provide the required information. As cooperative participants in the MLRRDP, CMT volunteered to share this information once obtained.

The final remediation strategy was developed based on all of the information gained by the MLRRDP, as well as a significant contribution from CMT, and previously collected DELM data.

4.6.2 Community consultation

Another round of community consultation was initiated once the range of remediation options was identified, but prior to the development of the final remediation strategy. This included public meetings in Queenstown and Strahan, and a Consultative Committee meeting. The aim of these meetings was to test the social acceptability of individual options, and to gauge the communities' views concerning remediation priorities based on the findings of the MLRRDP.

4.6.3 Timing of MLRRDP activities

As originally envisaged, the MLRRDP was to be an 18-month intensive effort to develop remediation plans for the Mount Lyell lease site. However, the complexities of the environmental issues, and the intricacies involved with developing remediation strategies, required that the program be extended an additional 10 months. Very generally, the timing of the program can be summarised as follows:

				1	9	9	5								1	9	9	6						1	9	9	7	
Program phase	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	May	June
Program Establishment Project Definition Consultant Selection	■	■	■																									
Projects Completed			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■											
Project Leader Workshop																	■											
Additional Information Collected and Trials Completed																		■	■	■	■	■	■	■				
Formulation of Final Remediation Strategy																							■	■	■	■	■	■

5 MLRRDP findings: State of the catchment

5.1 Introduction

The MLRRDP has completed a very wide range of investigations on the lease site, and in the rivers and harbour. Figures 5.1 to 5.3 depict the sampling sites and remediation trial sites associated with the MLRRDP's 15 investigative projects. Recent detailed biological, chemical and physical information obtained from the sampling sites combined with available historical information has allowed the MLRRDP to compile an accurate and meaningful picture of the present state of the King River catchment below Queenstown.

The findings of the MLRRDP are presented in two parts. Firstly, descriptions of the state of the lease site, rivers, delta and harbour are presented which summarise many of the findings of the MLRRDP as well as other available information. Secondly, the remediation options available for each of these catchment sections (lease site, rivers, delta, harbour) are presented and discussed.

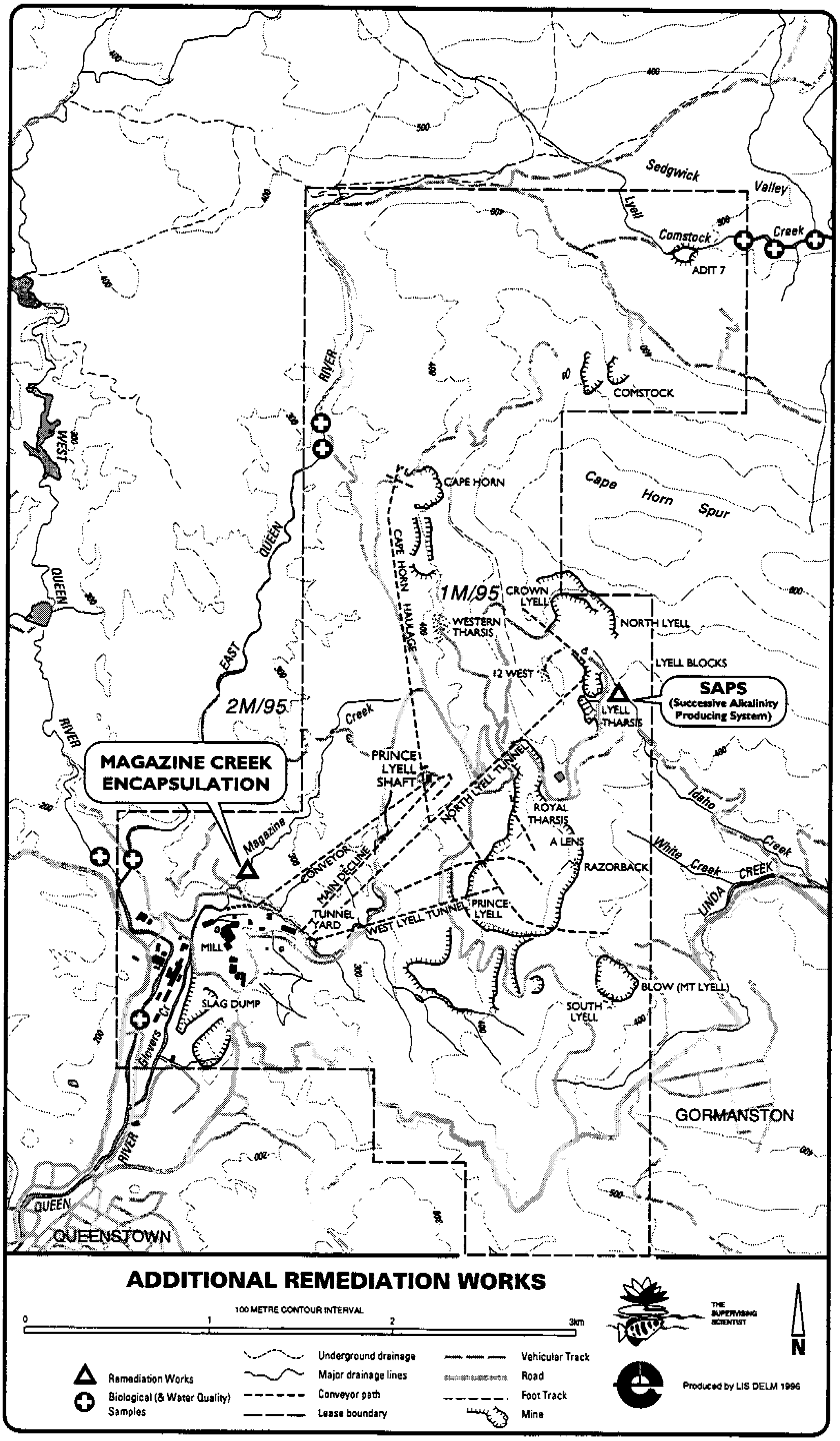

Figure 5.1 Location map of Mount Lyell lease site showing MLRRDP sampling sites and trial locations

