Taylor et al 1996) has identified a recommended remedial strategy involving an extension of natural processes currently operating within the tailings. Sulphate-reducing bacterial activity at the tidal interface zone on the delta is believed to be responsible for significantly lowering metal and acid release to the harbour. It was recommended that optimum conditions for the growth of these bacteria are established, and that such conditions are encouraged more widely throughout the delta. This strategy relies on altering the chemistry of the tailings and associated groundwater via biological processes.

This strategy has similarities to the identified acid drainage remediation strategy identified in project 2 (Miedecke 1996), which involved the construction of successive alkalinity producing systems (SAPS) which relied not only on sulphate reducing bacteria but also limestone induced alkalinity in anaerobic conditions.

The construction of depressions was recommended, with the depressions revegetated with wetland species and incorporating organic material and sulphate reducing bacteria to extend the natural processes currently operating within the tailings.

Tidal data and inspection of debris lines around the delta indicate that most of the delta is within the tidal range, or at least is affected by a combination of prevailing onshore winds and tide. The location of flotsam hard against the original shoreline suggests that revegetation of the delta will be affected by high tides and infrequent flooding. Nevertheless, some form of wetland/dryland construction is considered further in section 5.

River banks

In the river bank tailings deposits, project 5 (Taylor et al 1996) recommended the vigorous revegetation of appropriate (eg initially shallow-rooted) species on a substrate comprising clay (75–80%) + calcium/magnesium carbonate 10%) + organic debris/mulch (10%) to reduce acid and metal releases from the tailings. This is occurring naturally to some extent on the downstream end of some of the banks. All suitable native species including deep rooted species have been considered, as after establishment and possible death, they will have contribute to site stability and the build-up of organic matter.

A strategy involving a relatively thin cover (eg 5–30 cm) of such material is believed to have the combined effect of:

- lowering groundwater recharge
- enhancing runoff while minimising interaction between surface water and tailings
- enhancing water loss through evapotranspiration
- partially treating infiltration (acting as a chemical barrier) prior to entering the saturated zone
- acting as a self-sealing system in the event of unavoidable acid production
- ultimately lowering the water table and thereby reducing horizontal hydraulic gradients and groundwater discharge rates
- dampening groundwater level fluctuations by lowering recharge

The full effect of such an approach it is believed may not be evident for decades or longer, since cyclical die-back (postulated above) may be an essential part of the (natural remediation) process of building-up organic debris on the banks. A build-up of organic debris is likely to be an integral part of the feedback loop for enhancing additional plant growth and further water loss through evapotranspiration.

The revegetation trials to date have indicated that while revegetation can be achieved in such a manner, that the tailings banks are not homogeneous and that each bank has its individual characteristics.

Revegetation options are covered in detail in sections 4 and 5. Appendix 2 describes the revegetation trials carried out as part of this project.

King River diversion

The concept of diversion of the King River arose within the context of stabilisation of the tailings delta without the need to remove the tailings. The diversion would comprise the excavation of a major diversion channel between the King River and Pine Cove through the low ridge that currently separates the two features and provide material for capping the delta. The channel so excavated would become the new course of the King River. There could be some residual tailings from the King River which would flow along the channel and be deposited in the deep water of Pine Cove and Macquarie Harbour.

The engineering, environmental and hydraulic aspects of the proposal would have to be examined in some detail before such a proposal could be said to be a reasonable and cost effective solution to the tailings stabilisation. The key elements of the proposal are:

- The excavation of a river diversion cutting about 750 m long and ranging in depth up to about 35 m deep at the deepest point; generally the cutting would be less than 10 m.

- The excavation of a navigable channel, say 5 m deep below sea level; this channel could be excavated in the dry with coffer dams at either end which would be removed at the end of the work.
- The use of excavated material from the cutting to provide a cover for some of the tailings in the delta.

The positive elements of the King River Diversion proposal are that the channel excavated between the King River and Macquarie Harbour would permit a stable, self flushing channel to be available at all times for navigation along the King River and would completely overcome the potential for erosion of the existing delta. Thus the proposal would completely overcome the risk of delta remobilisation by erosion from the King River. The excavated spoil from the cutting on the surface of the tailings could be used to raise portions of the delta above high tide level and provide an inert stable cover for portions of the delta.

The negative aspects are seen as the overall cost and in particular, the capital investment which would be required before any tailings stabilisation could be carried out. There are questions to be resolved in terms of the engineering aspects of the project. These include construction methods, material types to be encountered in the excavation, excavation methods, suitability of excavated materials for reclamation, slope stability and ongoing maintenance and surveillance costs. There are unknowns in environmental terms relating to the acceptability of such a large cutting in aesthetic terms, the potential for dust and erosion products from the cutting entering Macquarie Harbour. Acceptable methods for re-vegetation would have to be found.

The concept would require a considerable expenditure by way of earthworks using large scale earthmoving equipment before the actual stabilisation of the tailings could even be commenced. It would not, be suited to a progressive implementation approach which permits a low initial capital investment and a continuing low level of investment. The proposal must be regarded as being one which is part of a larger land use planning scheme rather than a project somewhat marginal to the concept of tailings stabilisation which is the focus of the tailings remediation project as a whole.

Quantities

The channel and the cutting itself may be considered separately for the purposes of quantity estimates.

Cutting

Assuming an average depth of 12 m for the length of the cutting and batter slopes of 2H:1V, the total excavated quantity would be in the order of (12 x 20) + 2 x (12 x 24)/2 m^3, amounting to 528 m^3 per metre. Over the 750 m length of the cutting, this amounts to 750 x 528 m^3, that is 396 000 m^3.

Channel

Assuming a channel width of 20 m and depth of 5 m, the total channel excavation would be about 100 m^3 per metre of excavation. For the diversion cut length of 750 m, the total excavation would be about 750 x 100 m^3, amounting to 75 000 m^3.

The total excavation could probably be achieved in less than 12 months.

The filling available for delta reclamation would permit reclamation of only about 40 ha to a depth of about 1 m, leaving substantial areas of the current delta to be dredged or stabilised by other methods.

Costs

The cost of excavation of the channel could only be reliably estimated after a detailed site investigation and design, given the uncertainties of the excavation conditions both in terms of volume and ease of excavation. The cost of this proposal could exceed $12–15 per cubic metre. Thus the cost of excavation alone could exceed $6 million to which would be added engineering and monitoring costs.

Conclusions

The construction of the King River deviation has the potential to yield limited clean fill for delta capping, whilst at the same time providing a navigable self flushing channel into the King River. The deviation would have a high capital cost before any tailings are stabilised and would not resolve the stabilisation of the tailings delta by itself. The deviation should be considered as a potential engineering solution to be used in conjunction with other stabilisation techniques, but would have environmental implications which would have to be resolved before the proposal can be considered as feasible.

3.4 Recommended strategies

The most feasible strategy for remediation of the tailings deposits involves some combination of the options outlined above. The following sections examine the most feasible of these options in detail. Section 6 outlines a strategy that combines several of the options for the river banks and delta.

4 Detailed consideration of major options: River banks

In this section and the next, the options which have been discussed in the previous sections for further consideration are considered in more detail for remediation of the river banks and delta. Each option is considered using a similar framework so that comparisons can be made on a common basis. The framework adopted for the discussion of each option includes the following

1 **Description:** a brief description of the option, outlining the key characteristics and elements of the proposal.

2 **Achievement of objectives:** a review of the extent to which the option will meet the objectives outlined in section 1.3 of this report.

3 **Method:** a discussion of the technical methodology for achieving each option.

4 **Feasibility:** a discussion of the likely difficulties and limitations of the options and their feasibility.

5 **Further studies and monitoring:** a review of additional studies needed before undertaking any option, and any recommended follow-up monitoring.

6 **Costs:** an approximate listing of costs associated with the option, to the best extent possible at this stage.

7 **Timing:** any timing issues that will affect the option such as seasonal constraints, scheduling efficiencies or requirements.

The options for remediation of the river banks selected for detailed consideration are 'do nothing', revegetation and removal of bank material.

4.1 Do nothing

The option to 'do nothing' clearly implies no intervention in natural processes occurring on the banks. This option may be suitable for some banks well upstream of Teepookana Bridge that are inaccessible and where natural revegetation is occurring.

Achievement of objectives

The option to 'do nothing' does not achieve many of the objectives listed in section 1.3. As discussed earlier, the banks are contributing acid drainage and metals to the river. If there is no intervention for remediation, this will continue, with natural remediation due to revegetation and oxidation occurring over a very long period.

The visual impacts to the tailings banks will not be mitigated by a 'do nothing' option. As mentioned elsewhere, natural revegetation is occurring on the banks. However, the most visible banks are those close to the mouth of the King River, and these banks are the ones where natural revegetation is slowest or non existent. For example, Bank F is highly visible, with exposed tree stumps, and there is very little natural colonisation over the majority of its surface.

There would be no community benefits associated with this option. During the course of the MLRRDP there has been considerable community interest generated in the various projects. An expectation has developed of 'something happening' and this makes the do nothing option less feasible now than it would have been before the initiation of the project.

Additional studies/monitoring

If the option to do nothing is selected, there is still a need to monitor the contribution of acid drainage and metals from the banks. Erosional and revegetation processes should also be monitored, to help determine the likely time scales of such events.

4.2 Removal of bank material

This would involve movement of tailings into the river to allow the river to transport the material down to the delta.

Since the construction of the hydroelectric dam upstream on the King River, the frequency of floods and discharge durations has been altered. The higher sand bars along the river were deposited during high stage flood events when tailings were still being disposed of to the river.

During low flows, the tailings accumulated in sections of the river such as the junction of the Queen and King Rivers. The accumulated sediment was then flushed down the river during subsequent floods.

With the absence of frequent floods, the sand banks along the river are rarely, if ever, inundated and no substantial erosion/deposition of the sand banks is expected. Thus, if the existing sand banks are removed, no substantial re-deposition of tailings onto the banks may occur.

It is estimated that at least 95% of the acid drainage into the river originates from the old mine workings around Mount Lyell. The tailings on the river banks are believed to contribute about 2% with the remaining 3% from other sources. It is understood that with the interception schemes and treatment at the mine site, the main contribution may be eliminated. Thus, after the scheme at the mine is fully implemented, a major remaining contribution to acid and dissolved metals levels in the river will be from the tailings on the river banks,

The river bank deposits removal would progress from as far up the river as possible, preferably starting at the junction of the Queen and King Rivers, and work down towards the mouth of the King River. Only those areas not covered by substantial vegetation would be disturbed. The basic idea is to remove the tailings down to the old natural surface and allow/promote re-vegetation of the old banks of the river.

Achievement of objectives

The removal of the tailings will remove the contamination source and the potential problem of ongoing acid generation and will provide a substrate that is more amenable for revegetation and stabilisation of the tailings surface. However, there would be short-term effects on river water quality.

If removal of tailings material is followed by revegetation, the objectives outlined in section 1.3 could well be achieved.

Method

The most appropriate method of removing the material off the banks would be subject to a series of trials in various areas of the rivers. Different methods would be applicable to different areas, with the basic aim to remove the tailings with minimal disturbance to the natural soils or existing vegetation.

The material would be moved off the river bank by a combination of:

- long reach excavator picking material up and placing it in the river
- small dozer pushing material into the river or to the excavator
- barge mounted pump and monitors for sluicing material into the river

The disturbance of the tailings will result in a large increase in sediment, acidity and dissolved metals in the river for the period of disturbance. Balanced against this short-term effect would be the long-term improvement in water quality.

Burial on site is also an option which can be considered further.

Feasibility

Some of the practical difficulties with the methods are:

- Ensuring material placed into river channel is flushed down to the delta. Since the construction of the Crotty Dam, natural flood events have been significantly reduced. From table 2 it can be seen that what was a one in two year event is now a one in fifty year flood. Thus, significant flood events capable of adequately flushing tailings down the river to the delta are very infrequent.
- Quantifying the short-term effects on water quality. It may require work to be carried out at certain periods to minimise impacts—such as at times of power station operation.
- Re-deposition of material onto the banks by later floods, particularly in the lower reaches.
- Placing natural fine silt material into the river which may result in an increase in areal extent of fines deposition in harbour.
- Excavation of tailings from around established vegetation and trees.
- Re-establishment of vegetation along banks will take considerable effort and time. The situation will be worse for considerable time during and after such remediation.
- The work would be susceptible to flood damage during the operations and until protective vegetation can be re-established.

Table 2 Annual flood frequency series for the King River at the delta

Annual exceedance probability	Estimated flood peak	
(1:Y years)	Pre Crotty Dam (m^3/8)	Post Crotty Dam (m^3/8)
1.25	500	265
2	640	320
5	865	410
10	1025	470
20	1280	570
50	1460	640
100	1730	745

Additional studies/monitoring

The main justification for removal of the river bank deposits is for water quality improvements. The contribution of the tailings to the metal loads in the river, especially under 'flushing' events is uncertain and requires further investigation. Trials with associated water quality monitoring is also recommended to test the feasibility and effectiveness of this option. Some river bank deposits may be more amenable to removal, at least to the water table and some may be better revegetated in situ.

Costs

Table 3 outlines costs associated with bank removal. This is based entirely on the estimated river bank volumes and an approximate cost of $2 per cubic metre. In some cases these costs will either be an under or overestimate, depending on location.

