range of $2 to $5 per tonne which can result in very large amounts for current operations. Rehandling 10 Mt of waste could cost between $20 million and $50 million.

Alternatively, it might be necessary to place appropriate covers on wastes after mining has ceased. Because this would involve remobilisation of plant and obtaining suitable materials and probably extra transport of materials, the installation of covers after mine operations have ceased is likely to cost between $50 000 and $100 000 ha^{-1}. For a typical site of 130 ha, the cost of these covers could be between $6.5 million and $13 million. For historic sites the costs are estimated to exceed $100 000 per hectare, see section 5.2.

Additional costs could also include installation of a water treatment plant, perhaps $2 million initially plus $200 000 per year and possibly a wetland filter for rehabilitation of downstream surface waters.

This analysis has not included costs of remediating ground water contamination. Any requirement for remediation or containment of polluted ground water could add substantially to remediation costs.

5 Liability of historic mine sites

Australia has a large number of historic mines. In New South Wales there are about 20 000 locations scattered through the State from mining and prospecting activities; some are small scrapings, whilst others support currently operating mines (Department of Mineral Resources NSW 1996a). In Tasmania, there are 3000 recorded mineral deposits and mines, with probably a thousand historic sites of significance. In Queensland there are estimated to be 60 000 abandoned mining tenements (J Bywater, Qld Dept. Mining & Energy, pers comm, 27 March 1996). It is not known how many of these sites are releasing acid drainage, but perhaps between a tenth and a third involve potentially acid generating wastes. Most States are developing registers of contaminated lands or derelict sites which will include mine sites.

In 1995/96, the NSW Department of Mineral Resources with the support of the Department of Land and Water Conservation and the Environment Protection Authority began a 10-year program of orphan mine rehabilitation, with a funding of $500 000 per year (Department of Mineral Resources NSW 1996a). In addition the NSW Environment Protection Agency has assessed about 2000 derelict sites in the north of New South Wales. Twenty-four were considered to be high environmental risk, and acid drainage was the main concern at two-thirds of these sites (A Read, NSW Environment Protection Authority, pers comm, 1996).

A selection of the more significant historic sites in Australia that have released acid drainage are described in the following section.

5.1 Historic mines in Australia that released acid drainage

5.1.1 Agricola, Queensland

Gold was mined at Agricola in Queensland's Sunshine Coast hinterland between 1975 and 1988 when the company went into liquidation leaving a 12 ha contaminated site with a pit containing about 10 ML water and acid generating waste rock. The site was rehabilitated in 1995/96 by capping the tailings dam, treating pit water to remove copper, blasting the pit walls to fill the pit, and capping the pit with a 1.5 m clay layer. Rehabilitation will allow the site to be returned to the Conondale National Park (Department of Minerals and Energy Queensland 1996, Hirsch 1996).

The cost of the rehabilitation carried out by the Queensland Department of Mines and Energy and the Department of Environment was just under $1 million, equivalent to about $80 000 ha^{-1} of disturbed site (Hirsch 1996).

5.1.2 Ardlethan, New South Wales

The Ardwest-Wild Cherry tin mine, near Ardlethan (400 km west of Sydney), operated from 1912 to 1986, milling almost 9 Mt ore. The disturbed area covers about 650 ha and includes a 160 m deep open cut which now holds about 1 Mm^3 of acid water. A private company has proposed to use the open cut for disposal of 23 million m^3 putrescible wastes from Sydney (*Sydney Morning Herald*, 2 August 1996).

5.1.3 Brukunga Pyrite, South Australia

Nairne Pyrite operated the Brukunga mine between 1955 and 1972 to supply pyrite for production of sulphuric acid. Coarse waste rock produced during the excavation of the mine was dumped in two waste rock dumps containing about 3.5×10^7 m^3 of material. The sulphur content of the waste rock was about 2% and that of the tailings about 1.4%. Seepages from the base of the dumps, the tailings dam and the open cut quarry contributed an annual load of pollutants to the Dawesley Creek of 150 t iron, 200 t aluminium, 30 t zinc, 0.7 t copper and 0.15 t cadmium (Blesing et al 1975).