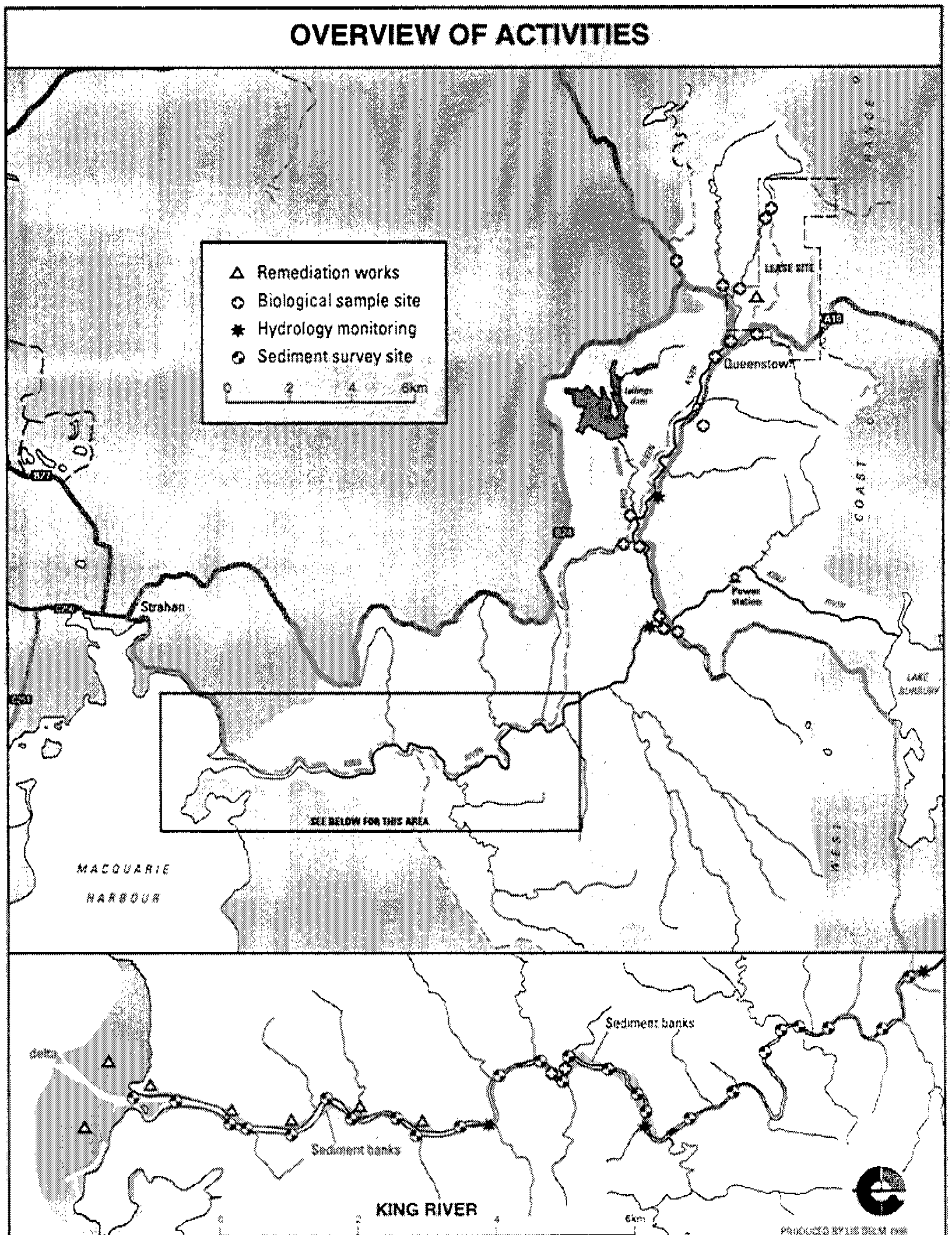

Figure 5.2 Overview of MLRRDP activities in the Queen River and King River catchment

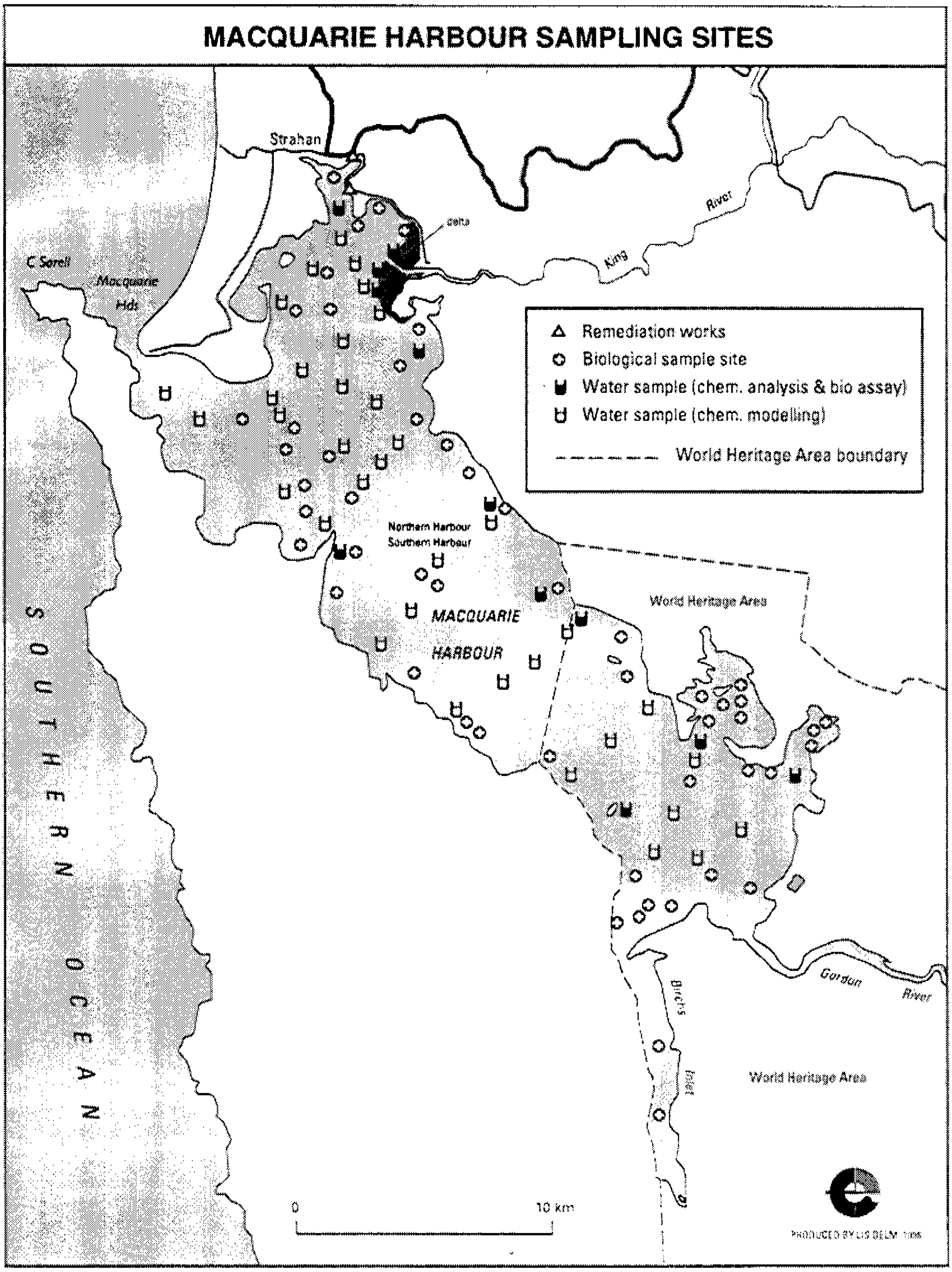

Figure 5.3 Overview of MLRRDP activities in Macquarie Harbour

5.2 State of the Mount Lyell lease site

Prior to the development of a remediation strategy, it was necessary to quantify the discharge of acid drainage from the lease site and establish the contributions of each source. McQuade et al (1995) synthesised the available information about environmental impacts associated with previous mining operations on the Mount Lyell lease site and compiled the following summary:

- vegetation has been completely cleared from over 15 km^2 which has increased runoff and accelerated erosion
- million tonnes of mill tailings were released to the Queen River prior to December 1994.
- large volumes of acid drainage leave the lease site which contain significant concentrations of metals.
- the median copper load leaving the lease site is approximately 2000 kg/day, and of that, more than 70% is from the underground workings (Prince Lyell and North Lyell). Nearly all of the copper load (98.7%) enters the Queen River via Haulage (Glovers) Creek.
- million tonnes of sulphidic waste rock are present on the lease in waste rock dumps. The acid drainage generated from these dumps accounts for about 20% of the total load leaving the lease site. The dumps are presently oxidising at a maximum rate, and are likely to continue producing acid drainage for greater than 600 years.
- Because of large hydrological and chemical variation on the lease site, the use of median values is less than ideal but necessary due to a limited dataset.