Table 3 Removal of bank material: Costs

Location	Subaerial surface area (sq m)	Perimeter along river bank (m)	Perimeter along harbour (m)	Average depth of tailings (m)	Volume of tailings (m^3)	Cost @ $2.00 ($000s)
Bank A	24600	686		0.5	12300	24
Bank B	26100	1128		1.3	33900	67
Bank C	11950	361		2.5	29900	59
Bank D	39525	925		3	119000	238
Bank E	17150	505		3.5	60000	120
Bank F	26875	652		4	108000	216
Bank G	17250	660		4.5	77600	155
Bank H	21900	679		4.9	107000	214
Bank I	2125	153		5	10600	21
Bank J	10925	503		5	54600	109
Bank K	4325	243		5	21600	43
Bank L	25725	689		5	129000	258
Bank M	27225	606		5	136000	272
Bank N	34150	501		5	171000	342
Bank O	24400	699		5	122000	244
Bank P	17450	379		5.2	90700	181
Bank Q	32150	634		5.4	174000	348
Bank R	46050	763		5.4	249000	498
Total	2490000	14747	3803		1700000	3412

Timing

If it was decided that removal of tailings from the banks was desirable, then the procedure would have to be carried out as the first phase of any rehabilitation option prior to any re-vegetation or downstream remedial works. The placement of the tailings into the river would result in a new range of deposition downstream of the activity and may need to be scheduled with periods of power station activity/and or river flooding. The procedure should also be completed soon, prior to substantial re-vegetation of the banks by remedial works or natural processes.

4.3 Revegetation

Revegetation is occurring naturally on some banks, particularly the high, stable and well oxidised banks above Teepookana bridge. The natural revegetation appears to be following a succession that includes mosses which stabilise the surface, rushes such as *Restio* and *Juncus* species, and rainforest species such as myrtle, sassafras, leatherwood and blackwood. On the lower areas, where the tailings are saturated, plant colonisation is occurring with wetland species such as reeds, rushes and sedges.

Observations of the existing revegetation on the river banks and on the delta and observations from the revegetation trials, have led to the following preliminary conclusions:

- Vegetation readily colonises stable oxidised tailings
- Colonisation is evident on permanently damp un-oxidised tailings
- Vegetation does not readily colonise transition zones between un-oxidised and oxidised tailings (banded profiles) and may be related to fluctuations in the water table. Taylor et al 1996 believe that these fluctuations are effective in bringing acidity and latent acidity into the root zone of plants in the lower banks.
- Wind erosion and consequent physical abrasion of establishing plants will limit revegetation success
- Build-up of wind blown tailings around the bases of established plants will ultimately suffocate and kill that plant
- HEC control of water level will reduce the frequency of flooding of the lower river banks, and may affect established plant survival

Revegetation as a remediation option refers to direct intervention to assist the natural process. The intervention may be relatively simple, such as placing slash and broadcasting fertiliser to encourage moss growth and assist succession. Interventions may be more complex, such as excavation of tailings material or importation of cover material, followed by cultivation, direct seeding and/ or planting of seedlings.

Achievement of objectives

The revegetation option performs well when compared with the five objectives outlined in section 1.3. A complete vegetation cover will assist in preventing further erosion of banks. This will mean fewer contributions to sediment, metal and acid fluxes to the river. However, the effects on the reduction of metal loads via 'flushing' and long-term groundwater movements is uncertain. These are not likely to be major.

Continuing bioremediation of the tailings by bacterial activity as proposed in section 3.7 is also favoured by a good vegetative cover. The plant roots provide sites with the appropriate microclimate for a range of bacteria involved in the processes of bioremediation.

Revegetation will dramatically improve the visual impact of the tailings deposits, screening and eventually obscuring the bare banks and dead tree stumps that are currently visible on many of the banks. Even in wetland areas, a dense community of wetland plants will be far more attractive a sight than grey or orange tailings.

Dust generation will be reduced, although the banks are not a significant source of dust at present. The surface relief of the banks indicates that there is substantial wind erosion, sifting and removal of material, and a vegetative cover will reduce this effect.

Enhanced amenity would result from revegetation, particularly for tourists and locals travelling up the King River in boats.

The community benefits with revegetation are also potentially significant. Some of the proposed revegetation methods are labour intensive, and could provide opportunities for the local residents to be involved in planting and other activities. There is considerable interest from the local landcare group in this regard. Opportunities exist for local propagation of planting material, with either the landcare group and/or the school gathering and growing suitable material.

Method

The barriers to natural revegetation include physical effects such as exposure, sand blasting with wind blown particles, surface instability and browsing pressure from wildlife. Observation has revealed that in areas that are sheltered due to aspect, topography or even fallen branches, natural colonisation is taking place (see plate 2).

The acidic nature of the unoxidised tailings is hostile to revegetation, however, observations of trials to date have indicated that the oxidised tailings can be revegetated successfully by many local native plant species. It appears that the saturated unoxidised tailings can also be revegetated successfully using aquatic (wetland) species.

The range of rehabilitation treatments which have been identified as feasible strategies include the following:

- Removal of the river bank tailings deposits to either expose underlying original soil profiles or excavate to the water table (saturated unoxidised tailings). This can be done by earthmoving equipment and/or sluicing the material into the river under favourable river flow conditions (high flow). Revegetation treatments will involve the establishment of appropriate native plant species in the constructed wet and dry areas (see fig 5).
- Excavation of underlying soil profile and burial of the tailings in the excavation, with the excavated materials used to cap surrounding tailings. Revegetation treatments will involve the establishment of the appropriate native plant species over the recovered soils (see fig 6).
- Cap the tailings with soil removed from a pit or quarry followed by native species revegetation.
- Direct revegetation of the tailings following remedial action such as lime and fertiliser application and surface cultivation.

The strategy is preliminary and based on the interpretation of revegetation trials which have been constructed (see appendix 2). The strategy will need to be reviewed following the trial monitoring over several seasons.

Plate 1 Aerial oblique view of King River delta, showing tailings material being removed from the harbour edge of the delta

Plate 2 Fallen branch on tailings bank near Teepookana Bridge. Note the vigour and variety of plant growth in the area sheltered by fine stems and leaves of the fallen branch.

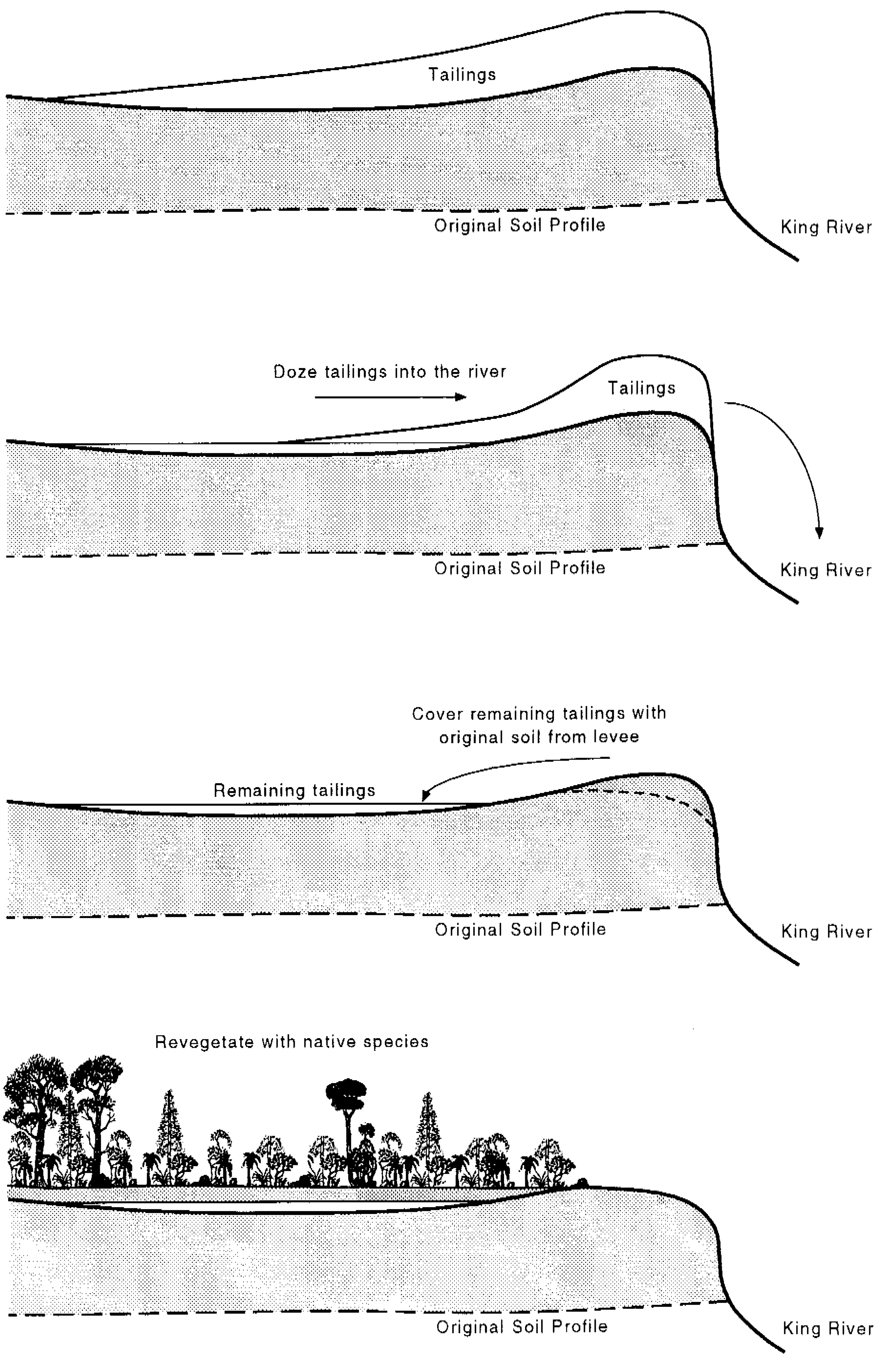


Figure 5 Revegetation option 1: Banks

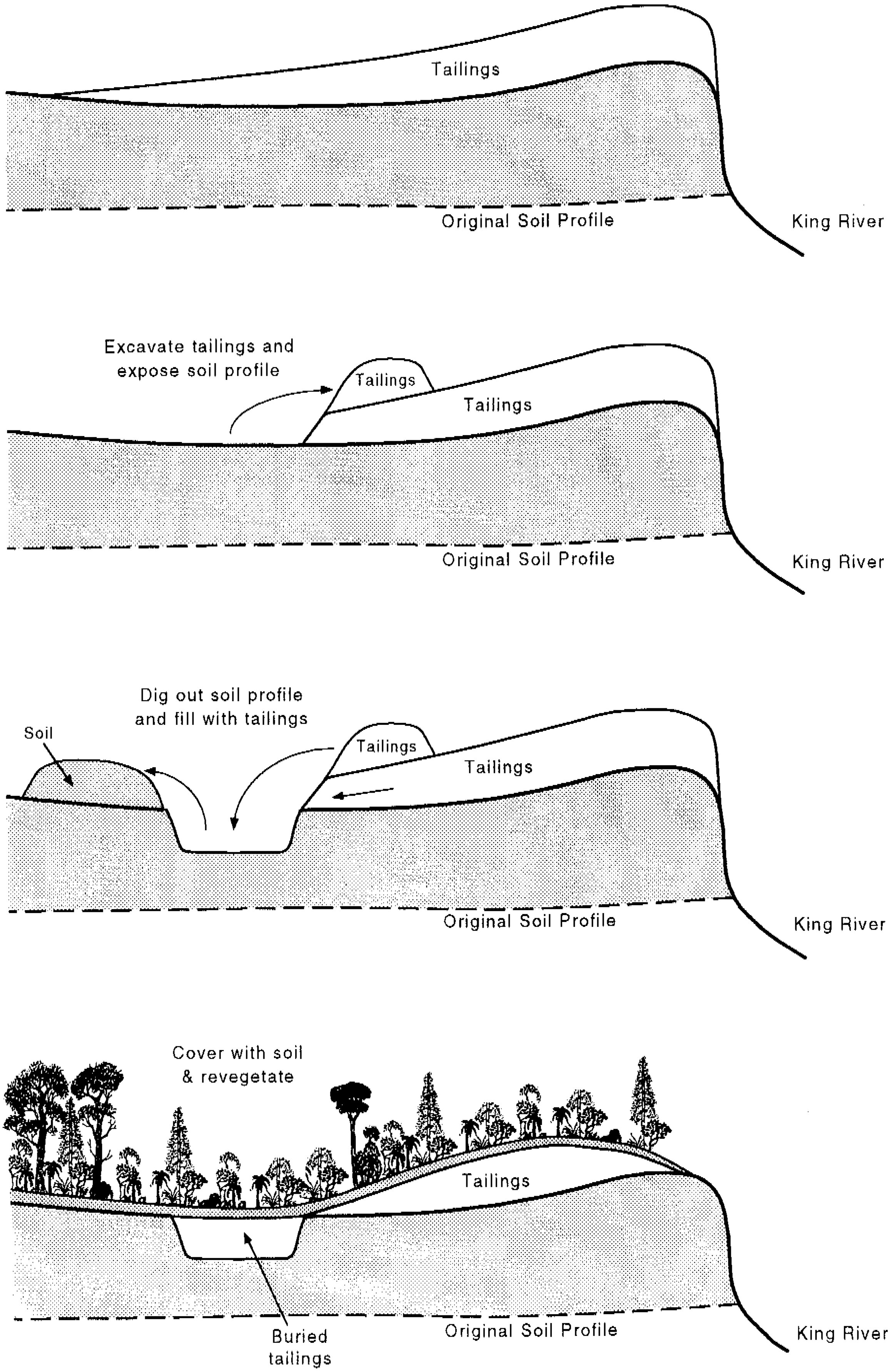


Figure 6 Revegetation option 2: Banks

Feasibility

Indications from the preliminary observations of the trials are that revegetation is a feasible option for the banks. Not all treatments work on all sites, but there is evidence to suggest that success can be achieved with a range of treatments tailored to meet the specific conditions of a given site.

