

Tasmanian Acid Drainage Reconnaissance

Report 1 Acid drainage from abandoned mines in Tasmania

MINERAL RESOURCES
TASMANIA



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Tasmanian Acid Drainage Reconnaissance

1. Acid drainage from abandoned mines in Tasmania

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FOREWORD

Acid drainage, resulting from the oxidation of sulphide-bearing rocks, is recognised as one of the major sources of heavy metal pollution in many of waterways proximal to metal mining sites in Tasmania. Prior to this investigation, only limited information was available on the extent of acid drainage impact from historic abandoned mine sites.

Section 37.5 of the Tasmanian *State Policy on Water Quality Management* (1997) requires that “an inventory of sources of acid drainage from historic mine workings should be carried out”. This reconnaissance investigation provides a basis for this inventory. The program is a component of the proposed *State Water Quality and Quantity* programs and was largely funded by the National Heritage Trust. Water analyses were carried out by the Department of Primary Industries, Water and Environment at the Analytical Service Tasmania laboratory. Geochemical analyses, map production and project management were carried out by Mineral Resources Tasmania.

This report primarily focuses on acid drainage from abandoned mine sites in Tasmania. It presents new data and the compilation of existing data on water chemistry and geochemistry associated with abandoned mine sites in Tasmania. The report accompanies a series of acid drainage impact maps and an inventory of acid-producing abandoned mine sites.

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EXECUTIVE SUMMARY

There are over 4000 recorded mineral activity sites in Tasmania. About 681 sites are classified as metal mining related abandoned mines that contain sulphide minerals associated with their deposit history. Commonly occurring sulphide minerals, such as pyrite and pyrrhotite, can generate sulphuric acid when exposed to oxidising conditions and in the presence of certain metallogenic bacteria. The resulting acid drainage can mobilise heavy metals which can seriously affect soils and water quality in the receiving environments. Several abandoned mines in Tasmania are currently producing acid drainage or have the potential to do so if disturbed.

Surface waters impacted by abandoned mine sites typically show high sulphate and metal distribution at a pH range of 2.0 to 5.0. The impacted waters generally show metal distribution in the high acid/extreme metal to low acid/low metal range. A similar trend was shown by sulphate distribution. Elevated levels of metals and sulphate downstream from several abandoned mine sites indicate that active sulphide oxidation is occurring and these sites may be potential point sources of metal pollution in the receiving environment. High correlation between metal and sulphate distribution suggests that sulphate distribution in surface waters may be used as a cost effective investigation tool for preliminary assessment of acid drainage.

Geochemical results indicate that occurrences of high sulphate and high metal waters are closely associated with abandoned mine sites containing sulphidic rock materials with high net acid producing potential (NAPP). Many of the volcanic-hosted mineralised metasediments in the West Coast mineral fields generally have NAPP >500 kg H₂SO₄/t and low to negligible acid neutralising capacity (ANC). Carbonate-hosted base-metal abandoned mine sites were found to be generally high acid producers, mainly because of the presence of high NAPP ore rocks and restricted availability of acid neutralisation from the host rock. Waste rocks and tailings materials at many of the abandoned mine sites also commonly contain anomalously high concentrations of trace metals (As, Cu, Pb, Zn, Sn and W). Similar high levels of trace metals reflected in surface waters and stream sediments proximal to mine sites suggest that there is a significant release of these metals into the receiving environment.

The reconnaissance survey indicated that several abandoned mine sites show acid drainage and heavy metal pollution problems. The extent of the impact on the receiving environment is difficult to assess from the currently available information. Detailed hydrogeochemical characterisation, together with baseline data on mass loadings and environmental parameters, need to be assessed prior to recommending cost effective remediation of problem sites identified in this survey.

ACRONYMS

ABA	Acid base accounting
AD	Acid drainage
AFR	Acid forming rocks
ANC	Acid neutralising capacity
ANZECC	Australian and New Zealand Environment Consultative Committee
BORIS	Groundwater bore database
DORIS	Drill hole database
HYDROL	Water quality database
EC	Electrical conductivity
MIRLOCH	Mineral deposits database
MPA	Maximum potential acidity
NAFR	Non-acid forming rocks
NAPP	Net acid producing potential
PAFR	Potential acid forming rocks
ROCKCHEM	Whole-rock and mineral chemistry database
TASGEOL	Rock unit database
TASSED	Stream sediment geochemical database

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INTRODUCTION

Acid drainage (AD) is defined as low pH-high metal and high sulphate-bearing waters, formed when rocks and sediments containing sulphide minerals are exposed to the atmosphere under an oxidising environment. Commonly occurring sulphide minerals, such as pyrite and pyrrhotite, produce sulphuric acid when oxidised in the presence of certain metallogenetic bacteria. The resulting acid drainage is a major pollution problem because of its ability to mobilise toxic levels of heavy metals which can have serious impact on the receiving environments. Mining operations can expose large quantities of sulphidic rocks, and produce mine waste rocks and tailings rich in sulphide minerals. A legacy of past mining activity are the numerous historic and derelict abandoned mines world-wide, many of which are potential or active sources of acid drainage.

Over the last decade there have been concerted efforts to understand the acid drainage generation processes in order that effective mitigation measures could be developed to minimise the impact on the receiving environments. Literature that specifically describe the basic chemistry of acid drainage generation processes from the oxidation of sulphide minerals and some of the innovative techniques for mitigation includes Parker and Robertson (1999), Evangelou and Zhang (1995), Alpers and Blowes (1994) and Nordstrom (1982). An Internet website (<http://www.infomine.com/technology/enviromine/ard/home.htm>) also contains relevant information on acid drainage and related subjects.

Although there are various studies and reports on acid drainage from mine sites across Australia, abandoned mine sites are often ignored except for their heritage values. In an Australia-wide survey of acid drainage at operating mine sites, Harries (1997) identified 317 sites (out of 517 significant mining operations surveyed) as containing potentially acid generating wastes. Seven of the mines (Beaconsfield, Hellyer, Henty, Mt Lyell, Renison, Rosebery and Savage River) are located in Tasmania. The data relate only to major deposits that contain significant amounts of pyrite and pyrrhotite and do not include hundreds of abandoned mines that have low sulphide but high acid generating potential. Acid drainage from abandoned mines is no doubt a serious environmental problem but to date there is no inventory showing the extent of its impact in Australia.

In Tasmania, there is no record of a statewide survey of acid drainage from historic mine sites. Heritage listing of historic mine sites has been carried out by Bell (1993) but does not discuss issues on acid drainage. Independent studies and research reports on acid

drainage and rehabilitation are available for a number of abandoned mine sites that have been recognised as currently having acid drainage problems. These sites include the Zeehan mineral field (ESPL, 1999; Oosting, 1998; Taylor, 1998; Parr, 1997; Ladiges, 1995), Razorback and Red Lead in the Dundas area (Lawrence, 1996), Storys Creek (Miedecke, 1998) and Endurance in the northeast tin mining area (de Jong, 1999; SEMF, 1998). Environmental impact assessment reports and research studies on acid drainage are also available for recently closed and operating mine sites (WMRL, 1999, 2000; Dellar, 1998; Smith, 1998; CMT, 1998; SEMF, 1998; PRM, 1996, 1998; ABM, 1996, 1997; HGM, 1997; Miedecke, 1996; EGI, 1996; Renison, 1995; Chilcott *et al.*, 1991). Although not part of this survey, there are also reports on acid drainage from road metal quarry sites, the most prominent being at Reekara and Pearshape on King Island (McKeown, 1999; Innes, 1993). The information from available reports and research studies are site-specific to known sites of acid drainage occurrence.

A statewide reconnaissance survey of acid drainage from abandoned mine sites was carried out during the 2000/2001 summer periods. The survey primarily focussed on assessments of water chemistry, the geochemistry of host rocks and the deposit history of abandoned mine sites. As a regional survey must also include information from current and recently closed operations, selected information pertaining to these sites was obtained from environmental management plans and incorporated in this report. These mines have, and continue to operate, under various permits, environmental management plans, environmental improvement plans and environmental decommissioning and rehabilitation plans which are available on the public record. No comment on these operations or the regulation thereof has been made in this report.

A combination of methods involving geology, geochemistry and surface water chemistry were used to build an inventory of the distribution of acid producing abandoned mine sites and their impact on the surface water quality. The results are presented in a series of acid drainage impact maps. This report is part of an integrated project comprising a statewide survey of acid drainage from abandoned mine sites and acid sulphate soils in Tasmania.

The inventory is in no way complete and its reliability is largely dependent on the accuracy of the historical data used for geochemical classifications of rock types at or proximal to abandoned mine sites. However, the information compiled so far can help aid in screening abandoned mines that are potential sources of acid drainage and warranting further investigations.

OBJECTIVES

The overall objective of this reconnaissance was to implement section 37.5 of the Tasmanian *State Policy on Water Quality Management* (1997):

“An inventory of sources of acid drainage from historic abandoned mine workings in Tasmania should be carried out and remedial programs developed to address priority problem areas”.

The specific project objectives were:

- to identify the extent of acid contamination of waterways through the drainage from sulphide-bearing rocks;
- to locate and define the extent of land and waterways affected by acid drainage;
- to define areas and geological units where there is the potential for acid drainage to occur as a result of development or disturbance; and
- to prepare a report defining these and to suggest strategies to limit the potential impacts.

ANALYSIS

Desktop evaluation of historical data

Water quality data

Historical water chemistry data extracted from various sources (Table 1) include analyses which roughly fall within the sampling period of this investigation (January–June). The bulk of the historical data lacked the sulphate and metal analyses required in the routine characterisation of acid drainage and most sites were located away from the abandoned mine sites

investigated in this survey. Water quality data from environmental monitoring reports are specific to recently closed and operating mines sites and are therefore outside the scope of this investigation. Data from independent reports and research were limited to sites such as Zeehan, Endurance and Storys Creek.

Groundwater data (from the BORIS database) were primarily from bores drilled on agricultural and urban lands and are therefore unsuitable for the purpose of this investigation. Limited data available from abandoned mine sites pre-date 1960 and the validity and sources of analytical results are questionable.

The majority of the historical water quality data lacked standard reporting procedures for concentration units. Because the analytical results were reported either in weight basis (ppm, ppb) or volume basis (mg/L; µg/L), it was necessary to standardise the units for data analysis in this report. For data analysis and interpretation in this study I have assumed ppm and ppb as equivalent to mg/L and µg/L respectively. This assumption is considered valid for relatively dilute concentrations, as is the case for most of the data in the HYDROL database.

In general, the available historical water quality data were found inadequate for assessing acid drainage from abandoned mines in Tasmania.

Geochemical data

Information on the geological setting and mineralisation history of the abandoned mines is useful in targeting areas of base-metal sulphide mineralisation with potential to generate acid drainage conditions. Paste pH, electrical conductivity (EC), total sulphur, acid neutralising capacity (ANC) and trace element concentrations are important parameters in geochemical assessments of acid-forming rock materials.

Table 1
Description of historical water quality data sources

<i>Data source</i>	<i>Description</i>	<i>Reference #</i>
HYDROL	Chemical and biological analysis of mainly surface waters	Dellar, 1998
BORIS	Groundwater analysis	BORIS database
Technical report	Mostly water analyses from West Coast mining sites (often repeated use of same historical data sets)	Koehnken, 1992; Miedecke, 1996, 1998; SEMF, 1998, 2000
EIP, EMP & EDP	Mine environmental monitoring reports	WMRL, 1999, 2000; CMT, 1998 (vol. 1 & 2); Lane, 1998; ABM, 1997; Laszczyk & Lane, 1997; PRM, 1995, 1996, 1998
Research reports	Water analysis on localised study areas	Innes, 1993; Ladiges, 1995; Lawrence, 1996; Oosting, 1998; Taylor <i>et al.</i> , 1996; Parr, 1997; Taylor, 1998; Dellar, 1998; Smith, 1998; de Jong, 1999.

Full listing under Reference section of this report.

