Abandoned Tin Mines in the Gladstone region of Northeastern Tasmania:

Review of Recent Environmental Impact Studies and Recommendations for Further Work and Remediation

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Executive Summary

The three main aims of this report are to: i) review recent environmental impact research studies on three abandoned tin mine sites in the Gladstone region of Northeastern Tasmania, ii) suggest possible future research studies and iii) provide information about and suggest possible remediation strategies for the three studied mine sites and others in the region. The recent studies focussed on studying acid drainage on the western end of the Endurance mine site and vegetation and sediment/soil/water geochemistry at the Endurance, Monarch and Star Hill mine sites.

Acid (water pH between 2.4 and 5) is being generated in and transported by groundwater in the tailings at Endurance and to a lesser extent at Monarch. There is no evidence of widespread acid drainage at Star Hill. The most likely source of acid at Endurance (and Monarch) is iron sulphide minerals (i.e., pyrite, marcasite) present in the tailings, although they were not observed directly. The impact of the acid drainage is clear in Conundrum Creek (Endurance site) where the pH of the water in the creek drops from greater than 5 (pH ~ 5 to 6 in unimpacted creek water) to less than 4 and typical iron staining and crusting is observed where the acidic groundwater enters the creek. High concentrations (above recommended water quality limits) of iron, sulphate, aluminium and silica were detected in groundwater, Conundrum Creek and Ruby Lagoon. Some heavy metals (Pb, Zn, Cu, Cr, Ni, Mo and U) may be potentially dangerous around the Endurance site; however, their concentrations in waters were above recommended limits in only a few samples. Groundwater flow in the tailings is downhill towards both Conundrum Creek and Ruby Lagoon, although in summer it appears that water from Ruby Lagoon is recharging the tailings around the lagoon. Acidic groundwater from the tailings appears to be flowing subparallel with the current ground surface and does not appear to be entering the original ground surface underlying the tailings. Groundwater discharges to Conundrum Creek and Ruby Lagoon were small (~19-20 m^3/day) relative to the stream discharge from the two creeks (>1000 m^3/day) entering the lagoon and do not appear to vary between summer and spring seasons. Estimated groundwater velocities in the tailings are on the order of 10s to 100s of m/year, which lead to estimated residence/travel times for groundwater of 10 years or more, depending on where water infiltrates the surface of the tailings. The main impact on Ruby Lagoon from acid drainage is from Conundrum Creek. Based on mass balance arguments, it is possible that iron oxyhydroxide minerals are precipitating in the bottom sediments of Ruby Lagoon and generating acid in the lagoon itself.

Vegetation is sparse on the tailings and mined areas at all three mine sites. Plant cover ranges between less than 10% and 40%, compared with 90-100% on established areas, with areas on the tailings that have been undisturbed the longest (e.g., ~50 years) having the highest percentage cover. The plants on the tailings and mined areas consist mainly of Banksias, Acacia (Wattle), Kunzia, Sheoke, evergreen shrubs, Eucalypts and sedges and rushes. On established areas, the dominant plants are Eucalypts, brackens/ferns, cyperaceae (Family), Manuka and Banksias in forested (higher) areas and sedges, ferns and rushes in sedge-heathland (lower, wetter) areas. Despite differences in vegetation (predominance of different plant species), biodiversity (species richness and diversity) is in general similar for all three mine sites and the established sites. There appears to be a greater biodiversity in tailings and mined areas closer to natural vegetation, presumably a result of seed availability.

There is little or no soil developed on most of the tailings and mined areas. The tailings and other sediment consist mainly of sands and gravels with small percentages of clay, organic

matter and many of the essential nutrients for plant growth. For macronutrients, carbon and hydrogen were in higher concentration in sediment covered by vegetation, nitrogen concentrations were below detection limits in all mine areas and phosphorous, potassium, calcium and magnesium concentrations were much lower in tailings than in the soils/sediments of the established areas. Many plants on the mine sites exhibit chlorosis, necrosis and/or misshapen leaves, indicating nutrient deficiencies (Mg, Cl, K and/or N). Of the known micronutrients (Cl, B, Fe, Mn, Zn, Cu, Ni and Mo) required for plant growth, manganese and possibly zinc and copper were in low concentrations in the tailings, relative to established areas. The only element that was identified at potentially toxic levels to plants on the tailings and mined areas is aluminium, although iron, lead, zinc and other heavy metals may be affecting plant growth adversely where acid drainage is evident. The sediments and groundwater in many areas of the tailings and mined areas are more acidic (pH = 4.4-5.4) than favourable for plant growth (pH = 5.6-7). Low Ca/Al ratios in the tailings may be limiting plant growth.

Poor availability of groundwater may also be limiting successful revegetation. Water tables were observed to be deeper than observed root depths of plants (e.g., commonly 10-15 cm) during the times of the fieldwork. Iron pans are developed, at least in part from acid drainage, in some areas of the mine sites and may limit plant growth by impeding root penetration.

Future studies of the mine sites should continue to focus on characterising acid drainage, geochemistry of sediment and water (ground and surface) and vegetation. Useful studies could include identification of point and/or diffuse sources for acid generation at the Endurance and Monarch sites (and other mine sites), hydrological studies (hydrologic budgets) at Endurance and perhaps other sites (including variations with time), water infiltration and erosion (water and wind) rates, toxicity of metals and other elements (Al, Fe, Pb, Zn), nutrient availability/deficiency (C, Ca, Mg, Cl, K, N, P, Mn, Zn), role of microorganisms (bacteria) in making nutrients available for plant growth (individual as well as multiple plant species).

Successful remediation will probably include a variety of individual strategies. Some of the individual strategies may be effective in both minimising acid generation/drainage and promoting healthy plant growth. Acid generation and drainage can be minimised by reducing the amount of water that infiltrates the tailings (by redirecting surface water, installing drains, installing surface barriers), minimising the amount of atmospheric oxygen entering the tailings (by minimising water infiltration and/or adding organic material or other chemically reducing materials) and/or bioremediation (e.g., addition of sulphate reducing bacteria, developing ecosystems similar to wetlands). Passive or active treatment strategies may be effective and economical for small-scale acid drainage problems (e.g., smaller than Endurance). Successful revegetation of the mine sites will require site preparation that includes both chemical and physical aspects. Chemical preparation could include liming and nutrient addition, both short-term strategies that will help plants to establish themselves better. Physical preparation could include ripping of the sediment, land imprinting (dimpling of ground surface or creating hummocks – may be particularly effective), addition of clay material, top soil and/or mulch (plant and litter cover is likely to be important). Revegetation may be best accomplished in patches. Nitrogen-fixing plants (such as acacias and legumes) may be helpful in developing long-term nutrient balances and soil profiles. Erosion control is probably necessary (by land imprinting and/or establishing wind and water barriers). Plant species selection should be based on natural species in the area, but perhaps adjusted to include a higher predominance of acacias (nitrogen fixers), sedges, rushes and grasses.

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1 Introduction

Historical tin mining in the Gladstone area of Northeastern Tasmania has resulted in adverse environmental impacts on the mine sites, areas immediately surrounding the mine sites and on receiving waterways in the Ringarooma and Great Musselroe basins. Approximately 40 million tonnes of sediment were released into the Ringarooma River during mining, followed subsequently by sediments being released onto areas surrounding the mine sites. The most obvious impacts are acidic lakes that fill the mined areas, sediments affecting the flow especially in the Ringarooma River, large areas of mine tailings around the mine sites and acid drainage problems associated with at least some of the tailings dumps. There are approximately 2500 hectares of adversely affected areas around the old mine sites. Some rehabilitation has been attempted, e.g., substantial revegetation projects on parts of the Endurance and Star Hill mine sites and slope and/or drainage stabilisation projects at the Monarch and Endurance mine sites. Although the revegetation strategies have been partially successful in some cases, there is still a need to develop effective methods of rehabilitation at many sites, the most important of which are Endurance, Star Hill and Monarch (identified by Mineral Resources Tasmania).

In order to understand more about the present environmental impact on the three most important sites, two recent Honours research projects were sponsored by Mineral Resources Tasmania in 1999. Those projects focussed on the acid drainage evident in and around Ruby Lagoon at the eastern end of the Endurance mine site (de Jong, 1999) and characterisation of the vegetation and geochemistry of the Endurance, Star Hill and Monarch mine sites (Bennett, 1999). The purposes of this report are to review the results of those two studies, identify and suggest useful future studies and provide some information and ideas for rehabilitation of tin mine sites in Northeastern Tasmania.

2 Review of Jacinta de Jong's Honours Research (Endurance Mine)

This study focussed on the western end of the Endurance Mine site and on the sediments, ground water and surface water between Blue Lake and Ruby Lagoon (Figure 1.1 of de Jong, 1999). The main scientific aims of this study were to:

- Determine the direction and magnitude of ground water flow and discharge
- Characterise the physical and chemical properties of the mine tailings
- Measure the geochemistry of the ground and surface water (i.e., water quality)
- Understand the geochemical controls on water and sediment compositions
- Estimate mass balances of water and elements to and from the receiving surface water (i.e., Ruby Lagoon)

2.1 Methodology

A total of 34 mini-piezometers were installed in between Blue Lake and Ruby Lagoon (Figure 3.1 of de Jong, 1999) in order to measure hydraulic heads and hydraulic conductivities and sample the ground water in the tailings. The porosity and infiltration rates of the sediment were measured and used in conjunction with the measured hydraulic heads and conductivities to calculate groundwater flow, discharge and runoff. In addition, several mini-piezometers were installed in the bottom sediment of Ruby Lagoon (Figure 3.1 of de Jong, 1999) to determine if there was any recharge or discharge through the lake bottom.

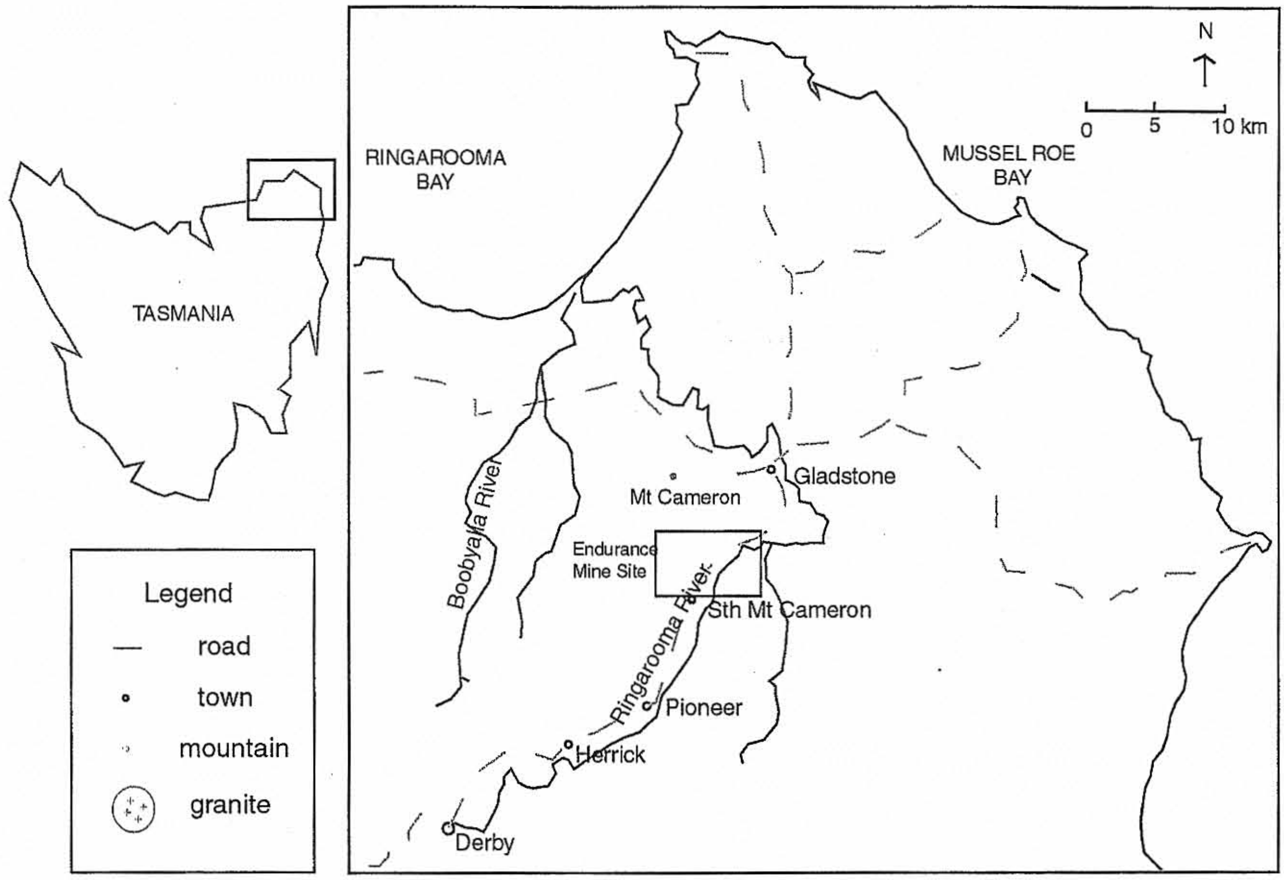

Figure 1.1a Location map of the Endurance mine site, NE Tasmania (adapted from Davis (ed), 1965, 21).