Since the report by McQuade et al (1995), CMT has established a more extensive monitoring network and continues to add to the understanding of pollutant discharge. Based on this new information, daily copper loads derived from the Conveyor Tunnel may be higher than originally estimated by McQuade et al (1995) from median data. For the nine-month period April–November 1995, the CMT data indicate daily copper loads of 1700 kg/day from Conveyor Tunnel, significantly greater than the previous estimate of 1200 kg/day. However, this monitoring period was preceded by a very dry period, statistically falling in the lowest decile for three-month precipitation measurements, and it will take considerably more monitoring before all of the processes controlling copper transport on the lease site will be understood.

Table 5.1 shows the chemical composition of the five major sources of acid drainage on the lease site and median flow rates as determined from historical data by McQuade et al (1995), and table 5.2 contains the approximate relative contributions of acidity and copper from each of these sources. The geographic distribution of these acid drainage sources is shown in figure 5.4. All of this information indicates that the most significant acid drainage sources are the Conveyor Tunnel, West Lyell waste rock dump, and the North Lyell Tunnel. Since the initiation of CMT's operations, the Conveyor Tunnel discharge has been diverted and now exits from the North Lyell Tunnel, so these flows can be considered as one (although they can still be monitored and managed independently by the company if required). From the above tables, this combined flow accounts for approximately 78% of the lease site copper load.

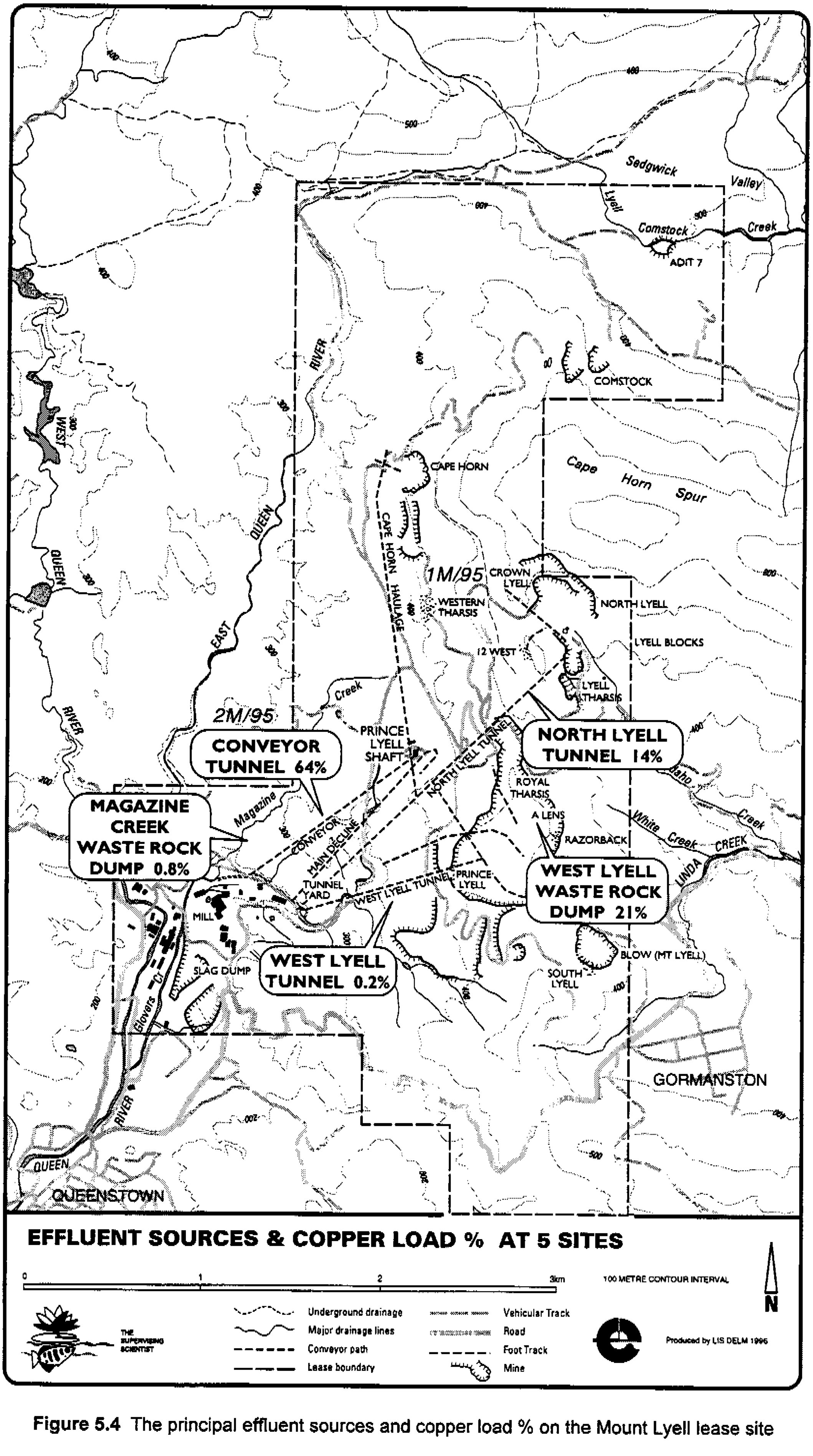

Figure 5.4 The principal effluent sources and copper load % on the Mount Lyell lease site

Table 5.1 Median composition of soluble components (ppm) of acid drainage from sources in the Haulage Creek catchment and median flow rates (after McQuade et al 1995)

Source	Cu	Fe	Zn	Mn	SO_4	pH	Flow rate (L/s)	%
West Lyell waste rock dump	82	777	5.9	46	6430	2.4	54	24
West Lyell Tunnel	14	223	4.7	38	2100	2.9	4	2
North Lyell Tunnel	54	319	4.6	21	1655	2.8	56	25
Conveyor Tunnel	134	246	16.6	167	3995	2.8	92	41
Magazine Creek (by difference)	22	599	-	412	4133	-	19	8
Haulage Creek (total)	90	421	9.3	120	3975	2.7	225	100

Table 5.2 The relative contribution of sources of acid drainage to total soluble copper and acidity fluxes from Mount Lyell; after Miedecke (1996) and L Koehnken & J Johnston (pers comm)

	Contribution (%)	
Source	Copper	Acidity
West Lyell waste rock dump	21.0	39.8
West Lyell Tunnel	0.2	1.1
North Lyell Tunnel	14.0	11.7
Conveyor Tunnel	64.0	33.5
Magazine Creek	0.8	13.9

It should be stressed that the copper, acidity and flow values are based on median flow conditions, and one aspect of the hydrology of the lease site which is not well understood is the role large rain events play in the discharge of contaminants. Because of the diminished soil cover in the upper Queen catchment, hydrographs of rain events in this area are characterised by very sharp rising and falling limbs due to increased overland runoff. The lack of an extensive water quality database associated with heavy rainfall 'events' makes it difficult to determine the relative importance of these events to more 'typical' flows. One major event which was monitored by DELM during the Intensive King River Monitoring Program documented that dissolved copper mass-loadings increased from 2 tonnes per day to greater than 9 tonnes per day during heavy rains (Koehnken 1996). These observations have been confirmed recently by CMT's investigations, which show that during storm events, copper concentrations in the creeks do *not* decrease as much as expected due to increased dilution (Imtech 1997). Although there is initially some reduction due to dilution, copper loads significantly increase during rain events, which indicates that copper discharge from the lease site is a transport limited process, and not a reaction limited process. In other words, there is more copper (and other metals) 'waiting' to be transported than water available to move it. The downstream environmental significance of this is that both downstream metal concentrations and loads are greater during storm events than would be expected. Concentrations are important in the rivers and northern harbour because of toxicological impacts, and loads have long-term implications for the total amount of copper 'stored' in Macquarie Harbour.