Table 2
Description of Mineral Resources Tasmania databases

<i>Database name</i>	<i>Description</i>	<i>Data extracted</i>	<i>Source</i>
MIRLOCH	Mineral deposits and locations	Abandoned mines, commodity mined, sulphide associations	
ROCKCHEM	Whole-rock geochemistry	Total S and trace metals	
TASGEOL	Geology of Tasmania	Background geology, rock type (RCODE)	
TASSED	Stream sediment survey	Stream sediment geochemistry	
DORIS	Drill core and logs	Core analysis (total S and trace metals)	
AMIRA Project P439	Geochemistry and mineralisation	Geochemical background of the Mt Read area	AMIRA, 1997

Mineral Resources Tasmania maintains several databases relating to geological investigations and mineral exploration. Databases relevant to this project are listed in Table 2. The major shortfall in these databases was the lack of sulphur analyses which are required in acid base accounting analysis (ABA) for calculating acid producing potential of the sample. The available sulphur data represented rock types for only a small area of the West Coast mineral field and were insufficient for statewide assessment of the geochemical distribution of acid-forming rocks. No paste pH, EC and ANC were found in the database.

Water sampling and analysis

Surface water sampling in this survey was carried out in the period January to June 2000. Field sampling protocols outlined in Ficklin and Mosier (1999) and laboratory analysis procedures in Rayment and Higginson (1994) and Crock *et al.* (1999) were followed closely. Over 385 sites were investigated with 285 sites being sampled.

Field measurements of pH, electrical conductivity (EC) and temperature (T) were carried out using a hand held Multiline P3 pH/LF WTW multimeter. Water samples for laboratory analysis were collected in acid washed 250 mL polyurethane bottles and dispatched to the Analytical Services Tasmania laboratory at the University of Tasmania within 48 hours of collection. Laboratory analysis was conducted for pH, EC, alkalinity, acidity, sulphate and a suite of dissolved and total metals (Al, As, Cd, Cu, Fe, Mn, Pb, Zn). In this report, EC is reported in dS/m, alkalinity and acidity in mg CaCO₃/L and sulphate, dissolved and total metal analysis in mg/L. Although flow data is an important component in quantifying pollutants in waters, it was not measured because of resource and time constraints on this project.

Geochemical sampling and analysis

A total of 153 rock and sediment samples for geochemical analysis were collected from selected abandoned mine sites, as well as samples of country rocks hosting the mineralised areas. Approximately 5–10 kg of samples were collected from each location and analysed at the Mineral Resources Tasmania

laboratory. Total sulphur (S%) and trace element concentrations (mg/kg) in the samples were determined by X-ray fluorescence in pressed powder pellets. The acid neutralising capacity (ANC) of the samples was determined by dissolving in 0.1 M HCl and back-titrating with standard 0.1 M NaOH standard solution to endpoint pH 7.0. Paste pH and EC were measured in 1:1 and 1:5 sample to deionised water ratio respectively.

Data analysis

A modified classification scheme of Ficklin *et al.* (1992) was used to characterise sulphate and metal distribution in waters from catchments impacted by abandoned mine sites. The Ficklin classification of acid drainage uses pH versus sum of dissolved metals (Cd, Co, Cu, Ni, Pb and Zn) plots to characterise acid drainage. Although Fe, Al and Mn are generally the most abundant metals in acid drainage, and since concentrations of dissolved base metals in the natural drainage are generally very low, these elements are also included in the plots as weighting factors. In the Ficklin plot, classified waters are used to generate acid drainage impact maps depicting spatial distribution of low pH-high metal surface waters in catchments impacted by abandoned mines.

A large part of the historical water quality data lacked complete metals and sulphate analysis for a particular site and most did not generally represent sites investigated in this survey. As both metals and sulphate distribution are pH dependent for a specific area or catchment, simple correlation equations were found suitable for predicting either metals or sulphate in surface waters impacted by abandoned mine sites. Generally samples with high dissolved metals also contain high sulphate, especially if the waters are sourced from sulphide-bearing sites where active oxidation is taking place. Significantly high correlation between sulphate and dissolved metals indicated that, in the absence of metal analysis, sulphate values may be used to characterise acid drainage. A classification scheme similar to the Ficklin plot but using sulphate was also introduced to generate a sulphate distribution map depicting low pH-high sulphate waters, indicating active acid generation at abandoned mine sites.

Table 3
Acid base accounting (ABA) analysis procedure

<i>Description</i>	<i>Units#</i>	<i>Calculations</i>
Maximum Potential Acidity (MPA)	kg H ₂ SO ₄ /t	Total S (%) * 30.6
Acid Neutralising Capacity (ANC)	kg H ₂ SO ₄ /t	Acid neutralised to endpoint pH 7.0
Net Acid Producing Potential (NAPP)	kg H ₂ SO ₄ /t	MPA - ANC

Also expressed as kg CaCO₃/t

Table 4
ABA screening criteria

<i>NAPP (kg H₂SO₄/t)</i>	<i>Rock Type</i>	<i>Geochemical Class</i>
NAPP >20	Acid-forming rocks (AFR)	I
NAPP 0-20	Potential acid-forming rocks (PAFR)	II
NAPP <0	Non acid-forming rocks (NAFR)	III

The acid-base accounting (ABA) analysis procedure is the commonly used static test for preliminary screening of acid-generating sulphidic rocks (White *et al.*, 1999; Ferguson and Erickson, 1988; Sobek *et al.*, 1978). The ABA analysis procedure involves determination of total sulphur (S%) and the acid neutralising capacity (ANC) of the rock materials to derive net acid producing potential (NAPP) of a sample (Table 3).

The ABA screening criteria used to categorise acid-forming properties of the rock types associated with abandoned mine sites are presented in Table 4. Theoretically, a sample will generate acid if NAPP > 0 but this assumption is not always true since other factors such as sulphide forms and reactivity, acid neutralisation capacity of host rocks and degree of exposure to local environmental conditions can affect the net acid being formed. The aim of the ABA analysis is to provide preliminary screening of rock materials with potential to generate acid and metal leaching capacity. Follow-up kinetic tests involving column leaching and field trials are necessary if prescriptive remediation measures are to be implemented.

In generating the geochemical map, assignment of NAPP values to different rock types was achieved by obtaining average total S and ANC values for each rock type. A total of 16,191 records of average NAPP values assigned to various rock types (RCODE) covering all of Tasmania were used to generate a digital spatial surface with a grid cell size of 200 metres.

ArcView Spatial Analyst was used to create the grid surface. The inverse distance weighted (IDW) interpolation method was used to create the digital elevation models from NAPP values and stream coverage. This method uses an iterative finite difference interpolation technique similar to global interpolation methods such as kriging and splines (Hutchinson, 1989).

Presentation of survey results

The final presentation of the survey results are listed below:

- this report;
- Acid drainage impact maps:
 - Map 1 – Distribution of low pH-high sulphate surface waters in catchments impacted by abandoned mines;
 - Map 2 – Distribution of low pH-high metal surface waters in catchments impacted by abandoned mines;
 - Map 3 – Geochemical distribution of potential acid-forming rocks hosting abandoned mines in Tasmania.
- inventory of abandoned mines (Appendix 1);
- water chemistry data (Appendix 2);
- geochemical data (Appendix 3).

RESULTS AND DISCUSSION

Impact of abandoned mines on water quality in Tasmania

Surface waters in catchments affected by abandoned mine sites showed wide variations in dissolved metals and sulphate concentrations at pH range 2.0–9.0 (Table 5). This wide variation in surface water chemistry suggests that characterisation of acid drainage requires multi-parameter analysis in routine environmental impact assessment. The insignificant differences between dissolved and total metal concentration in waters indicated that metal pollutants at low pH were primarily in dissolved forms. Except for pH, all the measured parameters in surface waters affected by the mines showed log normal distribution. The pH was generally <5.0 and showed a bimodal distribution, primarily controlled by the relative concentration of dissolved metals. Similar observations were also made in acid drainage from many coal mines in the United States and Canada (Brady *et al.* 1997). The mean surface water quality was generally ten times above the critical limits for aquatic environmental flow and the ANZECC (1992) standard for aquatic environments (Table 5).

The correlation of measured parameters (pH, EC, alkalinity, acidity, SO₄²⁻, Al, As, Cd, Cu, Fe, Mn, Pb, Zn) in surface waters indicated that (except for EC, As and Cd) pH was the dominant factor influencing the relative distribution in solution. EC was highly correlated with acidity, SO₄²⁻, and Al. Heavy metals Cu, Pb and Zn were significantly correlated with both Al, Fe and Mn, indicating that their relative mobility may be dependent upon co-precipitation with these metals as oxy-hydroxide gel formation at higher pH.

Distribution of sulphate in waters

Elevated levels of sulphate in waters sourced from abandoned mine sites containing sulphidic rock

materials are a good indication that acid generation might be occurring in the area. Sulphate levels in the acid drainage affected waters ranged from 0.20 to 13 900 mg/L at pH 2.0–9.0 (Table 5). Most metal analyses from impacted sites plotted below pH 5.0 in the Ficklin-type diagram, indicating that high acid/high sulphate waters are most likely to originate from mine sites that contain exposed or disturbed sulphidic materials undergoing active oxidation (fig. 1a). Low acid/high sulphate waters that plot above pH 5.0 may represent residual sulphate accumulated from periodic acid generation at the site.

Low acid/low sulphate waters are most likely to be depleted with sulphate, which is likely to be incorporated in the formation of sulphate minerals such as jarosite, alunite and gypsum. The sulphate level in the water is likely to be affected by the magnitude of the flow and presence/absence of alkaline materials in its flow path. Most natural background waters have low to high sulphate levels, generally in the range 0.2–100 mg/L and field pH > 5.0. The overall distribution of sulphate in surface waters impacted by abandoned mines is shown in Map 1.

Most abandoned mines with a base metal mining history generally released high acid/high sulphate waters (fig. 1b). The dominant base metals in most of the abandoned mines in the West Coast region are Cu, Pb and Zn, and these metals are likely to be precipitated as secondary sulphate minerals together with Fe and Al. In carbonate-hosted replacement deposits, such as at Zeehan and Mt Bischoff, surface precipitation of gypsum is evident at several sites where dolomitic waste rock and tailings dumps occur. At the Austral smelter site in Zeehan, a white precipitate of gypsum and zinc sulphate is formed on the slag surface during dry periods and is subsequently leached into Austral Creek during surface runoff.

Table 5
Average surface water quality in catchments impacted by abandoned mines

Parameter	No. of samples	Minimum	Maximum	Mean	ANZECC Aquatic (1992)
pH	850	2.00	9.0	5.45	6.5–9.0
EC (dS/m)	776	0.001	5.8	1.0	
Acidity (mg CaCO ₃ /L)	377	0.02	10 000	254	
Alkalinity (mg CaCO ₃ /L)	418	0.03	8 100	117	
SO ₄ ²⁻ (mg/L)	592	0.20	13 900	557	400
Al (mg/L)	532	0.0001	880	12.4	0.01
As (mg/L)	448	0.001	43.91	0.41	0.05
Cd (mg/L)	606	0.001	3.71	0.03	0.002
Cu (mg/L)	654	0.001	180	2.52	0.005
Fe (mg/L)	631	0.001	2 230	34.5	1.0
Mn (mg/L)	604	0.001	274	4.4	
Pb (mg/L)	650	0.001	27.4	0.21	0.005
Zn (mg/L)	672	0.001	728	7.45	0.01

Metal analyses are in dissolved form.