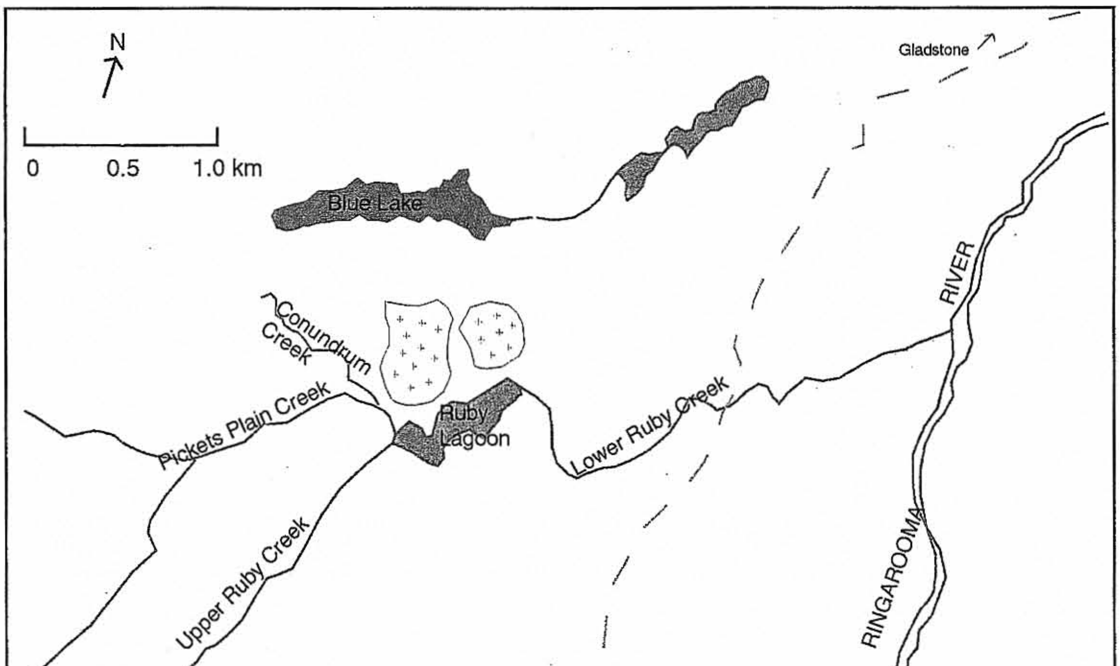

Figure 1.1b Major features of the Endurance Mine site, NE Tasmania (from Tasmania Topographic Survey, 1979 Sheet 8415 Edn. 2: Forester)

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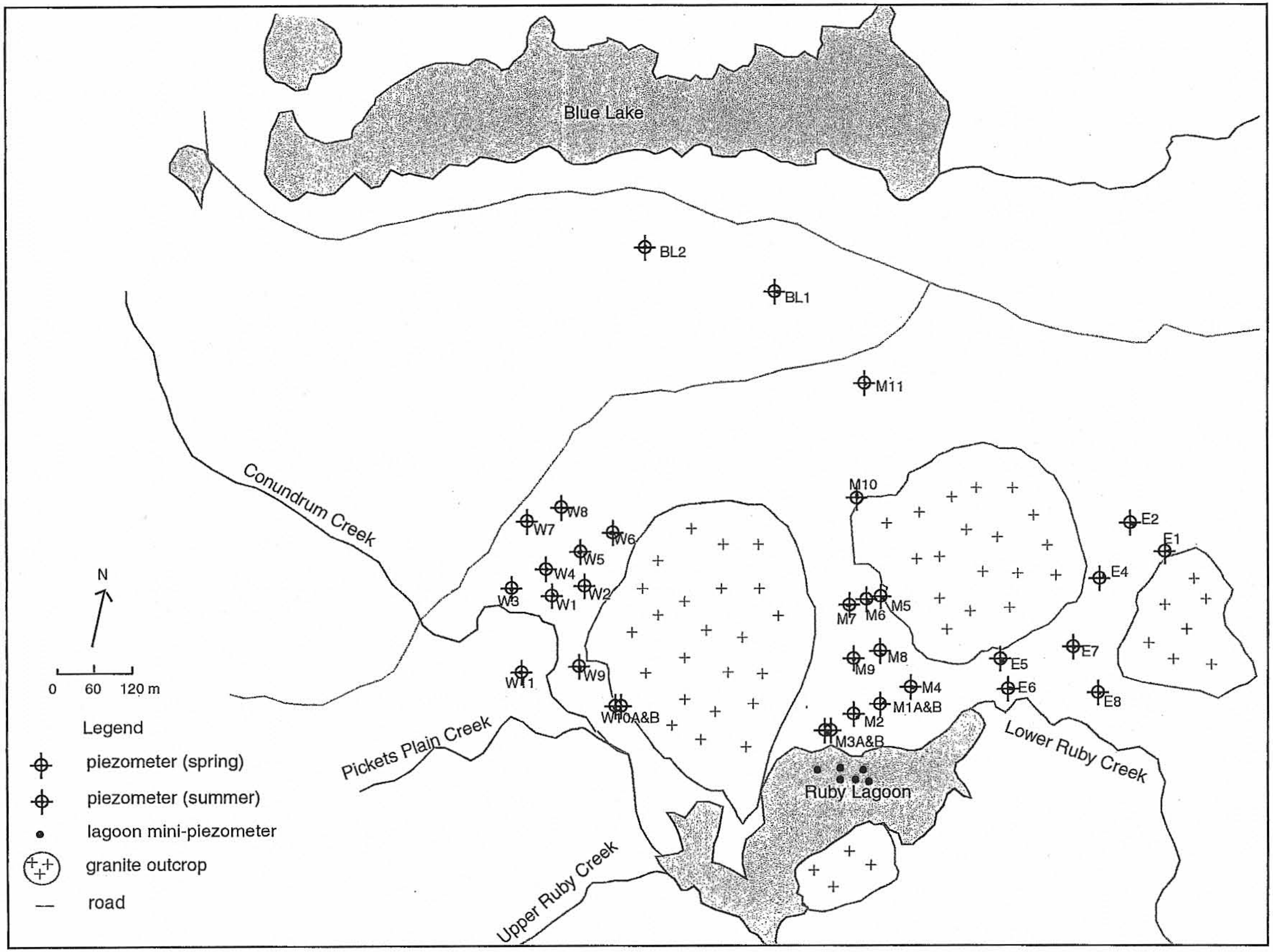

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Figure 3.1 Piezometer location map, Endurance mine

Surface water was sampled from the Blue Lake, Conundrum Creek, Upper and Lower Ruby Creek, Ruby Lagoon and the Ringarooma River. The composition of all water samples (ground and surface) was measured in the field and the laboratory (temperature, pH, Eh (redox or oxidation potential), electrical conductivity (EC) and major, minor and trace element concentrations). Sediment was also sampled and analysed for grainsize, mineralogy, bulk chemical composition and element speciation (i.e., how much of an element exists in different fractions of the sediment).

2.2 Sediment composition and properties

The primary mineralogy of the mine tailings sediment consists mainly of quartz (typically 90-95% by volume) with a grain size ranging between <0.1mm and 10mm. Some feldspar (plagioclase and K-feldspar) is observed but is typically weathered to mica and clay minerals. Pyrite is observed but represents <1% by volume of the sediment (note that a few tenths of a percent pyrite can be sufficient to generate acid drainage). In some samples, although not in the western areas of the Endurance mine site, clay minerals were observed but their structure and composition were not identified. Clay minerals may be important for affecting water acidity and contributing or trapping aluminium, a potentially toxic element to aquatic life. Iron oxide coatings were observed on the quartz and opaque mineral grains, creating a typical reddish iron staining. Increased oxidation/iron staining is observed towards the western end of the tailings, presumably because they were the first tailings deposited and have therefore been exposed to atmospheric (oxidising) conditions for a longer time. Alternatively, or in addition, oxygen may be able to enter the tailings more readily, and/or there may be a higher concentration of sulphide minerals towards the western end of the tailings. Organic matter was observed at depth during installation of piezometers and probably represents the original land surface. The organic matter may be important in limiting groundwater flow between the tailings and the original ground as well as acting as a potential chemical reductant that may help in minimizing acid drainage.

The depth of the tailings is difficult to know accurately. The original surface was intersected in a few piezometers, at depths between 1.5 m and 3.7 m, but not in other piezometers installed at greater depths. Presumably the tailings thin downhill towards Ruby Lagoon and Ruby Creek.

The tailings sediment exhibits layers of coloured (iron staining) and non-coloured sediment (mm to cm scale), although the grainsize and most other characteristics are mostly homogeneous. Grain size measurements indicate mainly poorly sorted sediment with mean grainsizes of approximately 0.3 to 2.8mm. Porosity (n) ranges from 0.14 to 0.36 with an average of approximately 0.29 over 10 samples, at the low end of values typical of fine sand (n = 0.26-0.53). The infiltration capacity of the sediment was variable (36 mm/hr to 144 mm/hr) with an average of 97 mm/hr for 8 measurements. The average intensity of storm events in the Mt. Cameron region is approximately 18-20 mm/hr, less than the measured infiltration rates. The evidence of overland flow (stream gullies and coarse lag deposits on the surface of the tailings) suggest that either the measured infiltration rates are not representative of the whole tailings area, or more likely that storm events have higher rainfall rates than the infiltration rates.

The bulk chemistry of the sediment (measured on 10 samples) consists mainly of the major oxides SiO_2 (72-97 wt.%), Al_2O_3 (2-15 wt.%), K_2O (0.5-4 wt%), Na_2O (0-0.2 wt.%), Fe_2O_3 (0.2-2.3 wt.%) with traces (i.e., < approximately 300ppm) of many elements. Most elements are present in concentrations less than those recommended in the ANZECC draft guidelines for sediment quality, except for Al, Fe, Cr, Ni, Cu, Zn, Mo, Pb and U. These elements are the most likely ones to be at toxic levels in the ground water and receiving waterways, and indeed in some samples were in concentrations higher than the ANZECC (1992) recommended guidelines for drinking water.

2.3 Water composition and quality

Major, minor and some trace element concentrations were measured in ground and surface water samples taken at the Endurance Mine site. In some samples, element concentrations were higher than recommended in the ANZECC (1992) guidelines for livestock watering or the World Health Organisation's guidelines for drinking water (WHO, 1996).

All ground and surface water samples are acidic, with pH values below the recommended range of 6.5 to 9.0 for drinking water. Creeks around the Endurance mine site (e.g., Upper Ruby and Conundrum Creeks) upstream of any impact from the tailings (Figure 3.1 of de Jong, 1999) are naturally acidic (pH ~5-6) because of the presence of organic acids that result from the breakdown of organic matter. Groundwater samples from the tailings are more acidic, with pH values of 2.4 to approximately 5. Some groundwater samples have pH values up to 6.4 but these are from soil and sediment beneath the tailings and probably represent uncontaminated groundwater in the area. Surface waters that are impacted by acid drainage have pH values between 2.7 and 5.5. The impact of acid drainage is clear in Conundrum Creek and Ruby Lagoon where pH values drop from approximately 5 to less than 4 where ground water from the tailings enters the creek and lagoon (Figure 6.14 of de Jong, 1999). There are no obvious seasonal differences in the groundwater pH; however, surface waters tend to be more acidic in summer.

It is not clear from the measured water chemistry whether the ground and surface water was oxidised or reduced, an important factor in the generation of acid drainage and transport of many heavy metals. The measurements suggest that the waters are transitional between oxidized (equilibrium with the atmosphere) and reduced (typical of deeper groundwater). It is likely that the surface water in the creeks and Ruby Lagoon is oxidized and the groundwater in the tailings and bottom sediments of the lagoon less oxidized.

Electrical conductivity (EC) of the water samples indicates how much material (e.g., major elements such as Na, K, Ca, Mg, Fe, Cl and sulphate, and possibly metals) is dissolved. EC in the ground and surface waters in and around the Endurance site was highly variable. Groundwater samples had higher EC in general and showed no obvious seasonal differences. Surface water samples taken from Ruby Lagoon, Conundrum Creek and lower Ruby Creek, however, had EC values in summer twice that in spring. This corresponds to observed higher acid contents and increased concentrations of Fe, Al and probably other minor and trace elements.

Dissolved elements in the groundwater and surface waters are dominated by Fe, Al, Si and SO_4^{2-}, where in general their concentrations were higher in the groundwater than in the surface water. The Fe and SO_4^{2-} are a result of iron sulphide oxidation and dissolution and acid drainage, whereas Al and Si probably result from chemical reactions with clay minerals in the tailings and naturally occurring sediment. Both Fe and Al concentrations exceed the recommended limits for aquatic ecosystems. No obvious seasonal variations were observed for many elements, except potassium concentrations were slightly higher in summer and sodium concentrations were almost an order of magnitude lower in summer. Iron concentrations in ground and surface water are probably controlled by the precipitation and/or

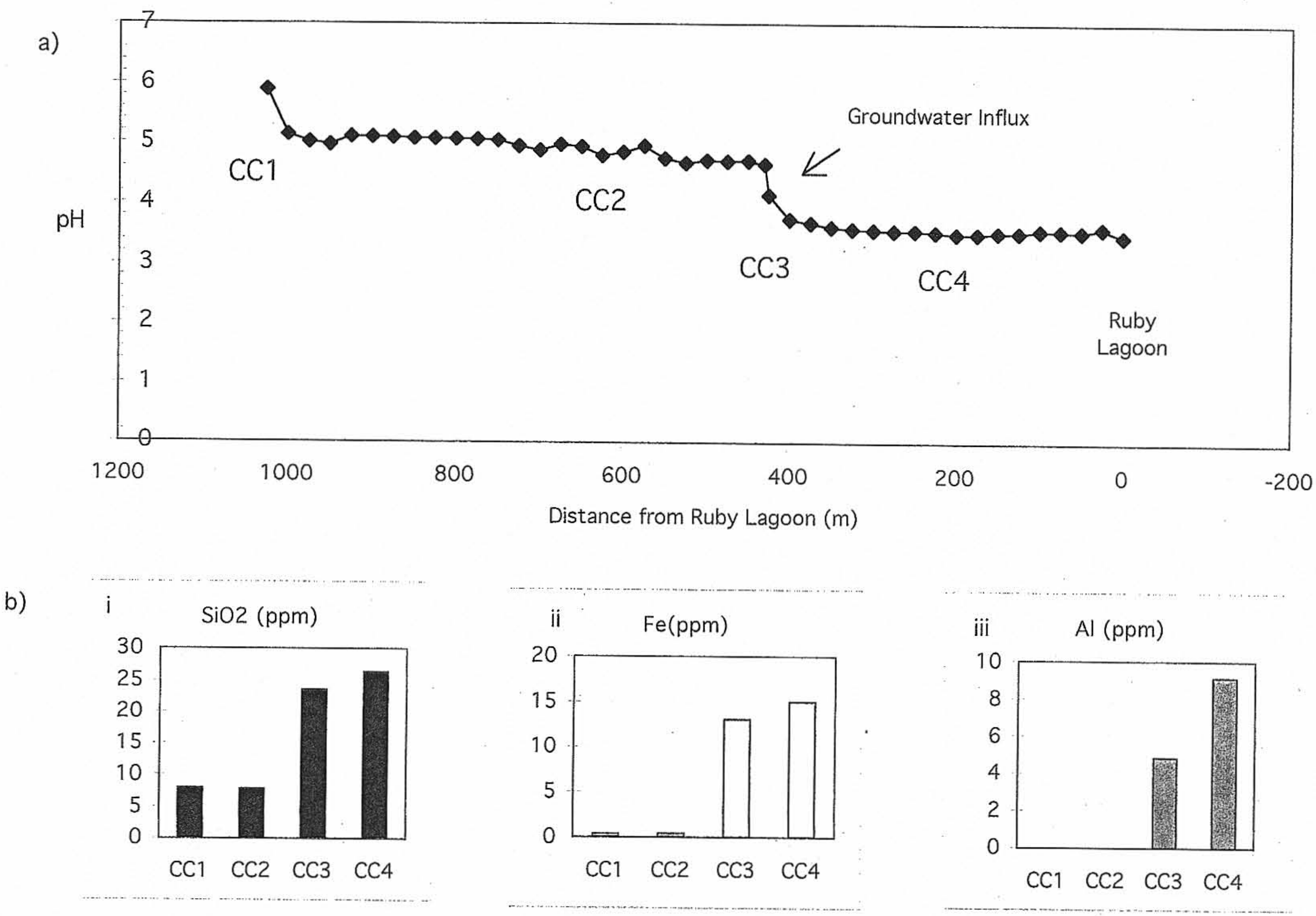

Figure 6.14 a) Changes in pH and b) i -iii major element concentrations down Conundrum Creek

dissolution of the observed iron oxyhydroxide minerals. Dissolved aluminium concentrations are probably controlled by the presence of kaolinite, amorphous aluminium hydroxide and aluminium sulphate minerals, although not all these minerals were observed in the sediments or tailings. Other elements that might pose potential environmental problems are Pb, Zn, Cu, Cr, Ni, Mo and U, although concentrations higher than recommended limits were detected in only a few groundwater samples.