Browsing pressure appears to be a significant limitation for revegetation, since fenced trial plots showed dramatically better growth (particularly of exotic grasses) than unfenced plots. It would seem impractical to attempt to fence all areas; however strategically located sites would benefit from exclusion of game.

Additional studies/monitoring

Over forty treatments covering a wide range of sites and conditions were established in the revegetation trials documented in appendix 2. These trials have provided valuable information to date about the likely success of various planting approaches. However, the value of these trials will be greatly increased if a program of continued monitoring is instigated.

Experience in other revegetation sites over many years has shown that a site may not respond quickly to a treatment, but that dramatic growth and native species recruitment has taken place after several seasons. Conversely, it has been known for sites to show a flush of growth, particularly of cover crops, and two years down the track no significant vegetation remains.

For these reasons it is strongly recommended that the trials set up during this project are maintained and monitored, at intervals of at least 6 months, for as long as possible, but at least for the next five years.

Further investigation and trials may be necessary for the more inaccessible banks on the left bank of the river, particularly those closer to the mouth, ie Banks B, E and G.

Transition zones mentioned in section 4.2 need to be determined by further studies. These include the lower banks from the delta to bank F.

Metal concentrations in both the tailings and within the underlying soil profile should also be investigated, because of their possible constraints on revegetation.

Costs

Costs for revegetation will vary according to the treatment chosen. These range from simple and relatively cheap methods such as broadcasting of fertiliser, to complex and therefore more expensive operations involving earthworks, planting of seedlings and fencing.

Simple fertiliser and seed broadcasting, using cheap labour could be achieved for approximately $2000 per hectare. Hand planting of seedlings or wetland plants, addition of fencing and construction activities could boost the cost up to $7000 per hectare. There are some fixed costs regardless of the method chosen, which include transport, organisation and monitoring and reporting.

On any given bank, it may be desirable to use a range of methods which have different costs. Table 4 outlines the cost of revegetation for each bank, giving a range of values from $2000–$7000 per hectare.

Costs will be influenced by the availability of labour for the more labour intensive operations. There are opportunities for local groups to supply seed and propagation material. Early indications are that such groups would be willing to supply cheap material if they can receive some assistance with set up costs, eg glasshouse.

Table 4 Revegetation costs: Banks

Bank	Surface area (hectares)	Cost (@ $2 000 - $7 000 per ha)
A	1.7	$3 400 – $11 900
B	2.8	$5 600 – $19 600
C	1.2	$2 400 – $8 400
D	1.2	$2 400 – $8 400
E	1.6	$3 200 – $11 200
F	1.7	$3 400 – $11 900
G	1.6	$3 200 – $11 200
H	1.5	$3 000 – $10 500
M	2.1	$4 200 – $14 700
Total	15.4	$31 000 – $107 800

Timing

Timing issues for the revegetation option include seasonal considerations and planning time needed to obtain seed and seedlings for planting.

Observations from the trial indicate that Autumn is the best time for planting materials, as this allows recovery and root development through winter. Spring plantings do not allow this, and there are indications that the planted material suffered from drought stress over Summer.

The revegetation could be done progressively, and this would allow for incorporation of information derived from further observations of the trials.

5 Detailed consideration of major options: Delta

5.1 Do nothing

The option to 'do nothing' clearly implies no direct interventions to remediate the tailings deposits in the delta.

The natural revegetation of the delta is limited to some colonisation of drainage lines by wetland species such as *Juncus* sp., and active colonisation by cordrush (*Restio*) at the vegetated perimeters of the delta. A decision to do nothing, therefore, will not assist this natural process, and it is likely that only a very small portion of the delta will naturally revegetate.

It is expected that the tailings comprising the delta—which were deposited subaerially—will continue to consolidate and the surface will continue to subside. These effects should be most noticeable where the depth of tailings is greatest—at the outer edges. Therefore, there may be some reduction in the surface area of the delta over time which will reduce the area of unsaturated tailings and therefore also reduce metal loads.

There is also some evidence that the underwater toe of the delta is unstable, and will tend to approach a shallower angle of repose than the one it currently exhibits, regardless of remediation efforts. Appendix 1 contains a paper that estimates the probable effect of wave action on the King River delta. This paper concludes that in shallow water of depth 2 m the sand in the delta can commence to move with very small wave heights of less than 0.25 m, which would represent the conditions with a high tide over the delta, and virtually any wave action. The required threshold wave height increases with depth; however even at a depth of 6 m the sand movement can be initiated by waves of about 0.75 m.

In general the equilibrium state of a beach, assuming that the sediment comprising the delta can be considered as such, depends on the interplay of wave forces and currents but can often be characterised by the grain size of the particles making up the beach. In the case of the delta the equilibrium slope is calculated to be approximately 1:40.

It is considered that given sufficient time and wave action of a reasonable magnitude, the sediment would eventually take up this slope from high water down into the harbour, since the replenishment from the tailings in the King River has now ceased. This effect would be modified by movement of the river mouth, and possibly by long-shore movement of sediment to the north.

Aerial photographs support this conclusion, with plumes of material from the face of the delta visible under certain tide and flow conditions (see plate 1).

Achievement of objectives

The discussion in earlier sections of this report, and the conclusions from project 5 (Taylor et al 1996) indicate that the 'do nothing' option will not achieve the desired objectives. The delta can be expected to continue to release metals to Macquarie Harbour for a long period of time—possibly centuries.

Since natural revegetation of the delta is very limited, the 'do nothing' option would not result in significant aesthetic or dust alleviation benefits in the medium term.

There would clearly be no community employment, ownership or pride benefits derived from this option.

Additional studies/monitoring

A decision to do nothing to the delta sediments would not remove the requirement for ongoing monitoring to assess the continued environmental effects. This monitoring should include water quality, sediment surveys, aerial photography, and topographic surveys.

The contribution of the delta to the metal loadings in the harbour remain to be quantified, as does the extent of any settlement and subsidence.

5.2 Dredging of tailings material

The option to remove tailings material by dredging is discussed here in three sections. The first section looks at the issues to do with dredging itself, regardless of the fate of the dredged material. The next two sections look at disposal of dredged material to the harbour floor and a tailings dam respectively.

Description

The total quantity of tailings deposited on the delta is about 85 million tonnes and complete removal is probably impracticable and undesirable. The tailings are relatively innocuous in salt water, thus it would be appropriate to store the tailings in a salt water environment low in dissolved oxygen where they can remain undisturbed.

The upper 1.5 m of the delta, containing about 4.4 million tonnes of tailings, is undersaturated with water and is the most significant source of acid and metals from the delta sediments. The delta appears to be a sink for copper associated with sediment particles, as well as a source of dissolved copper to the water of the harbour.

The water in Macquarie Harbour is low in dissolved oxygen, particularly in the deeper sections of the harbour. Sounding indicates water depths as great as 40 m (20 fathoms) within 3 km of the delta.

The delta could be dredged such that it remains covered in water at the lowest tide. The optimum depth of dredging will depend on balancing several factors including quantity to be dredged, exposure of surface to wave action, potential oxidation of the tailings, liberation of metals from tailings, acceptability of maintenance dredging and acceptable level of sand encroachment along shoreline. Each of these factors will be discussed below.

The area of the delta is about 250 ha and thus the quantity to be dredged is about 2.5 million cubic metres for each metre depth of dredging. There would be some reduction in area with deeper dredging, but this would require detailed knowledge of the depth of tailings over the delta and the surface contour levels of the original King River delta. The density of the tailings has been reported as 1.60 to 1.67 tonnes (t)/m^3. Thus, lowering the delta by 1.5 m would involve dredging of 3.75 million (M) m^3 or 6.26 Mt assuming a density of 1.67t/m^3. Dredging 2 m would involve 5 M m^3 or 8.35 Mt or about 10% of the tailings that have been deposited in the harbour.

Movement of tailings by wave action will result in the formation of submarine dunes, movement of tailings laterally into the dredged channel and onto foreshore beaches. Once exposed on a beach, the sand can be transported further inland by wind to form dunes.

Thus, some periodic maintenance dredging could be expected to be required to maintain the entrance channel similar to that required to maintain a natural river entrance channel and to control the quantity of sand moving up the beach.

Achievement of objectives

Removal of the tailings by dredging would improve the water quality and long term impacts associated with the tailings by removing the source of the problem. Aesthetic and amenity objectives would also be achieved by this option, as would a decrease in dust storms.

This option represents the best technical solution for remediation, but is also the most costly.

Method

The dredging operation could be carried out by two or more barge mounted cutter suction dredges that can operate in limited depths of water. A larger dredge, say a 14 inch dredge, would be used on the majority of the delta with a smaller dredge (10 inch dredge) used along the shore to remove the tailings from on top of the natural harbour sediments. The harbour sediments are expected to be cohesive so that their delineation in the dredging process should be relatively simple. Suitable choice of the cutter suction head will limit dredging of cohesive material.

The smaller dredge still requires 1.5 m of water to operate effectively and there will be problems with removal of tailings close to the old shoreline and delta.

It may be necessary to move the tailings out to the dredge by excavator dozer or other means.

Some disturbance and siltation plume can be expected at the dredge and discharge areas. The silt plume at the dredge(s) is usually not a problem and can be controlled by operating the dredge within a silt curtain or by dredging from a dredged pond within the delta and leaving the outer edge of the delta intact until the final sessions for removal. In this way, the limited perimeter depth will involve net flow towards the dredges and maintain reasonably calm conditions within the delta area.

On the delta, the upper (0.5 m or so) tailings material is exposed at low tide and this has become oxidised with the interstitial water having a low pH. At depth, there is no available oxygen and the pore water has a more neutral pH. The dredged product will be a mixture of the most oxidised (most acidic) material, the deeper unoxidised material and additional water for transportation to the disposal site. More studies are required to assess if this mixing process will involve release of extra metals from the unoxidised material and the effect of the temporary shock on the dredging and disposal sites.

Channel dredging

This option involves dredging a navigation channel through the delta area to the King River. The channel is about 2 kms long and to dredge a 30 m wide channel 2 m deep would involve about 120 000 m^3 of material. If a 100 m wide channel is dredged, the quantity could be about 300 000 m^3.

Similar to the delta dredging proposal, the dredging would be carried out by a small barge mounted dredge with the material being deposited at the edge of the delta or in a deep water area within the harbour.

The channel can be expected to silt up and require re-dredging at intervals due to deposition of material flushed down the river or due to movement of sand/sediments from the delta area from wind, tides and wave action.

It can be expected therefore, that maintenance dredging on say a five yearly basis would be required to maintain a navigable channel.

The material being dredged will be dredged from beneath existing water level and will remain in the aqueous state. The material will be unoxidised and will probably have a similar acidity to that of the existing river water. Thus, there should be only a limited release of acid and metals by the dredging operation.

Feasibility

The wave action on the dredged delta suggests that movement of sand still occurs at water depth of over 6 m for wave heights of about 0.7 m. Thus, to eliminate all sand movement, the delta would require to be dredged to perhaps 10 m. Clearly this is not possible. Some movement of the sand must be tolerated. Movement of the sand may result in oxidation of the tailings releasing metals into the water. Movement of sand occurs at the present time on the delta, particularly on the outer edges where wave action during rising tides results in reworking of the material. The upper sand at the edge of the delta was clean and uncemented with the lower sand discoloured from oxidation and slightly cemented. The depth of reworked sand decreases with distance from the edge of the delta. Away from the edge, the sand is oxidised and cemented on the surface with some gravel sized particles of cemented material.

Shoreline re-establishment

The basic aim of the dredging operation is to reinstate the shoreline profile to as near as possible to the pre-mining condition. Only the tailings will be removed by the dredge. As such, the bottom slope should be similar to the original condition and the shoreline should be as stable as the original shoreline.

Re-establishment of the shoreline at the rear of the delta may involve movement of the excess tailings out to the area where the dredge can relocate it to the disposal area. The material may contain timber, stumps and other foreign matter which would have to be screened out to make it pumpable. The material could also be relocated by truck.

Alternatively, the existing tailings along the shoreline could be left in place and stabilised by re-vegetation. This may involve covering with topsoil and planting suitable vegetation.

Drainage behind shoreline

The area behind the shoreline is poorly drained with shallow water ponding behind the delta and associated dunes. Local residents have indicated that the drainage has been getting worse with the lower paddocks and area wetter than previously. This could be difficult to prove one way or the other since the area is naturally poorly draining and the delta has been gradually increasing over the last eighty (80) years. Reinstatement of the original condition may not be possible except by detailed work along the shoreline to remove the existing dune and tailings. Even with substantial dredging of the delta, some movement of sand on shore must be expected.