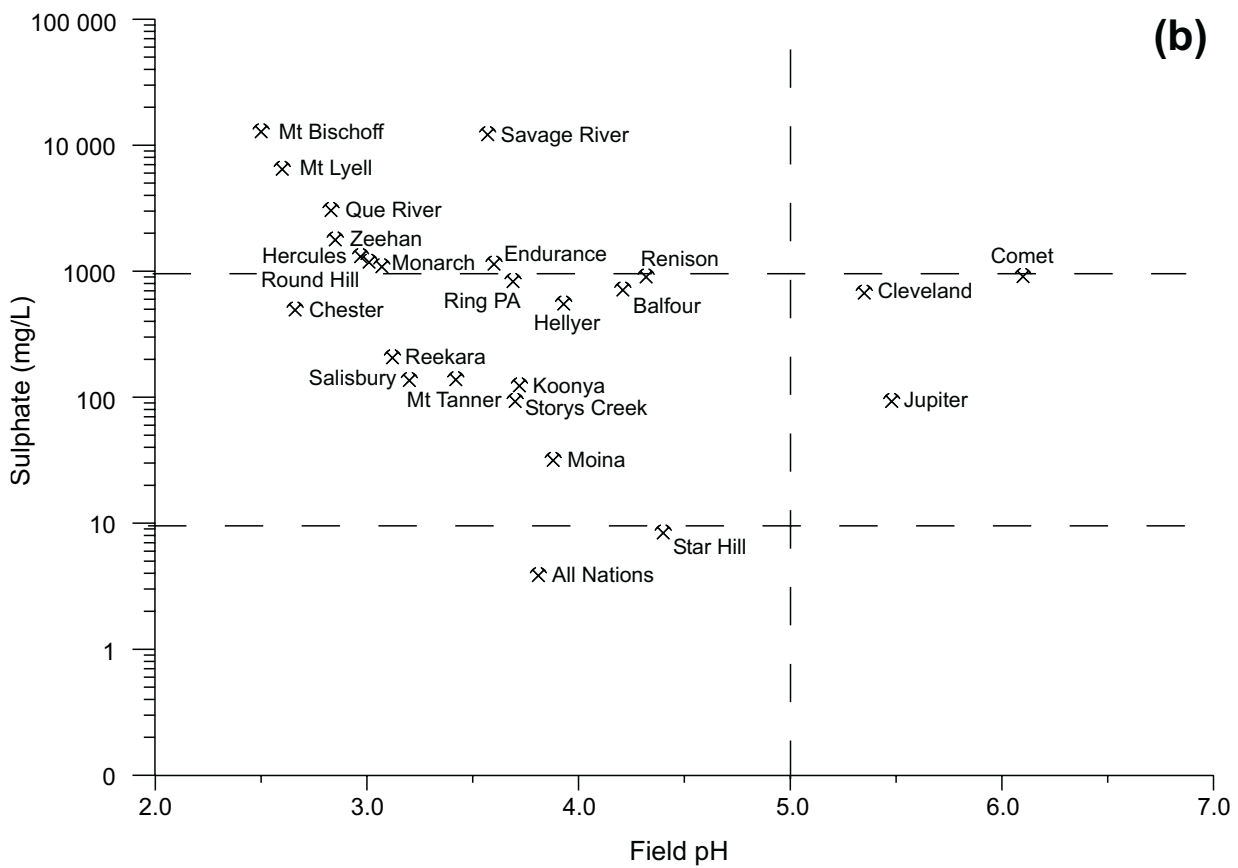
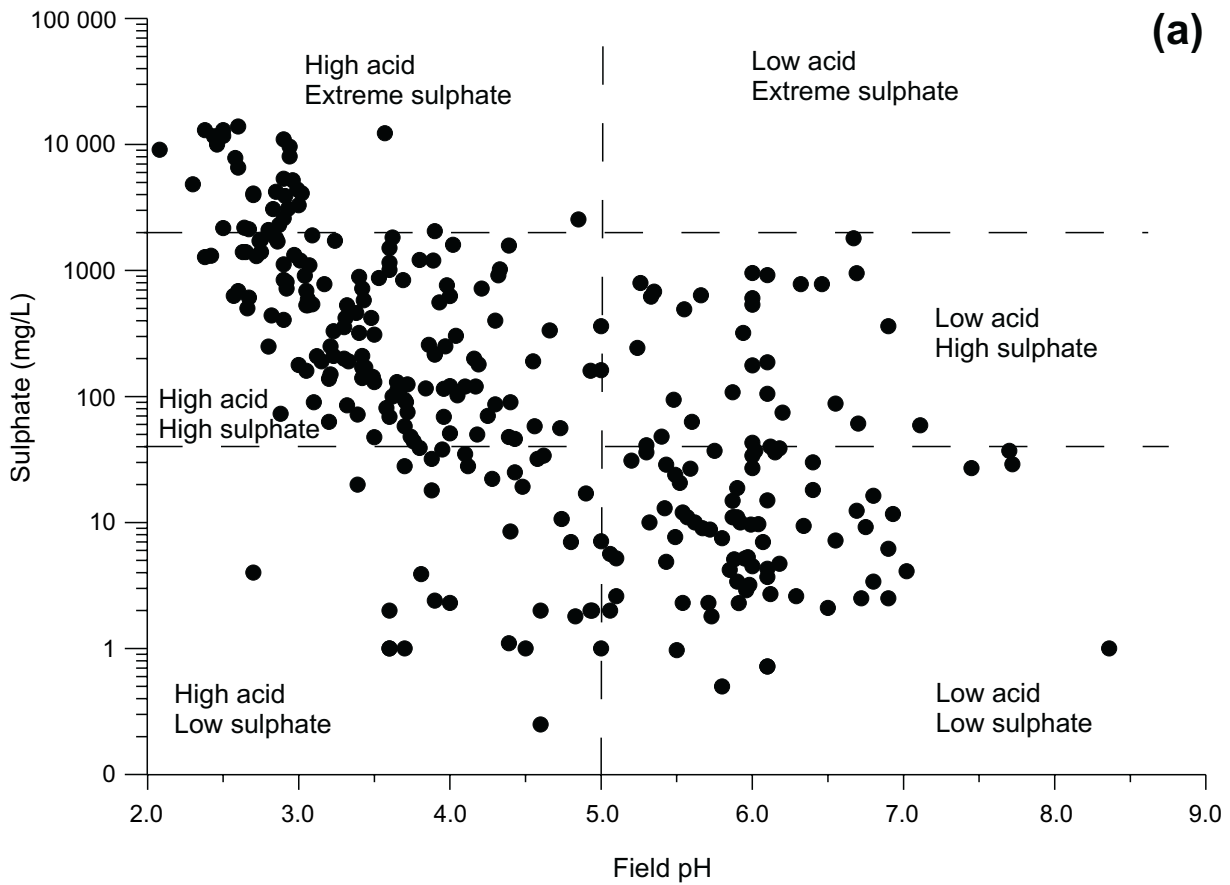


Figure 1

(a) Distribution of sulphate in waters impacted by abandoned mines
 (b) Selected site characterisation by sulphate levels in water

Distribution of metals in water

Dissolved metal concentrations in the abandoned mine impacted surface waters ranged from 0.01 to 4366 mg/L at pH ranging from 2.0 to 5.0 (fig. 2a). The overall mean concentration of dissolved metals were in the order Al > Zn > Cu > As > Pb > Cd. High acid/high metal waters generally originated from mines that have a history of base metal mining (fig. 2b). Low acid/high metal waters are likely to represent precipitated metals accumulated during periodic acid generation at the site, while high acid/low metal waters may indicate the possible formation of sulphate-induced secondary minerals.

At low pH, dissolved As, Cu and Pb were the most common metals while Al and Zn remained mobile throughout the pH range of 2.0–8.0. Because of their high tendency to adsorb into colloids, Cu and Pb are the dominant species found in low pH waters while Zn, which has a limited adsorption capacity, was predominantly mobile at a wider pH range. Surface waters draining several sulphide-bearing abandoned mines in the West Coast mineral field had near-neutral pH but contained elevated levels of dissolved metals, especially Al and Zn. Therefore, near-neutral waters sourced from some mine sites may contain toxic levels of metals likely to be hazardous to the aquatic environment.

Both sulphate and dissolved metal distributions were found to be equally expressive in depicting acid drainage characteristic in surface waters affected by abandoned mine sites. The base metal deposits of the West Coast mineral field are generally associated with high metals/high sulphate waters compared to granite-induced tin and gold deposits of the northeast tin mining areas (except for Endurance, where panned concentrates of pyrite in fast-weathering granite tailings have resulted in perched AD plumes). The concentrations of dissolved metals in impacted waters are likely to be affected by the magnitude of the flow and presence/absence of alkaline materials along the flow path. Wide variations in the distribution of metals suggest that mobility of metals in acid to near-neutral waters is largely controlled by the wide solubility characteristics of these metals.

Surface waters impacted by abandoned mines during base flow period (January–June) are generally high acid/high sulphate/high metals, and for a particular mineral field can be represented by the following correlation equations where [sulphate] and [metal] concentrations are in mg/L:

$$\text{pH} = 6.4 - 0.44 \text{ Log} [\text{sulphate}] - 0.86 \text{ Log} [\text{metals}] \quad (R^2 = 65\%)$$

$$\text{Log} [\text{sulphate}] = 2.4 - 0.18 \text{ pH} + 0.42 \text{ Log} [\text{metals}] \quad (R^2 = 59\%)$$

$$\text{Log} [\text{metals}] = 1.5 - 0.36 \text{ pH} + 0.44 \text{ Log} [\text{sulphate}] \quad (R^2 = 69\%)$$

The above correlations are likely to vary with intensity of runoff and magnitude of the surface water flow. The metal carrying capacity and the rate of precipitation is normally dependent on the acidity of the acid drainage

waters and the distance to the receiving environment. Although rapid precipitation of iron and aluminium hydroxides with increasing dilution of acid drainage may in fact trap metals such as Mn and Zn in the hydroxide sludge (Plate 4), a large build up of sludge in the headwaters poses a significant danger to downstream habitat during major flood events. Diffusion of AD from multi-sources can be a major problem for mitigation and may result in streams being permanently 'dead' (Plate 9).

The distribution of abandoned mines according to dissolved metals shows a similar trend to the site characterisation by sulphate distribution (fig. 2b). The distribution clearly shows the relative metal polluting capability of each mine site according to their distribution in the pH-metal field of the Ficklin-type plot. Most abandoned mines with a base metal mining history release waters that contain high to extreme metal concentrations at pH ranging from 2.0 to 5.0. The low sulphide containing abandoned tin mines of northeast Tasmania generally plot in the high acid/low metals range of the Ficklin-type classification. The overall distribution of metals in surface waters impacted by abandoned mines is shown in Map 2.

Geochemical classification of abandoned mines

The geochemical control of the composition of acid drainage is an important criterion in evaluating acid generating properties of the sulphidic materials from abandoned mine sites. The concentration of heavy metals in acid drainage generally reflects their relative abundance in the host rocks. Local geology, deposit type, physiography, density of drainage pattern and environmental conditions have a predominant influence on the variation in acid drainage quality sourced from impacted sites.

The common acid-producing sulphide minerals found at most of the mine sites in Tasmania are pyrite (FeS₂) and pyrrhotite (FeS). Although carbonate-hosted replacement deposits and skarns are generally rich in carbonate minerals, acid drainage generation is still evident at a number of sites, especially at the Balfour copper mine (Plates 1 and 2), Mt Bischoff tin mine (Plates 3 and 4) and in the Zeehan area (Plate 8). In general, the richer the mines with base-metal sulphides, the greater the amount of dissolved heavy metal constituents released in the mine-sourced drainage. Because of the abundance of sphalerite (ZnS), chalcopyrite (CuFeS₂), arsenopyrite (FeAsS) and galena (PbS) in many of the abandoned base metal mines in the West Coast mineral fields, metals such as Zn, Cu, As and Pb are the dominant trace elements in the sulphidic waste rock and tailings deposits. Waste rocks and tailings deposits at most of these mines are exposed to oxidation processes and generally also have very high NAPP. A similar trend in the relative distribution of these metals in the resultant acid