2.4 Groundwater flow and discharge

In order to estimate groundwater flow rates and discharge, it is necessary to know the hydraulic conductivity of the tailings, the hydraulic gradients (change in hydraulic head (i.e., water levels in piezometers) over distance) and porosity. Measured porosity values are summarised above (i.e., average porosity of 0.29). Hydraulic conductivity values were calculated from rising head tests done in the field. The calculated values for the tailings range between 3×10^{-5} m/s and 5×10^{-4} m/s, which are typical of published values for silty to fine sand. Three measurements in the soil/sediment below the original land surface indicate much lower hydraulic conductivity values of between 2×10^{-8} m/s and 4×10^{-6} m/s. The contrast in hydraulic conductivity means that groundwater flow in the tailings will be largely parallel to the original ground surface. It probably also means that little contaminated groundwater from the tailings will flow into the original land surface underneath the tailings.

Groundwater flow directions and hydraulic gradients were determined from hydraulic head measurements in the piezometers. Contour maps of hydraulic head show that ground water flows downhill towards Ruby Lagoon and intersects Conundrum Creek along its course (Figure 5.3 of de Jong, 1999). Note that water flow is perpendicular to the contours in this case. Lower Ruby Creek also receives some groundwater discharge directly from the tailings. Shallower hydraulic gradients are evident in the western edge of the Endurance site, indicating slower groundwater flow and probably less groundwater volume entering Conundrum Creek. Average values of hydraulic gradient are approximately 0.021-0.025 m/m in the tailings between and to the east of the granite knolls and 0.008 m/m in the tailings to the west that drain into Conundrum Creek and the western end of Ruby Lagoon. Average gradients did not vary between spring and summer of 1999; however, close to Ruby Lagoon the gradients reversed direction during the summer season, indicating that at some times of the year, water from the lagoon may be recharging the tailings near the edge of the lagoon.

Groundwater discharge into Ruby Lagoon and Conundrum Creek from the tailings was estimated using the hydraulic conductivities, hydraulic gradients and estimated discharge areas. Total discharge into Ruby Lagoon from the tailings was estimated to be 20 m^3/day during spring 1999 and 19 m^3/day during summer 1999. It is possible that there is groundwater discharge from the south side of the lagoon, but based on the shallow slope there and the observed low hydraulic conductivity in soil/sediment underlying the tailings, it is likely that any discharge from the south would be at least 10 times less than that from the tailings.

Groundwater velocities were estimated from the estimated discharges and average measured porosity. The values ranged between 12 cm/day to 62cm/day. The travel time for groundwater along flow paths ranges between 66 m/yr and 458 m/yr, which correspond to residence times of groundwater in the tailings of up to 10 years or more over the whole length of the tailings between the Blue Lake and Ruby Lagoon. Note that water can infiltrate into the tailings anywhere along the flow paths, so the residence time for some packets of groundwater could be much less.

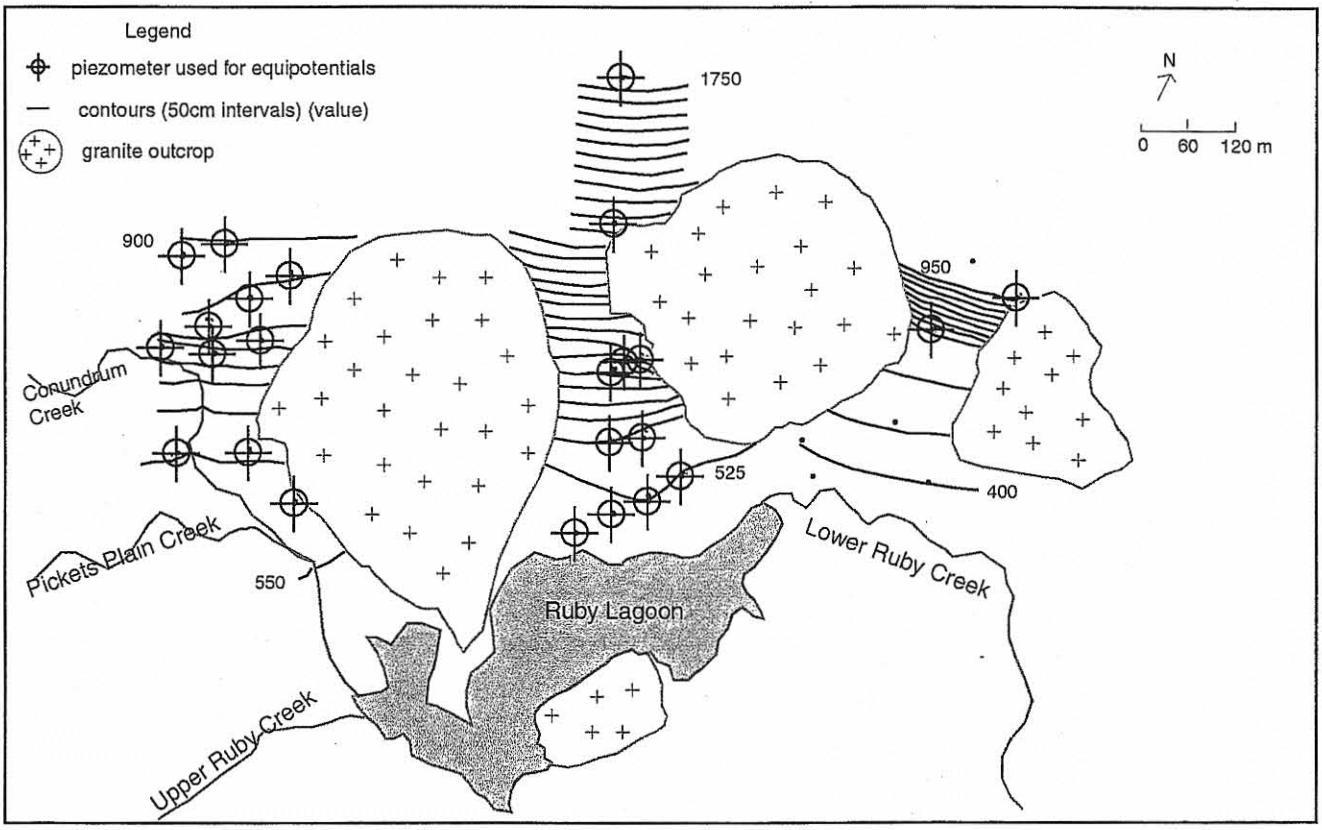

Figure 5.3a Hydrogeology of the Endurance mine tailings: equipotentials for spring

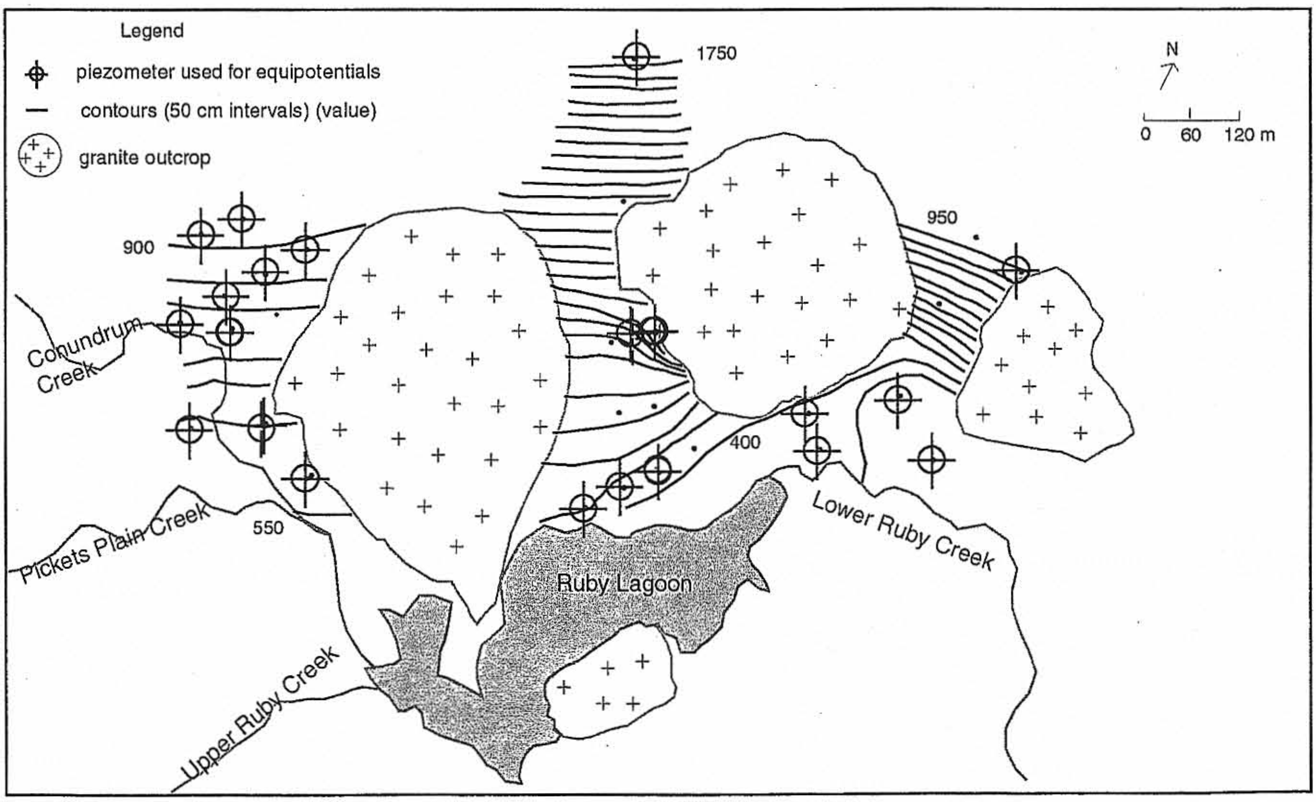

Figure 5.3b Hydrogeology of the Endurance mine tailings: equipotentials for summer

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2.5 Impact of groundwater contamination on surface waters

The impact of groundwater on Conundrum Creek, Ruby Lagoon and Lower Ruby Creek was estimated by calculating the volume balances of water (hydrologic budget) and chemical elements/compounds (mass loadings and budgets) into and out of Ruby Lagoon. The hydrologic budget of Ruby Lagoon is dominated by inflow and outflow of creeks, with a small component of groundwater input. However, because of the high acid and element concentrations in the tailings groundwater the mass loadings have a significant adverse impact on water quality in the creeks and the lagoon.

The hydrologic budgets were calculated based on measurements made in short timeframes (e.g., days) and there is no available information about rainfall events and transpiration of plants. There is good evidence that there is overland flow on the tailings (i.e., gullies and coarse lag deposits), but it cannot be quantified with available information. It is unknown how much variability there is in the flow volumes in the estimated hydrologic budget, although at least we have information for the spring and summer of 1999. In the spring of 1999, water input to Ruby Lagoon was 1227 m3/day from Conundrum Creek, 1236 m^3/day from Upper Ruby Creek and 20 m^3/day from tailings groundwater. Output was 217 m^3/day by evaporation and 2359 m^3/day to Lower Ruby Creek (Figure 7.1a; de Jong, 1999). Based on these estimates, there was a *net loss* of 95 m^3/day from Ruby Lagoon (corresponds to 2-3mm/day drop in water level for the approximate area of 40,000 m^2 for Ruby Lagoon,). During the summer of 1999, the water input into Ruby Lagoon consisted of 1633 m^3/day from Conundrum Creek, 1236 m^3/day from Upper Ruby Creek and 22 m^3/day from the tailings groundwater. Water output during summer consists of 352 m^3/day by evaporation, 1849 m^3/day to Lower Ruby Creek and 2 m^3/day to groundwater (Fig. 7.1b; de Jong, 1999). This leads to an estimated *net gain* to Ruby Lagoon of 683 m^3/day (i.e., ~17mm/day rise in water level). Note that these estimates are based on measurements from short-term studies (e.g., several days) and may not represent medium- to long-term (e.g., weeks, months or longer) losses or gains to Ruby Lagoon. They may indicate that the water levels in Ruby Lagoon change significantly (e.g., 10s of centimetres) on a weekly basis, something that may be important on developing strategies of diverting water around the lagoon.

Mass loadings and balances of elements were calculated based on estimated volumes and discharges of ground and surface water and measured element and acid concentrations. Most of the contaminating or potentially elements enter Ruby Lagoon from Conundrum Creek, although ultimately they result from the acid drainage carried in groundwater from the western edge of the tailings. The main contributions of SiO_2, Al, Fe Pb and Zn to Ruby Lagoon are from the acidic groundwater, through Conundrum Creek, with lesser amounts directly from the tailings. Acid loading to Ruby Lagoon consists of approximately equal amounts from Conundrum Creek and the tailings directly. Preliminary estimates indicate that Ruby Lagoon is a sink for Fe (consistent with observations of iron oxide precipitate in the bottom sediment) and a source of acid to Lower Ruby Creek. Acid could be produced in Ruby Lagoon if iron is oxidizing and precipitating in the lagoon.

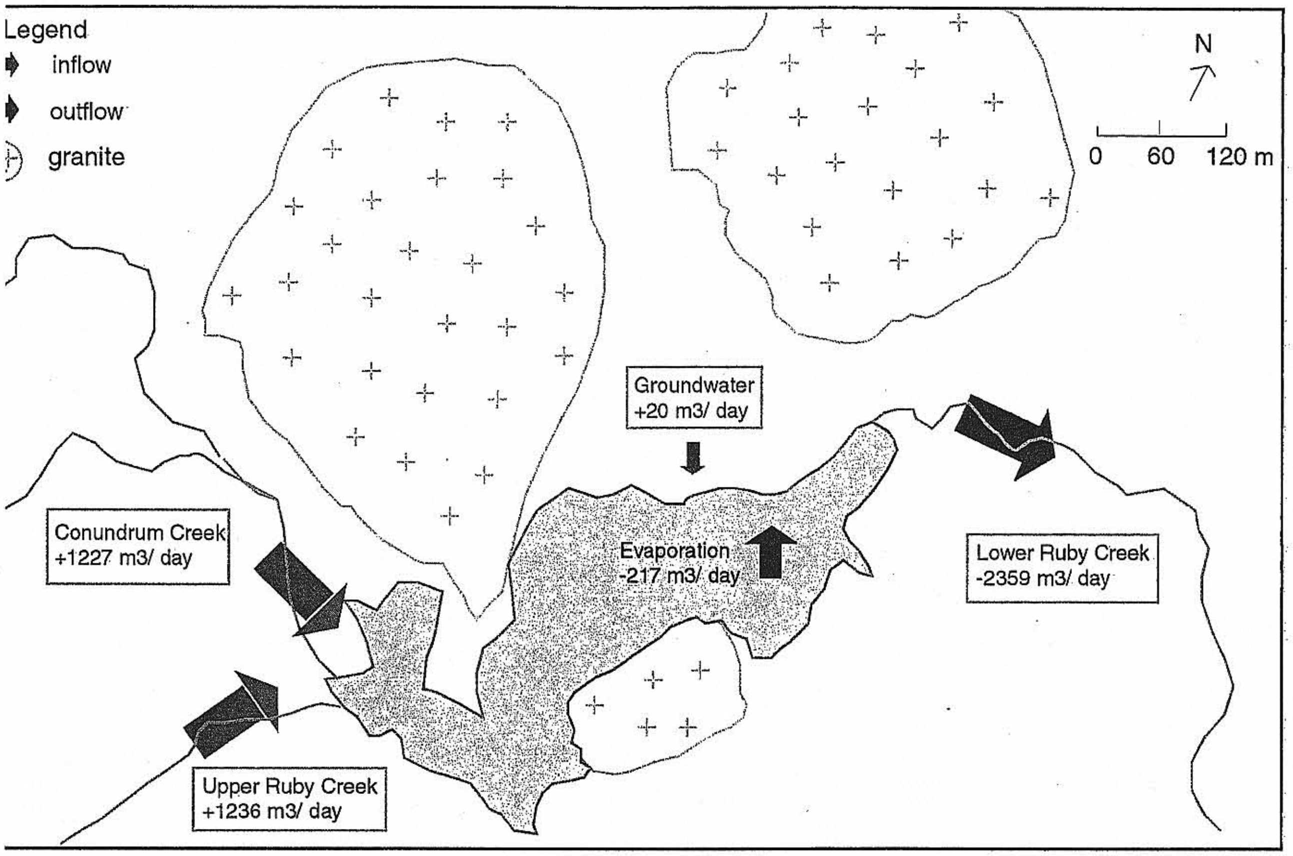

Figure 7.1a Hydrologic balance of Ruby Lagoon, Endurance mine (spring)