The drainage could be improved by excavating a drain within the wetlands parallel with the shore and providing stormwater type discharge points at regular intervals to the beach. Further investigation would be required to check for the presence of acid sulphate soils that could contribute to acidic discharges. Some detailed research is warranted to check the details of the shoreline prior to tailings deposition.

Additional studies/monitoring

There is a considerable body of literature on the assessment and management of mine tailings deposited in aquatic systems (eg Salomons & Forstner 1988a, b; Poling & Ellis 1993; Ellis et al 1994; Kline 1994); with some relevant to the assessment of Macquarie Harbour sediments.

In order to make a quantitative assessment of the impacts of sediment dredging and disposal specific additional studies would be required. The work required to carry out a remedial investigation of the contaminated sediments sufficient to evaluate remedial alternatives, evaluate their environmental impacts and select the most appropriate alternative would include the following:

- An accurate determination of the extent, thickness, volume and composition of the sediments;
- An assessment of the human health and ecological risks of:
  - leaving the contaminated sediments in place, and
  - carrying out the proposed disposal of the material within the harbour;
- Predication of the behaviour of sediments during remediation including the extent of disturbance of sediment during dredging, disposal and any other remedial activities;
- Knowledge of the nature and extent of any release of metals or other substances from the sediments during remediation and their subsequent fate and ecological effects in the marine environment;
- Consideration of oceanographic factors (particularly currents which may affect pollution control during the remediation operation or result in dispersal of pollutants throughout the harbour;
- Determination of the chemical behaviour of contaminated sediments deposited in the harbour, particularly any characteristics of the sediment which could lead to ongoing or future pollution;
- Evaluation of the environmental impacts and benefits, feasibility and cost of each remedial strategy including the 'do nothing' option.

The results of these studies would enable decisions to be made as to whether the sediments pose a significant threat to organisms in situ, if so, whether remediation would pose an equal or greater threat to the environment that leaving the sediments in place, and if not, what are the most cost-effective and environmentally sound remediation options.

The projects carried out under the MLRRDP to date have gone a long way towards providing the data necessary for this evaluation; however some issues particular to subaqueous disposal in the harbour have not yet been fully investigated, and this restricts the quality of the assessment that can be made. In particular there is insufficient data on dispersal of sediments and release of metals from them, some data gaps need to be filled before an ecological risk assessment can be carried out (eg on exposure of organisms and toxicity to them) and there is insufficient knowledge of current patterns in potential disposal areas.

Using the data available, remediation must be considered in the light of factors that militate against remediation including:

- Determining whether or not contaminants will be naturally rendered harmless over time, and if so, what time scale is involved;
- Determining if the contaminated material will eventually be buried by clean sediment or lowered below the water surface by failure or consolidation of the delta;
- Determining whether or not the site would become recontaminated by material moving down the river.

Further studies are required to assess the optimum depth of dredging and investigate the desirability of including pockets of additional dredging that may capture moving sand before it moves onto the beach or along the foreshore.

Costs

The costs of establishing and dis-establishment of the dredge is about \$500 000 per 14 inch dredge or \$250 000 per 10 inch dredge and about \$50 000 per booster station and associated pipe.

The running costs of the dredges are about \$3 to \$4 per cubic metre with an additional \$1.50 for each booster station required to convey the dredge material to the disposal sites. A dredge by itself is limited to a distance of approximately 2 kms. Booster stations would be required at about 1.2 km intervals for the 10 inch dredge and at about 1.7 km intervals for the 14 inch dredge.

To this should be added the cost of moving any material from the beach to the point where the dredge can pick it up. This aspect requires further consideration in the design stage once the depth and distribution of the tailings on the delta are known.

Thus, the cost of dredging 3.75 million m^3 of tailings is about \$15 million to \$25 million depending on the size of dredges adopted and the distance to the disposal area.

Timing

There is no point in considering any remediation of the delta until upstream sources of contamination (in particular the substantial quantities of tailings stored in the bed and banks of the King River) have been remediated, otherwise the delta would become recontaminated by periodic flushing of contaminated sediment downstream. However, once the tailings have been removed from the river system remediation of the delta may proceed, if appropriate.

The size and number of dredges will be dependent on the design dredging rate which is controlled by a number of factors including availability of funds, need for local employment, weather conditions and timing. An extended period of dredging would provide a larger period of increased local employment, although this may result in an extended period of sediment disturbance.

A 14 inch cutter suction dredge would have a production rate of about $2000m^3$/shift or about 100 $000m^3$/dredge per month for about a fifty (50) shift month. A 10 inch dredge would have a production rate of about half the above. Thus, two dredges operating at full capacity would take about 2.5 years to dredge 3.75 M m^3 and 3.5 years to dredge 5 M m^3.

5.3 Relocation of dredged material to harbour

This option is to dredge the top 1.5 m of undersaturated sediment off the delta and place it in a suitable subaqueous disposal area elsewhere in Macquarie Harbour, where the material would be saturated and have only the same capacity to release metals as other harbour sediments.

The basic approach would be to relocate some of the tailings to the deep water sections of the harbour and return the delta to its original form. Alternatively, the tailings could be relocated to the relatively deep water adjacent to the delta area where there already exists a considerable depth of fine tailings.

A number of references describe the range of options for removal of contaminated sediment. Given that the proposed disposal option is subaqueous disposal elsewhere within Macquarie Harbour some form of dredging is required. Various types of dredgers are evaluated by USEPA (1993a), Herbick (1995), and Pelletier (1995). Hydraulic dredges create much less turbidity at the dredge site, but because they add water to transport the sediment as a slurry, turbidity can be greater at the dump site. However, the advantage of a hydraulic dredge is that the dredged sediment can be pumped as a slurry via a pipeline to the disposal area and released at the harbour bottom, thus minimising turbidity in the surface layers as well as allowing more careful placement of the material. For these reasons a suction or cutter suction dredge is recommended, and such dredges should be readily available.

Achievement of objectives

The advantages of this option would be that the area covered already by the fine tailings close to the delta would in effect be covered by coarser tailings (representing the coarser silt and sand materials from the delta) which have a lower potential for liberation of heavy metals upon removal. This would assist in achieving the water quality objectives.

Method

The recommended procedure is to use a cutter suction dredge to skim the surface 1.5 m of sediment off the top of the delta. The dredged slurry would then be pumped via a floating pipeline to a barge-mounted underwater diffuser unit which would allow the dredge material to be placed onto the bottom of the disposal depression. A silt curtain would be used around the dredging area to control turbidity and escape of contaminated water during dredging. Silt curtains cannot be used in deep water and no measures can be used to control turbidity at the disposal site apart from careful placement at the bottom using a diffuser which ensures that the discharge has low velocity.

The necessity for capping the disposed sediment with clean material obtained from elsewhere in the harbour would be evaluated in a more detailed dredging feasibility study if this option were to be further considered. However, given that the sediments in the north central part of the harbour appear to have a similar composition to the delta sediments, capping is probably not necessary.

Options for transport of the dredged spoil are restricted to the following:

1 A pipeline. This can be used for distances up to 20 km, although 5 km is a more normal limit.

2 A hopper dredge. The dredged material is dewatered by overflow as the hopper is filled. A disadvantage is the considerable turbidity created when the spoil is dumped, which will create a plume that may affect large parts of the harbour.

3 Loading onto a barge for disposal. This method has the same disadvantage as the hopper dredge.

Feasibility

Ideally a suitable disposal area would be a natural depression in the bottom of the harbour large enough to accommodate the quantity of material requiring disposal, within a reasonable distance from the dredge site to minimise transportation costs, already contaminated by tailings, not exposed to significant bottom currents, biologically impoverished and with low dissolved oxygen levels in bottom waters so as to assist in the development and maintenance of reducing conditions in the dumped sediments.

As far as can be determined from the limited bathymetric and water quality data available, there is only one location in the northern half of the harbour that goes close to meeting these requirements. This is an elongated depression located in mid-harbour west of Connelly's Point and Sophia Point. The depression is the deepest location in the northern half of the harbour (in excess of 50 m) and the sediments have metal levels comparable with the levels in the delta. Both surface, mid-depth and bottom waters in the vicinity also contain high levels of copper (Koehnken 1996). Dissolved oxygen levels in the bottom waters are low, although the waters are not completely anoxic. The available data on bottom currents does not appear to be adequate to determine precisely how suspended sediment or metals released during disposal would move from this site.

Other depressions in the northern part of the harbour appeared to be too small to accommodate the amounts of material proposed to be dumped. Depressions in the southern part of the harbour were poorly defined due to a shortage of bathymetric data. In any case disposal here would be more costly on account of the much longer transport distances and the area is unsuitable because of the much better water and sediment quality.

Dredging of the delta sediments will result in some deterioration in water quality during the dredging operation, due both to release of the significant quantities of metals in the pore water of the sediments and to an increase in turbidity. However cutter suction dredges do not cause high turbidity at the dredge site, and most of the material that is disturbed is drawn into the suction head, so it is believed that with careful management and use of silt curtains, water quality deterioration at the delta will be minimised. Nonetheless it is not possible to entirely eliminate pollution during the dredging operation and turbidity and released heavy metals may have some adverse effects on organisms living adjacent to the dredged area. Further testing and modelling would be required to assess the extent of such impacts. The containment barrier and the pipeline would need to be protected from accidental damage from vessels or equipment which could cause a locally serious pollution incident.

Some soluble nutrients, eg nitrate, nitrite, ammonia, and phosphates, are also likely to be released, resulting in a short-term increase in nutrient levels in the vicinity of the dredging operation. The extent of this cannot be estimated without further data on the levels of available nutrients in delta sediments.

Water quality modelling would be required to confirm any prediction of the impact of seepage of water-borne contaminants through the silt curtain on the organisms living in the harbour.

The greatest potential for contaminant release will be at the outlet of the disposal pipe, but the extent of this cannot be determined without further testing. Some of the released metals are likely to be reabsorbed on the sediment particles in the pipeline, and reincorporated in the sediments on settlement, but the balance between the metals associated with the suspended material and the dissolved fraction cannot be predicted at this stage. Likewise the proportion of released contaminants moving away from the disposal depression cannot be predicted without data on the chemical speciation of the individual contaminants, bottom currents and modelling.

Contaminants could also be progressively released from the relocated sediment after placement, in pore water forced upwards during compaction. No data are available on the levels in the overlying water than could be expected during this time from this source. Data could be obtained by suitably designed tests, however.

A significant risk to the environment could also come from an accidental release of contaminated sediment, perhaps due to a pipeline rupture or damage to the silt curtain. Suitable procedures would need to be put in place to minimise the risk of such accidents.

Additional studies/monitoring

If the dredging option were to be given further consideration, more detailed investigations would be required to determine the release rate of metals from the sediments under simulated dredging conditions, the composition of the dredge disposal water, the bottom currents at the disposal site and circulation modelling of the behaviour of the dredge spoil during the disposal operation.

The required studies are:

- Grainsize analysis and hydraulic testing to determine the settling characteristics of dumped sediment (ie the proportion that would settle out within the area of the dump site as opposed to the fraction that would be transported elsewhere by currents in the harbour;
- Tidal current studies under various tidal, wind and seasonal conditions to determine whether silt curtains can be used effectively during dredging, and to provide data to model the dispersion of suspended sediment plumes and contaminants during and after disposal of the sediment. Although some such data are available (Koehnken 1996), the data would probably have to be supplemented for modelling;
- Elutriate testing to provide actual data on the release of metals from the sediments during dredging and disposal. It is recommended that the USEPA's Standard Elutriate Test (which involves shaking sediment samples with water taken from the dredging site for a specified period of time, followed by centrifugation and analysis of the supernatant) be modified so as to simulate as accurately as possible the mixing conditions that would occur during the disposal operation;
- An ecological risk assessment for the proposed remediation. This would have the following key components:
  - *Exposure assessment:* obtaining data on the ways that organisms could be exposed to contamination and how much of each pollutant they would be exposed to. This would require quantification of contaminant release, migration and fate; characterisation of exposure pathways and receptors, and measurement or estimation of exposure point concentrations;
  - *Ecological effects assessment:* determine whether contaminated sediments at the delta (and sediments of comparable metal levels on the harbour bottom) are actually having adverse effects on the organisms in the harbour. This would require biological

surveys and toxicity tests (including sediment toxicity tests) linking contaminant concentrations to effects on receptor organisms);

- *Risk characterisation:* determine the severity of effects at the present time and predict future effects.

Costs

The cost of relocating this material to the harbour bed is included in the dredging cost (section 5.2, Costs).

Timing

The disposal of dredged material to the harbour bed would be carried out as fast as any dredging program. The timing of this operation would therefore be the same as for the dredging program (section 5.2, Timing).

Conclusions

Providing environmental concerns relating to water quality can be satisfactorily addressed, the relocation of the tailings to a submarine disposal area within the harbour represents a viable option.

5.4 Relocation of dredged material to a tailings dam

The construction of a tailings dam for the permanent storage of tailings dredged from the King River delta is one of the options which has been considered in conjunction with the dredging option of the delta. The proposal would be that tailings would be dredged from the King River delta into a tailings dam rather than the disposal of these tailings into a deeper portion of Macquarie Harbour for permanent storage. The tailings dam is considered an option since it minimises disturbance of sediments in the deeper portions of Macquarie Harbour.