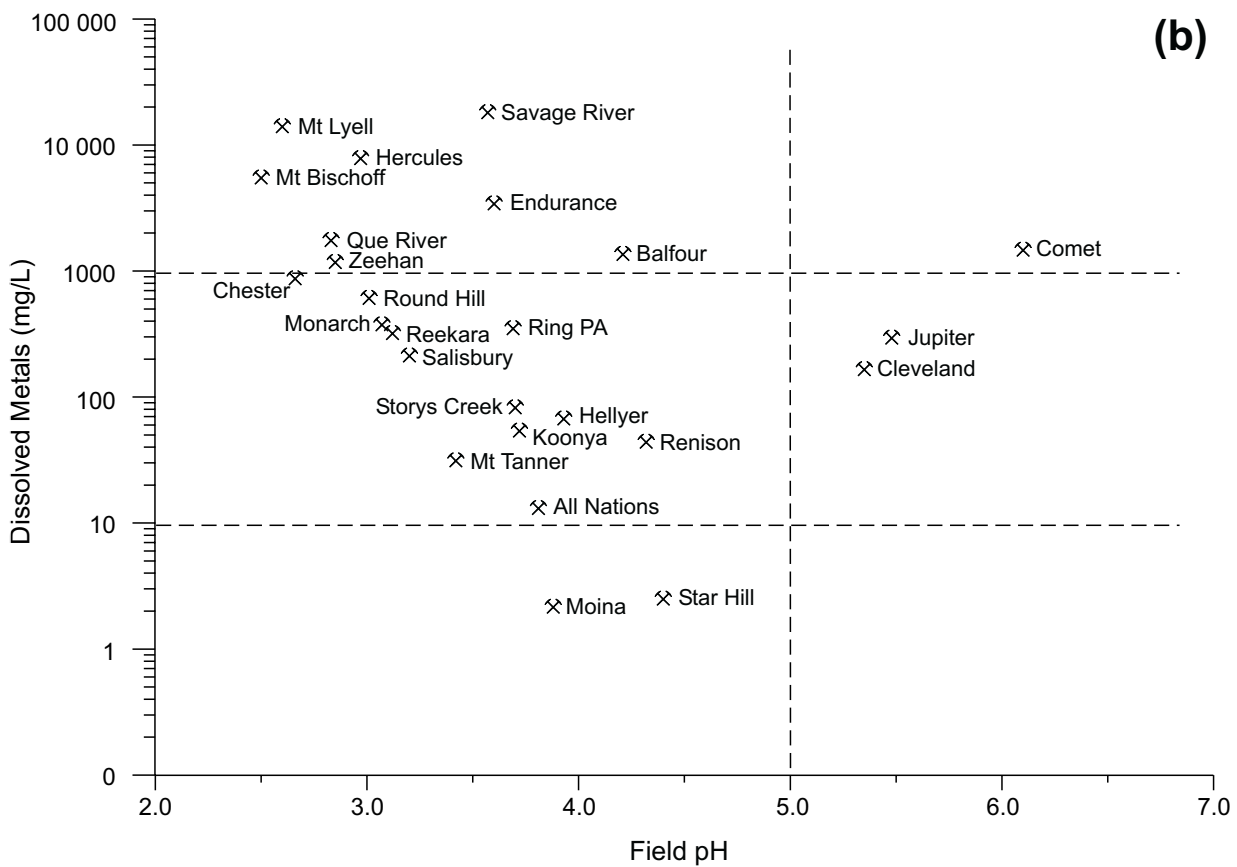
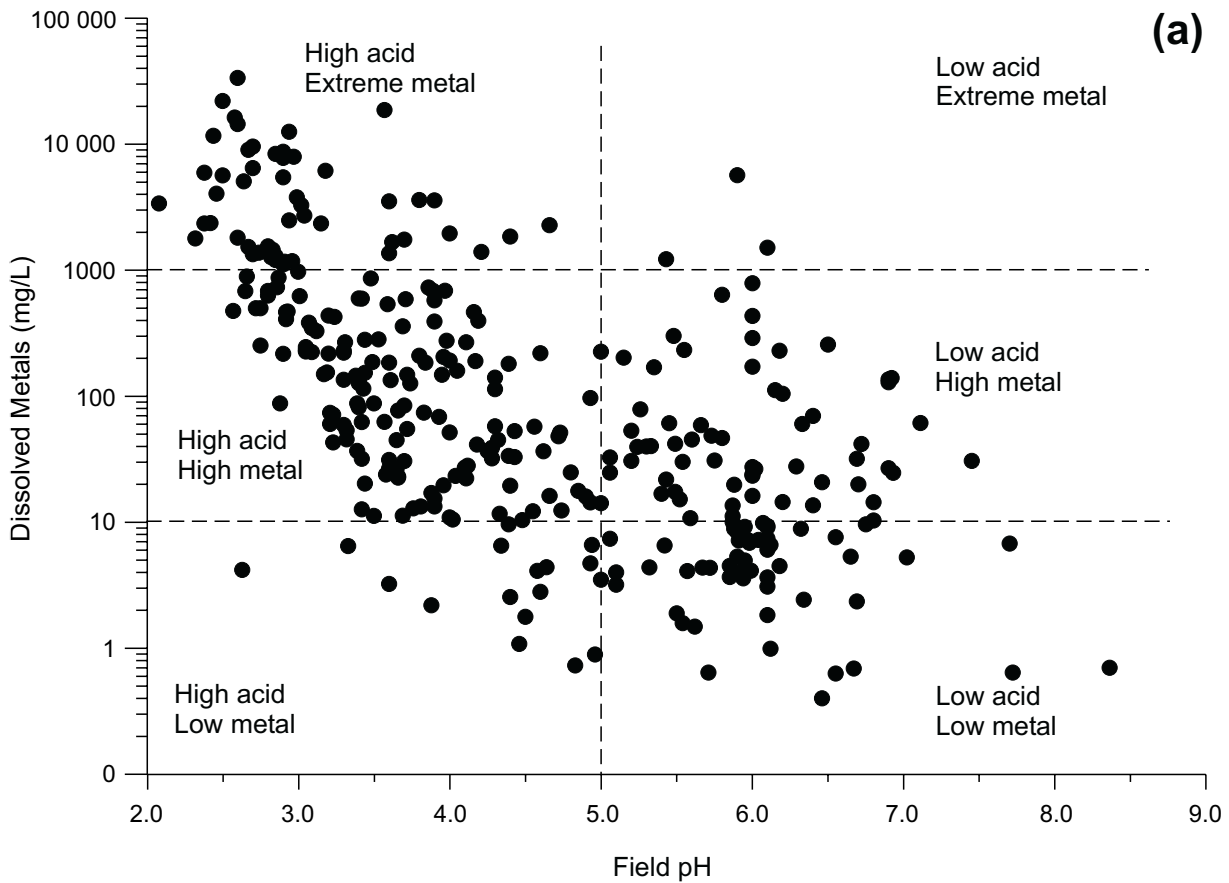


Figure 2

(a) Distribution of metals in waters impacted by abandoned mines
 (b) Selected site characterisation by metal levels in waters

drainage from these mine sites indicated that these metals are likely to be major contaminants discharged into the receiving environment during peak flow events.

Most base metal sulphide deposits in northwest Tasmania are hosted by volcanic rocks and associated pelitic metasediments. Locally, the host rocks have significant pyrite content and at some locations, for example the Mt Read and Mt Lyell areas, barren rocks are prone to weathering and oxidation. Because of the complex nature of the geology in the Mount Read Volcanics complex, the evaluation of the composition of surface waters draining geologically similar deposits located in a similar physio-environment cannot be generalised to predict the likely future water quality in the area impacted by abandoned mine sites. The localised events of acid drainage from specific abandoned mine sites can only be used to predict the likely geochemical environment for acid generation.

The net acid-producing potential of the majority of the base metal deposits in the North West mineral field are relatively high compared to the sulphidic metasediments of the northeast tin mining areas. Comparison of the different deposit types according to their reactivity (relative ease of production of acid) show that acid generation and metal release is not entirely dependent on the quantity of sulphide minerals but on the degree of exposure and weathering index of the host rocks. This is evident at Endurance and Storys Creek, and at the Reekara and Pearshape quarries on King Island. A plot of paste pH against NAPP can be used to classify the reactivity of exposed sulphidic materials according to their relative ease of acid producing capacity (fig. 3). Most base metal deposits have NAPP > 100 kg H₂SO₄/t and negligible ANC to neutralise the acid being produced.

The low sulphide containing waste rocks and tailings at abandoned tin mining sites in northeast Tasmania

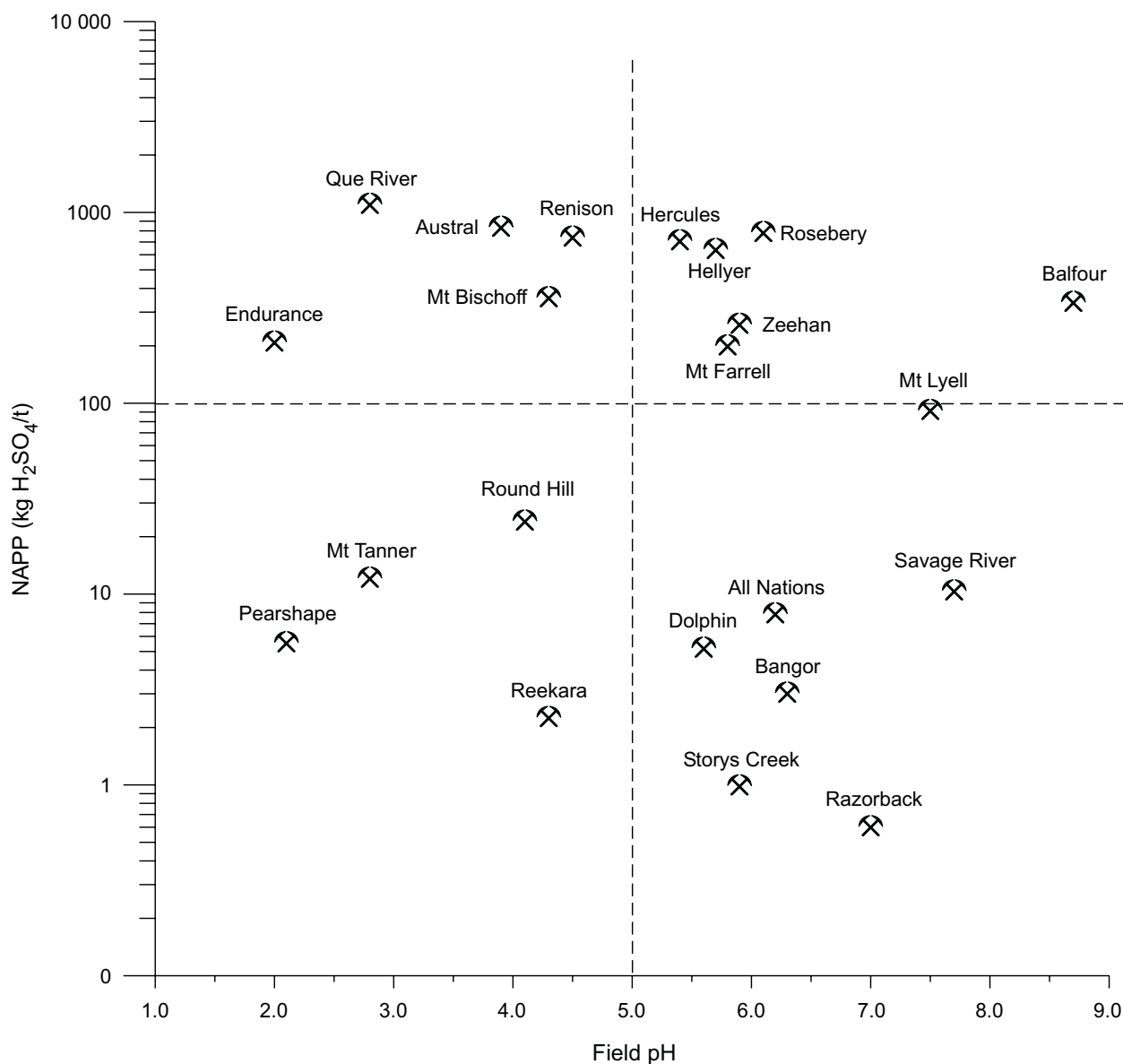


Figure 3

Comparative distribution of selected acid-producing mine sites (recently closed and some operating mines are also plotted for comparison)

generally plot in the low reactivity zone (fig. 3) except for the Endurance tin mine which plots in the high reactivity zone due to the high sulphide liberation capability of the rapidly weathering granite tailings. Most of the volcanic-hosted base metal abandoned mines in the North West mineral fields plot in the low to high reactivity zones, even though the host rocks commonly have NAPP ranging from 100 to 800 kg H₂SO₄/t.

The geochemical map (Map 3) generated from the digital elevation model surface expression of average NAPP values clearly shows the relative distribution of acid-forming rocks (AFR), potential acid-forming rocks (PAFR) and non-acid forming rocks (NAFR) in Tasmania. The majority of the potential acid producing abandoned mines were found to be located within AFR and PAFR zones in the geochemical map.