This information has several implications for the development of a remediation strategy. Firstly, the pumping of the underground workings is the major source of acid drainage on the lease site and any successful strategy must incorporate the treatment of this water. Secondly, because of the geohydrology of the Mount Lyell mine, it is not possible to stop the ingress of water into the workings, and therefore, it is not possible to eliminate this source of acid drainage as long as the underground mine is active. Additionally, because copper loads increase with flow, it is necessary to remediate water associated with storm events.

On the more positive side, because the major source of acid drainage is pumped from the mine at one site, most of it can be easily collected and treated. The West Lyell waste rock dumps, which are the other major acid drainage sources present on the lease site, can also be considered to be point sources which report Haulage Creek.

More recent investigations by Imtech (1997) for CMT, including several lease site water balances, suggest a higher median flow in Haulage Creek (280 L/s) and identify ephemeral creeks as a significant component of lease site hydrology. As shown in table 5.3, which compares Imtech's (1997) flow rates with the MLRRDP information, the relative contribution of the sources is very similar, despite the difference in flow rates, especially if the Imtech 'unaccounted' component is attributed to the upper Haulage Creek where the West Lyell waste rock dumps are located. In must be noted, however, that the 6 lease site flow balances which were used to derive the Imtech statistics were completed during the winter of 1996, and this could result in an over estimation of median flows unless balanced by information from dry periods as well.

Table 5.3 Comparison of recent Imtech flow investigations with historical flow summary information as compiled by McQuade et al (1995)

Source	Imtech flow summary		Historical flow summary	
	Flow L/s	% Contrib.	Flow L/s	% Contrib.
Upper Haulage Cr/West Lyell waste rock dumps	44	13	54	24
West Lyell Tunnel	4	2	4	2
Conveyor Tunnel & North Lyell Tunnel	163	64	148	66
Magazine Creek	23	7	19	8
Unaccounted	46	15		
Total	280	100	225	100

5.2.1 Resultant water quality in Haulage Creek

The impact the acid drainage has on the quality of water exiting the lease site is extreme and severe. Table 5.4 contains a statistical summary of water quality in Haulage Creek between December 1994 and April 1995. The metal concentrations vary considerably over 2 orders of magnitude depending on flow conditions. The highest concentrations are associated with times of very low flow, when the relative contribution from the Conveyor Tunnel is at a maximum. The maximum copper concentration detected (835 mg/L) is 167 000 times higher than the ANZECC (1992) water quality guideline for the protection of aquatic ecosystems.

Table 5.4 Water quality in Haulage Creek, between December 1994 and April 1995

n = 475	Copper* (mg/L)	Iron (mg/L)	Manganese (mg/L)	Aluminium (mg/L)
Maximum	835	1230	706	460
Minimum	8.36	23.4	3.04	51.6
Mean	98.4	361	103.3	179.1
Median	80.6	310	93	169

* The copper data is somewhat skewed due to one sample returning a copper concentration of 835 mg/L. The next highest copper concentration in the data set is 357 mg/L.

5.2.2 Summary

- The water discharge from the underground workings constitutes the major source of pollution on the Mount Lyell lease site, with the waste rock dumps the next largest source.
- Exact pollutant loadings are difficult to calculate because of the lack of a long term water quality data base and limited flow data.
- Copper (and other metals) concentrations appear to respond to recent weather patterns, and large storm events are a very important contributor to the overall pollutant load to the Queen River.
- Both the acid drainage discharge from the underground workings and from the waste rock dumps occur as point sources, which could facilitate water treatment remediation options.
- Due to acid drainage, the resultant water quality exiting the Mount Lyell lease is *extremely* poor, and is undoubtedly the worst source of mining related pollution in Australia, and one of the worst in the developed world.

5.3 State of the rivers

The approximately 280 L/s of acid drainage impacted waters flowing from the Mount Lyell lease site enter the Queen River in Queenstown, and a short distance (10 km) downstream the King River and ultimately Macquarie Harbour. Table 5.5 lists the median flows for these rivers.

Table 5.5 Median flows in rivers impacted by acid drainage from the Mount Lyell lease site, and the dilution (percent) of Haulage Creek water downstream

River	Median flow (L/s)	Dilution of Haulage Cr	
Haulage Cr	225	–	
Queen River	1436	1:6.4	(15%)
King River—Power Station off	6856	1:30	(3%)
King River—Power Station on	86856	1:386	(0.3%)

5.3.1 The Queen River

Haulage Creek and its associated acid drainage flows into the Queen River in Queenstown. Despite the many years during which tailings flowed down the Queen River, surprisingly few tailings deposits have developed due to its steep slope. Precipitation of oxyhydroxides associated with the mining discharges have resulted in the cementation of the natural cobble bed of the Queen in many places. Channelisation works carried out by the local council have also altered the bed of the Queen River.

Water quality

Based on median flows in the Queen catchment, as listed in table 5.5, about 15% of the water present in the Queen River below Queenstown at Lynchford originated above or on the Mount Lyell lease site and is impacted by acid drainage. Table 5.6 shows dissolved metal concentrations statistics for the Queen River sampling site. As can be seen, dissolved copper concentrations in excess of 30 mg/L and dissolved aluminium concentrations in excess of 90 mg/L have been documented by DELM; these higher values are generally recorded during low flow periods. Comparison of maximum and minimum values for these two metals, which are toxic in the aquatic environment, indicates that the concentrations vary more than 25-fold and 40-fold for copper and aluminium respectively.

Table 5.6 Queen River water quality at Lynchford (December 1994 through April 1995)

n=226	Copper (mg/L)	Iron (mg/L)	Manganese (mg/L)	Aluminium (mg/L)
Maximum value	34100	274000	41000	93800
Minimum value	1230	538	750	2130
Median value	10900	12500	12400	26200

Table 5.7 Ratio of median Haulage Creek dissolved metal concentrations to median Queen River metal concentrations (Haulage/Queen)

	Copper	Iron	Manganese	Aluminium
Haulage: Queen	7.4	2.5	7.5	6.5

The ratios in table 5.7 suggest that the dissolved copper, aluminium and manganese concentrations in the Queen River at Lynchford can be accounted for by about a 7-fold dilution of Haulage Creek water (ratio of metals in Haulage : metals in Queen), assuming that these metals are not precipitating out of solution in the river. This is a valid assumption for the pH range observed in these two rivers (pH 2.5–3.5), and this predicted dilution factor is quite consistent with the flow ratio between the two rivers of 6.4. This relationship does not hold for iron because there is significant precipitation of this metal at the pH range found in the rivers and iron is contributed by other tributaries of the Queen River. Therefore, future water quality in the Queen River can be expected to reflect the water quality discharged from the lease site with about a 7-fold dilution. However, because acid drainage is pumped from underground at a fairly uniform rate, this dilution factor will be significantly less during periods of low flow.