Achievement of objectives

The use of a tailings dam for disposal of the dredged material would allow tailings to be permanently located in a stable, safe storage away from the King River or Macquarie Harbour in an area which could be rehabilitated to a state which does not lead to continuing contamination of the King River or the Macquarie Harbour. However, the disposal of sulphitic tailings to a tailings dam to follow world best practice will require the tailings to be stored underneath a permanent water cover to prevent oxidation and creation of acid drainage and there will be ongoing maintenance and responsibility for the structure.

The positive elements of the dredged option for the tailings disposal are that the tailings dam could be constructed in a relatively short time frame, say 6 to 8 months, and be immediately ready to commence tailings storage.

The negative aspects of this proposal are the need to find a potential site for the tailings disposal and to disturb an area which is currently in a natural state. The other negative aspect of this proposal is seen as the need for long-term maintenance and monitoring of the structure and management of potentially acid and contaminated leachate.

Method

The option of the tailings dam for the storage of dredged material from the King River delta represents a viable engineering solution to the disposal of dredged material from the delta which would have minimal continuing environmental or contamination impacts on the King River or Macquarie Harbour, but with some risks to the environment in the vicinity of the tailings dam and downstream. When adopted in conjunction with the dredging this approach would allow the delta itself to be lowered by some 1 to 2 m as discussed earlier.

The engineering, environmental and hydraulic aspects of the proposal would have to be examined in some detail before the proposal could be fully evaluated. The key elements of the proposal are:

- the construction of a tailings dam with the capacity to hold about 5 million cubic metres of dredged tailings;
- the establishment of dredged lines and pump boosting stations between the dredged establishment on the King River delta and the tailings dam;
- the re-circulation of dredge water between the dredging area on King River delta and the tailings dam, all water materials being kept within the confines of either the tailings dam, the pump lines or the silt curtain within the dredge area;
- the rehabilitation and/or flooding of the tailings dam following completion of tailings deposition;
- the possible continued water treatment of excess seepage waters, from the tailings dam;
- monitoring and environmental assessment over a period of several years during the stabilisation period for the tailings dam.

In the proposed concept the tailings would be remobilised by dredging and transported to the site of final deposition by a slurry pump line forming an extension of the dredging operations on the delta. The potential also exists for some of the tailings also to be transported by truck from the delta to the tailings disposal area allowing substantial portions of the tailings to be removed by a combination of excavator and truck transport prior to the establishment of the dredge itself. However, this would be at substantial additional cost.

There are questions to be resolved in terms of the engineering aspects of the proposal. These include the actual siting of a suitable site for the permanent storage of tailings from the delta. A site has not as yet been identified, but it would need to be located close to the delta, possibly on the northern side of the King River in the hills behind Strahan. In addition, the site selected would need to be suitable for a permanent tailings dam storage having a surface area of between 100 and 150 ha and capable of providing storage up to 10 m deep over this area. The area and height of the tailings dam is not seen as a major engineering structure and there are many tailings dams constructed of substantially greater dimensions than required for the modest storage of about 5 million cubic metres of tailings dredged from the harbour.

The dam would require normal engineering investigations including geotechnical investigations to locate a suitable site. The drilling and proving of the foundations and suitable materials for construction of the embankment, etc. In addition, there would be the need to locate and construct haul roads to the dam from the borrow areas and access road to the dam site from the dredge area to permit initial trucking of tailings into the disposal site, if this was required. It should be possible to find a site in which materials could be excavated from within the proposed storage itself to provide the materials for construction of the embankment and the ultimate rehabilitation of the area.

As mentioned earlier, the King River delta has an area of 250 ha. This means that for each metre of lowering of the delta by dredging and/or excavation 2.5 million cubic metres of tailings per metre could be removed. Assuming that 2 m of tailings could be removed by a combination of dredging and excavation this would mean that some 5 million cubic metres of tailings storage would be required.

Given the topography of the hinterland behind Strahan, it could be expected that the maximum area which could be covered by a tailings dam of reasonable height would be say 50 ha. A tailings dam of moderate height, say 10 to 12 m high in such an environment would be capable of storing the 5 million cubic metres dredged or excavated from the tailings delta and to be covered again by stripped material taken from the tailings dam site and from adjoining land. Such a dam would need to be about 600–800 m long and as discussed above, some 10–12 metres high. The total volume of embankment material required for such a dam would be in the order of 300 000 to 400 000 cubic metres which could largely be derived from the storage area of the tailings itself, thus providing double benefit by way of decreasing the height of the dam and permitting the tailings to be stored in ground which is more likely to have a low permeability than the closer near surface soil layers.

Feasibility

The tailings dam would need to be located within an area underlain by shallow bedrock into which a cut off could be excavated and a stable foundation provided for the embankment. A possible area is located some 1 to 2 km east of the township of Strahan. This site would have to be examined in detail to confirm its suitability as a potential tailings dam site. Generally, however, in areas of bedrock given favourable topography, it should be possible to construct a tailings dam in a number of areas in this general location so this is not seen as a major constraint on the option of constructing a tailings dam.

The dam is a simple homogeneous embankment constructed out of available ripped rock fill materials taken from the storage area with batter slopes sufficiently flat that vegetation could be established as a long-term stabilisation for the dam. The dam would have slopes some 2.5:1 (H:V) upstream and some 3:1 (H:V) downstream. The crest area of about 6 m is provided to permit access for construction equipment and maintenance equipment. The dam would need to be constructed using conventional dam construction techniques involving placement and compaction of earthfill layers. The need for the dam to be capable of storing tailings under water (ie full hydraulic head) may require a drainage filter zone. To control water flow on the site, it is envisaged that diversion drains would be constructed around the tailings dam to divert catchment flow from the catchment upstream of the dam, so that only waters from the dredged area and direct rainfall into the dam would need to be stored. The impermeable element of the dam would be provided by compacted earth core drawn from thinly placed layers of material excavated from the storage area, and compacted in accordance with standard engineering practice. It would be envisaged that the compaction required would be some 98% of the standard compaction. It is also envisaged that the majority of the material removed from the storage area/borrow area would be ripped rockfill materials which would be comprised of a mixture of clayey soils, sand and some cobble and boulder sized rocks. Placement techniques would be employed in the construction of the dam to ensure that the finer materials were placed upstream and the coarser materials were graded out to the downstream slope thus providing stability and drainage for the embankment as well as enhancing the impermeable water tight characteristics of the earth fill.

The dam would need to be flooded and the tailings stored under a permanent water cover as an abandonment measure.

The dam would have to be constructed in accordance with safety standards such as those recommended by the Australian National Committee on Large Dams (ANCOLD) and by the requirements of the State of Tasmania.

Additional studies/monitoring

Environmental assessment of potential tailings dam sites would be necessary.

Detailed design of the tailings dam would be required. This detailed design should consider:

- the location of suitable tailings storage site and its permeability characteristics
- tailings particle size characteristics
- borrow area soil characteristics
- maintenance and on-going water treatment resulting from leaching of the metals from the tailings
- preferred drainage and rehabilitation options for the tailings themselves and, for the tailings dam as a whole
- environmental impact of the dam
- construction of haul roads between the King River delta and the tailings dam

Costs

The cost of the tailings dam option would be additional to the previously identified cost of dredging. The costs for the tailings dam itself would include mobilisation costs of the required earthmoving equipment, excavation, construction, monitoring, water treatment rehabilitation and engineering. Given a dam with some 500 000 cubic metres of earthworks the cost of the dam could be in the range of $5 million to $10 million.

This estimate is only very approximate and gives an order of magnitude of the type of costs which would be involved if the tailings dam were to be chosen as an option for the storage of tailings from the delta.

Timing

The timing for this project would be subject to the need for further studies, approvals and consultation. Once begun, a tailings dam could be constructed in 6 to 8 months.

5.5 Revegetation/establishment of wetlands

Revegetation using dryland species can only be achieved by the stabilisation of the surface, elevation above inundation from salt water intrusion and the amelioration of acid conditions. However, the treatment of the delta surface to provide an environment more conducive to revegetation of dryland and wetland species for at least a portion of the surface is feasible. The strategy is preliminary and based on the interpretation of revegetation trials which have been constructed (see appendix 2). The strategy will need to be reviewed following the trial monitoring.

Achievement of objectives

The revegetation of the delta assists in achieving many of the objectives. The revegetation option performs well when compared with the five objectives outlined in section 1.3.

A vegetation cover will assist in reducing metal loads to the harbour by stabilising the delta surface and providing some bioremediation of the tailings by bacterial activity. However, because only part of the delta is likely to be able to be effectively revegetated the expected beneficial effects on water quality are likely to be small.

Revegetation will dramatically improve the visual impact of the delta from the shore, by screening and eventually obscuring the bare areas that are currently visible on many of the banks. Even in wetland areas, a dense community of wetland plants will be far more attractive a sight than grey or orange tailings.

Dust generation will be reduced, although some areas of the delta will remain bare.

Enhanced amenity would result from revegetation, particularly for tourists and locals travelling up the King River in cars along the shoreline. Passing boat traffic and passengers up the King River will also have an improved amenity.

The community benefits with revegetation are also potentially significant. Most of the proposed revegetation methods are labour intensive, and could provide opportunities for the local residents to be involved in planting and other activities. There is considerable interest from the local landcare group in this regard and there will be opportunities for local propagation of planting material.

Method

The preliminary revegetation strategy is as follows:

- Wetland/dryland creation by excavation and intersection of water table to form shallow depressions and flushed by fresh water directed from existing wetlands, with the design to encourage flushing in winter months. These could be constructed by the use of an excavator to construct shallow depressions each side of a raised dryland section. The wetland areas would be transplanted with *Juncus* and *Restio* species, fertiliser, organic material (not peat—sawdust, vegetation, compost) and crushed limestone. Figure 7 shows the approach. The organic material would provide an environment conducive for sulphate reducing bacteria and the limestone additional alkalinity.
- Dryland tailings stabilised by exotic grass species following lime application (commencing at protected delta sections). Trial colonising with Acacia species (which are able to cope with exposure similar to coastal conditions) following lime application and/or soil capping.
- Construction of dune formation and subsequent stabilisation with chemical stabilisers and colonising native species, similar to sand mine rehabilitation. Dune construction should be conducted in the coarse wind blown deposits adjacent to existing vegetation. This will protect the existing vegetation from sand particle abrasion that is currently occurring at the southern end of the north delta.
- Continuous fertiliser application to vegetated perimeter.
- Wind control fencing to protect vegetation.

The delta can be divided into various zones which have varying likelihood of revegetation success. These areas are discussed in detail in section 6 and illustrated in fig 8.

Feasibility

The revegetation of the entire expanse of the delta will not be possible because of:

- periodic inundation of the delta surface by saline water
- fluctuation in watertable and related tailings chemical variability
- the acidic nature of the tailings materials
- exposure to wind effects and sand movement

The trials to date indicate that revegetation of the delta will be significantly more difficult than revegetation of the banks. This is related chiefly to exposure and inundation, and also the nature and variability of the tailings material.