Inventory of acid-producing abandoned mines in Tasmania

Several abandoned mines, as well as recently closed and operating mines, were investigated in this survey. Many of the abandoned mine sites contained exposed sulphidic waste rocks and tailings deposits that are prone to oxidation processes and hence acid generation. A catchment breakdown of the inventory of mines with potential to produce acid drainage from oxidation of sulphidic materials is given in Table 6. The abandoned mine inventory with geochemical classification is presented in Appendix 1.

The following sections briefly describe the hydrogeochemical expression of acid drainage in catchments impacted by abandoned mines in Tasmania. Maps 1, 2 and 3 accompanying this report show the statewide status of acid drainage from abandoned mine sites. Local geology, mineral deposit types and geochemistry of the host rocks were used in delineating the geochemical distribution of acid-forming rock types in each catchment area. The geological descriptions of the rock types in each catchment area are from the *Geology and Mineral Resources of Tasmania* (Burrett and Martin, 1989). The

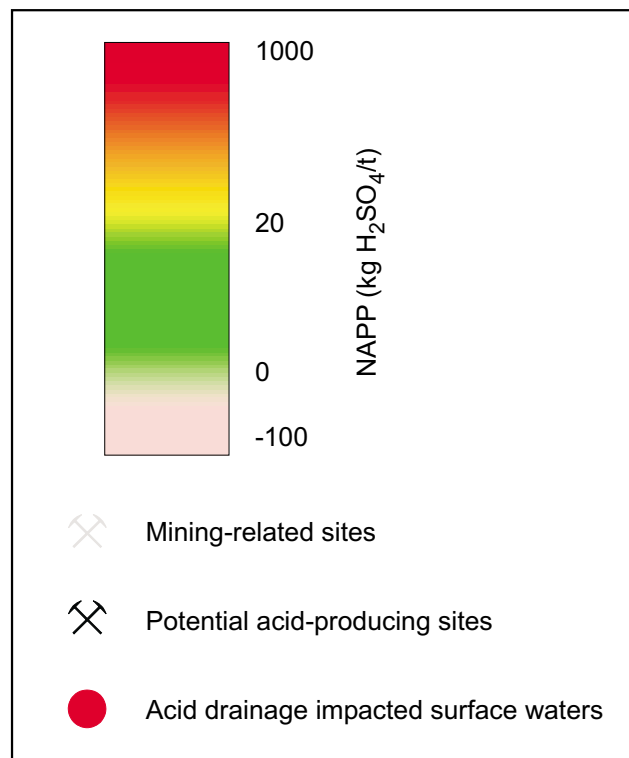


Figure 4

Hydrogeochemical legend for Figures 5 to 12

legend (fig. 4) applies to all the catchment figures in this section.

Arthur River catchment

There are over 100 mineral activity sites in the Arthur River catchment, with ten abandoned mines being identified as acid producers. Most of these acid-producing sites are located in the Mt Balfour and Mt Bischoff areas, which contain dominantly acid-producing rock types (fig. 5). Geochemical classifications show that waste rocks and tailings materials at the Balfour copper mine sites have NAPP values in excess of 300 kg H₂SO₄/t and negligible ANC. Trace elements of concern are Cu (102 500 mg/kg), As (70 mg/kg) and W (160 mg/kg). Cassiterite Creek and Emmetts Creek are the main

Table 6

Catchment-wise inventory of potential acid-producing abandoned mines in Tasmania

Catchment	Mineral activity sites (Status 1-9)#	Mine sites (Status 3-5)#	Potential acid producers	% potential acid producers
Arthur River	103	16	10	9.7
Pieman River	558	133	26	4.7
King River	170	45	11	6.5
Little Henty River	298	111	25	8.4
Ringarooma River	479	212	9	1.9
South Esk River	261	158	9	3.4
King Island	41	5	2	4.9
Flinders Island	15	1	0	0
Tasmania	4036	681	215	5.3

refer Authority tables for MIRLOCH data for status code under MIRLOCH.STA (McClenaghan *et al.*, 1996).

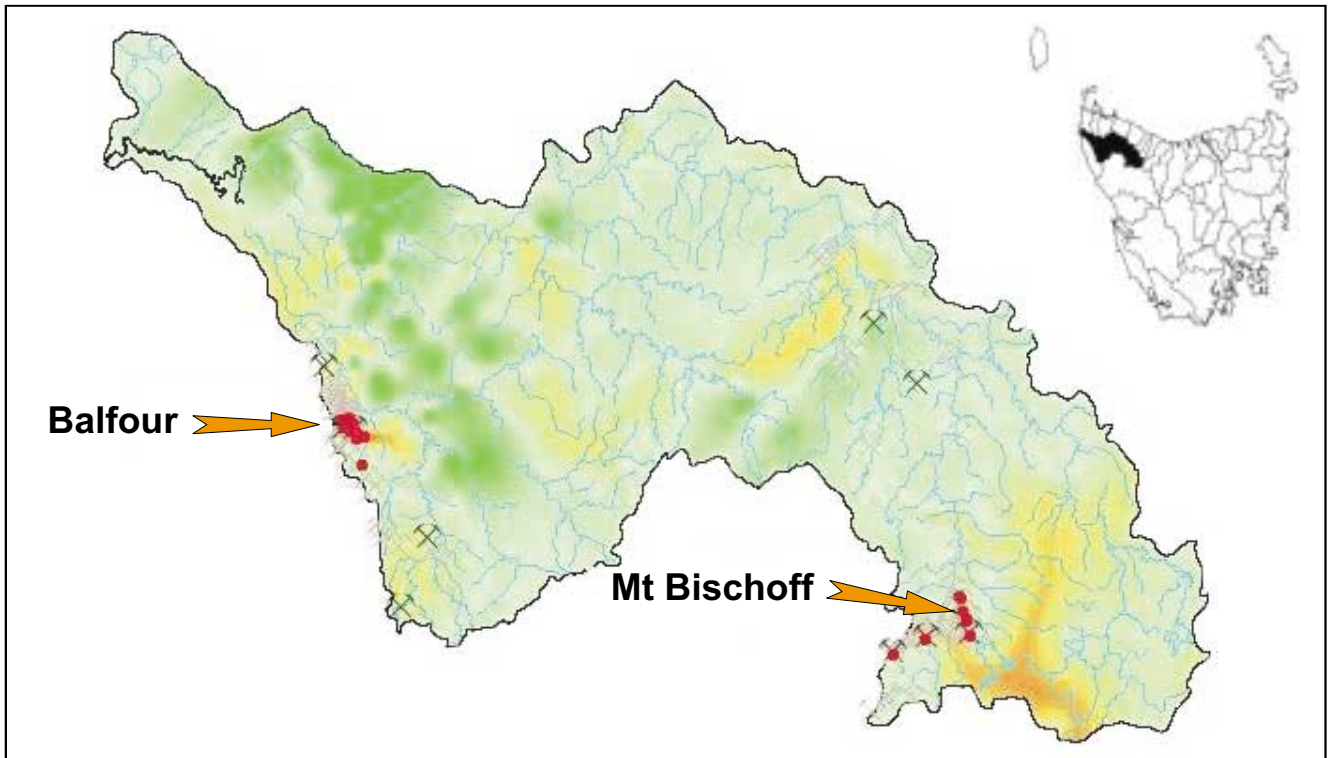


Figure 5

Hydrogeochemical expression of acid drainage in the Arthur River catchment

drainages over the abandoned mine sites. These creeks flow into the Frankland River about two kilometres downstream of the mine area. Surface waters at the mine site (runoff and Cassiterite Creek) are typical of active acid drainage sites, with high acid/high metal/high sulphate waters being affected by high trace metals released from the sulphidic rock materials (Plate 1). Open mine shafts and wetlands containing extremely acid waters and trace metal concentrates pose both physical and environmental hazards at the site (Plate 2).

Acid drainage at the Mt Bischoff tin mine is one of the worst in northwest Tasmania. Continuous discharge of high acid/high metal/high sulphate waters from the main adit has resulted in the accumulation of several thousand tons of oxidised sediments enriched with toxic levels of metals at exposed sites above the headwaters of the Waratah River (Plates 3 and 4). Typical NAPP values of over 450 kg H₂SO₄/t of the mineralised carbonate host rock means that the available ANC of 116 kg H₂SO₄/t is either insufficient or too restricted to neutralise the high amount of acid being generated. High concentrations of Sn (5100 mg/kg), Cu (320 mg/kg), Pb (97 mg/kg) and Zn (89 mg/kg) in the mineralised host rock indicate that these metals can be progressively leached by surface waters that drain into Waratah River and finally to the Arthur River some three kilometres downstream.



Plate 1. *Surface runoff of acid drainage at the Balfour copper mine*

Although base flow transportation of metals downstream may have minimal impact, the mass flux of metal-laden mine waste sediments during 50 or 100 year flood events can seriously impact on the ecosystem of the receiving environment.



Plate 2. Acid drainage in open shaft at the Balfour copper mine



Plate 3. Acid drainage discharge from Mt Bischoff tin mine adit



Plate 4. Acid drainage at Mt Bischoff

Pieman River catchment

The Pieman River catchment contains the highest number of mineral activity sites (558). Over 133 abandoned mines occur in the catchment, most of which fall within the current leases held by the operators of the Rosebery, Renison and Savage River mines. Geochemical classifications show that the rock types hosting many of these mine sites generally have NAPP > 20 kg H₂SO₄/t and insufficient or unavailable ANC for neutralisation of the acid being produced (fig. 6).

Many of the abandoned mines located in the Pieman River catchment have a history of acid drainage pollution problems and as such, have had a major impact on water quality in the area. Downstream environmental impacts on water quality in the Pieman catchment have been reported by Koehnken (1992, 1999) and the direct impacts from mining operations are being monitored by the operating mines in the area (Renison, Rosebery and Savage River). Several abandoned mines in the Rosebery mineral field area have been identified as having acid drainage problems which are seriously impacting on the Ring River, which drains into the Pieman River below the Renison tin mine. Abandoned mines in the area (Jupiter, Koonya, Salisbury, Blacks PA, Burns Tunnel) and the TME sites have been identified as potential acid drainage producers (Dellar, 1998). Several point and diffuse sources of acid drainage, as well as known discharge from the recently closed Hercules mine site (Smith, 1998), may have significant impact on surface and groundwater quality in the catchment.