In 1980, a water treatment plant costing $640 000 was commissioned to raise the pH of the seepage water from 6 to 9 using lime waste. In 1985 funds were approved to run the plant on a full time basis with capital expenditure estimated to be $330 000 from 1985–1988 with a yearly recurrent expenditure estimated to be $250 000 initially and reducing to $100 000 in the long term. In 1986, a submission was presented to the South Australian Cabinet requesting $2.6 million to rehabilitate the tailings dam (Smith & Hancock 1992).

Rehabilitation options are still under discussion and water treatment continues. As part of its assessment of rehabilitation options, Environmental Geochemistry International Pty Ltd (1995) estimated that:

- covering the dumps with a 3 m low permeability layer (design hydraulic permeability less than 1×10^{-8} m s^{-1}) on the sides and 2 m on the top with minimal reshaping would cost $5 per m^3 placed cover based on local availability of suitable clay equivalent to between $100 000 and $150 000 ha^{-1};
- reshaping the dumps to achieve less than 3:1 slope would cost about $3 m^{-3};
- relocating the waste rock and then selectively placing acid and non-acid rock would cost about $3.5 m^{-3};
- liming the wastes to neutralise soluble acid would need about 5 kg t^{-1} lime at a cost of about $30 t^{-1} crushed limestone;
- the cost of the suggested rehabilitation option was estimated to cost in the order of $12 million.

5.1.4 Captains Flat, New South Wales

Mining commenced at Captains Flat in 1874 and continued periodically until 1962. Over 4 million tonnes of ore were milled to produce zinc, pyrite, lead, copper and gold. About 2.5 million tonnes of mine waste were left in dumps covering an area of 15 hectares. Underground workings were incompletely backfilled with quarried rock.

The wastes were stored in above ground dumps at two locations, the northern dumps and the southern dumps. The fine fraction of the wastes were pumped to earthen dams which were continually built up with fresh material. The coarser fraction was dumped in the northern solids dump.

The operation of the mine and the dispersion of tailings resulted in high levels of zinc and other heavy metals in the Molonglo River between Captains Flat and Canberra. The source of this pollution was erosion and leaching from the dumps, flow of water through the mine, and accumulated bed sediments in the creeks and Molonglo River. In 1939 one of the dams burst and released polluted water and fine tailings into the river, and in 1943 one of the dumps collapsed and 30 000 m^3 of fine tailings was released into the town water supply reservoir. Then in 1945 a flood in the Molonglo River spread the polluted sediments downstream (Hogg 1991).

Initially the southern dumps had a total mass of 289 000 t, but 39 000 t (30 000 m^3) was lost in the 1943 slip leaving about 250 000 t covering 4.55 ha and with a volume of 114 000 m^3. Wastes in the southern dump contained 21.1% total sulphur which is equivalent to 39.5% total pyrite. The northern dumps have a total mass of 2 190 000 t and cover 10.08 ha. The amount lost in the 1939 slip is not known. Waste in the northern dump has 17.4% total sulphur equivalent to 32.5% total pyrite (Hogg 1991).

A Joint Government Technical Committee was formed in 1972 and remedial measures were carried out in March–December 1976 at a cost of $2.3 million (Corkery 1977, Gray 1977). By stabilising and covering the dumps, the rehabilitation works reduced the likelihood of another catastrophic pollution event and reduced pollution levels in the Molonglo River. Pollutants are still released from seepages at the site and polluted river bed sediments (Jacobson & Sparksman 1988).

In 1993, Dames and Moore assessed options for remediating Captains Flat (Dames & Moore 1993). The cost of conventional chemical treatment was estimated to be $641 000 with annual operating costs of $81 000. Alternatively a combined chemical and biological treatment was estimated to cost $680 000 with annual operating costs of $30 000. Treatment of diffuse sources by covers etc was estimated to cost over $1.5 million.

5.1.5 Drake, New South Wales

Over 20 derelict mines are located near Drake, in northern New South Wales, some sites of which cause heavy metal pollution in Plumbago and Sawpit Creeks. In 1995/96, the NSW Derelict Mined Lands Rehabilitation Program spent $135 000 on site works for rehabilitation of mine sites adjacent to Plumbago Creek plus $20,000 for assessment and planning for ongoing works (3 to 5 year program) (Department of Mineral Resources NSW 1996a). A further $100 000 was budgeted in 1996/97 to complete the rehabilitation of the first three relatively small mine sites including the associated waterways. Rehabilitation of a further three separate sites and the Drake lease itself is being planned.