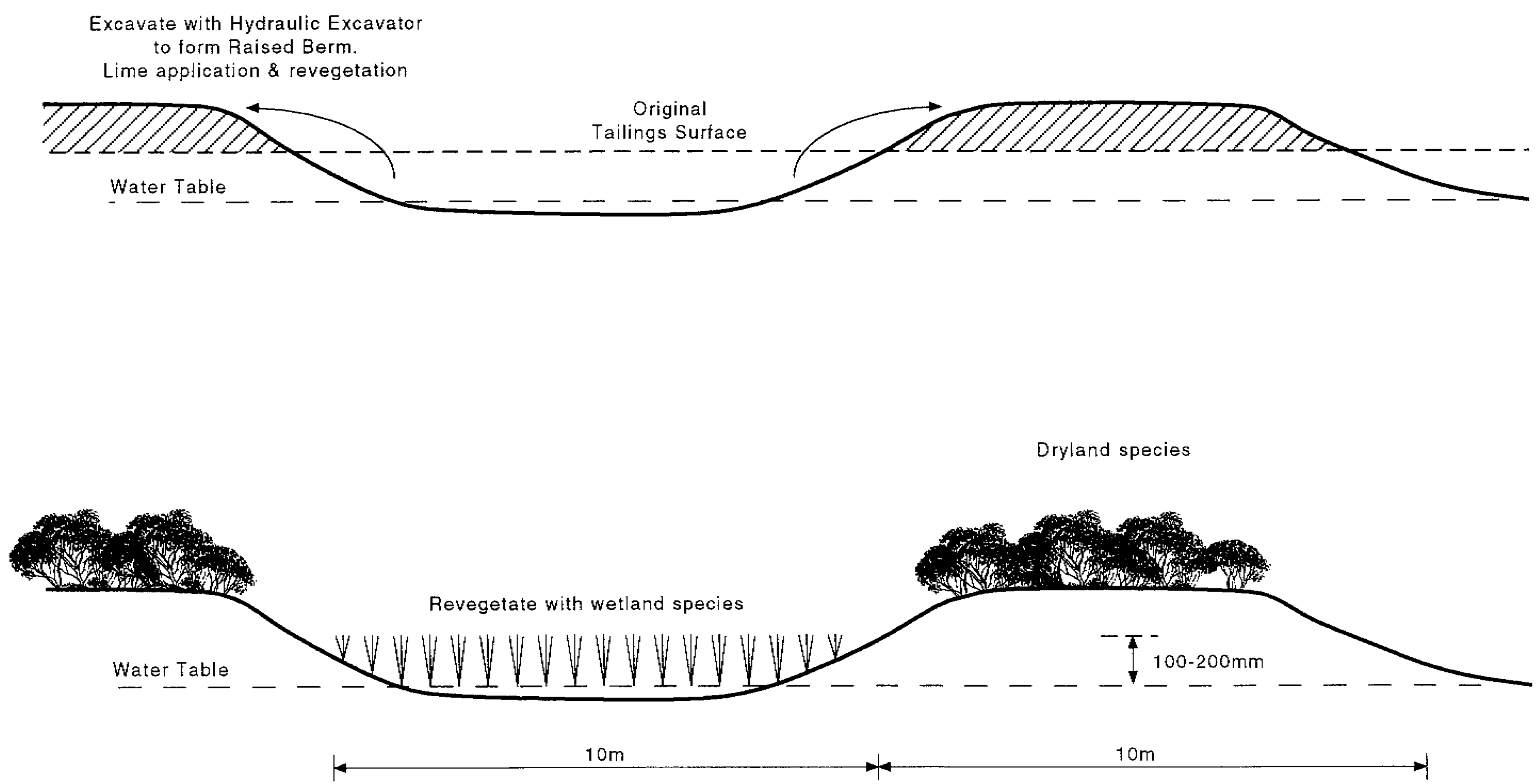


Figure 7 Revegetation: Delta

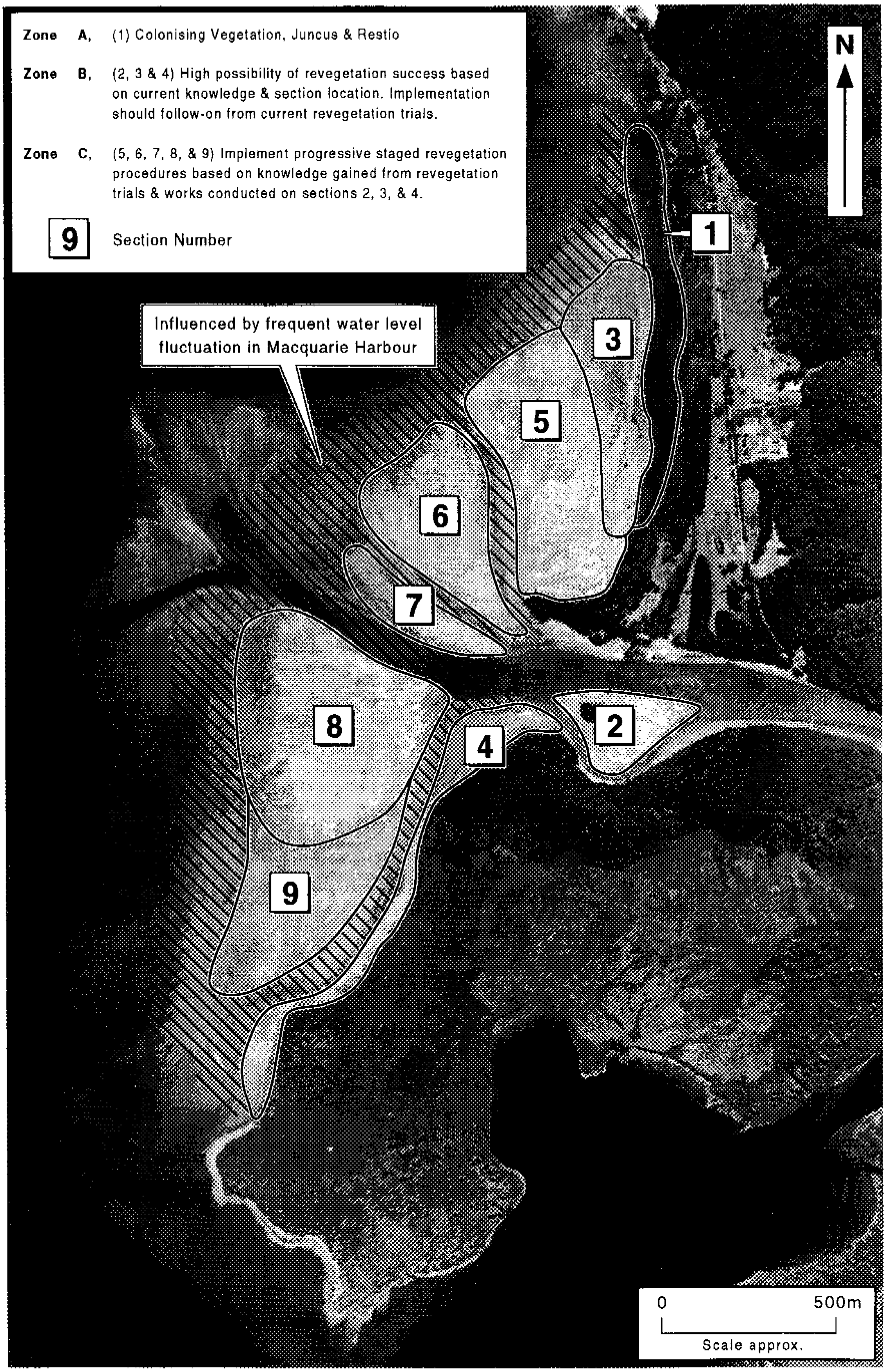


Figure 8 Delta zones

Additional studies/monitoring

Further monitoring of the trials established as phase three of this project will provide information as to the most likely successful measures for revegetation of the delta. However, wetland/dryland trials should be established in the areas which are most amenable. These trials will need to be of sufficient scale to properly trial the various treatments.

Costs

Costs associated with revegetation of the delta will vary according to the treatments used. Section 6 discusses in greater detail the various zones of the delta, and treatments that are recommended in them. These include relatively cheap treatments such as broadcasting of fertiliser which could be done for less than $1000 per hectare. More expensive treatments include planting of seedlings and wetland species into constructed wetland and dryland systems. This type of treatment will cost much more, and estimates vary from $10 000 to $15 000 per hectare.

Table 5 shows the costs of rehabilitation of the various zones of the delta.

Timing

The wetland/dryland construction timing would be subject to the implementation firstly of trials. The earthworks could be constructed in summer with revegetation in autumn or early winter.

Table 5 Rehabilitation of delta: Costs

Zone	Section	Area (Ha)	Cost per Ha	Cost per zone
A	1	11	$1000	$11 000
B	2	6.2	$5000–$10 000	$154 000–$307 000
	3	13.9		
	4	10.6		
C	5	23.5	$5000–$10 000	$470 000–$940 000
	6	15.3		
	7	5.5		
	8	31.4	*(Unlikely to succeed)*	
	9	17.2		
Total		134.6		$635 000–$1 260 000

6 Recommended strategy

6.1 Overview of remediation options

A wide range of remediation options was considered for the remediation of the tailings deposits both on the banks in the King River and in the delta in Macquarie Harbour. The options ranged from advanced specialised techniques which include vitrification and in situ thermal treatment, to more practical options such as capping, removal by dredging and revegetation in situ. Many of the options were impractical and too costly for use on such a scale and were discarded for further consideration. The 'do nothing' option was also considered in each case.

The following are regarded as feasible, practical and suitable for implementation:

- do nothing
- tailing revegetation in situ
- tailings removal via mechanical means and either disposed of within the harbour or in a purpose built tailings dam

There remains considerable uncertainty about the effects on water quality of the tailings as they exist today, and as both the improvement of water quality in the King River and within the harbour is one of the primary objectives of remediation, this information is critical to the final remediation strategy selected. If unacceptable effects on water quality are identified as a consequence of leaving the tailings in situ, there will be little alternative other than removal of tailings above the water table to prevent ongoing oxidation and metal load generation. Revegetation, while it can fulfil most of the remediation objectives considered in the study, is not expected to be effective in achieving a marked improvement in water quality.

The recommended approach to remediation of the tailings deposits is to use a combination of the removal and relocation with revegetation of the tailings in situ.. This enables the most suitable treatment to be applied to a given area, and takes account of the unique and variable characteristics of the deposits. The remediation can also be staged as funds become available and information from monitoring provides the necessary information on remediation needs and goals. Cost effective revegetation could be implemented quite rapidly and targeted where a high probability of success is likely. As the need is demonstrated, more costly remediation (such as dredging and relocation) could be considered.

For the river banks, a strategy is proposed in section 6.2 involving a variety of treatments for the individual sediment banks. This could be staged and ranges from complete removal and disposal of tailings to the King River for eventual transport to the delta and harbour, through partial removal and/or burial on site, to simple and significantly less costly revegetation.

The strategy prepared for the delta (section 6.3) is one which involves revegetation of the perimeter and more amenable areas, combined with possible dredging the surface tailings so that the balance of the delta tailings remains permanently submerged. The dredged tailings could be relocated to either another location in the harbour or a constructed tailings dam. The dredging option is costly.

Section 7 shows the estimated costs for the treatment options discussed in the following sections. These costs are only preliminary and have been prepared for a broad consideration of options and will be subject to further more detailed studies and design.

6.2 River banks

The river banks have been grouped according to characteristics which affect their suitability for revegetation. These factors include morphology, surface water distribution, particle size distribution, level of oxidation of materials and status of existing revegetation. A different strategy is recommended for each group. These are outlined below. The banks can be classified according to their suitability for these treatments.

Group 1: Bank A

The tailings deposits are quite shallow on Bank A and natural colonisation is occurring by *Restio sp.* and several hundred seedlings have been planted. Bank A should therefore remain without any mechanical treatment. Active seed, seedlings and fertiliser application should encourage more rapid site recolonisation. This bank, being readily accessible, visible and likely to respond well to revegetation treatments, would be a good focus for community planting activities.

Group 2 :Banks C and D

Banks C and D may be difficult to revegetate due to the possible fluctuations in the water table affecting tailings chemistry. The chemical variation in the root zone of the plant may make the sites unsuitable for plant establishment in part. This is indicated to some extent by large populations of colonising *Juncus* and *Restio* which appear to be stressed and dying.

Good tree and shrub growth has been observed in small nearby banks where road material and clays have been pushed out over the tailings.

The following treatments are suggested:

- excavate tailings material and deposit in river
- create wetland or permanent damp areas in remaining tailings
- cap with available soils (imported or from original levee)
- establish wetlands in damp areas and native tree and shrub species on soil covered sites

The timing of the excavations and depositing of material in the river would need to be managed carefully to minimise the impacts. The best time for such an operation would be during a period of high flow, either occurring naturally or supported by sympathetic operation of the John Butters Power Station.

Group 3: Banks B, E and G

Additional investigations are required on these banks before revegetation strategies can be prepared (they are on the southern bank). However, it is likely that they will have similar characteristics to one of the groups outlined in this section, and therefore will require similar treatment.

Group 4: Bank F

Based on current trial observations, Bank F has not responded to any treatment including the establishment of wetland species in damp areas. This bank exhibits unique crusting characteristics and contains a high proportion of slag and is composed of alternating layers of oxidised and un-oxidised tailings.

The bank is found on a relatively straight section of the river, and has large river cobbles embedded in the cemented surface material. Many stumps of trees are exposed on the surface, and some large, living trees are found close to the river edge of the bank.

These observations indicate that the original bank material is likely to be close to the surface in this bank.

The recommended revegetation treatment is:

- excavate material and deposit in King River
- cap with available soils (imported or from original levee)
- revegetate with native tree and shrub species

This strategy is preliminary, and there are still some unresolved questions about the likelihood of removal of imported material during high flows.

Group 5: Banks H to R

The tailings depth is greater on these banks than from the banks between the delta to Bank G. The proportion of oxidised tailings is higher and the banks are generally unaffected by tidal influence. The tailings surface in exposed sites are often composed of wind blown (aeolian) deposits. The site are chemically more stable than the lower banks subjected to water table fluctuations.

On these banks there is considerable natural colonisation, and it is not recommended that they be disturbed with major earthworks.

The following treatment is recommended:

- permanently damp areas to be planted out with *Juncus* and *Restio*
- stable sites to be revegetated with native species
- moss colonisation following nutrient application to be encouraged; this will encourage colonisation by rainforest species derived from natural seeding
- sites prone to wind erosion to be stabilised by exotic non-persistent grasses and/or wind proof fencing; native species to be re-introduced following stabilisation.

All treatments will be encouraged by the placement of tree branches and slash as available.

6.3 Delta

General strategy

The tailings sediments in the delta are expected to continue to be mobilised by wave and storm action, as well as the King River outflow. The surface elevation may also change, as settlement continues and the outer slopes are also expected to be mobile for a considerable period of time.

If a significant improvement in water quality is the primary objective, the best strategy for the delta is to remove the surface 1.5 m of the tailings sediments to ensure that the remaining tailings are fully submerged and therefore not available for oxidation and acid generation. Areas remaining above water level would be revegetated. This strategy would achieve all of the identified objectives but at a high cost. Further investigation is required before a recommendation can be made as to the disposal of the dredged material. The two options are disposal to a tailings dam or to the floor of Macquarie Harbour. The former option would be significantly more costly to implement, would have a long-term management cost, and possible significant environmental impacts in the short term.