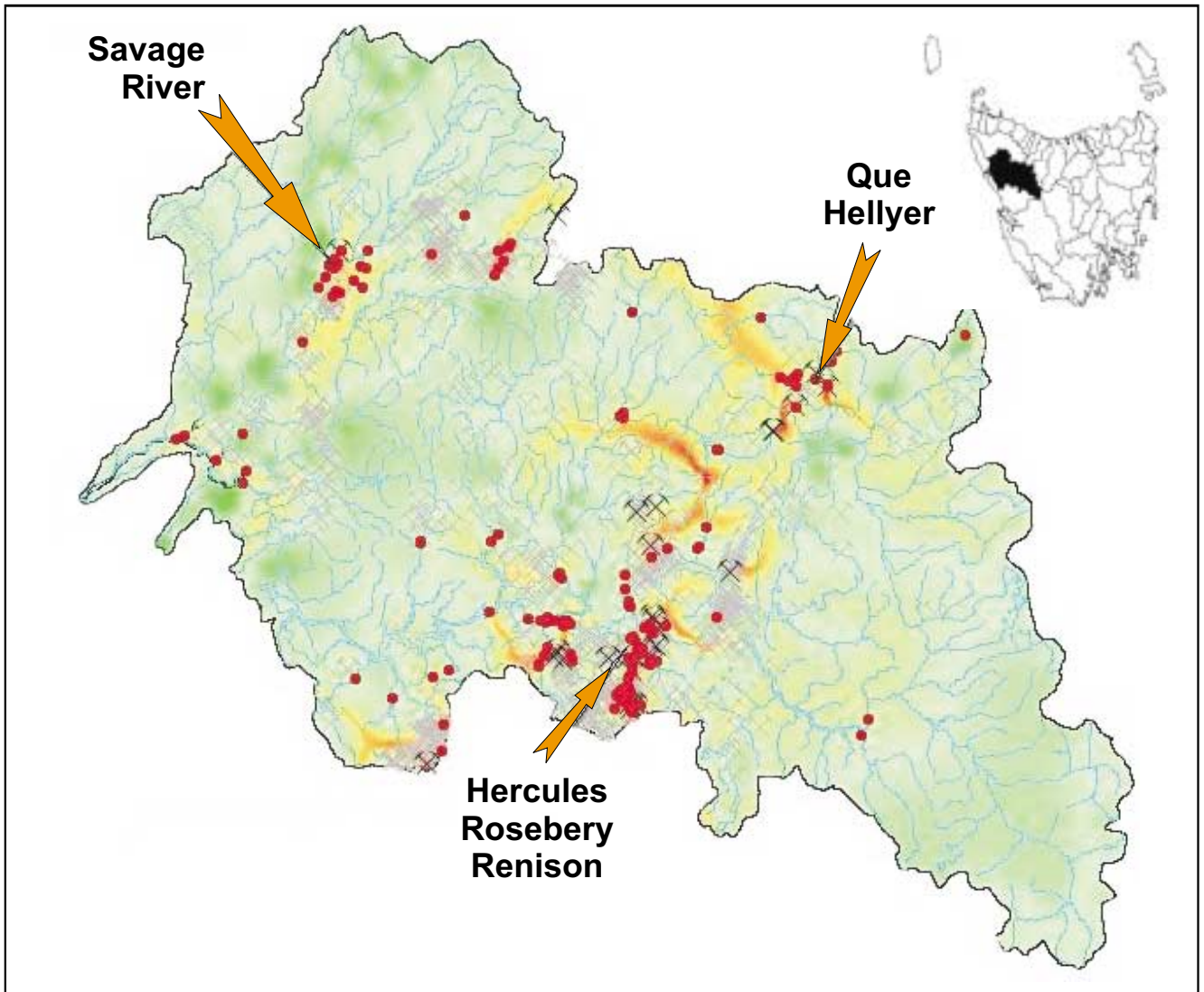


Figure 6
Hydrogeochemical expression of acid drainage in the Pieman River catchment

King River catchment

There are over 170 mineral activity sites in the King River catchment, with 45 abandoned mines having a history of base metal and tin mining in the catchment. Eleven of the mine sites are identified as either potential acid producers or are currently releasing acid drainage. Most of the mine sites are located on the Mt Lyell mineral field which contains dominantly acid-producing volcanic metasediments of the Mount Read Volcanics suite of rocks (fig. 7). Geochemical characterisation shows that exposed host rocks, mine waste and tailings materials have NAPP commonly in excess of 90 kg H₂SO₄/t and negligible ANC at the majority of sites in the Mt Lyell area. Trace elements of concern in the weathered sediments are mainly Cu (>9000 mg/kg) and Zn (~200 mg/kg).

Several reports are available on the environmental impact on water quality from acid drainage at Mt Lyell (Klessa *et al.*, 1997; Koehnken, 1997; Locher, 1997; Miedecke, 1996; Taylor *et al.*, 1996; McQuade *et al.*, 1995; de Blas, 1994). The major streams affected in the catchment are Linda Creek (Plate 5), Queen River and the King River. Numerous runoffs from the exposed Mt Lyell area also carry acid drainage into the Queen River during wet seasons. Various reports have described the acid drainage problem in the Mt Lyell area and the mine sites are still under a currently operating Mining Lease. Figure 7 shows the distribution of potential acid-forming mines located in the catchment.

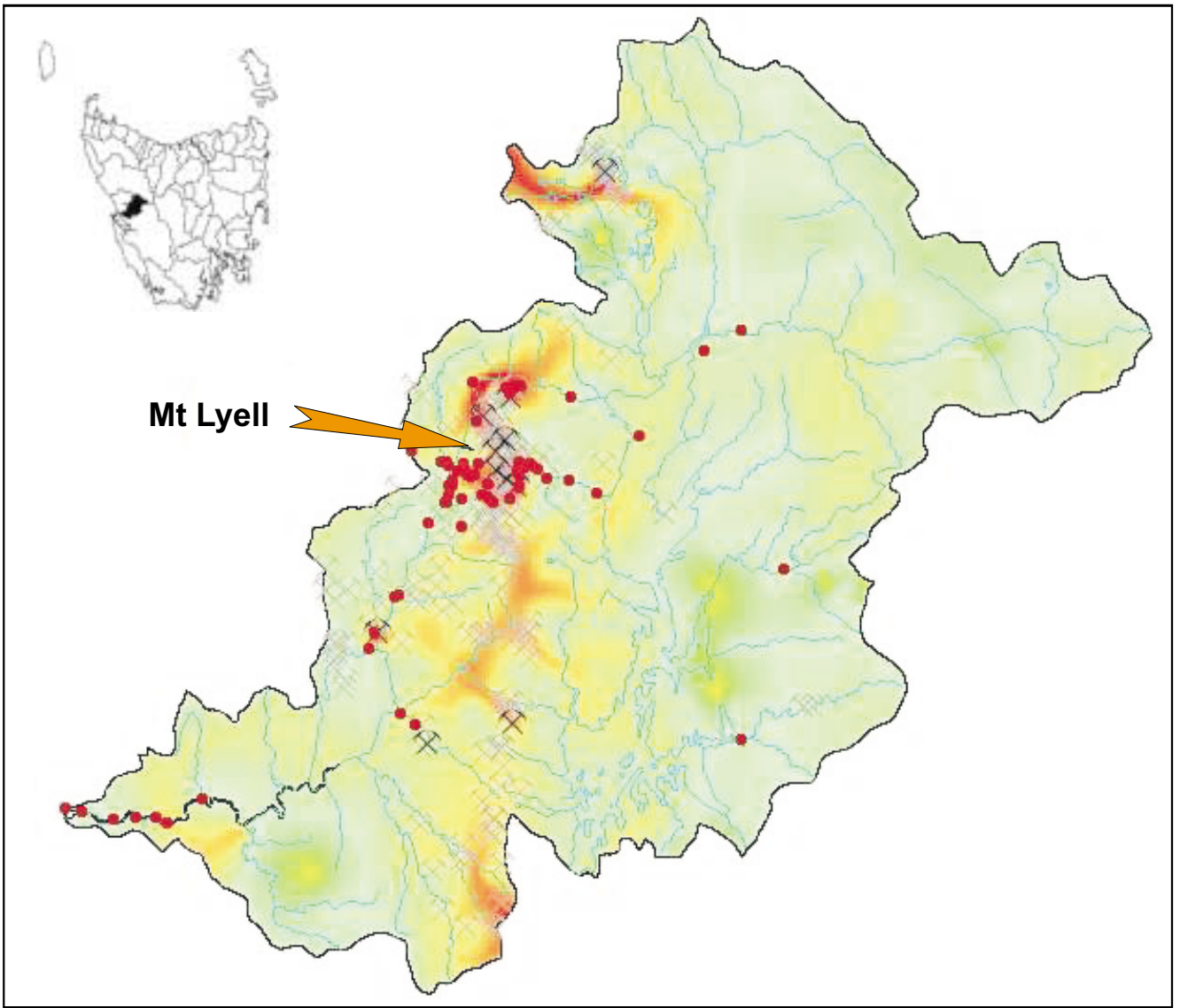


Figure 7
Hydrogeochemical expression of acid drainage in the King River catchment



Plate 5
Acid drainage impacted Linda Creek, Mt Lyell

Little Henty River catchment

The Zeehan mineral field contains the largest concentration of abandoned mine sites in the catchment of the Little Henty River. There are over 111 abandoned mine sites with potential to produce acid. Around 25 mines have been identified as currently producing acid or as having a high incidence of acid drainage at the site. Host rocks and mine waste rock materials associated with abandoned mines in the Zeehan area generally have high NAPP (>20 kg H₂SO₄/t) and trace elements (Pb, Zn and As). The rock types in the area are dominantly pyritic, as indicated by the spatial distribution of acid-forming rocks in the catchment area (fig. 8).