Biological status of the Queen River

As expected from the table of water quality, Davies et al (1996), determined that the water quality of the Queen River is highly toxic to aquatic biota, and that the river is in extremely poor ecological health, having no fish and a very depleted macroinvertebrate fauna. It was also found that tributaries which are not affected by acid drainage have a diverse and abundant macroinvertebrate fauna which would be a ready colonisation source if conditions in the Queen improved (Davies et al 1996).

Water quality is not the only impediment to improvement of the biological status of the river. Although there is little storage of mill tailings in the Queen River due to the steep gradient of the river (Locher 1995) the cobble bed has undergone significant cementation and is an unsuitable substrate for colonisation (Davies et al 1996). It is also probable, though not demonstrated, that trapped tailings in the bed of the Queen would present toxicity problems for the re-establishment of a healthy ecosystem.

5.3.2 The King River

Tailings deposits in the King River

Aside from contributing to water quality problems, the tailings deposits and dead tree stumps present along the banks of the King River constitute significant visual pollution, which is an important issue for the Strahan-based ecotourism industry (plate 2). Locher (1997) determined the distribution of tailings deposits in the lower King River and estimated that a total of 1.2 million tonnes of tailings are present in the banks of the King River and 2.7 million tonnes of tailings and slag are present in the bottom of the river. Combined, this volume accounts for less than 4% of the total tailings discharged by the Mount Lyell mine. Within the river, most of the tailings are found in the river bed below Teepokana, with only a thin cover present on the river banks above Teepokana. Locher (1995) concluded that substantial portions of the bank deposits will probably be stable over time scales of tens to hundreds of years under the present flow regime, after a relatively short (5 year) period of re-adjustment. Recent observations by Locher (pers comm) confirm that there has been some readjustment, and in places the 'natural' banks have been re-exposed.

Taylor et al (1996) examined the composition of the tailings and found that the river deposits contain rock, crystal and slag fragments, with sulphide minerals accounting for about 2–3% of the deposits. The sulphide minerals were determined to be the source of many of the heavy metals, and, overall, the river tailings deposits contained an average of 0.085% copper.

The reactivity of the river tailings was also assessed by Taylor et al (1996) and both the oxidation of sulphidic material and the dissolution of slag were suggested to be responsible for the release of metals. An assessment of ground water concluded that it is a minor source of contaminants to the King River, contributing only about 5 kg/day dissolved copper to the river and harbour.

Based on the estimates from Taylor et al (1996), the additional inputs of pollutants into the King River through the oxidation of tailings and dissolution of slag are minimal, and including contributions from the delta (discussed below), are equivalent to 1% to 5% of the fluxes entering the river system from the lease site. Surface runoff and groundwater inputs were estimated to contribute roughly equivalent amounts of copper to the river. However, there was no detailed investigation of the effects of rising and falling water levels associated with the operation of the John Butters Power Station, and as discussed below ('Hydrology and water quality'), it is possible that these inputs can, under some conditions, contribute significant quantities of dissolved metals to the river.

Hydrology and water quality

The hydrology and water quality of the lower King River (below the confluence of the King and Queen Rivers) are very complex owing to the operation of the John Butters Power Station on the King River, which controls the majority of water flow, and the variable and high pollutant input from the Queen River.

Prior to the formation of Lake Burbury, the flow in the King River was always significantly greater than that in the Queen. Under the present regime, however, if the power station is off, the contribution of water in the lower King from the Queen River can be equal to or even exceed that originating from the lower King catchment. This results in a very wide range of water quality in the lower King, as shown in tables 5.8 and 5.9, which contain water quality statistics for both low flow (<7 m^3/s) and high flow (>70 m^3/s) conditions in the King. For the period sampled, the low flow condition was met about 40% of the time, and the high flow scenario, which corresponds to the operation of the power station, occurred about 35% of the time.

Table 5.8 Lower King River water quality under *low flow conditions* (<7 m^3/s, 5 km above mouth of King River), December 1994 through April 1995

n=440	Copper µg/L	Iron µg/L	Manganese µg/L	Aluminium µg/L
Maximum	9010	6230	12680	19640
Minimum	84	50	150	<100
Mean	2620	840	3640	5670
Median	1230	620	1570	3630

Table 5.9 Lower King River water quality under *high flow conditions* (>70 m^3/s, 5 km above mouth of King River), December 1994 through April 1995

n=147	Copper mg/L	Iron mg/L	Manganese mg/L	Aluminium mg/L
Maximum	2720	3170	3070	4950
Minimum	110	40	160	<100
Mean	570	380	700	990
Median	390	290	480	980

It is interesting to note that while there is an increase in flow of 12-fold between 'power station on' and 'power station off', the water quality statistics do not indicate as substantial a dilution of dissolved metal concentrations. A possible additional source of metals to the lower King River would be from the tailings deposits (bed and banks) located in the King. The flushing of tailings (Locher 1995), and increases in dissolved metal concentrations (Koehnken 1996) associated with the initiation of power station operation have been previously documented in the lower King River, and are undoubtedly an additional source of metal to the system.

Taylor et al (1996) who investigated metal release from the river tailings, concluded that the additional input from the sediments was only 1–5% of that emanating from the lease site, though the impact of episodic flooding events or fluctuating river level due to power station operation was not investigated.

The discrepancy between the chemical dilution data and the water dilution ratios, may in part be the result of the timing of the DELM Intensive Monitoring campaign in the lower King River. The DELM data reflect conditions immediately after mine closure, when the pH in the Queen and King would have decreased one or more pH units. It is possible that high metal fluxes from the banks may have occurred for a limited time as the banks were exposed to lower pH water, and a new equilibrium was established.

Additionally, because the beginning of 1995 was very dry and the power station was not often in operation, river levels were very low which would have resulted in the oxidation of tailings not normally exposed. Finally, during this period, metal fluxes from the Mount Lyell lease site were actually quite low, due to low rainfall, so inputs from the banks would appear as a larger proportion of the total. In summary, the above data may reflect minimum inputs from the Queen and maximum inputs from the banks. To determine the present situation, DELM intends to conduct another intensive monitoring campaign in the lower King River, because the river has had two years to acclimate to the new conditions, and substantial quantities of tailings have eroded from the river banks.

For the purposes of developing a remediation strategy, the inputs from the banks and bed of the King River are being considered to be small (<3%) when compared with inputs from the lease site.

Biological status of King River

Results from biological investigations indicate a similar situation exists for the King River downstream of the King–Queen confluence as for the Queen River (Davies et al 1996), namely, that the river is in extremely poor ecological health, has no fish, and a depauperate macroinvertebrate community.

An interesting finding of Davies et al (1996) is that in the past there has been intermittent recruitment of native fish into tributaries of the lower King River catchment. The ages of native fish and eels collected from tributaries of the lower King ranged from 6 years to 28 years, with the distribution suggesting that migration into the tributaries was not an annual occurrence (Davies et al 1996).

This was in contrast to the fish collected from control rivers, namely small tributaries entering directly into Macquarie Harbour, the Gordon River and the Henty River, where ageing of fish confirmed annual migration in each of the rivers (Davies et al., 1996).