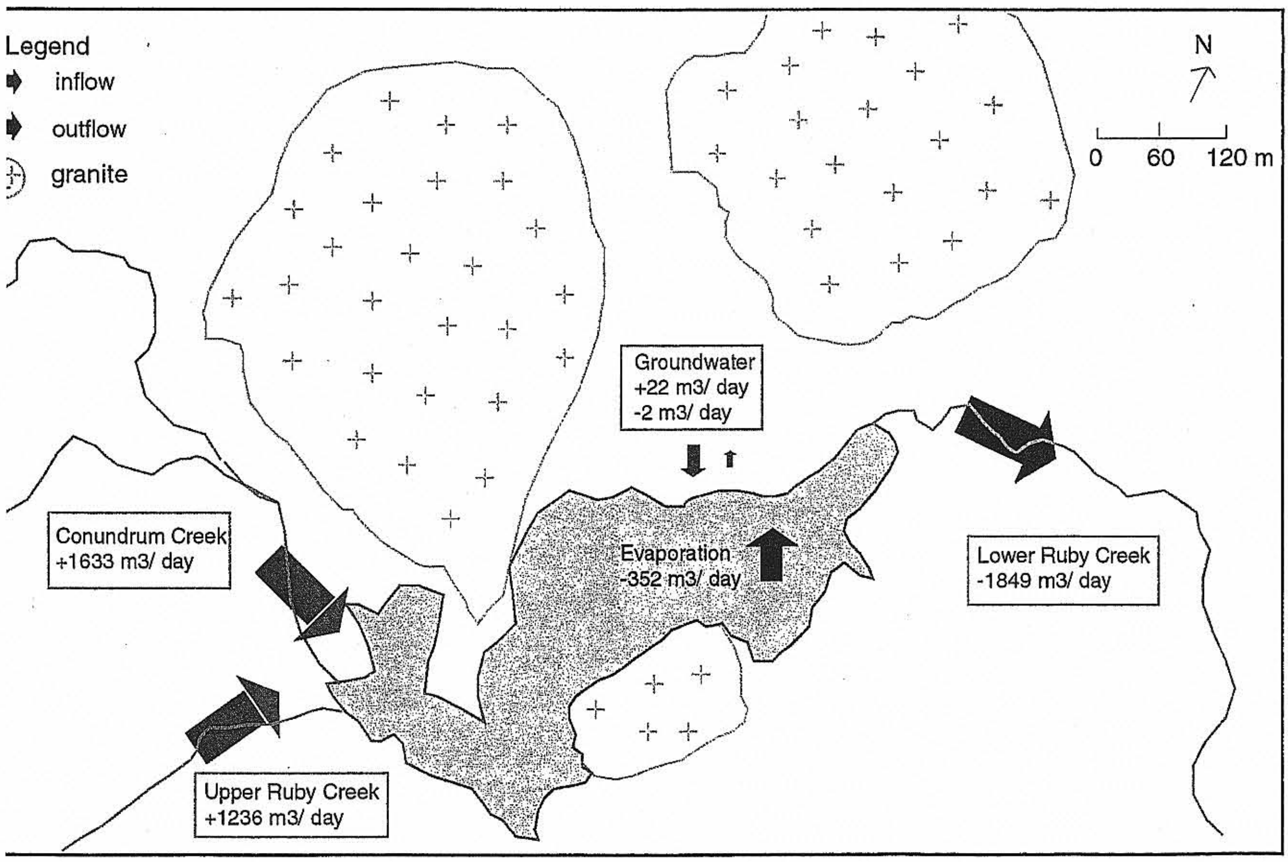

Figure 7.1b Hydrologic balance of Ruby Lagoon, Endurance mine (summer)

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3 Review of Rachael Bennett's Honours Research

This study focussed on characterising the vegetation and physical and geochemical properties of tailings sediment and groundwater on three historic mine sites in Northeastern Tasmania: Endurance, Monarch and Star Hill. These sites were chosen from a priority list established by Mineral Resources Tasmania. The principal aim was to provide data and information that will help in designing effective revegetation strategies to help in the rehabilitation of tin mine sites in Northeastern Tasmania. More specifically the aims were to:

- Measure the plant cover and identify different plant species on the mine sites and surrounding areas
- Characterise the physical and chemical properties (e.g., porosity, infiltration rates, chemical composition) of the mine tailings sediment and soils
- Understand the physical and chemical conditions that may prevent or enhance plant growth on the mine sites and tailings areas
- Make recommendations on revegetation and rehabilitation strategies

3.1 Methodology

There were two field seasons for this project: February 1999 and April/May 1999. The three mine sites (Endurance, Monarch and Star Hill) were mapped to record the general types and areas of sediment and vegetation (i.e., plant cover, dominant plant species and areas of revegetation, tailings, mined and overburden). See Figures 3.1a, b and c from Bennett (1999).

Three locations at each mine site were chosen for detailed measurements of vegetation, soils, groundwater and surface water. The locations were selected to study areas within each site that represent different "environmental zones" (see Table 3.1 of Bennett, 1999). In addition, a site between the mine sites was chosen to characterise the vegetation and soil characteristics of an established (i.e., natural) area.

Plant species were identified and percentage plant cover (both individual species and total) was estimated quantitatively in sampling domains known as quadrats. For each of the three locations on each mine site, three quadrats were measured. Quadrat size varied between locations and sites and was chosen by doubling an initial small size until no additional species were identified between one size and the next (range in area was 2-20m^2). Plant health was inferred from observations of abnormal leaf colouring (e.g., chlorosis), abnormal plant shape and necrosis.

Sediment and soil were analysed for soil strength, porosity and infiltration rates in the field and moisture content and grainsize in the laboratory. Mineralogy and textures were determined by thin section/petrographic analysis in 11 samples that were considered representative. Many chemical properties of sediment grab samples were analysed:

- **Soil electrical conductivity and soil pH** (slurries of 1:1 sediment to water ratios) were measured in the field;
- **Bulk element concentrations** (major, minor and many trace elements) were measured using X-ray Fluorescence (XRF);
- **Extractable and "bioavailable" major, minor and trace element** (Na, K, Ca, Mg, Mn, Fe, Al, Si, Pb, Zn, Cu, Cd, Co, Cr, Sn, Ni and Mo) concentrations were measured using both ammonium acetate and HCl (0.5 molar) extractions (1:25 weight ratio of sediment to extractant);