Plate 6

Surface runoff of acid drainage at the Austral tailings site, Zeehan

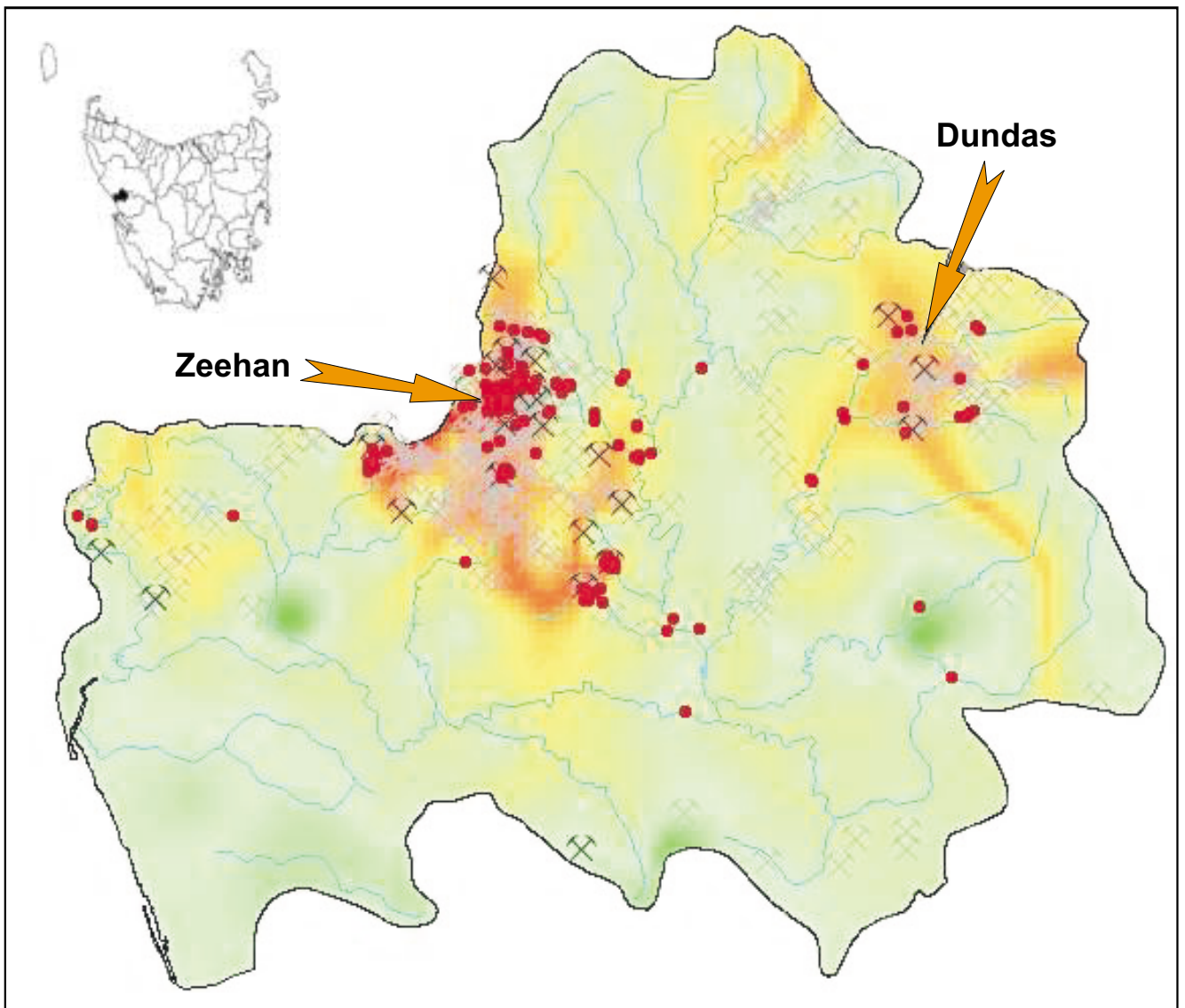


Figure 8

Hydrogeochemical expression of acid drainage in the Little Henty River catchment



Plate 7. *Low pH-high metal wetland sediments near the Florence mine, Zeehan*

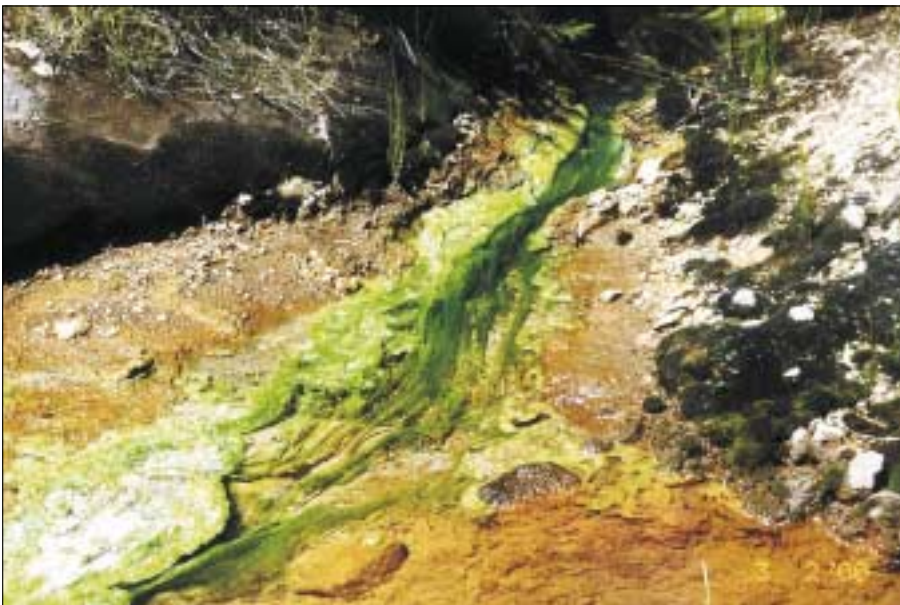


Plate 8. *Acid drainage discharge from Queen Hill adit, Zeehan*



Plate 9. *Acid drainage impacted Zeehan Rivulet*

The underlying Gordon Limestone appears to provide little acid neutralisation, mainly because of its restricted availability for neutralisation and the relatively high NAPP of the ore rocks. Abandoned mine sites such as Queen Hill, Spray, Florence, Oceana and Austral (Plates 6–8) are significant acid producers. Other sites, such as Razorback and Red Lead in the Dundas area, also produce acid drainage with typical high acid-high metal composition. Much of the Zeehan area contains pyritic sediments from past mining activity.

Most surface waters draining the Zeehan mineral field are impacted by acid and metal released from the abandoned sites. Major streams such as Zeehan Rivulet (Plate 9), Silver Lead Creek and Austral Creek are heavily impacted by acid drainage and may carry significant contaminant loading to the Little Henty River during peak flow events. Dominant metal contaminants of concern are Pb and Zn, which also have low adsorption capacity and a greater transport distance over a wide pH range.



Plate 10. Acid drainage discharge from Round Hill adit, Sheffield area



Plate 11. Surface ponding of acid drainage, Endurance tin mine tailings



Plate 12. Acid drainage impacted Ruby Creek, Endurance tin mine

Ringarooma River catchment

The Ringarooma River is a major catchment heavily impacted by tin mining activity in northeast Tasmania. There are over 479 recorded mineral activity sites, with 212 being in the abandoned mines category. Geochemical classification indicates that around nine of these sites are potential acid producers (fig. 9). The main sites currently producing acid drainage are the Endurance, Monarch and Star Hill tin mines. Acid drainage problems at these sites have been investigated and rehabilitation programs are being progressively implemented (Bennett, 1999; de Jong, 1999; SEMF, 1998).

The pyrite in the acid-producing sites is possibly reworked panned concentrates derived from overburden Tertiary sediments buried in granitic tailings. Although the tailings are not acid forming, as indicated by SEMF (1998), pockets of cemented gossans within the tailings have high NAPP (150–200 kg H₂SO₄/t) and low paste pH (~2.0), indicating active pyrite oxidation below surface. Because of the porous nature of the tailings, oxidation of the buried pyritic sediment may be occurring continuously. The acid generated is continuously being released into Ruby Creek by perched groundwater flow along the hardpan surface. Possible hardpan at depth is indicated by surface ponding during rainfall (Plate 11). Similar conditions may occur at Monarch and the Star Hill tailings.

Ruby Creek and several diffuse seepages from the tailings areas discharge high acid–high metal waters into the Ringarooma River some two kilometres downstream. Most streams in the area are impacted by tin mining tailings.

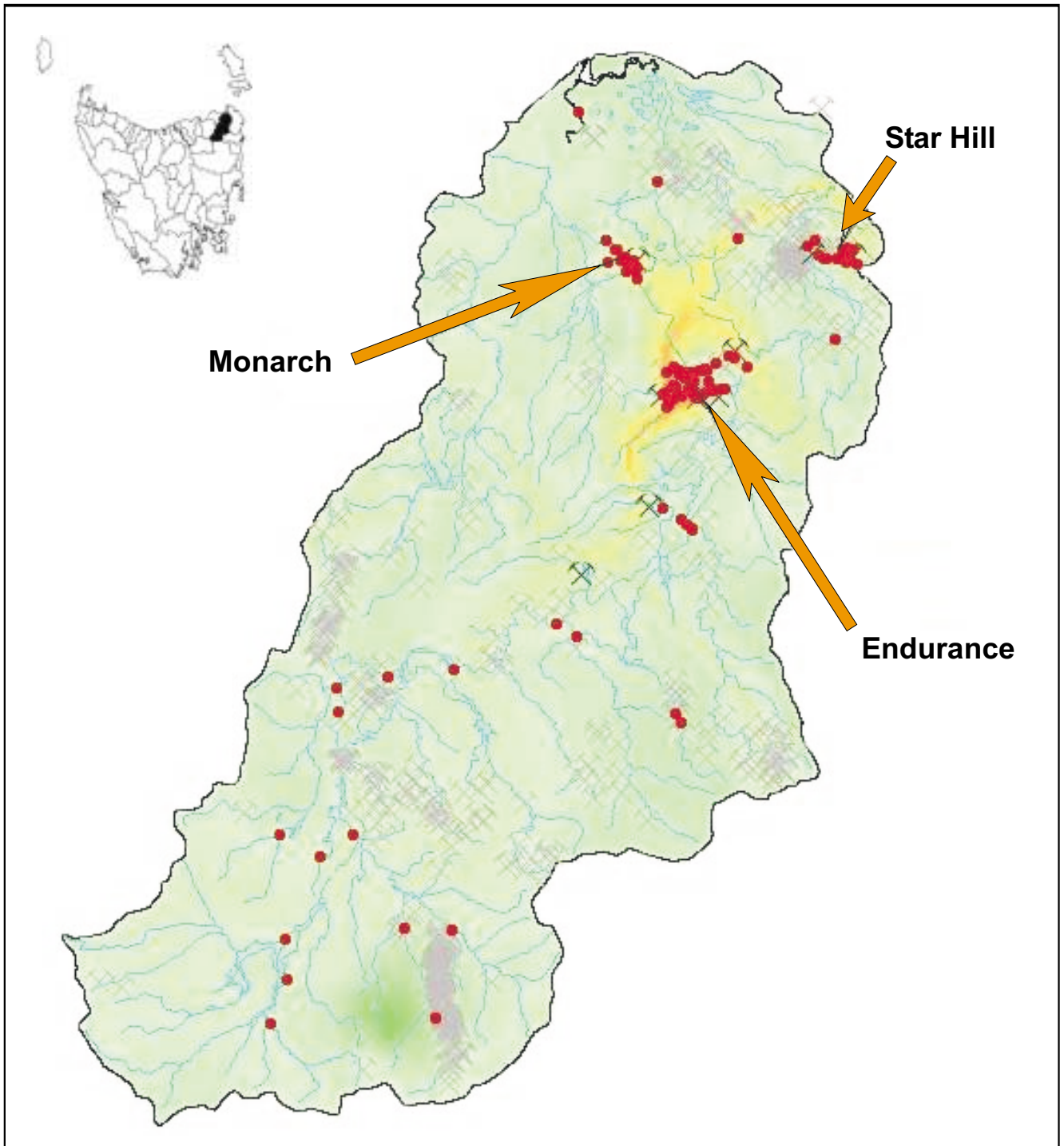


Figure 9
Hydrogeochemical expression of acid drainage in Ringarooma River catchment

South Esk River catchment

Over 261 mineral activity sites are located in the South Esk River catchment, out of which 158 are classed as abandoned mines. Most of the mines are associated with alluvial gold and tin mining in the area. Rock types in the mining areas are predominantly Mathinna suite metasediments consisting of mudstone, slate and quartzite sequences. Geochemical classification shows that rocks proximal to granite intrusions are mineralised with quartz sulphide veins and disseminated sulphides in the slate and mudstone. About nine abandoned mines have rock types that

show positive NAPP (0–20 kg H₂SO₄/t) and are therefore potential acid producers (fig. 10). Although the Mathinna Beds host rocks may be non-acid forming, waste rocks and tailings may be possible acid producers mainly because of pyrite segregation. This may be the case at Storys Creek and is a likely scenario in greisen-vein granite-induced tin-tungsten mineralised rocks in which pyrite may occur as discrete late phase quartz-sulphide veins.

Main contaminants of concern in the surface waters in the catchment are As, Cd, Zn and Sn. The low alkalinity and high bed loading of tailings are

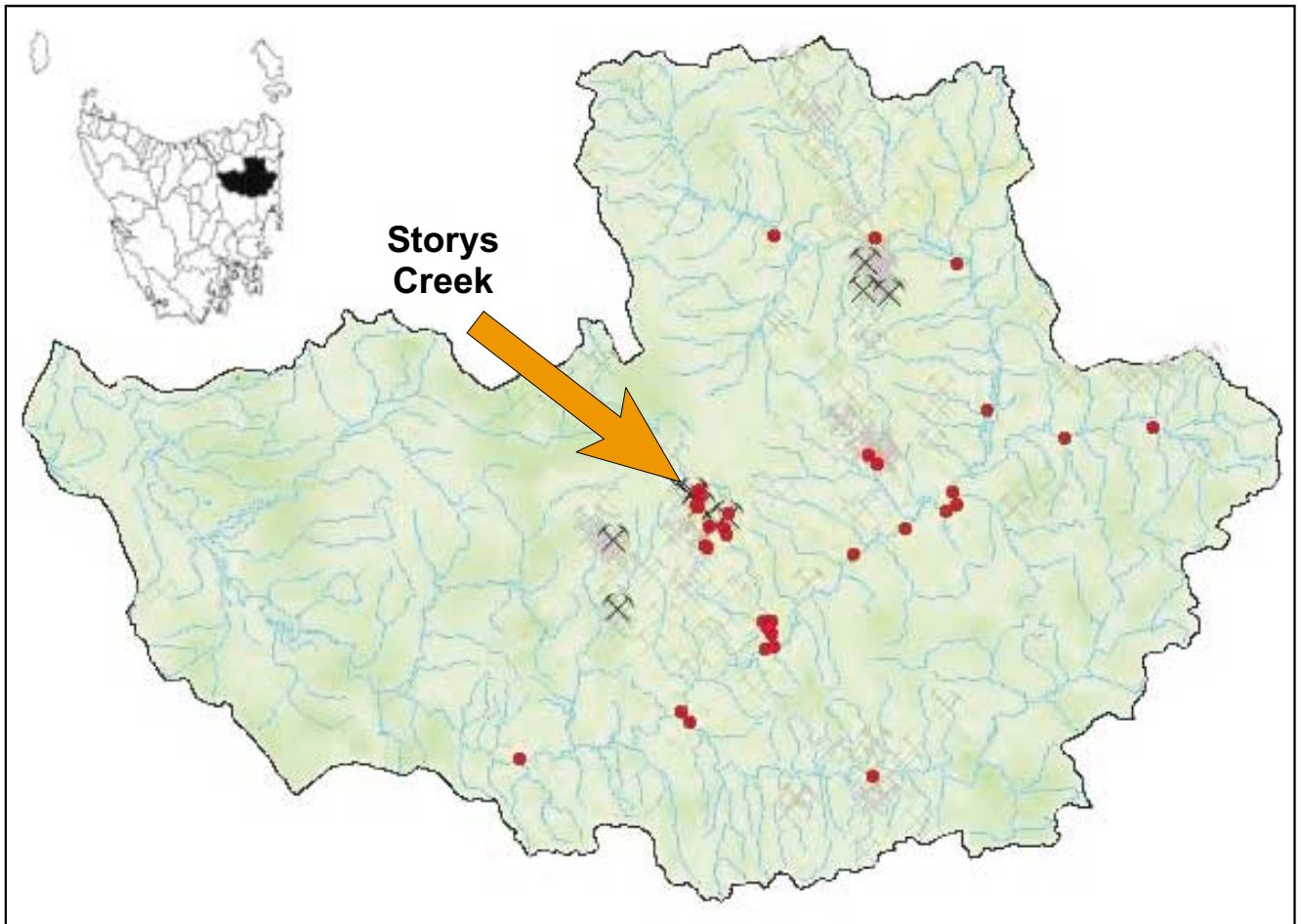


Figure 10

Hydrogeochemical expression of acid drainage in the South Esk River catchment

generally the main factors facilitating mobilisation of metals in the impacted waters. The large quantities of tailings deposited along stream banks may provide a continued source of acid drainage during progressive scouring of the channel bed. Downstream displacement of such materials during major flood events may also pose a serious impact to the aquatic environment. The impact on the South Esk River from such an event at Storys Creek is a likely possibility. Remediation of acid drainage sources in the Storys Creek area is being carried out by Mineral Resources Tasmania (Miedecke, 1998).