A significant area of the Delta is expected to be amenable to revegetation, and while this may not achieve a significant improvement in water quality, it would satisfy most of the other objectives, especially those relating to aesthetics and dust suppression. This work could be implemented at a reasonable cost and would be a cost effective remediation strategy which could be implemented over a number of years. It would also allow continued monitoring of the delta and its environs to determine remediation needs. The strategy is discussed in more detail below.

Progressive revegetation strategy

For revegetation planning purpose, the delta has been divided into three zones, based on topographic information, aerial photographs and site investigations. The zones are shown in fig 8. Zone A is an area of active vegetation colonisation by wetland species. Zone B is the area which has a high probability of revegetation success. Zone C is the area which will be difficult to revegetate. The zones are further divided into sections which have discreet characteristics.

Zone A Active colonisation

Zone A consists of mainly damp areas which are being colonised by wetland species. It occurs in a thin strip along the shore perimeter of the northern lobe of the delta. Growth in these areas would be assisted by periodic fertiliser treatment and maintenance.

Zone B High probability of revegetation success

This zone contains areas having different characteristics, which are defined as three discreet sections. The zone covers areas closest to the river mouth and shore perimeters of the delta.

Section 2 Sheltered site

This section refers to the small island on the southern side of the river mouth. It is partly vegetated already. Revegetation works conducted in section 2 should follow-on from the trials already in place. However, remedial works such as lime and fertiliser application and cultivation will be required in order to prepare the site for vegetation establishment. Revegetation procedures will probably involve the establishment of native species from seed and seedlings. *Juncus* and *Restio* can be established at the perimeter of the section in any damp areas. Surface stabilisation techniques such as a cover crop, chemical stabilisers and wind proof fencing should also be used.

Areas of tailings that are subject to ground water level fluctuation and consequent alterations in acidity need to be identified and possibly avoided in the revegetation treatments. More work is required to identify this zone accurately.

Section 3 Damp site northern lobe

Revegetation treatments in this area should consist of:

- Excavation of alternate shallow wetland/dryland system running parallel to the prevailing wind condition and perpendicular as trials.
- Wetland plant species introduced to excavated low sections. Construction to tap into the adjacent vegetated wetlands during the winter months in order to allow fresh water through the wetland system as a mean of flushing.
- Drylands may require remedial works such as lime and fertiliser application and cultivation to prepare the site for vegetation establishment. Revegetation procedures may require the establishment of native species from seed and seedlings. Surface stabilisation techniques such as a cover crop, chemical stabilisers and wind proof fencing should also be used. Peat bunds can also be used as windbreaks as well as a medium for plant growth.

The procedures described above are illustrated in fig 7 (see section 5.5, Method) and a conceptual layout shown in fig 9.

Section 4 Driftwood site

This section hugs the shore perimeter of the southern lobe, and is an area with large amounts of driftwood logs and stumps that have been carried down the river.

Sow and plant native tree and shrub species amongst the accumulated drift wood for protection. Lime and fertiliser application will be required.

Zone C Low probability of revegetation success

Areas with a low probability of revegetation success are identified as being subject to groundwater level fluctuation, chemical instability and physical exposure. These areas are shown as sections 6, 7, 8 and 9 on fig 8.

These areas are also the most physically unstable and should be monitored to determine the extent of changes over time. If remediation is required, the most feasible strategy is expected to be dredging and relocation.

The areas of the various zones and sections are given in table 5 in section 5.5 (Costs).

7 Summary of costs

Option	Total cost	Major components	Cost per component
River banks			
Bank removal all banks	$3.4 million	Remove 1.7 million cubic metres of tailings material	$2.00 per cubic metre
Bank removal banks C, D, F only	$514 thousand	Remove 257 000 cubic metres of tailings	$2.00 per cubic metre
Revegetation banks A–M	$31–$108 thousand	Revegetate 15.4 hectares	$2000–$7000 per Ha
Delta			
Dredging: Disposal to harbour floor	$15–$25 million	Dredging	$15–$25 million
		Disposal to harbour floor	No additional cost
Dredging: Disposal to tailings dam	$20–$31 million	Dredging	$15–$25 million
		Construction of tailings dam	$5–$6 million
Revegetation Zones A and B only	$318–$472 thousand	Revegetate Zone A	$11 000
		Revegetate Zone B (includes construction of wetlands and drylands)	$307 000–$461 000
Revegetation Zones A, B and C	$1.3–$1.87 million	Revegetate Zone A	$11 000
		Revegetate Zone B (includes construction of wetlands and drylands)	$307 000–$461 000
		Revegetate Zone C (includes construction of wetlands and drylands)	$940 000–$1 400 000 *(Unlikely to succeed)*

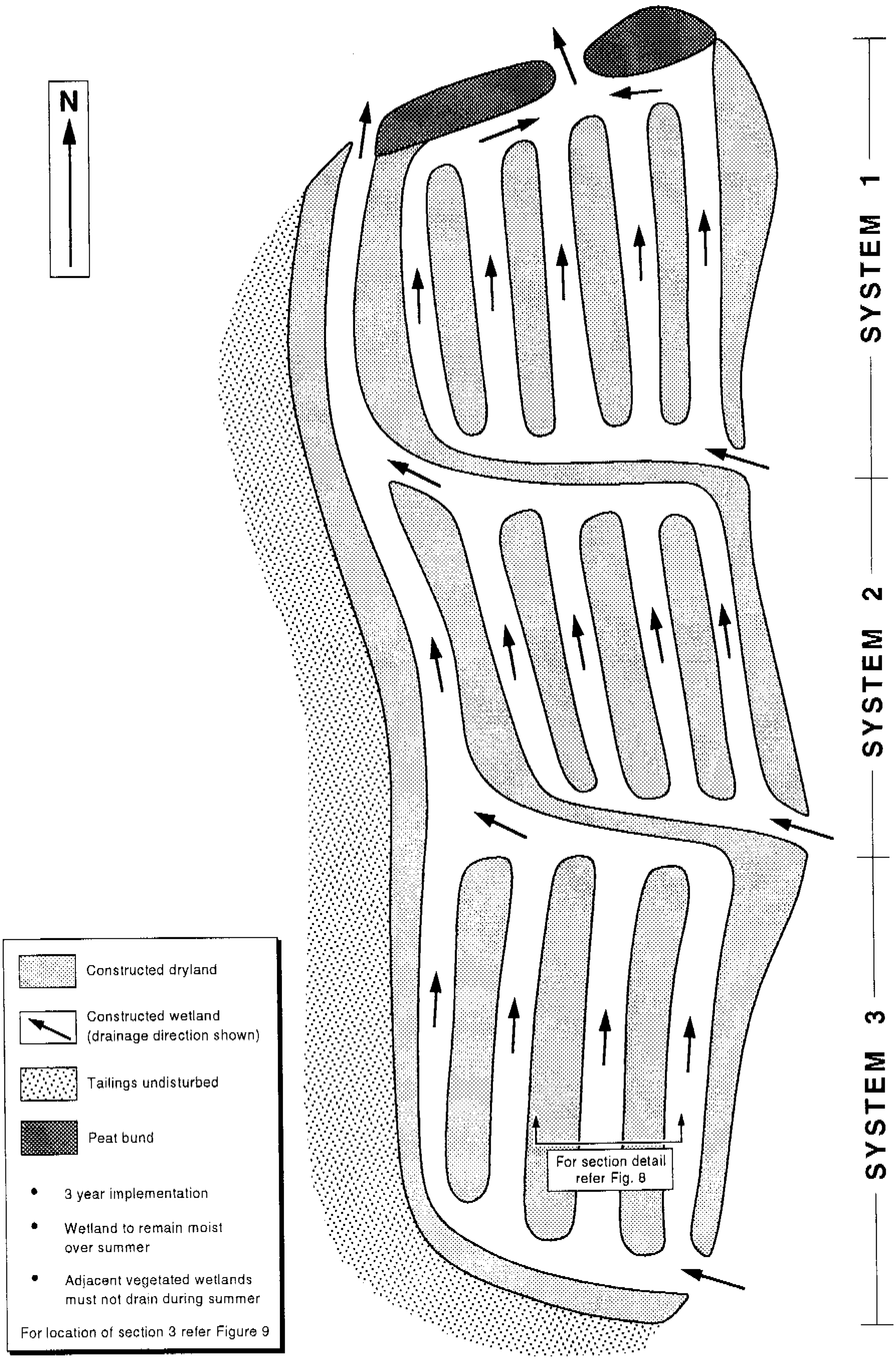


Figure 9 Wetland/dryland layout on delta

Appendix 1 Wave action

Michael Hunn–John Meidecke and Partners Pty Ltd

Estimation of the probable effect of wave action on the King River delta

These calculations are based on the following information:

- the delta is composed of a non-cohesive sediment with a specific gravity estimated as 2.65, and a mean grain size of 0.18mm, obtained from sieve results from DELM
- the maximum water level is about 2.2 m above chart datum, or about 1 m above AHD
- there is a fetch of 13 km from the southwestern end of the harbour to the delta, based on the strongest prevailing wind being from that direction
- hydrographic survey information from the HEC, shown on drawings G310587 and G310709

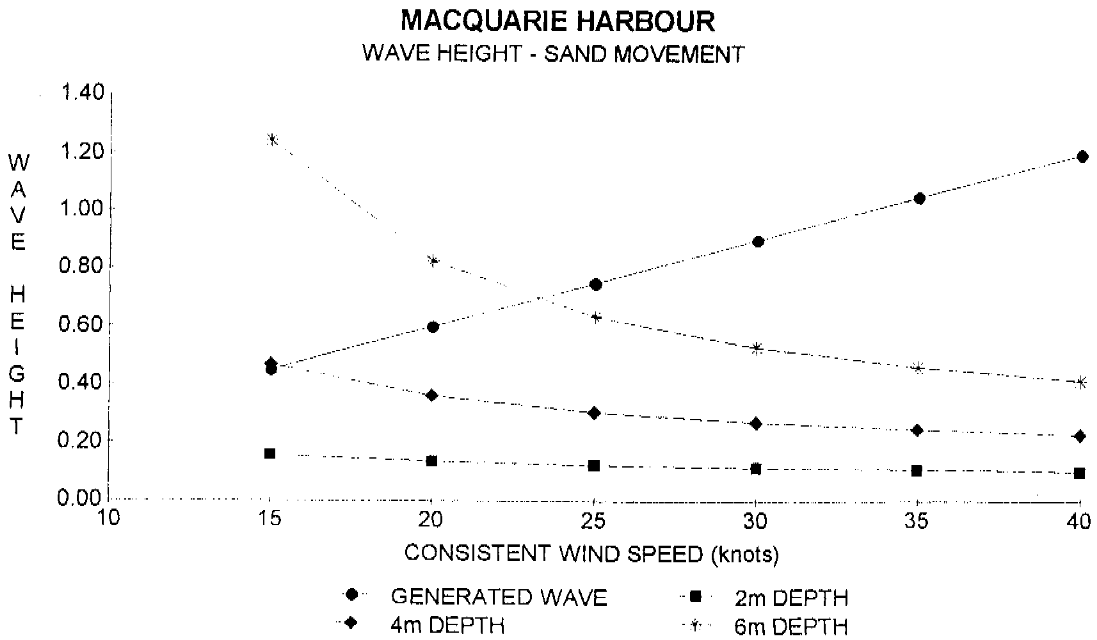
Based on this information, a preliminary estimate of the wave height (Hm) and period (Tm) can be made. The minimum duration of each storm required to generate the waves (t) can be compared with meteorological data to determine the probability for each event.

The wavelength (L) of the generated wave is determined from the period and water depth.

An estimate of the threshold water velocity required to initiate sand movement is determined from the mean grain size (D_{50}) and the specific gravity of the sediment.

The water velocity at the required depth is then compared with the threshold velocity to determine the minimum wave height (Hmin) which will initiate sand movement.

This information is shown on the following graph.



It can be seen from this graph that in shallow water of depth 2 m the sand can commence to move with very small wave heights of less than 0.25 m, which would represent the conditions with a high tide over the delta, and virtually any wave action.

The required threshold wave height increases with depth, however even at a depth of 6 m the sand movement can be initiated by waves of about 0.75 m.

The minimum time required to develop the wave heights in the graph is shown below.

Wind speed						
(knots)	(m/s)	Fetch (km)	Hm (m)	Tm (sec)	t (hr)	L (m)
1 5	7.7	13	0.45	2.90	2.50	13.11
20	10.3	13	0.60	3.19	2.27	15.88
25	12.9	13	0.75	3.44	2.11	18.43
30	15.4	13	0.90	3.65	1.98	20.81
35	18.0	13	1.05	3.84	1.88	23.07
40	20.6	13	1.20	4.02	1.80	25.21

The maximum significant wave height of 1.20 m would be generated by a 40 knot wind blowing for at least 1.8 hours, although a storm of this intensity would be rare, and it can be assumed that the maximum wave height would normally be around 1 m.

The outflowing current from the King River would alter the wave directions and heights in the vicinity of the river mouth, although an accurate assessment of the extent of this would require more detail on the direction and intensity of the current. In any case, the configuration of the river mouth presumably alters with time, making such an assessment problematical.

Long-term effect of wave action

In general the equilibrium state of a beach, assuming that the sediment comprising the delta can be considered as such, depends on the interplay of wave forces and currents but can often be characterised by the grain size of the particles making up the beach. In this case the equilibrium slope is approximately 1:40.