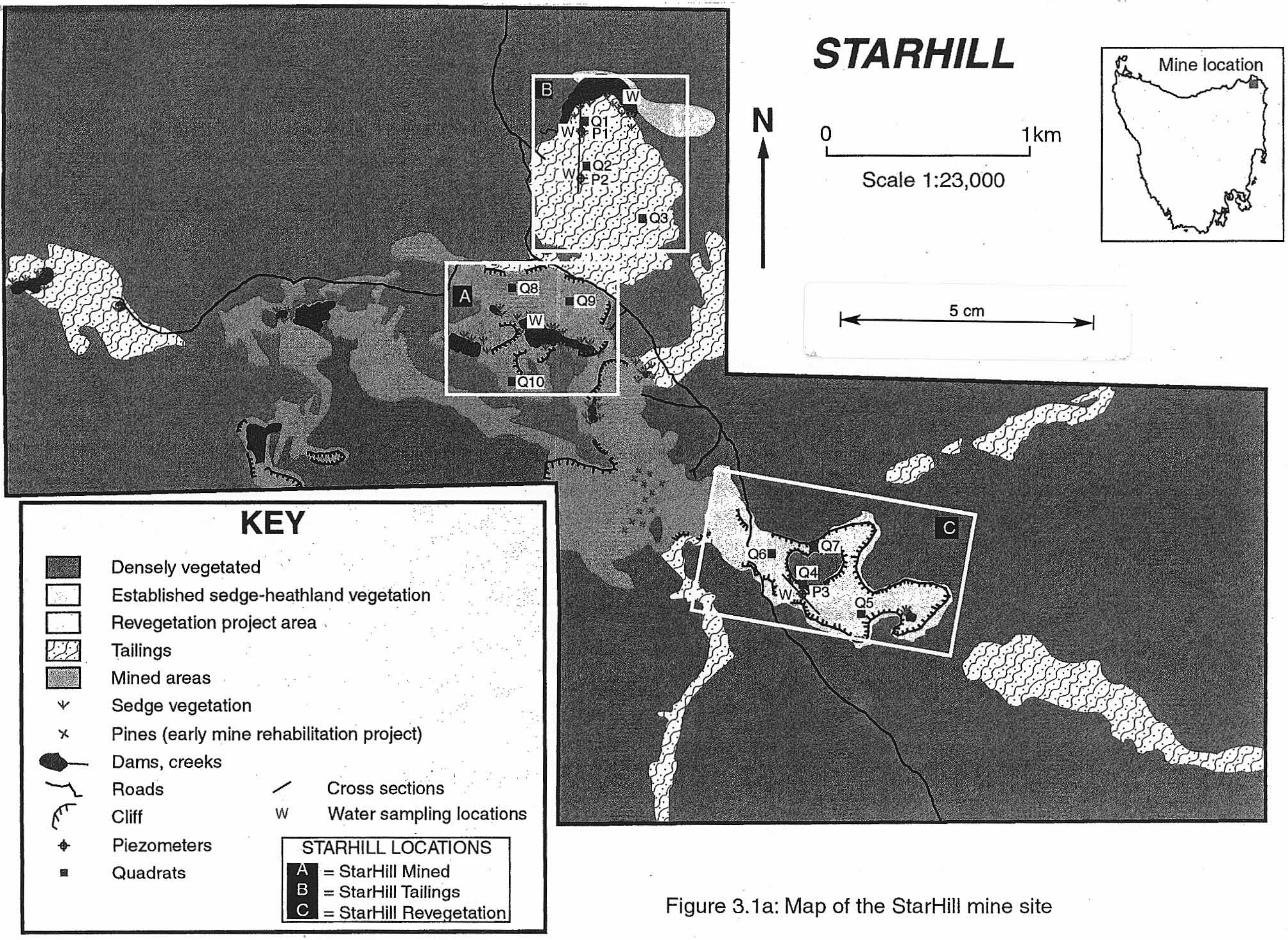

Figure 3.1a: Map of the StarHill mine site

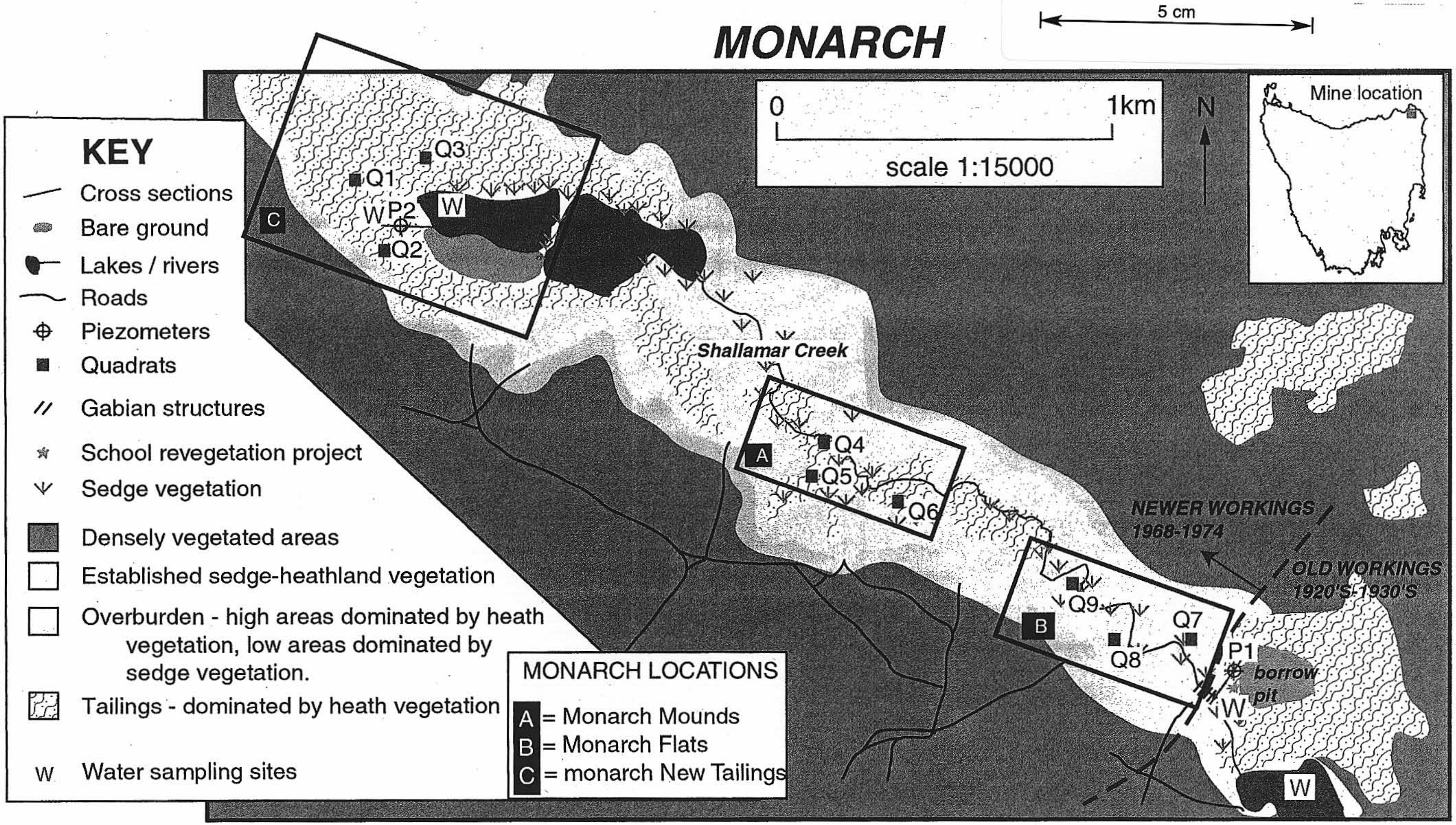

Figure 3.1b: Map of the Monarch Mine

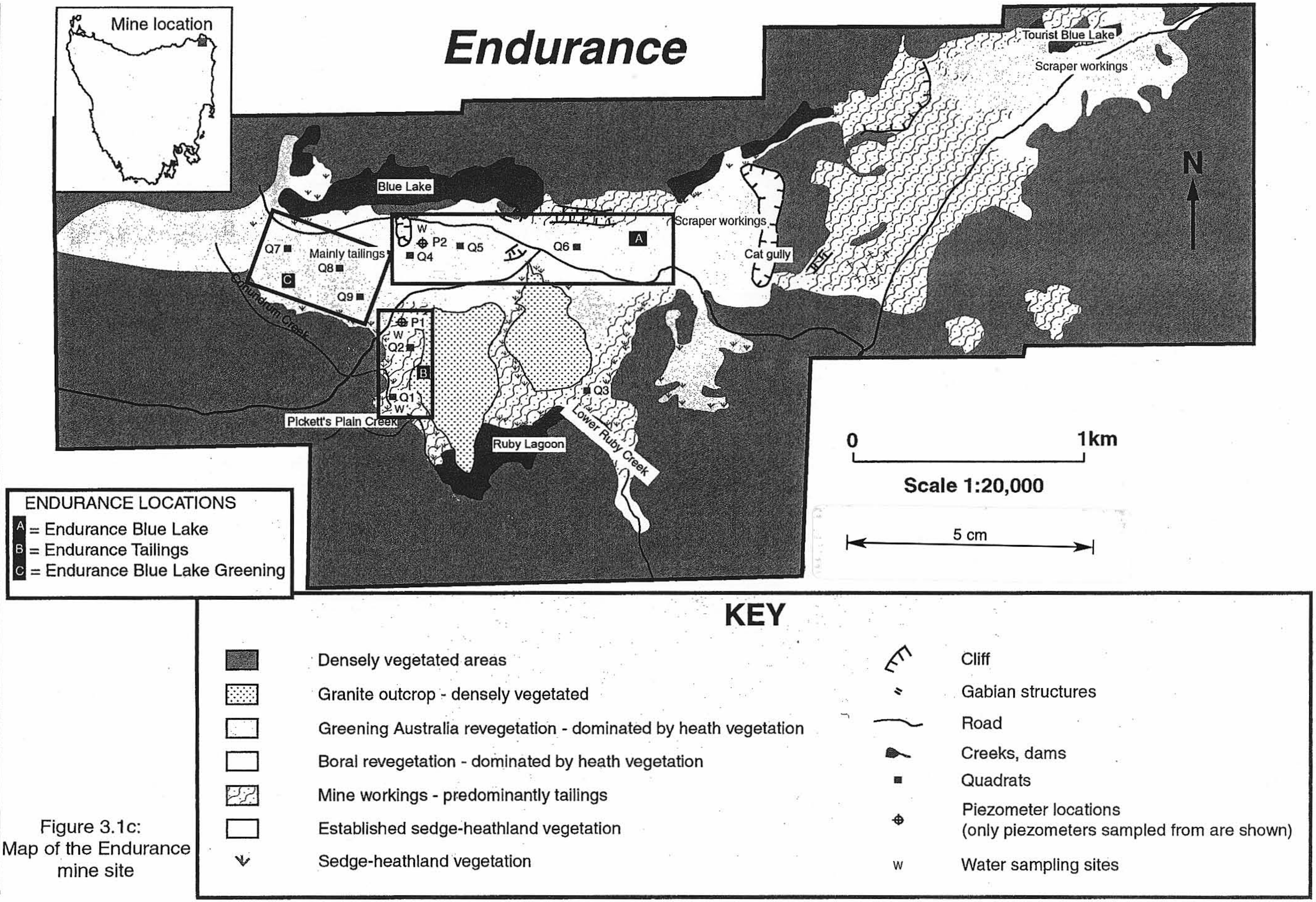

Figure 3.1c:
Map of the Endurance
mine site

Table 3.1: Chosen study locations within each mine and established site and their abbreviations (after Bennett, 1999)

MINE / ESTABLISHED SITE	CHOSEN STUDY LOCATIONS	ABBREVIATION
Monarch	Monarch New Tailings	MNT
	Monarch Flats	MF
	Monarch Mounds	MM
StarHill	StarHill Tailings	SHT
	StarHill Revegetation	SHR
	StarHill Mined	SHM
Endurance	Endurance Tailings	ET
	Endurance Blue Lake	EBL
	Endurance Blue Lake Greening	EBLG
Established	Established Forest	EF
	Established Grass	EG

- **Exchangeable bases** (Na, K, Mg and Ca) and Al (included in the analyses for extractable/bioavailable concentrations) for understanding nutrient availability;
- **Cation exchange capacity** (CEC) was measured by treating samples with NaCl (1 molar), followed by rinsing and treating with KCl, and measuring concentrations of Na in the KCl solutions;
- **Carbon, hydrogen, nitrogen** (LECO analyser) and soluble reactive phosphorous were measured on selected samples.

Surface and groundwater (3 piezometers at Star Hill, 2 piezometers at Monarch, Endurance from de Jong's study) samples were analysed for temperature, pH, Eh, EC in the field and major, minor and some trace elements in the laboratory (Na, K, Ca, Mg, Mn, Fe, Al, Si, Pb, Zn, Cu, Cd, Co, Mo and Sn).

3.2 Vegetation characteristics

Vegetation in the region consists of sclerophyll forests and sedge-heathland communities. The latter are typically found in lower areas that are usually wetter than the surrounding areas. Eucalyptus trees dominate higher (i.e., forested) areas, with the main species being *Eucalyptus amygdalina* (common name: Black Peppermint), common in areas with low-fertility soils. Other eucaplypt species in the Gladstone region are *E. pulchella, E. sieberi* (Silver Top), *E. obliqua* (Messmate), *E. viminalis* (Manna Gum), *E. pauciflora* (Snow Gum) and *E. ovata* (Swamp Gum). Understory shrubs consist mainly of *Banksia marginata* (Silver Banksia), *Acacia mucronata* (Narrow Leaf Wattle), *Allocasurina stricta* (Sheoke), *Persoonia juniperina* (Prickly Geebung) and many species of the epacridaceae family (evergreen shrubs).

3.2.1 Established site

The common species and their average percentage cover on the established site are listed in the following table (taken from Bennett, 1999).

TABLE: Common plant species and their percentage cover on an established (natural) site in the Gladstone region, northeastern Tasmania.

Sedge-heathland	**Forest**
family cyperaceae (sedges; 40%)	*E. amygdalina* (Black Peppermint; 23%)
Gleichenia microphylla (Scrambling Coral-fern; 22%)	*Pterridium esculentum* (bracken/fern; 23%)
Restio complantis (Flat Cord-rush; 3%)	Family cyperaceae (11%)
Empodisma minus (Spreading Rope-rush; 2%)	*E. viminalis* (10%)
Leptospermum scoparium (2%)	*Leptospermum scoparium* (Manuka; 8%)
	Banksia marginata (Silver Banksia; 7%)
	Melaleuca squarosa (5%)
	E. obliqua (Messmate; 3%)
	Epacris impressa (2%)

3.2.2 Mine sites

The most striking difference between established sites and the mine sites/tailings areas is that the mine sites and tailings areas have much less plant cover (see below). In addition, there is no canopy at the mine sites, mainly because eucalypt trees are too young. Patches of vegetation are evident on the mine and tailings areas, and show a higher abundance of species in wetter areas.

3.2.2.1 Endurance

The three locations on the Endurance site were: i) the tailings at the southwestern end of the mine site, ii) the revegetated tailings of Boral south of Blue Lake and iii) the revegetated tailings of Greening Australia on the western-most end of the whole mine site (Figure 3.1c of Bennett, 1999). On all locations, the most common cover plants are *Banksia marginata* (Silver Banksia), *Acacia mucronata* (Narrow-leaf Wattle), *Kunzia ambigua* (White Kunzia) and *Allocasurina monilfera* (Sheoke), although the coverage is low. There are differences in the dominant species between the three locations. The predominance of *Acacia mucronata* (Narrow-leaf Wattle) at the two revegetated locations is probably a result of the revegetation projects, as it does not occur in areas where there is no known revegetation. It does, however, occur in the Gladstone region as an understory shrub. "Edge effects", i.e., proximity of tailings areas to natural densely vegetated areas, probably influence the establishment of plant species, e.g., *E. amygdalina* (Black Peppermint) is more common near the edges of tailings areas in places where there are no known revegetation projects.

3.2.2.2 Star Hill

The three locations on the Star Hill site were: i) tailings, ii) a mined area and iii) an area revegetated in 1998 by Scientists, Engineers, Managers and Facilitators (SEMF). On the tailings area, the most common cover plant species are *Allocasurina monilifera* (Sheoke) and *Kunzia ambigua* (White Kunzia), whereas on the mined area the most common plant species are *Kunzia ambigua* and *Gahnia grandis* (sedge). Less common cover species on the tailings area are *Banksia Marginata* (Silver Banksia) and *Lepidospermum concavum* (Sand-hill Sword Sedge) on the mined area they are *Allocasurina monilifera, B. Marginata, Restio complantis* and *Epacris impressa.* The revegetation project is on a mined area and the most common plant species are *Kunzia ambigua, Allocasurina monilifera, Acacia terminalis, Eucalyptus seeberi, E. amygdalina* with lesser common species being *Banksia marginata, E. pauciflora, Leptospermum scoparium* and *Acacia mucronata.* The plant species and increased diversity of species in the revegetated area reflect the seed mix used in the revegetation project, although it may be that some plants result from natural processes.

3.2.2.3 Monarch

At the Monarch site, most of the vegetation on the tailings and mined areas has regenerated naturally, except for a small revegetation project by a local high school. All studied areas are on tailings, where the western-most area is on the most recent tailings and the other two areas are on relatively flat and mounded topography, respectively. Compared to the other mine sites, there is a higher percentage of cover at Monarch, especially in the mounded area towards the eastern end of the mine site (Figure 3.1b of Bennett, 1999). The most common plant species in the most recent tailings area are acacias (5 species), *Banksia marginata* and *Eucalyptus amygdalina*, whereas in the flat and mounded areas the most common species are *Kunzia ambigua, Gahnia grandis, Leptospermum scoparium, Allocasurina monilifera* and

Banksia marginata. There is a higher number of plant species in the most recent tailings, including acacia species that are much more common than at other areas at Monarch as well as the other two mine sites. The common occurrence of acacia species at Monarch is puzzling because they are not common in the surrounding natural vegetation.

3.2.3 Plant Cover

Plant cover is much lower on the mined areas and tailings compared to the established areas (90-100% cover). The percentage cover at the Endurance site was approximately 30% in the area revegetated by Boral, but less than 20% in the area revegetated by Greening Australia and the tailings area. The cover at Star Hill was less than 10% on the three areas studied, including the recently revegetated area. The Monarch site had a higher percentage cover, especially in the mounded area (~40%) and more recent tailings area (~30%).

There are many factors that can influence the magnitude of plant cover. The principal ones include time since last disturbance, size of the disturbed area and the success of new seedlings. The time since last disturbance is not known accurately for most of the areas within the mine sites, especially since the deposits were mined in an irregular pattern. Monarch has had more time to recover than either Star Hill or Endurance. Mining stopped at Monarch in the 1930s and restarted for approximately 6 years between 1968 and 1974, whereas at Endurance and Star Hill it ceased around 1982. Size may also be a factor as Monarch has the smallest disturbed area and has the greatest cover (~25%), compared with Star Hill (~5%) and Endurance (~19%).

3.2.4 Other vegetation characteristics

The success of new seedlings depends on many physical and chemical factors, such as animal predation (e.g., grazing) and disturbance (e.g., off-road biking and driving), wind erosion and water erosion, in addition to nutrient availability and element toxicity. Grazing was observed during the fieldwork of these studies and there is ample evidence of off-road driving. Increased plant growth is evident to the leeward side of plants or mounds. In addition, litter cover was more evident in sheltered areas of the mine sites (litter is important for water retention, nutrients and habitat for microorganisms). Water erosion of seeds and sediment was not directly observed but the coarse lag deposits on the tailings at Endurance and Star Hill indicates that it is likely to be a problem on slopes.

One of the most interesting, and potentially critical, results of this study is that biodiversity was almost the same on mined and established sites. Biodiversity is important in influencing the productivity and resilience of an ecosystem and is estimated by species richness (number of species present) and species diversity (calculated value between 0 and 1 based on the number and proportion of species – 0 is no diversity and 1 is highest diversity). Species richness is similar on all three mine sites and the established sites, except it was lower on the Star Hill tailings area and higher on the Monarch new tailings area (Figure 4.9a of Bennett, 1999). Species diversity shows a similar pattern (Fig. 4.9b of Bennett, 1999). Biodiversity and cover appear to be greater in areas close to natural dense vegetation, e.g., "edge effects" mentioned above, although this could not be determined unequivocally in this study.

Statistical differences between plant species and their abundances on different locations and sites may be useful in designing effective remediation/revegetation strategies. Statistical analysis of the plant species and abundances showed that although many species are common