5.1.6 Horn Island, Queensland

Gold was discovered on Horn Island in the Torres Strait in 1894, and there was small scale mining from 1894 to 1900. A larger mining operation started in 1988 but ceased in December 1989 because of financial difficulties. A security deposit of $500 000 was held by the Queensland Department of Minerals and Energy and a further $600 000 was raised by sale of the company assets. Problems at the site included contamination of ground water through leaching of heavy metals from tailings and acid drainage from mineralised waste rock.

The Department rehabilitated the site between 1992 and 1994 at a cost of $2.2 million, which included $300 000 for monitoring vegetation establishment and groundwater over 3 years. Rehabilitation work included relocating tailings in two dams into one dam and covering with geotextile and a clay layer with a minimum thickness of 400 mm (Department of Minerals and Energy, Queensland 1994).

5.1.7 Kangiara, New South Wales

The Kangiara copper mine was opened in 1902. Its most productive period was between 1909 and 1914 with operations ceasing in 1939. It was originally an open cut mine but later went underground with a main shaft 126 m deep. The mine site is 20 km south of Boorowa on the Yass-Boorowa road. Seepage from mine wastes contained copper, lead, zinc, manganese and cadmium. Water quality was 'extremely poor' (Corkery 1977, Scown 1996).

In 1994, the site was rehabilitated by treating leachate using anoxic limestone drains, construction of diversion banks and a sediment dam, diversion of clean water around the site and revegetation. The anoxic limestone drains contain 420 t limestone. The cost of rehabilitation was $95 100 (Scown 1996).

5.1.8 Mt Lyell, Tasmania

The Mt Lyell copper mine commenced operations in 1896 using open cut methods. Both open cut and underground techniques have been used over the years to produce a total of 100 million tonnes of ore (Ayre & Hartley 1986). An estimated 96 Mt of sulphidic tailings were disposed of into the Queen and King River system (Taylor et al 1996). The majority of the tailings now form a delta in Macquarie Harbour. The abandoned mine continues to release acid seepage water from the mine workings and the waste dumps which flows into the King and Queen Rivers. The main contaminants are iron and copper, together with minor zinc and lead values. A new mining operation by Copper Mines of Tasmania began at Mt Lyell in 1995 which has resulted in marked improvements in the environment of the lease site (Miedecke 1996). Copper Mines of Tasmania has no responsibility for pollution from the historic operation.

The Office of the Supervising Scientist and the Tasmanian Department of Environment and Land Management jointly sponsored a $2 million remediation research and development program to identify cost effective remediation options for Mt Lyell (Waggitt & Jones 1995). This program developed and costed a range of remediation options for the site. There are three major issues: the waste rock dumps, the seepage from adits and the tailings deposited along the King River and in Macquarie Harbour.

The waste rock dumps at Mt Lyell cover about 70 ha, but as they are built on the slope, the top surface is only 25% of the area. The difficult terrain increases the costs of covers. The estimated costs for covering the main dumps with a 1 m compacted clay cover on top and 1.5 mm HDPE geomembrane on the side were (Miedecke 1996):

- covering without reshaping $8.5 million or $120 000 ha^{-1}
- covering with clay $13.0 million or $186 000 ha^{-1}
- clay on top surface and HDPE slopes $19.5 million or $280 000 ha^{-1}

The main source of pollutants from the Mt Lyell site is seepage from adits and underground workings. For this seepage water, the only proven technology is considered to be conventional water treatment. A neutralisation/precipitation plant (225 L/s, 50 tonne limestone per day) capable of reducing the copper and metal loading in the effluent by 98% was estimated to cost $2.8 million total capital cost (plus or minus 30%), with operating costs of $450 000 per annum. The copper concentrations might be high enough for an SX/EW plant as part of the treatment system to be a potential source of revenue (Miedecke 1996).

As an alternative to an on-going water treatment, construction of a pipeline to take the polluted seepage water directly to the ocean was estimated to cost $7 million.

Options for the tailings along the river and in Macquarie Harbour are still being reviewed. There is a large quantity of tailings and any attempt to move a significant fraction of the tailings could have adverse environmental impacts.