It is considered that given sufficient time and wave action of a reasonable magnitude, the sediment would eventually take up this slope from high water down into the harbour, since the replenishment from the tailings in the King River has now ceased. This effect would be modified by movement of the river mouth, and possibly by long-shore movement of sediment to the north.

Slope protection

If the existing profile is reconstructed to provide a steep bank of,say, 1V:3H, the face of the bank would need to be protected by armour rock to prevent erosion by wave action.

Taking the maximum wave height as 1 m, the armour rock would be approximately 750†kg, or about 0.28 cubic metres taking a specific gravity of 2.65. This equates approximately to a rock of 0.65 cubic metres.

The extent of the rock protection would be approximately 2 m vertically above high water down to 2 m vertically below low water, as shown in the diagram below.

Appendix 2 Revegetation Trials, Phase 3

Tim Duckett and Christina Giudici

Introduction

Trials were established on the banks and Delta of the King River to assess various revegetation techniques as Phase 3 of the MLRRDP project 6. The aim of these trials was to gain as much information as possible about the likely success of various means for revegetating the sites.

Timing for the trials was limited, with a maximum of 10 months between establishment and final observations for the longest running trials. This is a short time for monitoring of a revegetation trial, since it is less than one complete growing season. Some of the trials were only run for 3 months before writing of this report. Therefore, the observations and conclusions documented here are preliminary only, and further monitoring which extends over several growing seasons is highly recommended.

Treatments

The range of treatments trialed in this project were determined following observations of the natural revegetation processes on the King River tailings and other tailings sites on the West Coast of Tasmania. The natural revegetation processes on the dry banks often followed a succession from mosses which stabilised the surface material to rushes which provided shelter and a nursery environment for rainforest tree species. In places where the natural forest canopy was close by, a fallen branch could provide shelter, organic material from its leaves and protection from browsing. Several sites were observed where this had happened with dramatic growth of mosses, rushes and rainforest trees in the branch shelter.

These observations indicated those conditions which may limit revegetation. These conditions are outlined below:

Physical constraints

- exposure
- unstable surface
- sand blasting or smothering by wind blown tailings
- varying water conditions (eg drought on the higher banks and waterlogging and inundation on the delta and lower banks)
- browsing by animals

Chemical constraints

- varying state of oxidation of tailings
- high metal concentrations
- acid conditions in surface layers

A range of treatments and planting times were devised to test which of these constraints could be overcome, and which methods of revegetation would suit the varying characteristics of the banks and delta. These treatments included:

- broadcasting of fertiliser
- planting of wetland species (*Juncus* and *Restio*) at different seasonal times and with and without fertiliser
- direct seeding with exotic grass species, with the addition of lime and fertiliser

- direct seeding with native tree species, with the addition of lime and fertiliser
- planting of native tree seedlings, with the addition of lime, fertiliser and fertiliser tablets

The treatments were repeated at more than one site, with different planting times (Spring 1995 and Autumn 1996) in some cases. Fencing was used on two sites Bank M and the Left Bank of the Delta), and trials repeated at fenced and unfenced sites.

Experimental layout

Plots were established as 10m x 10m squares, with the exception of the general fertiliser broadcast areas. They were generally sited on a given Bank is a position which gave some variation across the plot, for example a plot may be set so that it runs from a dry area down into a damper zone.

Juncus and *Restio* plots were planted with these species at 1 metre intervals. Plant material was gathered from a range of sites nearby and divided if necessary to provide propagules of suitable size. Mattock holes were made, the plant material placed in these, then the tailings material firmly tamped down around the base. Fertiliser for the *Juncus* and *Restio* plots was at a rate of 5 kg per $100m^2$ of 8:4:10 high analysis fertiliser, which was hand broadcast over the plot prior to planting.

Native tree seedling plots were also planted at 1 metre spacing. Locally collected seed was grown for approximately six months prior to planting out. Two months before planting, 100 kg of Agricultural lime per $100m^2$ was hand broadcast on the site and raked in. The species planted included *Acacia melanoxylon, A. dealbata, A. mucronata, A. verticillata, A. sophorae, Eucalyptus nitida, E. obliqua, Leptospermum scoparium, L. lanigerum, Melaleuca ericafolia, M. squarrosa*. A fertiliser tablet was planted with each seedling, and 5 kg per $100m^2$ of 8:4:10 high analysis fertiliser was hand broadcast on the plot prior to planting.

The direct seeding of exotics involved hand broadcasting of 200kg per $100m^2$ of agricultural lime two months prior to seeding. The lime was raked in. Immediately prior to seeding, 5 kg per $100m^2$ of 14:16:11 high analysis fertiliser was hand broadcast over the plot. Two kg of seed per $100m^2$ was hand broadcast. The species included infertile Ryecorn (*Triticale*) and Concorde short rotation ryegrass (*Lollium*).

The direct seeding of native species was similar, however the rate of lime application was half that used for the exotic plots. The fertiliser rate was the same, however the fertiliser type was 8:4:10 high analysis. The native seed mix was bulked with clean sand to assist even distribution of seed during hand sowing.

Observations

The following tables record treatments for each bank and a brief description of observations made immediately prior to writing of this report in July 1996.

Bank	Plot	Treatment	Date establ'd	Observations
DELTA				
Right Bank	Note: This site prone to inundation. Material of experimental site sandy, with oxidised and unoxidised layers visible in mattock holes.			
	1	*Juncus/Restio*, no fertiliser	Spring '95	Above ground part of plants died, very few new shoots emerging.
	2	*Juncus/Restio*, + fertiliser	Spring '95	Above ground part of plants died, very few new shoots emerging.
	3	*Juncus/Restio*, no fertiliser	Autumn '96	Above ground part of plants died, very few new shoots emerging. Some *Restio* still have green colour.
	4	*Juncus/Restio*, + fertiliser	Autumn '96	Above ground part of plants died, very few new shoots emerging. Some *Restio* still have green colour.
	4A	Fertiliser around perimeter	Autumn '96	No observable result at present.
Left Bank	Note: Accumulated material at edges of fence and some branches washed into the plots indicate that this site is inundated on occasion. Surface crusting was severe in some parts of the experimental area, with varying depths of sandy material deposited of the hard layers.			
	5	*Juncus/Restio*, no fertiliser (fenced)	Autumn '96	Above ground part of plants died, very few new shoots emerging.
	6	*Juncus/Restio*, + fertiliser (fenced)	Autumn '96	Above ground part of plants died, very few new shoots emerging.
	7	Native tree seedlings, + lime and fertiliser (fenced)	Autumn '96	Trees alive, not much growth, show signs of stress (particularly eucalypts) and evidence of inundation.
	8	Direct seeding exotics, + lime and fertiliser (fenced)	Autumn '96	Good germination of grass, growth to 5 cm.
	8A	Direct seeding natives, + fertiliser around perimeter	Autumn '96	No observable result at present.

Bank	Plot	Treatment	Date establ'd	Observations
RIVER BANKS				
Bank A	Note: This site extends form vegetated edges of bank to river; one strip approximately 10 m wide was left with no fertiliser as a control.			
	9	Fertiliser broadcast	Spring '95	Some new growth of *Restio* at perimeter, no obvious difference to unfertilised site.
Bank C	Note: Trials were established on the higher, sandy sites on this bank. There was some layering of unoxidised and oxidised material in the mattock holes.			
	10	*Juncus/Restio*, no fertiliser, slash placed in windrows.	Spring '95	*Restio* survival and growth good in drier sites, *Juncus* survival and growth good in damper sites.
	11	*Juncus/Restio*, + fertiliser, slash placed in windrows.	Spring '95	*Restio* survival and growth good in drier sites, *Juncus* survival and growth good in damper sites.
	12	*Juncus/Restio*, no fertiliser, slash placed in windrows.	Autumn '96	As above, however healthier and more survival than Spring plantings. No observable difference between Fertilised and unfertilised plots.
	13	*Juncus/Restio*, + fertiliser, slash placed in windrows.	Autumn '96	As above, however healthier and more survival than Spring plantings.
	14	Native tree seedlings, + lime and fertiliser	Autumn '96	Good seedling survival and growth, *Acacia melanoxylon* seedlings heavily browsed.
	15	Fertiliser broadcast	Autumn '96	No observable result at present.

Bank	Plot	Treatment	Date establ'd	Observations
Bank D	Note: Mattock holes showed very locally variable conditions, with 1–2cm layers of oxidised and unoxidised tailings. The upstream end of the bank still had some unoxidised tailings on the surface, and widespread growth of *Juncus* and *Restio* which appeared to have been killed.			
	16	*Juncus*/*Restio*, no fertiliser, slash placed in windrows.	Spring '95	Above ground plant material mostly died, some growth from rhizomes. *Restio* better in drier areas, *Juncus* better in wetter areas.
	17	*Juncus*/*Restio*, + fertiliser, slash placed in windrows.	Spring '95	As above. No observable difference between fertiliser and non fertilised plots. Note: good exotic grass and weed growth where imported in soil material during planting.
	18	*Juncus*/*Restio*, no fertiliser, slash placed in windrows.	Autumn '96	As above, however better survival of plants, particularly *Restio.*
	19	*Juncus*/*Restio*, + fertiliser, slash placed in windrows.	Autumn '96	As above. Note: 10 cm eucalypt seedling germinated in slash (many seed capsules on slash material)
	20	Fertiliser broadcast	Autumn '96	Some moss evident.
	20A	Direct seeding exotics, + fertiliser	Autumn '96	Good germination, some browsing evident. Growth to 5 cm.
Bank F	This bank has unique characteristics which differentiate it from the other banks. The surface is strongly cemented, and large river cobbles and slag material are incorporated in this later. Many tree stumps are scattered over the surface, and there appears to be no great change to the original height of the bank.			
	21	*Juncus*/*Restio*, no fertiliser	Spring '95	Some survival, particularly *Juncus* in wet sites with free standing water.
	22	*Juncus*/*Restio*, + fertiliser	Spring '95	As above.
	23	*Juncus*/*Restio*, no fertiliser	Autumn '96	As above. Note: many *Restio* plants have fallen over.
	24	*Juncus*/*Restio*, + fertiliser	Autumn '96	As above.
	25	Fertiliser broadcast	Autumn '96	No observable result at present.

Bank	Plot	Treatment	Date establ'd	Observations
Bank H	This bank has similar characteristics to Bank M, and all treatments established on this bank were repeated on Bank M inside game-proof fencing. The tailings material was generally well sorted sands and silts, with semi permanent fresh water streams on the landward side.			
	26	*Juncus/Restio*, no fertiliser	Spring '95	Variable survival; *Juncus* better in wet areas.
	27	*Juncus/Restio*, + fertiliser	Spring '95	As above. Note: many *Caryx* and other seedlings observed.
	28	*Juncus/Restio*, no fertiliser	Autumn '96	Most plants still healthy.
	29	*Juncus/Restio*, + fertiliser	Autumn '96	As above.
	30	Native Tree seedlings, + lime and fertiliser	Autumn '96	Trees growing well; Eucalypt seedlings purple colour, looking stressed; *A. melanoxylon* seedlings heavily browsed.
	31	Fertiliser broadcast	Autumn '96	No observable result to date.
	32	Direct seeding exotics, + lime and fertiliser	Autumn '96	Grasses germinated and 3–5cm tall, good ground cover.
	33	Direct seeding natives, + lime and fertiliser	Autumn '96	Native seedlings just visible, less than 1 cm tall.

Bank	Plot	Treatment	Date establ'd	Observations
Bank M	This bank had similar characteristics to Bank H. The surface was well sorted sandy material, and showed deflation hollows and other features associated with wind erosion. The landward edge of the bank was being colonised by mosses and a dense population of *Restio*. This fringe serves as a nursery for rainforest species, which are colonising the bank from the existing rainforest edge.			
	34	*Juncus/Restio*, no fertiliser	Spring '95	Most plants still growing, new growth from rhizomes evident.
	35	*Juncus/Restio*, + fertiliser	Spring '95	As above. Note: some myrtle seedlings transported with soil material growing at bases of plants.
	36	*Juncus/Restio*, no fertiliser	Autumn '96	Plants still healthy following transplanting.
	37	*Juncus/Restio*, + fertiliser	Autumn '96	As above.
	38	Native tree seedlings, + lime and fertiliser (fenced)	Autumn '96	Excellent growth of all species.
	39	Fertiliser broadcast	Autumn '96	Visible brightening of mosses, and increase in extent of moss covered areas.
	40	Direct seeding exotics, + lime and fertiliser (fenced)	Autumn '96	Vigorous and dense growth of exotics, up to 20 cm tall.
	41	Direct seeding natives, + lime and fertiliser (fenced)	Autumn '96	Natives germinating, some 2–3cm tall, better growth than similar trial on Bank H.
	41A	Direct seeding exotics, + fertiliser	Autumn '96	Some germination evident, but very few plants visible, suspect heavy browsing in comparison to fenced plot.
Demo site	This site was chosen as a demonstration site because of its visibility and ease of access for establishment. It is a well formed, small bank in an eddy, and has good moss growth, particularly in the lee of established trees. This site showed the results of a branch which had fallen out of the rainforest canopy onto the tailings. There were numerous species flourishing in the area protected by the branch.			
		Juncus/Restio, native tree seedlings, + lime and fertiliser	Autumn '96	Wetland species not surviving well; trees growing slowly; moss growth good.

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