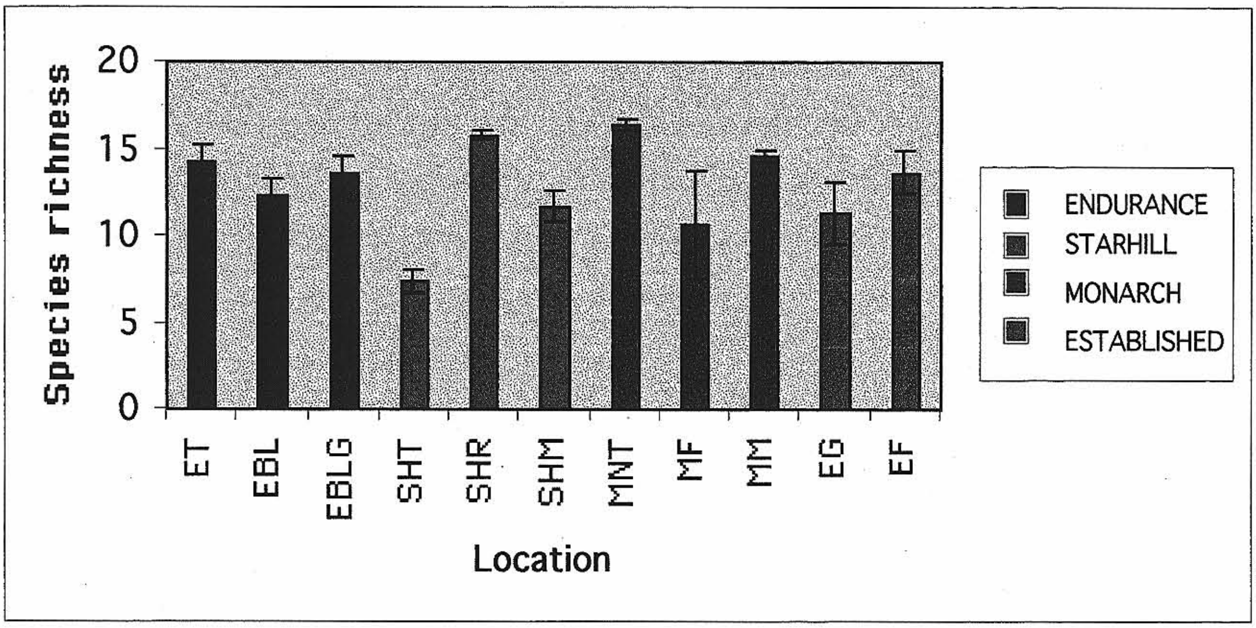

Figure 4.9a

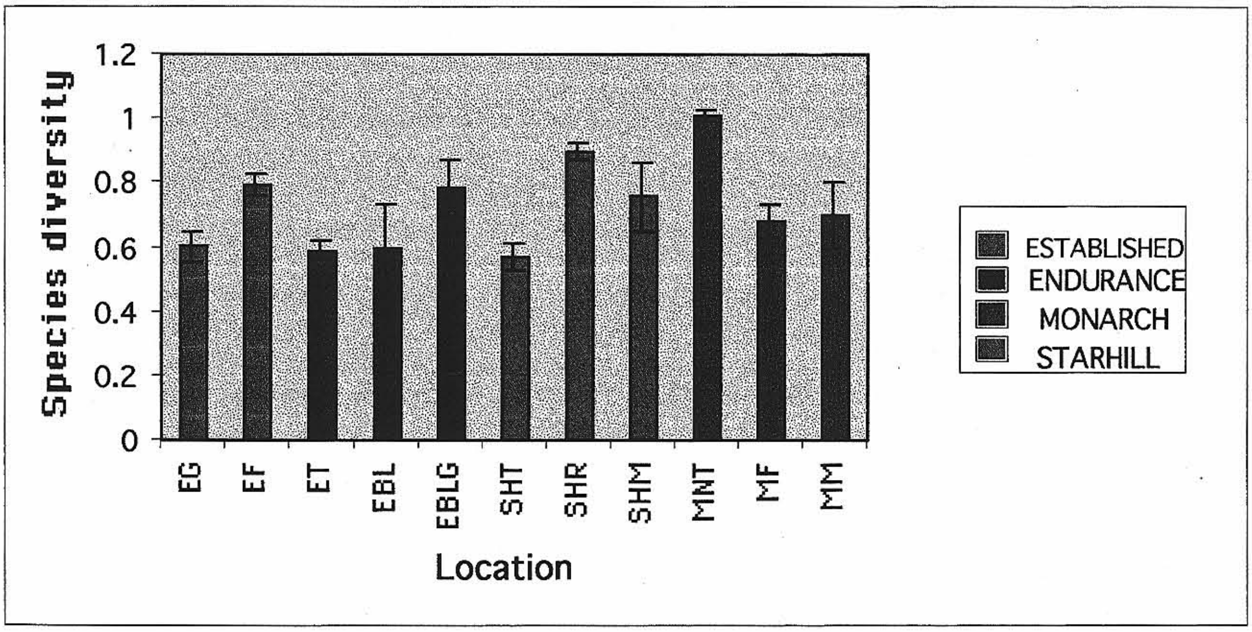

Figure 4.9b

Figure 4.9ab: Average species richness (Figure 4.9a) and species diversity (Figure 4.9b) within each location at the established, Endurance, StarHill and Monarch sites. Abbreviations for locations are outlined in Chapter 3.

to all mine and established sites, the different abundances of particular species lead to statistical dissimilarities between sites. The species that contribute to the dissimilarities are *Gleichenia microphylla, Pterridium esculentum, Eucalyptus amygdalina* and the cyperaceae species. The differences/dissimilarities may be a result of several factors, e.g., conditions are unsuitable for some species in some areas, some species have low dispersal characteristics and possible successional processes were not complete.

3.3 Sediment Characteristics

Many physical and chemical characteristics of the soils and sediments were measured on samples from the mine and established sites. A brief summary is provided here.

3.3.1 Physical characteristics

- **Soil development:** Little or no soil is evident on the tailings or mined areas. The mined areas were stripped of soil and there has not been enough time for soil profiles to develop.
- **Texture:** The mined areas and tailings consist mainly of sands and gravels (some loamy texture), with small percentages of clay (typically less than 5 vol.% but up to 25 vol.% in some cases) compared with sandy loam or loamy sand with 10-20 vol.% clay content in the established sites.
- **Composition:** The sediment consists mainly of quartz (70-95 vol.%) in the tailings and sediment, in contrast with 50-60 vol.% at the established sites. Organic matter contributed up to 30-50 vol.% of the soil at the established sites, but much less in the mined or tailings areas.
- **Iron pan:** observed at Endurance at a depth of approximately 25cm and at Star Hill at depths of approximately 60 cm and 108 cm. No iron pan was observed at Monarch. Most roots do not penetrate the iron pan, probably because of its hardness; however, chemical analysis showed elevated levels of some elements (V, Cr, Pb and As) so it is possible that the iron pan may be chemically toxic to some plants.
- **Soil structure:** apedal at the mine sites and weakly pedal at the established sites.
- **Soil strength:** variable within and between mine sites and no correlation was found with successful plant growth.
- **Porosity:** Soil/sediment porosity ranges between 22% and 31% at the mine sites and between 57% and 77% at the established sites. The contrast is likely a result of finer grainsize and higher organic content in the soils at the established sites, although the high values at the established sites may be over estimated due to the measurement technique. Porosity affects water infiltration and storage capacity indirectly.
- **Infiltration rates:** vary within and between sites (Figure 5.3 of Bennett, 1999). There was no obvious correlation although the infiltration rates were lower at Star Hill compared to the other mine sites.
- **Moisture contents:** variable but in general were higher at the established sites. This is likely due to the higher content of organic matter and a corresponding increase in the capacity for water retention. The lack of vegetation and animals (e.g., insects and burrowing organisms) on the mine sites adversely affects revegetation by limiting water retention capacity, decomposition of organic matter and nutrient cycling.
- **Erosion:** higher at the mine sites because of the lack of vegetation. Large and small gullies at the mine sites indicate significant erosion in response to rainfall/storm events and sheet erosion is evident from the coarse lag deposits on the surface of tailings, in particular at the Star Hill and Endurance mine sites. Wind erosion is evident at all

mine sites. Revegetation can be limited by both water and wind erosion as seeds and seedlings can be washed or blown away.

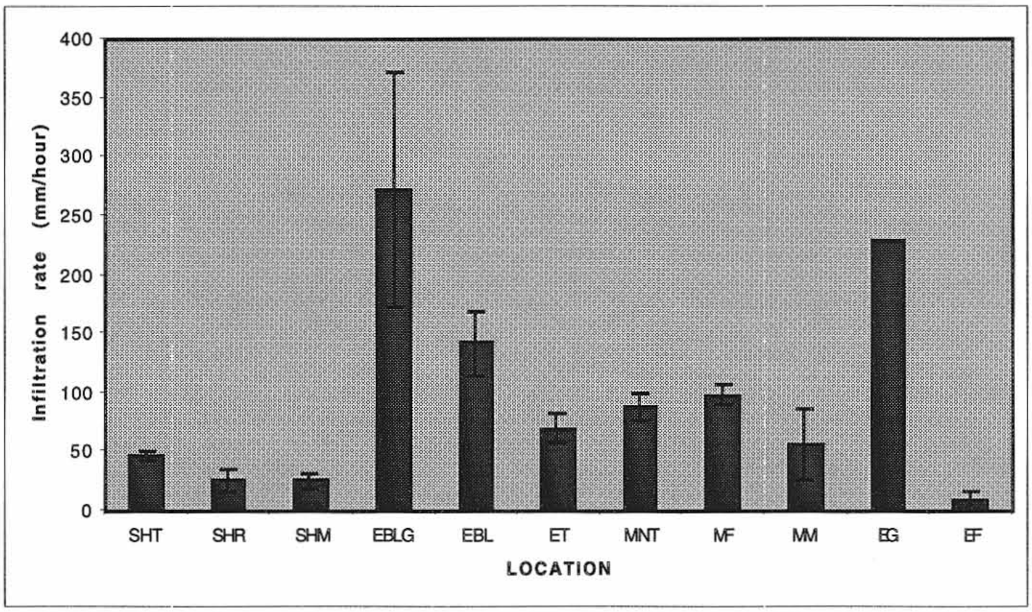

Figure 5.3 Average infiltration rates measured within the Endurance, Monarch, Star Hill and established sites (Bennett, 1999). Location abbreviations are in Table 3.1 above.

3.3.2 Chemical characteristics

The chemistry of soils and sediments affects plant growth. There are 17 known nutrients relevant to plants (9 macronutrients and 8 micronutrients) and different plants have different nutritional requirements. It was beyond the scope of Bennett's (1999) study to determine if the nutrients were limiting plant growth; however, comparisons between mined and established sites may indicate potential problems.

3.3.2.1 Macronutrients

Concentrations of most of the macronutrients (H, C, O, N, P, K, Ca, Mg and S) in the sediment of the mine sites are low and some may be too low for adequate plant growth. Sulphur was not measured because in general it is rarely deficient in plants.

- **Hydrogen, carbon and oxygen** are in general rarely in limited supply; however, H and C (organic) are in much lower concentrations in the sediments of the mine site compared with the established sites (Figure 6.2 of Bennett, 1999). There was a positive correlation between C + H and plant cover, either suggesting they are limiting nutrients or that the increased plant cover resulted from other factors and provided increased C + H to the sediment.

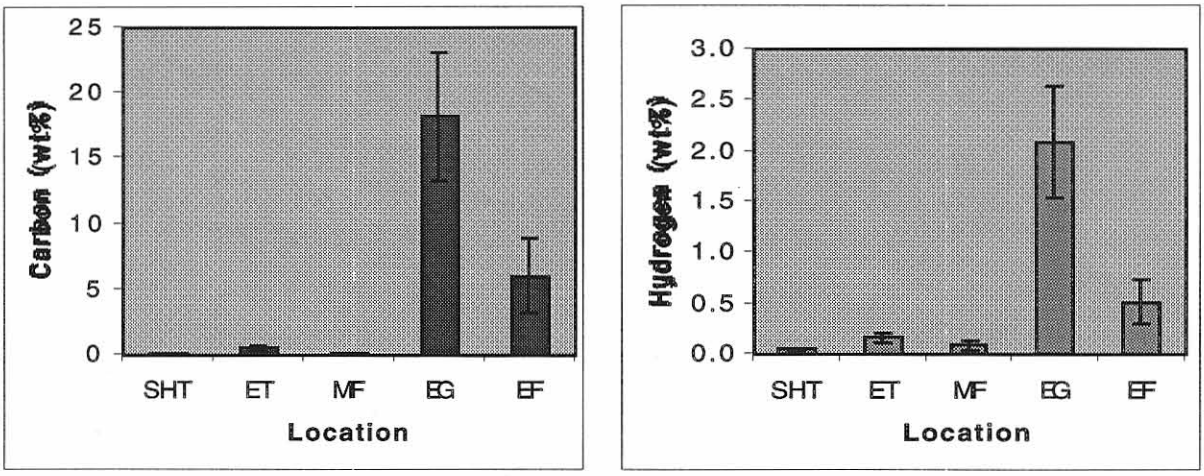

Figure 6.2: Average total carbon and hydrogen (wt% of sample) in surface sediments at selected locations within the StarHill, Monarch, Endurance and established sites; SHT, ET, MF, EG and EF (after Bennett, 1999).

- **Nitrogen** concentrations in the tailings were below detection limit (0.01%), and far lower than in the established areas (Fig 6.3 of Bennett, 1999), indicating that nitrogen is also limiting plant growth. Note that most plants rely on microorganisms to convert nitrogen into bioavailable nitrate or ammonia, and the environment in the sediments is unlikely to promote bacterial growth.

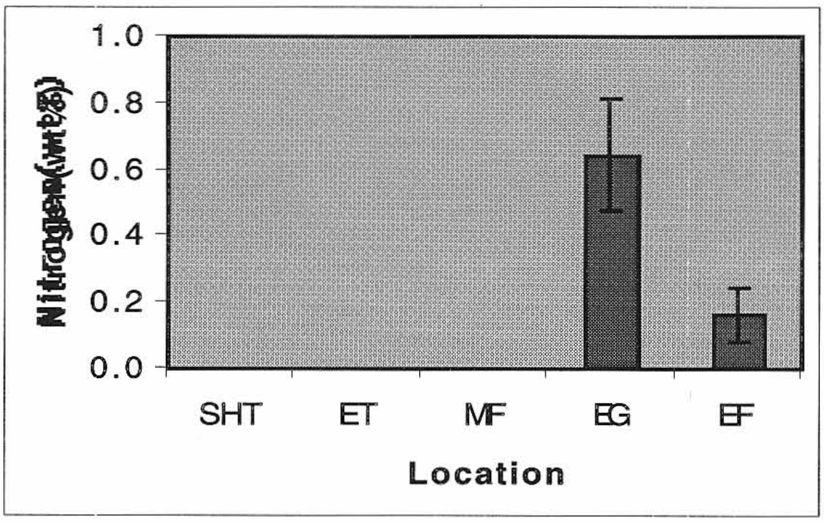

Figure 6.3: Average total organic nitrogen (wt% of sample) in surface sediments at selected sites. Note: Concentrations of nitrogen at the mine locations (SHT, ET and MF) were below the detection limit of 0.01wt% (after Bennett, 1999)

- **Phosphorous** concentrations in the tailings sediments were also low (mostly below typical soil concentrations) and for the most part lower than in the soils of the established area (Figure 6.4 of Bennett, 1999).

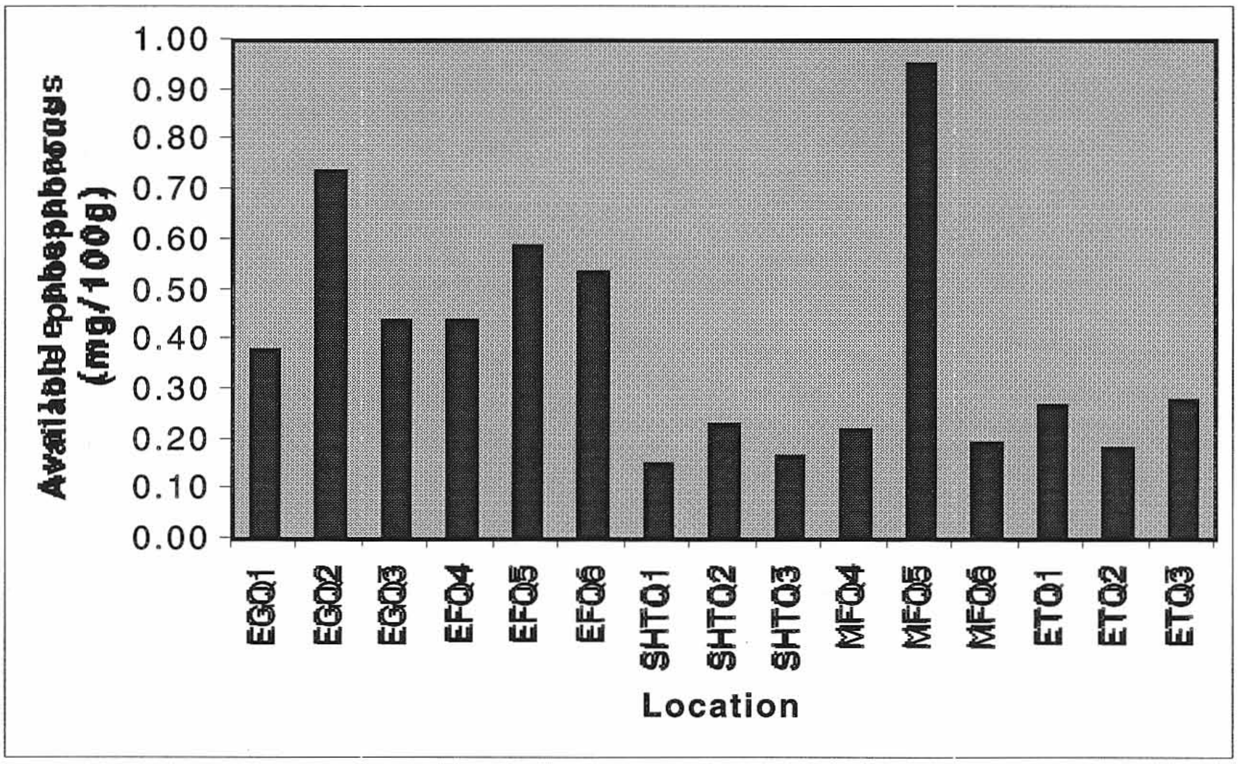

Figure 6.4: Available P (mg/100g) in surface sediment samples at selected locations within the Endurance (ET), Monarch (MF), StarHill (SHT) and established (EG & EF) sites (after Bennett, 1999)

- **Potassium, calcium and magnesium** concentrations were measured as exchangeable bases (K^+, Ca^{2+} and Mg^{2+}) extracted from the sediment. All are in low concentrations compared with the established sites (Figure 6.5 of Bennett, 1999).