5.1.9 Mount Morgan, Queensland

Mining at Mount Morgan commenced in 1882 and acid water concerns were first recorded in 1890. Mount Morgan Limited vacated the site in December 1992, and was released from obligations under agreement with the Queensland Government. Between 3 and 10 million tonnes of mine wastes (principally tailings) have accumulated in the bed of the Dee River since mining commenced and up to 50 km of river is polluted. Studies are proposed on how to manage the release of water from the site and improve the quality of water in the Dee River. In 1993/1994, the Queensland Department of Minerals and Energy spent $225 000 to ensure that the water pump back system at the mine site was maintained.

The Mount Morgan site contains about 370 ha of disturbed land and about 150 ha has been rehabilitated. Dump materials include 94 Mt overburden, 28 Mt retreated tailings, 23 Mt slag, tailings and other materials. The open cut is 1000 m x 650 m x 210 m, with a water capacity of 11 000 ML and, in May 1995, contained 8000 ML and was slowly filling (Cliff Jones, Dept. Minerals & Energy Queensland, pers comm, 9 August 1996). The open cut was used formerly as a sink for polluted water. If other management strategies are not implemented, the open cut could overflow once every 7 to 10 years. The Government is considering options for managing water on the site to reduce the potential impact on the downstream water quality in the Dee River.

5.1.10 Ottery, New South Wales

Underground operations at the Ottery mine were carried out between 1881 and 1958. The mine produced about 2700 tonnes of tin oxide concentrate and 1900 tonnes of arsenic trioxide. Water from an adit had more than 5 ppm arsenic. The water pollution problem was aggravated during wet weather by runoff across mill tailing dams, mineralised mullock heaps and mine workings spread over about 8 ha. In 1976 some rehabilitation work was undertaken including sealing adits and building diversion drainage channels around the site (Foskett 1976). The quality of water close to the mine site was very poor with pH 2.5 and high cadmium, copper and zinc (Corkery 1977).

In 1995, further rehabilitation was undertaken by the NSW Department of Mineral Resources including moving the slimes dump and covering with an impermeable material, reinstating the tailings dam wall and making the open shaft safe. Very little acid water now escapes from the site (Department of Mineral Resources NSW 1996b).

5.1.11 Peelwood, NSW

The Peelwood Hill Silver Mining and Smelting Co began operations in the Tuena area in 1874 and, apart from a five year break, continued operations until 1895. The dumps were reworked in 1927 and 1947. The 7 ha area immediately around the mine and smelter would not support vegetation because of leachate from residual ore, wastes and slag (Department of Mineral Resources NSW 1997).

Rehabilitation on the Peelwood site works was carried out between 1989 and 1997 at a total cost of $246 000. Waste material was buried in the shafts which were backfilled and sealed with clay; erosion was controlled by reshaping and installing berms; a sediment dam was built and the site revegetated (Department of Mineral Resources NSW 1997).

5.1.12 Rum Jungle, NT

Open cut mining to extract uranium/copper ore was carried out at Rum Jungle in the Northern Territory, Australia, between 1954 and 1964. The East Branch of the Finniss River flows through the site. When the site was abandoned in 1971 there were three water-filled open cuts, four waste rock dumps containing pyritic material, a tailings disposal area and a pile of low grade ore where an attempt had been made to extract copper by heap leaching. Significant pollution of ground and surface waters by acid and heavy metals was apparent when mining operations ceased. The major sources of pollution were the waste rock dumps and the heap leach pile, copper being the main heavy metal pollutant.

The Rum Jungle mine site was rehabilitated between 1983 and 1986 by the NT Department of Mines and Energy (NTDME) using money provided by the Commonwealth Government (NTDME 1986, Bennett et al 1988a, 1988b, 1989, Richards et al 1996). The total cost was \$18.6 million: made up of \$8.6 million for earthworks etc, \$6.2 million for treating water in the opencuts and \$3.8 million for engineering and project management (NTDME 1986 table 13.1).

The tailings and the heap leach material were collected and placed in Dysons open cut and covered with a low permeability cover. The cleared areas were then vegetated. The total amount of tailings and heap leach material moved was 0.68 million m^3 from an area of 38 ha. The total direct cost of this operation (stage 4) was \$3.4 million, to which should be added 20% for overheads giving a total cost of \$4.1 million. This corresponds to \$108 000 ha^{-1} or \$6 per m^3.