The minimum age of the fish and non-continuous age distribution suggest that migration of fish into the King has not been as frequent in the past as in nearby rivers, and has not occurred at all in the last 6 years. Davies et al (1996) suggest that migration of native fish into the King only occurred in the past when there was a large flood event which resulted in temporary, significant improvements in water quality in the lower King River during the migratory season (September to November). The minimum age of the fish probably corresponds with the time since flow in the King has been regulated (5 years). Since that time, the operation of the power station has precluded the occurrence of the required conditions for native fish migration. The discrepancy between the initiation of regulated flow (5 years ago) and the last fish migration (6 years ago) can be accounted for by examining the hydrograph for the King River for the year prior to dam closure. The data indicate that there were no significant flood events during the appropriate migration season, so the lack of 5 year old fish is not surprising (Davies et al 1996).

The work by Davies and coworkers suggests that in the past, recruitment of native fish into tributaries of the lower King River was modified due to water quality, whereas now, recruitment has been eliminated due to the post modified-flow water quality. A conclusion from the work is that an interim target of remediation should be to improve water quality in the lower King River such that recruitment of fish will again take place in the tributaries of the King River, even if the mainstem of the King remains uninhabitable (Davies et al 1996). As improvements in water quality are achieved, the environmental flow regimes required to promote fish migration will need to be identified in conjunction with the HEC.

5.4 State of the delta

The delta at the mouth of the King River is, like the bare hills of Queenstown, a landmark which is directly associated with the past operations of the Mount Lyell copper mine. Unlike the bare hills of Queenstown, however, the delta is not considered a tourist attraction by the local community: instead it is viewed as a bleak reminder of poor past environmental management and the death of a river system.

During the 75 years of tailings disposal, the delta front has prograded greater than 1 km into Macquarie Harbour, and greater than 100 million cubic metres of infilling has occurred in the northern harbour (Koehnken 1996). In addition to being a source of visual pollution, the delta presents navigational problems at the mouth of the King River due to shifting bars. During dry periods, dust clouds originating from the surface of the delta have also caused concerns for the residents of Strahan.

In terms of contributing pollutants to Macquarie Harbour, the delta was found to generally be a small source, with oxidation of sulphidic minerals present in the top 1.5 m being the most reactive (Taylor et al 1996). It has, however, been associated with high copper bearing plumes in the harbour when river flow and tidal conditions result in the inundation of the delta surface (Koehnken 1996). Additional monitoring of storm events is required to evaluate the long-term importance of this phenomenon.

A 'natural' remediation process was identified as actively operating in the tidal zone of the delta by Taylor et al (1996). Sulphate reducing bacteria (SRB), which convert dissolved sulphate and metals to insoluble sulphide minerals, were identified in inundated zones containing organic material. The ground water associated with these regions was found to contain far lower concentrations of metals than in other regions of the delta not suitable for SRB activity.

The sediments present on the inundated delta front have been found to contain high concentrations of metals which are biologically available based on acid volatile sulphide tests (Koehnken 1996, Teasdale et al 1996). Benthic chambers employed by Teasdale et al (1996), indicated that metals were both removed from the water column by sediments near the delta and released from the sediments back into the water column. Based on a limited sampling, Teasdale et al 1996, determined that while there is a net loss of metals from the water column to the sediment, the shifting sediment banks near the delta front accounted for a significant release of metals back into the water column from the sediments. A more comprehensive discussion of metal cycling in Macquarie Harbour is presented in section 5.6.2.

5.5 Toxicological issues associated with the 'recovery' of the King and Queen Rivers

Freshwater toxicological investigations with the aim of estimating the degree of remediation required to achieve the Environmental quality objectives in the rivers were completed by Humphrey et al (1997). Mixtures of untreated acid drainage, neutralised acid drainage, and unimpacted river water were created to mimic possible remediation scenarios and subsequent downstream dilution. Two cladoceran species were initially tested using various ratios of neutralised (to pH 6.5) to raw Mount Lyell mine acid drainage (65:35, 80:20 and 95:5), each serially diluted with West Queen River water. Although the species ultimately proved intolerant of the soft, naturally acidic diluent water, results were sufficient to establish that all the 65:35 and 80:20 mixtures resulted in 100% mortality of the test organisms, and returned NOEC (no observed effect concentration) and LOEC (lowest observed effect concentration) concentrations of 15 and 30 µg/L soluble copper respectively (Humphrey et al 1997).

Additional toxicity testing using *Hydra viridissima* focused on evaluating neutralisation regimes of 95:5 and 99:1 (neutralised acid drainage to raw acid drainage) in serial dilution to mimic downstream conditions. The NOEC and LOEC values obtained from averaging the results of these tests were 15 µg/L and 18 µg/L soluble copper respectively, which are generally higher than Australian guideline values (Humphrey et al 1997).

Geochemical modelling results obtained by Klessa et al (1997), predict that if 99% of the acid drainage is neutralised on the lease site to pH 6.5, soluble copper concentrations in the lower King River will be approximately 10 µg/L when the power station is operating (high flow in King River). However, during times of power station inactivity, soluble copper concentrations would be expected to range between 74 µg/L and 235 µg/L. Because the NOEC value is intermediate between these ranges, the potential may be present for some partial recovery of the King River, although the effect of pulsed and episodic exposure to organisms of high copper concentrations has not been evaluated (Humphrey et al 1997).

The modelling and toxicological results show that virtually *all* of the acid drainage from the lease site must be neutralised to pH 6.5, if water quality objectives for the ecological recovery of the King River are to be met. Unfortunately, the results also indicate that even 1% of untreated acid drainage entering the Queen River could be expected to result in median copper concentrations of about 360 µg/L, far exceeding the NOEC value, and even a modified ecosystem would not be expected to develop.

The identification of the bed of the Queen River as an unsuitable substrate for recolonisation by macroinvertebrates (Davies et al 1996), and finding which indicate the tailings deposits in the river bed could be toxic to invertebrates (Hince 1993, Taylor et al 1996), suggest that improving the water quality alone may not be sufficient for the recovery of the ecosystem. While there may be an eventual improvement in the substrate of the lower King River, as suggested by Locher (1996) due to the winnowing of finer tailings from the river bed and subsequent armouring with natural river cobbles, the leaching of metals from trapped tailings may continue to inhibit recolonisation.

5.6 State of Macquarie Harbour

5.6.1 Water quality

As the receiving environment for the King River, the water quality of Macquarie Harbour has been severely impacted by mining operations on the Mount Lyell lease site. During the three year period between 1993 and 1996, monthly and bi-monthly sampling of harbour waters indicated that virtually all samples exceeded the ANZECC (1992) Water Quality Guideline for the 'preservation of aquatic ecosystems', 5 µg/L total copper (Koehnken 1996). Teasdale et al (1996) obtained similar results from a more limited survey.

Extremely high copper concentrations have been detected on the surface of northern Macquarie Harbour when King River water persists as a plume. This occurs under conditions of high discharge from the King River and low or no wind, which minimises the mixing of King River water with more saline waters.

As expected in the mixing zone at the mouth of the King River, copper does not behave conservatively due to a combination of precipitation reactions involving the oxidation of iron and co-precipitation of copper as the fresh water mixes with more saline waters (Teasdale et al 1996, Koehnken 1996).