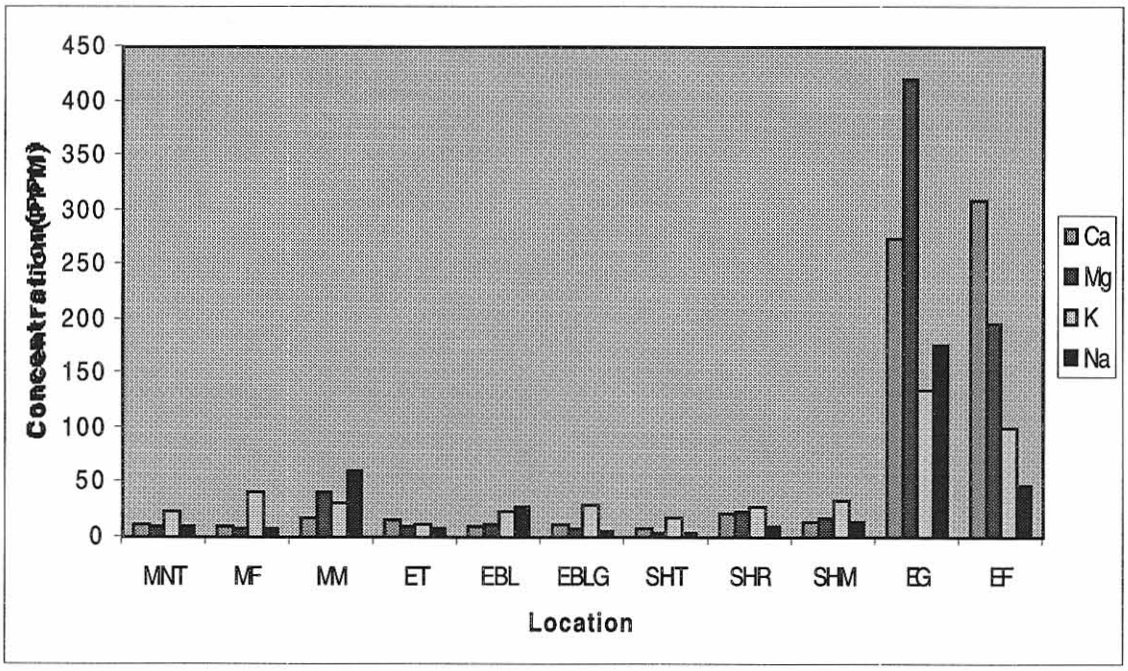

Figure 6.5: Concentrations (ppm) of available macronutrients Ca, Mg, K and Na from surface sediment samples at mine and established sites (after Bennett, 1999).

3.3.2.2 Micronutrients

Eight known micronutrient elements are Cl, B, Fe, Mn, Zn, Cu, Ni and Mo. "Bioavailable" concentrations of the elements, with the exception of Cl and B (not normally limiting, although the role of B is not known well), were measured in sediment samples at all sites (Figure 6.6 of Bennett, 1999). If any of these elements were limiting plant growth, the most likely one would be manganese. No obvious trends were observed within and between sites for iron and molybdenum concentrations. Manganese was below detection limits for the sediments of the mine sites, but easily detectable in the established site. Zn concentrations were variable, but higher in the established site, and below detection limits in several areas of the mine site (i.e., tailings area of Star Hill, Monarch tailings and mounded areas and the revegetated area of the Endurance). Copper concentrations were also variable and below detection limits in some of the mine site areas, although there is a large uncertainty (e.g., 30%) in the analytical results. Nickel concentrations were below detection in all samples from mine and established sites.

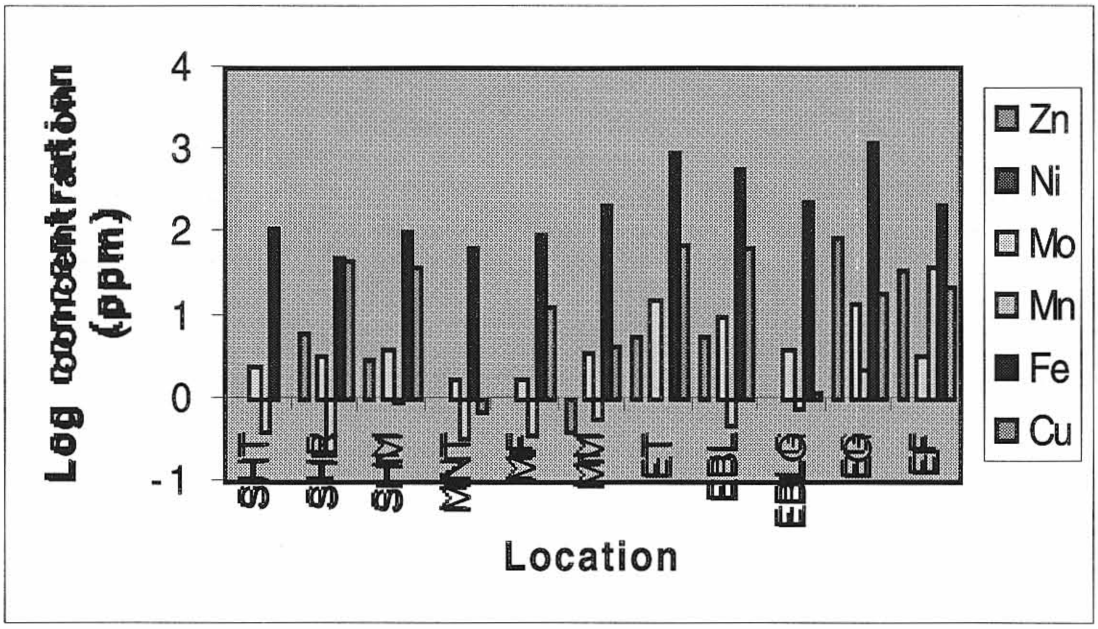

Figure 6.6: Concentration of selected micronutrients from surface sediment samples within the Endurance, Monarch, Star Hill and established sites (after Bennett, 1999). Abbreviations in Table 3.1 above.

3.4 Toxicity and Nutrient Deficiency

Elements can be toxic to plants, depending on their form and concentration. Heavy metal concentrations (e.g., Cu, Pb, Zn, Cr, Ni, Mo, Mn, Fe) in "bioavailable" form in sediment are below recommended guidelines and probably do not represent a problem for plant growth; however, there is a possible problem with aluminium toxicity combined with calcium deficiency. The sediments at the mine sites are acidic (soil pH ranges between 4.4 and 5.4, compared to a favourable range of soil pH = 5.6 to 7), suggesting that aluminium in the soil solution (i.e., pore water) could be present as the ion, Al^{3+}, in which case it would compete with macronutrients Mg^{2+} and Ca^{2+} at root uptake sites and possibly lead to Ca and/or Mg deficiencies in plants. Measured Ca/Al molar ratios in the sediment on the mine sites are well below 1 and may be limiting plant growth, as the Ca/Al ratios measured in soils at the established sites are 1.33 and 12.10. The acidic soil pH can also limit the availability of phosphorous (because of precipitation of Fe, Mn and/or Al phosphate minerals – not identified in existing studies of the mine sites), one of the other macronutrients important to plant health. This is common in acidic soils but it results where there is an excess of Fe, Mn and/or Al and the precipitation of phosphate minerals. It is unknown whether such minerals are present at the mine sites.

Cation exchange capacity is another indicator of appropriate conditions for plant health and growth. The measured values for the mine site sediments are lower than those at the established sites (Figure 6.9; Bennett, 1999). This is a result of the coarse grainsize (sand to gravel) and lack of organic matter in the sediments on the mine sites.

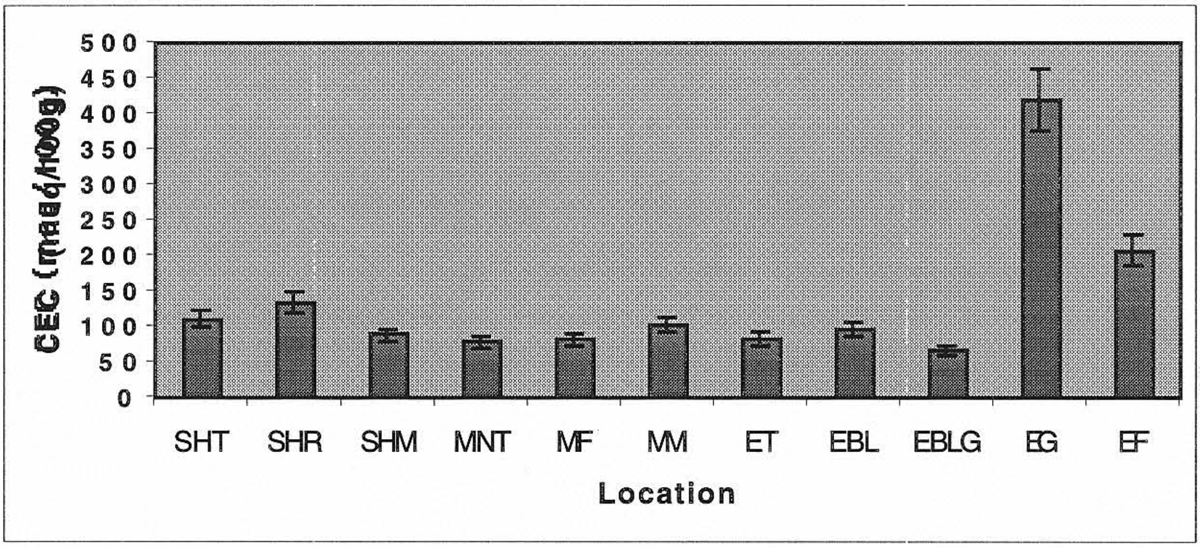

Figure 6.9: Cation exchange capacity (CEC) at the Monarch, Endurance, Star Hill and established sites. Location abbreviations are in Table 3.1 above (after Bennett, 1999).

There is ample evidence of nutrient deficiencies at the mine sites. Many plants exhibit chlorosis (yellowing of normally green leaves), although the effects are variable within and between sites. Older leaves show the most chlorosis, indicating deficiencies in Mg (most common), Cl, K and/or N. The most affected species are *Banksia marginata* (Silver Banksia) and *Kunzia ambigua* (White Kunzia). Dead or dying plants are observed at all mine sites, possibly indicating that plants are deficient in nutrients (and/or a possible lack of water) and shutting off parts of their structure. Stunted growth of plants, especially the heath species *Epacris impressa* and *Epacris languinosa*, may indicate a lack of nitrogen and/or phosphorous (possibly sulphur and/or copper to a lesser extent). In contrast, reedy plants, e.g., *Restio complantis* (Flat Cord-rush), appeared to be healthy on the mine sites.

3.5 Water Availability and Quality

Shallow groundwater flow typically follows topography at all mine sites. A detailed groundwater study was made at the Endurance site (de Jong, 1999 – see above) and a few piezometers were installed at the Monarch and Star Hill minesites as part of Bennett's (1999) study. In general the depth to the water table in the tailings and sediments at the time of these studies was greater than 10 cm, the depth to which many plant roots were observed to penetrate. This may limit the amount of groundwater that is readily available to plants, although the rainfall before the field seasons of this study was below average and is probably reflected in lower water table levels. The high infiltration rates and low moisture contents of the sediments may indicate that the sediment does not retain sufficient water for plants.

The groundwater quality in most areas of the mine sites is probably poor for plant growth. Groundwater is typically acidic (i.e., from acid generation and drainage) at the Endurance (pH ~ 2 to 4) and Monarch (pH ~ 3 to 5) mine sites, but less so at Star Hill (pH ~ 6). The pH of surface waters was variable but in places showed the impact of acid drainage at all sites. Creek and dam water typically becomes more acidic (lower pH) as it receives acidic groundwater from tailings. The measured pH values of water at the established site, and in creeks upstream of the tailings, are somewhat acidic (e.g., pH ~ 5 to 7). This is a result of organic acids sourced from the breakdown of organic matter and is typical of waters in the area. The acid drainage problem is most pronounced at Endurance but is present to a lesser extent at Monarch and Star Hill. Aluminium, iron, lead and zinc were above recommended guidelines for drinking water in many groundwater and surface water samples at all three sites, although Endurance had the highest levels. In some samples, molybdenum and copper were also in concentrations higher than recommended drinking-water guidelines. Metal concentrations increased downstream in creeks, further indication of acid drainage and contaminated waters from the tailings.

3.6 Potential Limiting Factors for Plant Growth

Based on the research presented by Bennett (1999), here is a summary of factors that may be important in limiting plant growth on the mine sites in Northeastern Tasmania. The most likely ones are:

- Little or no soil profile developed on the mined and tailings disposal areas
- Lack of organic matter and fine-grained sediment (e.g., clay content), and absence of microfauna in the tailings (low cation exchange capacity, low water retention, lack of environment for microorganisms)
- Presence of iron pan in some areas of the mine sites
- Increased erosion on the mine sites
- Lack of nutrients in the sediments of the mine tailings and mined areas (macronutrients nitrogen, potassium, calcium, magnesium and possibly chlorine (as chloride?), carbon, phosphorous and sulphur; micronutrients manganese and possibly copper)
- Possible toxicity from elevated aluminium concentrations and deficiency in calcium and/or magnesium (i.e., low Ca/Al ratios in mine tailings and mined areas)
- Acidic soil pH
- Poor groundwater quality
- Lack of ground water/low water table

Other factors may be important; however, it is necessary to know more about the biochemistry and ecology of plants to understand how each plant and plant populations respond to the physical, chemical and geological factors described above.

4 Future Studies

There are many scientific and other studies that would be useful. Engineering studies would also be useful and are included in the section below on remediation options and recommendations. The following list includes possible areas and projects for study, with no particular order of preference/recommendation. The areas and projects are posed mainly as questions with some recommendations on the type of methods that could be used to answer the questions.

- **Acid drainage** is already identified and a significant problem in some areas (e.g., western end of the Endurance site) but there is also evidence of acid drainage (iron staining, low groundwater pH) in the middle areas of Endurance (flats east of Blue Lake, drainage into Blue Lake) and Monarch. There is no evidence of widespread acid drainage at Star Hill.
    - What is the source of acid generation? Presumably it is a result of oxidation and dissolution of pyrite, marcasite and/or other iron and sulphide minerals, but is acid being generated in small areas (e.g., point sources) or is it widespread (i.e., diffuse source)? Possible methods of detection include piezometry (as used in the studies reviewed above) and/or electrical geophysics (e.g., Induced Polarisation (IP), Time-Domain ElectroMagnetic (TEM)).
    - How widespread is acid drainage on the mine sites in Northeastern Tasmania?