The waste rock dumps were rehabilitated by reshaping to reduce slopes and covering with a three layer cover: a 225 mm compacted clay moisture barrier, a 250 mm moisture retention zone, and a 150 mm erosion resistant zone, with thicker layers on the sides of the dumps. The direct total cost of rehabilitating Whites, Whites North, Intermediate and Dysons dumps was \$2.83 million which, with the 20% overhead, gives a total cost of \$3.4 million. As the total area of the overburden dumps was 51 ha, this cost is equivalent to \$67 000 ha^{-1} or \$6.7 m^{-2}.

The water treatment plant treated 2.1×10^6 m^3 water from Whites Open Cut, used 6672 tonnes lime and produced 75 600 tonnes filter cake (30% solids). The design capacity of the plant was 10 000 m^3 per 24 hour day (116 L/s). The water treatment plant cost \$2.0 million, supply of chemical cost \$2.8 million, and operations cost \$1.4 million, to which should be added 20% project management costs.

The 'area of pollution' at the Rum Jungle mine site was 204 ha. Hence for the site as a whole, the \$18.6 million is equivalent to \$91 000 ha^{-1}.

5.1.13 Teutonic Bore, Western Australia

Teutonic Bore, about 270 km north of Kalgoorlie was a polymetallic sulphidic deposit mined between 1970 and 1985 to recover copper and zinc. The waste rock dump complex is characterised by dumping of sulphidic wastes along the top and exterior margin of the dump which are now oxidising. Very little rehabilitation was carried out when mining ceased. The pit itself is neutral. Seepage occurs during the episodic rainfall events (Williams 1995).

5.2 Potential costs of rehabilitating historic mines

The costs discussed in the previous section for the management and rehabilitation of historic sites are summarised in table 5.1. These costs suggest that the rehabilitation of potentially acid generating wastes at historic abandoned mine sites is likely to cost \$100 000 ha^{-1} or more. The costs of remediation of historic sites is greater than the operational costs of managing potentially acid generating wastes at operating sites estimated in section 4.3 to be between \$20 000 to \$50 000 per hectare. These costs do not include the costs of treating water in open cuts containing polluted water or the control of acid drainage from mine workings.

Table 5.1 Costs of rehabilitating historic sites in Australia

Mine Site	Date	Cost	Cost per unit
Agricola	1995–96 (work done)	\$1M	\$80 000 ha^{-1} disturbed site
Brukunga	1986 (proposal) 1995 (proposal)	\$2.3M for tailings dam Total cost of the order of \$12 million	Covers \$100 000 to \$150 000 ha^{-1}
Captains Flat	1976 (work done) 1993 (proposal)	\$2.3M Proposal \$1.5M (covers etc) \$600 000 capital, \$80 000 per year water treatment	
Drake	1995–97 (work done)	\$255 000 (first stage of 3 to 5 year program)	
Horn Island	1992–94 (work done)	\$2.2 million	
Kangiara	1994 (work done)	\$95 000	
Mt Lyell	1996 (proposal)	\$8.5 to 19.5M	Covers \$120 000 to \$280 000 ha^{-1} (steeply sloping site)
NSW derelict mines	1995–2005 (commitment)	\$5M (acidity and other environmental issues) over 10 years	
Peelwood	1989–1997 (work done)	\$0.246M	Whole 7 ha site \$35 000 ha^{-1}
Rum Jungle	1983–1986 (work done)	\$18.6M (\$6.2M water treatment, \$2.8M dumps \$3.7M other earthworks \$3.5M engineering and management)	Tailings (removal to open cut) \$108 000 ha^{-1} or \$6 per m^3. Waste rock dumps (reshape and cover) \$67 000 ha^{-1} Whole site (including water treatment) \$91 000 ha^{-1}

6 Discussion and recommendations

6.1 Technologies used for managing sulphidic wastes

The comments on the questionnaires and visits to mine sites showed that a wide range of isolation, cover and encapsulation methods are being used to manage potentially acid generating tailings and waste rock. These include selective placement, encapsulation within waste dumps, isolation within waste emplacements, different cover designs and sometimes use of separate dumps for potentially acid producing wastes. A discussion of management strategies is given in section 2.3. Although most of these technologies appear to be suitable for the long-term management of potentially acid generating waste, few have been monitored over a long enough time to prove their effectiveness.