Concentrations have been found to be highest near the mouth of the King River, for both total and dissolved copper. The nature of the currents in Macquarie Harbour results in a transport of copper southward in the eastern half of the harbour. Further south, the copper-rich water is overlain by 'cleaner' Gordon River water, and underlain by 'clean' marine derived water (Koehnken 1996). The predominant process controlling the mixing of copper in the water column is wind driven mixing at the surface.

It has been found that once the King River water has passed through the mixing zone and a salinity of about 15 ‰ is achieved, the copper is mixed conservatively throughout the rest of the harbour. Mid-depth (20 ‰ salinity) concentrations in the northern harbour have been found to be directly related to the copper fluxes entering the harbour from the King, with low fluxes associated with dry summer periods resulting in a lowering of copper concentrations in the harbour (Koehnken 1996).

5.6.2 Harbour sediments

In excess of 100 million cubic metres of infilling has occurred in the northern harbour since 1935 (Koehnken 1996). No estimate of infilling in the remainder of the harbour has been made due to poor historical bathometric records. Koehnken (1996) and Teasdale et al (1996) found that based on acid volatile sulphide measurements, 'free' metals at the sediment water interface exceed the available metal-binding capacity of the sediment. In the southern harbour and central harbour, deeper sediment core segments (6–9 cm) were found to have metal binding capacity in excess of available metals, and hence act as a sink for metals (Koehnken 1996). Benthic chamber experiments (Teasdale et al 1996) confirmed the uptake of metals from the water column by the sediments in the southern harbour.

Copper budget for Macquarie Harbour

Teasdale et al (1996), developed a sediment–copper budget for the harbour. Their results indicate that in the northern harbour, about 46 tonnes of copper per year are entering the sediments, with 36 tonnes/year being released, resulting in a net sink of 10 tonnes/year in this region. The shifting sediment deposits associated with the delta front were found to have the highest rate of metal release. In the southern harbour, they estimated 85 tonnes of copper per year were being taken out of the water column by the bottom sediments, resulting in a net sink of 95 tonnes per year in the harbour.

Based on DELM monitoring data for the King River, this quantity of copper accounts for only about 10–15% of that entering the harbour, which suggests that the vast majority of copper entering from the King River exits the harbour. Based on freshwater inflows and estimates of brackish outflows through the harbour entrance, to achieve this rate of removal, an average copper concentration of 30 ppb would be required. This is in very good agreement with field data (Koehnken 1996).

Although the flux of metal from the sediments into the water column in the northern harbour is very small compared with that entering the harbour from the King River, it would become the major source of copper to harbour waters if remediation of the lease site were accomplished, and raises issues about metal remobilisation if the sediments associated with the delta were to be relocated.

The cycling of copper in Macquarie Harbour can be summarised as follows. A minimum of 730 tonnes of dissolved copper per year are entering northern Macquarie Harbour via the King River. In the northern harbour, approximately 46 tonnes per year are removed from the water column by the sediments, and at the same time, the sediments are re-releasing 36 tonnes per year back into the water, so the northern harbour is a net sink of 10 tonnes per year. In the southern harbour, the sediments are a sink for copper and up to 85 tonnes per year are being removed from the water column in this region. This results in a total of 13% of the copper entering the harbour from the King River entering the sediments, leaving 87% of the copper in the water column, which eventually exits the harbour.

5.6.3 Harbour biology

As part of the MLRRDP, a pilot biological survey of Macquarie Harbour was conducted which had the aim of identifying a community best suited as a long-term monitor of the ecological health of the harbour. The vertebrate, invertebrate and floristic communities in Macquarie Harbour were examined, and benthic invertebrates were recommended for assessing the 'health' of the harbour (O'Connor et al 1996). Subsequent sampling and data analysis lead the authors to conclude that the 84 species of benthic infauna identified in the harbour were less numerous and diverse than might have been expected, and suggest that 100 to 200 benthic species would be expected to be present if the harbour were unimpacted, based on comparisons with other south-east Australian estuaries (O'Connor et al 1996, Talman et al 1996).

Talman et al (1996) found that sediment copper concentration and organic content appear to be the main factors controlling the current population structure of the benthic invertebrates, as species richness, total abundance and species distribution were all well correlated with these parameters. Other factors, such as sediment grain-size, water depth and temperature did not appear to affect the abundance and diversity of benthic invertebrates (Talman et al 1996).

Similar to the situation in the lower King River, even if the water quality of the harbour is significantly improved, the presence of vast deposits of highly contaminated sediments will remain an impediment to the recovery of the benthic communities. This is especially true in the northern harbour, where the metal concentrations in the sediments are very high, metals are being released into the water column, and no benthic invertebrates were present. If remediation of the lease site were achieved, the release of metals from the bottom sediments in the harbour could become the largest source of metals to the water column. At present, it is unknown for how long metal release would continue, but given the quantity of sediments and concentrations of metals, it is likely that it would be very long term.

Compared with Bathurst Harbour (a nearby estuary), the abundance and diversity of fish species in Macquarie Harbour is relatively low, with only 24 collected fish species. In contrast, in the Port Davey/Bathurst Harbour region, which is considered to have low species diversity possibly due to its southern location (Edgar 1991), a total of 90 species have been documented. The phytoplankton in Macquarie Harbour were also characterised by low species abundance and domination by freshwater species, most likely reflecting the freshwater layer which generally occupies the euphotic zone.

5.6.4 Toxicity results from Macquarie Harbour

A preliminary risk assessment completed for the MLRRDP (Stauber et al 1996) suggested that copper concentrations in Macquarie Harbour need to be reduced by 30-fold in order to 'protect' 95% of the algal species 90% of the time. However, toxicity testing of copper-rich mid-salinity water from the harbour revealed that there were no significant effects on algal growth, amphipod and juvenile flounder survival, or osmoregulation, or copper accumulation in flounder (Stauber et al 1996). The lack of observed toxicity suggests that copper in these waters is not present in bioavailable forms, and it is possible that colloidal iron, manganese and aluminium oxides/hydroxides bind copper at the algal cell surface, preventing uptake into the cell (Stauber et al 1996). In some tests, histopathological changes in juvenile flounder were observed, but the investigators surmise that copper in Macquarie Harbour water was not the sole cause of these changes, and that other metals or compounds in the harbour water may contribute to these effects.

A second risk assessment incorporating the Macquarie Harbour toxicity testing suggested that a 50% reduction in copper concentrations in the harbour would provide the same level of protection to the ecosystem as the 30-fold reduction originally calculated based on literature information (Stauber et al 1996).

The results from lab based toxicity testing using rainbow trout, one of the species cultured in marine farming operations in the harbour, were judged not able to be easily extrapolated to Macquarie Harbour because harbour water was not used and harbour conditions were not reproduced (eg changes in pH and salinity, Nowak & Duda 1996). However, the results from the toxicity testing and available literature values led the authors to conclude that 'extreme caution' should be applied if salmonid fish were to be cultured in the areas of the harbour most affected by copper pollution at present levels (Nowak & Duda 1996).

The 'complexed' nature of copper in Macquarie Harbour waters is suggested by the results of a combined chemical and physical model of the harbour in which runs using conservative mixing of copper for the southern harbour best replicate field results (Tong in prep). This supports the theory that copper is not reactive or 'biologically available' in much of the harbour environment and is 'passively' moving around the harbour resulting in a reduction of toxicological impacts and preventing rapid removal from the water column.