- **Hydrology:** At the best studied site so far, Endurance, it would be useful to know more about the ***streamflow, precipitation, evapotranspiration*** (i.e., hydrologic budget) that contribute to Ruby Lagoon and Ruby Creek. Do contaminated waters from Ruby Lagoon enter the groundwater to the south of the lagoon (e.g., underneath the adjacent pasture land)? More information on how flows vary in ***time*** (e.g., seasonal, monthly, weekly, even daily perhaps) would help in understanding how water moves through the tailings and into and out of receiving waterways (e.g., Ruby Lagoon). It would also help to know more about the ***infiltration rates*** and ***water retention capacity*** of the tailings and affected areas on and around the Endurance site. The same understanding, plus more about groundwater hydrology, would be useful in understanding existing or potential contamination at other mine sites. The impact of groundwater on water quality in receiving creeks, rivers or lakes can be estimated with a combination of groundwater and geochemistry, similar to de Jong (1999)

- **Erosion:** What are the masses/volumes and processes of erosion on the mine sites? Is water or wind erosion the predominant process? How do infiltration rates affect the amount of water that enters the tailings or runs off the surface? How do the processes of erosion affect the retention of seeds and/or organic matter that might be added to provide a substrate for plant growth?

- **Toxicity of metals and other elements to plants and animals:** Are any elements or compounds present at toxic concentrations? Based on Bennett's (1999) study there are several elements that may require further study. Different plants and animals have different tolerances to individual elements or compounds, so it would be useful to understand how each plant (and animal) responds to different conditions.
    - ***Aluminium*** concentrations in many water samples were higher than recommended limits for drinking water, especially in acid drainage waters at Endurance but also in some samples from Monarch and Star Hill. In addition,

many of the soil/sediment samples had high concentrations of bioavailable aluminium, which may affect the availability of nutrients such as calcium and magnesium to plants. What are the effects of the elevated aluminium concentrations on aquatic life and plant life in and around the mine sites?
  - ***Heavy metals***, such as ***iron, lead and zinc***, were detected in acid-drainage-impacted ground and surface waters at levels in excess of recommended guidelines for drinking water, and may pose a risk to aquatic and plant life. Further study of heavy metals may be warranted in areas affected by acid drainage.

- **Nutrient availability/deficiency**
  - ***Hydrogen plus carbon concentrations*** are low in tailings and sediment in mined areas. Is this limiting effective plant growth? How much carbon, organic or otherwise, is necessary for good plant growth on the mine sites?
  - Are the tailings and sediment in the mined areas deficient in the ***macronutrients Ca, Mg, Cl, K and/or N***? Chlorosis, evident especially for *Banksia marginata* (Silver Banksia) and *Kunzia ambigua* (White Kunzia), may be evidence that Mg, Cl, K and/or N are deficient.
  - Are the concentrations, and forms, of ***phosphorous*** sufficient for effective plant growth?
  - Any ***micronutrients*** limiting plant growth, particularly ***manganese*** and possibly zinc?

- **Microorganisms**: is there a presence or absence of necessary microorganisms (e.g., bacteria, others?) important for plant growth? The presence of appropriate types and populations of microorganisms may depend on an appropriate substrate (e.g., organic carbon in tailings and sediment).

5 Remediation Options and Recommendations

Remediation of the abandoned tin mine sites in Northeastern Tasmania involves two main issues: i) minimisation or elimination of acid mine drainage and ii) revegetation of the tailings and mined areas. It is likely that no single technique would suffice to remediate acid drainage, and the same is probably true for successfully revegetating the affected areas. Ideally a combination of techniques will be most effective and there are some that would be useful in addressing both the acid drainage and revegetation issues. Note: Schuiling (1998) provided an excellent review of categorising remediation measures from a geochemical engineering perspective and showed a number of examples of solutions to environmental problems.

The remediation issues and potential strategies for acid mine drainage and revegetation are reviewed separately below, followed by a summary of recommendations.

5.1 Acid Mine Drainage

The remediation of sites effected by acid mine drainage (AMD) is in general best achieved by a combination of prevention and treatment protocols. This involves both the treatment of the problem by addressing the acid conditions and high metal contents (e.g., Fe, Al, heavy metals) using both natural (bioremediation) and artificial methods, and the prevention or reduction of further acid generation.

The best set of strategies/protocols would ideally be self-regulating and require minimal external intervention and control. Protocols would therefore ideally include natural bioremediation and revegetation systems which would result in the revegetation of the area with local species and restoring the balance in the groundwater hydrology and chemistry. The rates of restoration are generally proportional to their cost and need for human intervention to maintain their progress.

Many of the imbalances created by AMD lead to conditions (e.g., acidic water, low nutrient and high metal contents) within the groundwater, tailings, waste rock and, where present, soil profile that inhibit simple revegetation. As a result one of the first protocols involves site preparation (e.g., Australian Mining Industry Council, 1990). This almost always involves procedures to minimise the production of acid, increase the amount of organic matter and other nutrients and promote the development of soil profiles (also useful/necessary in revegetation).

Neutralisation of acidic waters is necessary for successful revegetation. Plant growth at pH values below 4.5 is severely limited (Australian Mining Industry Council, 1990). Minimising acid production in the waste rock pile can be achieved by several methods:

- **Water management** - reduce the volume of water passing through tailings and/or waste rock. This can be addressed by redirecting surface and rainwater run-off away from site (e.g., Koehnken, 1997) by installing drains (e.g., anoxic limestone drains, open limestone drains; e.g., Environment Australia, 1997) and setting up surface barriers to aid in the redirection of surface waters. As these strategies generally only reduce the amount of water (and oxygen) available for the production of AMD, in severely affected areas such as at Endurance the collection and treatment of ground water run off may also needed.

- **Hydrodynamic isolation** - stop or reduce the flow of water into and out of the tailings and/or waste rock, using impermeable barriers such as clay barriers and the layering of overburden and soils with barriers to stop water penetration into the pile (e.g., Koehnken, 1997; Gavaskar et al., 1998).

- **Minimisation or exclusion of oxygen** from the tailing using surface and/or subsurface barriers (Gavaskar et al., 1998).

- **Addition of lime or other alkaline materials** will increase pH, resulting in precipitation of base and heavy metals (e.g., Koehnken, 1997). However, this generally involves the addition of large quantities of alkaline materials and is often not cost effective as a sole treatment strategy.

- **Bio-remediation** can decrease the production of AMD by introducing specific bacteria (e.g., sulphate reducing; *Desulfovibrio*) and developing ecosystems such as those found in wetlands. This can also decrease the populations of acid-tolerant bacteria such as *Thiobacillus ferroxidans* that are responsible for increasing the rates of acid production.

These methods all assist in the reduction of the volume of acidic groundwater produced and help prepare the ground for revegetation. Many of these strategies for the reduction of AMD may not suit the site conditions and therefore it is likely that some combination of the above procedures may be necessary to reduce AMD to a level to which revegetation of the site can be achieved.

In addition, passive or active treatments of acid drainage may be successful and practical, e.g., trapping acid water in drains or other impoundments and treating the acid with lime, biotechnology (bacteria + alcohol addition in "bioreactors", e.g., Berkeley pit at open pits at Butte, Montana) or other chemicals. See also the summary of results at the Mt. Lyell Remediation, Research and Demonstration Program (Koenhken, 1997). If the volume of acid drainage is too large, then it may not be possible to use such methods to remediate effectively or economically. The volumes of acid drainage at the Endurance site may be too large, but other sites in the area may be small enough to consider passive or active treatment strategies.

5.2 Revegetation

An effective way of sustainable, self-regulating site remediation is to revegetate the affected areas. As pointed out above severe conditions of AMD production need to be addressed prior to embarking on a revegetation strategy. Additional assessment of the soil/sediment conditions (e.g., pH, nutrient content, soil strength/impedance) will probably also be necessary.

- **Site preparation** should include a combination of chemical and physical methods. Liming of acidic tailings should increase soil and water pH, exchangeable Ca and Mg and microbial activity (e.g., Johnson et al., 1995). Nutrient addition (e.g., fertilizers) is probably necessary. Nitrogen, phosphorous and carbon are essential and others may be useful or necessary. Both liming and nutrient addition are short-term strategies that will promote the development of a soil profile. Physical methods include ripping of the sediment and land imprinting (e.g., dimpling of the ground surface to reduce erosion, trap water and provide growth areas for seeds; Dixon, 1997). The latter may be more effective than ripping the soils into rows. Adding clay may improve both physical and chemical properties (e.g., water retention, cation exchange capacity) but may also limit water infiltration (good for minimising AMD but possibly bad for water availability to plants). In addition to the physical and chemical methods, it may be worthwhile considering addition of microorganisms (e.g., adding soils/sediment/organic matter from established areas near the mine sites)

- **Topsoil** - 0.2-0.3 m of topsoil is desirable for non-toxic substrates (Australian Mining Industry Council, 1990). Addition of mulch (plant and litter cover) is preferred to the application a thin layer of topsoil. If this is too costly or impractical then strips or patches of topsoil and/or mulch could be used.

- **Direct revegetation of overburden** – existing trials at all three mine sites have been at least partially successful. Additional trial plantings may be useful to establish the best methods of direct revegetation. Nitrogen-fixing plants such as acacia species would help in developing nutrient availability. Patches and/or strips of revegetation would be helpful in reinstating the landscape. Revegetated patches could be promoted by also adding organic matter (e.g., piles of branches).

- **Erosion control** - Preventing the removal of topsoil or fertile overburden capable of sustaining plant growth is crucial is revegetation strategies. Erosion can be reduced in the early phases of revegetation by:
  - Installing wind barriers, either natural or manufactured materials over the soil to reduce stripping;
  - Establishing wind breaks to decrease surface stripping of soils;
  - Minimising water erosion - redirect run off via banks, channels and/or dimpling (land imprinting);
  - Surface preparation in arid sandy areas - produce a hummock surface / dimple effect (best for slopes < 12°) using topsoil heaps ~ 1.5 m high.

- **Water quality and availability** – Water quality may be improved by liming (especially in acid drainage areas). Soil moisture contents would be improved by the addition of organic material (mulch and leaf litter). This would also help to promote the development of microfauna (e.g., bacteria) that will help in breaking down plant matter and creating a soil profile.

- **Species selection** - The selection of appropriate plant species for revegetation is crucial. Local species are preferred over new species being introduced to the area due to their ability to grow under the climatic conditions. Matching of species from similar soil and drainage conditions to that of the site to be rehabilitated is an advantage (e.g., plants from forested and sedge-heathland communities). Plant species that self propagate (i.e., produce abundant seed) are advantageous. Legumes are good colonisers and would help to improve soil fertility. Acacia species would also be useful as nitrogen fixers (as mentioned above).

6 Summary and Conclusions

The results of two recent environmental impact research studies quantify groundwater and surface water contamination, vegetation and sediment geochemistry in three historical tin mine sites in Northeastern Tasmania (Endurance, Monarch and Star Hill).

At the Endurance mine site, groundwater is contaminated by acid drainage and is released into Conundrum Creek and Ruby Lagoon, which drains into Lower Ruby Creek and then into the Ringarooma River near Gladstone. Groundwater discharge directly into Ruby Lagoon is approximately 20 m^3/day, compared with discharges of greater than 1200 m^3/day from Conundrum (contaminated with acidic groundwater) and Upper Ruby Creeks. Most of the contamination in Ruby Lagoon enters through Conundrum Creek. Aluminium and several heavy metals (Fe, Cr, Ni, Cu, Zn, Mo, Pb and U) are above recommended guidelines in the tailings at the western end of the Endurance mine site. Ground and surface waters have acid pH values of between 2.4 and 5.5 and have high concentrations of Fe, Al, Si and sulphate, a result of acid drainage. Other potentially hazardous elements in the waters are Pb, Zn, Cu, Cr, Ni, Mo and U, as they were detected in concentrations higher than recommended limits for livestock watering in some samples.

Vegetation on the mine sites and surrounding areas consists of sclerophyll forests and sedge-heathland communities. Eucalyptus trees dominate the forested areas, with some Banksias, Acacias (wattles) and Sheoke. Sedges and rushes dominate the sedge-heathland areas. There are differences in the predominant plant species within and between mine sites. Some of the differences reflect revegetation trials. The most notable differences are the predominance of acacias in the most recent tailings areas at the Monarch site (acacias are nitrogen fixers) and the predominance of some plant species (e.g., Black Peppermint gum) near the edges of tailings (possibly important "edge effects"). Plant cover is much lower on the mine sites compared with established areas, although the older areas of the Monarch site have cover up to approximately 40%. Importantly, biodiversity on the mine sites was nearly the same as on the established sites, indicating that regrowth is not limited by differences in biodiversity. Tailings are too acidic and the Ca/Al ratios are too low (low Ca and/or high Al) for effective plant growth. Cation exchange capacities are low in the tailings relative to the established soils. There is ample evidence (chlorosis, stunted growth, necrosis, misshapen leaves) of nutrient deficiencies, in particular nitrogen and/or phosphorous and possibly sulphur. Other macronutrients (e.g., carbon, potassium, calcium and magnesium) may also be in short supply in the tailings. The lack of some micronutrients (e.g., manganese, and possibly zinc and copper) may be limiting plant growth in some areas of the tailings. Groundwater quality is poor in the studied mine sites and water tables may be too deep (e.g., greater than 10 cm) for many juvenile plants to access easily. High infiltration rates may also contribute to a lack of available water for plants.

There are many potential future scientific research studies, e.g.,

- Determining the source (point, diffuse) areas for acid drainage,
- Acid drainage surveys of other mine sites in the region,
- Infiltration rates and water retention capacity of tailings,
- Erosion (wind and water),
- Toxicity of elements (e.g., aluminium and heavy metals) to plant and animal life,
- Nutrient availability (in particular for different plants in the region),
- Populations (ecology) of microorganisms (e.g., bacteria).

Remediation of the mine sites should focus on minimising acid drainage and revegetating the tailings and mined areas. It is likely that a combination of strategies will be most effective and would include:

- Water management – minimise the volume of water entering the tailings by adding clay and organic matter (e.g., mulch, leaf litter, branches) to the ground surface,
- Minimisation of oxygen ingress into the tailings by adding organic matter to the ground surface,
- Addition of lime to raise pH and precipitate heavy metals – also to increase Ca nutrient concentration and raise Ca/Al ratios important for plant growth,
- Bio-remediation – introducing bacteria (e.g., sulphate-reducing) and developing ecosystems such as found in wetlands,
- Site preparation for revegetation – liming of tailings, addition of nutrients such as nitrogen, phosphorous, carbon and possibly micronutrients such as manganese, land imprinting (creation of dimples and/or hummocks on tailings), addition of organic material,
- Revegetation in patches or strips, with plenty of organic matter (mulch, leaf litter, branches) – acacias and other nitrogen-fixing plants as well as plant species from established areas (eucalyptus species in forested/higher areas, sedges and rushes in lower, wetter areas)
- Prevention of erosion – wind barriers, land imprinting

Based on the results of the vegetation studies, in particular the lack of cover on tailings and mine areas and the similarity in biodiversity between established areas and mined/tailings areas, revegetation is already underway naturally. Appropriate remediation strategies will accelerate natural processes. The area that has had the longest time to recover (since the 1930s), i.e., one area at the Monarch site, has up to ~40% plant cover, compared with 90-100% cover on established areas. This suggests that natural revegetation will take at least 100 years, and perhaps several hundred years. By minimising acid drainage and providing a suitable substrate for plant growth the time for effective revegetation could be reduced, perhaps to ones to tens of years.

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