5.6.5 Human health issues in Macquarie Harbour

Past studies have identified elevated concentrations of copper in mussels near the mouth of the harbour and elevated concentrations of mercury in some of the commonly consumed fin fish species in the harbour. In association with the biological survey of the harbour completed as part of the MLRRDP, 24 fish were collected and tissue samples were analysed for copper, lead, mercury, selenium and zinc. Copper and zinc concentrations in all individual fish for all species collected were well below the Australian Food Code Guidelines. One red cod was found to contain lead concentrations above the guideline, though the average of the sampling, on which the guideline is formulated, was well below the limit. Similar situations exist for mercury and selenium, where the average of the sample was below the guideline, though 3 individual fish contained concentrations of mercury exceeding the Australian Food Code but not the Tasmanian Standard, and 2 individuals contained 'high' selenium concentrations.

Due to the low numbers of individual fish that were collected during the initial survey, a supplementary collection and analysis of shellfish and fin fish was completed by the MLRRDP. This involved the collection of 15 flounder, 3 brown trout, 6 Australian salmon and 8 cod. The results generally agreed with the initial fish survey, and indicate that the flounder and cod contained selenium concentrations greater than the September 1995 Australian Food Code (AFC) guidelines. The mercury, lead, zinc and copper concentrations were well below the AFC.

Shellfish (mussel and oysters) were also collected and analysed as 2 composite samples, one consisting of 'large' individuals, and the other of 'small' individuals. Both oyster samples were found to contain very high copper concentrations, on the order of 25 to 30 times the AFC, and zinc levels 30% higher than the AFC. Metal concentrations in the mussels were all found to be below the AFC.

5.7 Summary of MLRRDP findings

The MLRRDP has successfully quantified and prioritised the sources of pollution as initially set out at the beginning of the program. Because our understanding of the important environmental processes in the King River and Macquarie Harbour have been greatly enhanced, and the sources of pollution quantified, the requirements for a successful remediation strategy have been precisely identified. This ground breaking environmental work will allow the forthcoming engineering and implementation phase of remediation to be focused on achieving the desired environmental outcomes. Because understanding the problem is the first step towards fixing it, the MLRRDP results establish a new benchmark in the long environmental history of Mount Lyell—one which marks the beginning of recovery for the region.

The program has overwhelmingly identified the lease site as the major source of acid drainage related pollutants to the rivers and harbour, with releases of metals from tailing and slag deposits being very minor in comparison. Within the lease site, the water from the North Lyell Tunnel, which includes the water pumped from underground (previously known as Conveyor Tunnel), has been identified as containing approximately 78% of the lease site copper loading, with the combined discharge of the West Lyell Tunnel and runoff from the waste rock dumps accounting for another 21%. The other '1%' of discharges is coming from a variety of smaller sources. This breakdown is based on copper loadings, whereas acidity contributions vary significantly, with only 45% of the acidity associated with the North Lyell discharge, and about 40% associated with the waste rock dumps.

Water quality in the Queen and King Rivers and Macquarie Harbour can be directly linked to discharges emanating from the lease site, and any successful remediation strategy must address the high concentrations and loadings leaving the lease site. Chemical and hydrological modelling of the river systems and toxicological investigations indicate that a very high percentage, probably 95 to 99% of the acid drainage must be neutralised if the lease site discharges are to meet the downstream environmental quality objectives identified through the MLRRDP for the rivers. Other environmental factors, such as the state of river substrates and flow regulation may also affect ecosystem recovery. In Macquarie Harbour it has been suggested that a 50% reduction in dissolved copper concentrations in the *saline* waters (>20‰) would 'protect' 95% of the algal species 95% of the time. However, because under certain meteorological conditions fresh water King River plumes persist for hours to days in northern Macquarie Harbour, to really protect the harbour from toxicological impacts associated with acid drainage, the same conditions must be met in the harbour as for the lower King River.

The MLRRDP has also identified periodic high river flows associated with storm events as being an important yet difficult to quantify pollutant source from the lease site, and to a much lesser extent, from the tailings banks and delta. Additional investigations by Imtech (1997) for CMT have confirmed this finding, and suggest that water management practices and suitable infrastructure need to be implemented such that all storm waters as well as normal flows are contained and 'treated'.

It has been found that the contaminated sediments in the King River and Macquarie Harbour contribute a relatively small proportion of the total pollutant load entering the harbour, and it is not realistic to address these issues unless the lease site is remediated. An exception to this would be the revegetation of the tailings banks and delta which, while only minimally reducing pollutant loads, would significantly improve the visual aspect of the region and reduce dust.

Due to the volume and extent of the contaminated sediments in Macquarie Harbour, and their minor contribution to water quality issues, it is not practical nor economically feasible to pursue remediation. Additionally, toxicological work in the harbour has shown that in the vast majority of the harbour, copper toxicity would not be an issue if the lease site pollutant source were eliminated.

In the words of a Strahan resident upon hearing the range of remediation options 'if I had $100, I would spend $98 on fixing the lease site...and the other $2 on a party to celebrate it being fixed' (D Gerrity, pers com).

6 MLRRDP findings: Remediation options for the lease site

6.1 Overview and criteria for evaluating remediation options

An extensive review of remediation options applicable to the Mount Lyell lease site was completed as an MLRRDP project (Miedecke 1996).

The *ultimate* goal of remediation is to achieve the downstream EQOs, and the MLRRDP must define a path to reach this goal. However, this path must take account of economic and technical realities. Therefore, interim measures which will partially achieve the EQOs or at least be a 'step in the right direction' have also been given serious consideration. It cannot be strongly enough expressed, however, that based on the findings of the MLRRDP, virtually *all* of the acid drainage presently exiting the lease site must be eliminated for the EQOs to be achieved.

This view holds for both the rivers and harbour, because although toxicity results suggest that reducing the copper concentrations by one-half in the harbour will reduce the risk to acceptable levels in saline waters, the harbour is subject to freshwater King River plumes. In effect, the King River 'flows' over the surface of the Harbour, creating the same toxicological threat as exists in the river, in the harbour. Historically, these plumes have been implicated in fish kills in the harbour, and because of this, the harbour cannot be considered 'safe' until the incoming King River water is no longer toxic to organisms.

This approach is reflected in the criteria which have been chosen by the MLRRDP for evaluating possible remediation options for the Mount Lyell lease site, rivers and harbour.

- The *effectiveness* of the option is of primary importance and has been evaluated in terms of its ability to promote the downstream EQOs in both the short and long-term time scales.
- The *feasibility* of potential remediation options has been considered, including issues associated with using 'new' technologies. Mount Lyell presents some unique problems because of the scale and magnitude of the acid drainage problem, and it is often difficult to determine whether a technology which has successfully been employed on a much smaller scale will be effective at Mount Lyell.
- The *cost* of each remediation technique has been evaluated, including costs associated with the initial establishment or installation of the remediation technique, and ongoing running and maintenance costs over the life of the technique.
- Remediation strategies have also been considered with respect to *social acceptability*. The views of the community need to be reflected in a remediation plan, as does waste reduction, waste minimisation and 'best practice environmental management' policies as currently adopted by both State and Commonwealth Governments.
- Other issues considered by the MLRRDP are the *flexibility* of the remediation option to take advantage of new technologies or respond to radically changed conditions (such as reduced flow of acid drainage or variation in composition), and the *impact of mine closure/development* on the option.