King Island

There are over 41 mineral activity sites located on King Island of which five are listed as abandoned mines. The two major mine sites on King Island are the Dolphin and Bold Head scheelite deposits which contain host rock skarn associated with granitic intrusions. The host rocks in these mines have a very low potential for acid forming but tailings and waste rock materials from these mines may contain isolated pockets of pyrite concentrate that are susceptible to oxidation and localised acid seepage. The background geology

indicates that the correlates of the Rocky Cape Group metasedimentary rocks, that roughly cover the southern half of the island, contain sporadic mineralisation with pyrite and pyrrhotite, especially at the contact zones with the granite intrusions. Rock types exposed at these sites are predominantly pyritic metasediments with NAPP of 0–20 kg H₂SO₄/t (fig. 11).

Field expression of acid drainage is evident at a number of localities, notably at the Pearshape and Reekara quarries where pelitic metasedimentary rocks (containing disseminated pyrite) are mined for road metal (roads constructed with aggregates from these quarries are likely acid producers). Surface waters (seepage and ponds) are highly acidic with Al, Cu, Mn and Zn being the main elements of concern. Downstream impact on the Seal River from acid drainage discharge at Pearshape has been studied by Innes (1993). The quarry is now flooded to minimise acid drainage generation and therefore the release of metal contaminants into the Seal River is likely to be minimal. Any metal contaminants during peak flow are likely to be adsorbed by richly organic sediments at Colliers Swamp.

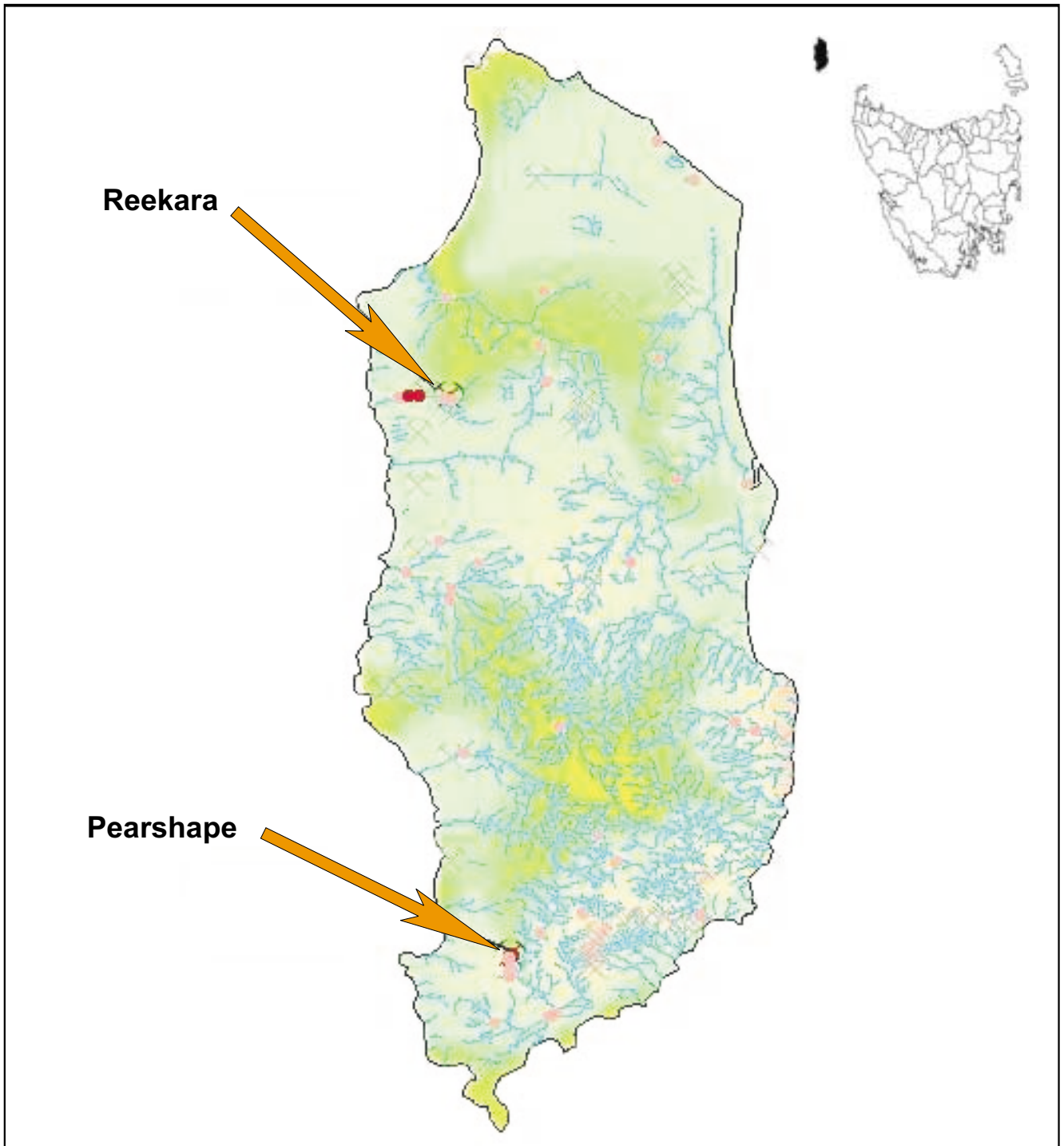


Figure 11
Hydrogeochemical expression of acid drainage on King Island

Flinders Island

Distribution of low potential acid-forming rocks on Flinders Island is limited to small patches of Mathinna Group rocks around Whitemark and the Lady Barron area. Most of Flinders Island consists of Quaternary sediments and intrusive Devonian granitic rocks which are generally non-acid forming types. There are about fifteen small mineral activity sites on Flinders Island but only the abandoned Mt Tanner tin mine site is considered a significant acid producer (fig. 12).

Weathering of isolated quartz-sulphide veins in the granite jig tailings may have been responsible for acidic waters in ponds and in seepages that drain into Mine Creek. The jig tailings at Mt Tanner do not contain any significant trace metal concentrations.

Surface water quality on Flinders Island is not impacted by mining activity except at Mt Tanner and at Officers Creek near Whitemark, where mine waste dumps have had a significant impact on the creek channel beds. General water quality in the major

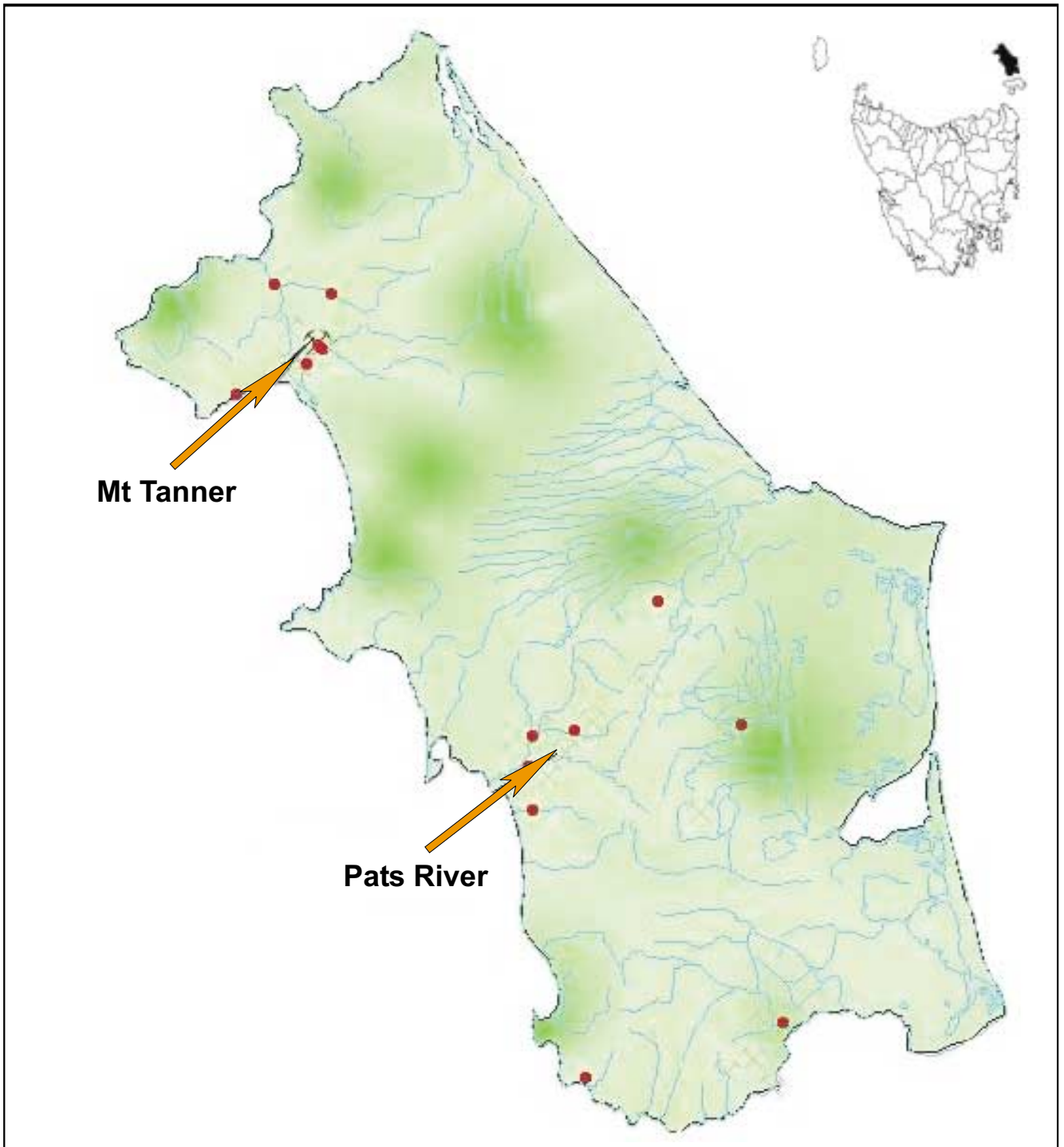


Figure 12
Hydrogeochemical expression of acid drainage on Flinders Island

drainage (Pats River, Samphire River and Patriarch River) is poor and with increasing demand on the island's limited water resources (from increased land use practices) water development and water quantity are likely to be issues of concern. Limited groundwater

data indicate that high Fe and salinity are possible water quality problems affecting the island's groundwater resource.

CONCLUSIONS

Tasmania has over 215 abandoned mine sites that are potential acid producers or are currently producing acid. A majority of these sites also fall within current mining leaseholds. The high incidence of abandoned mines in areas dominated by acid forming rocks indicates that acid drainage is likely to occur in many of these sites.

Abandoned mine impacted waters range from high acid/extreme metal to low acid/low metal. A similar trend was also shown by sulphate distribution. High correlation between metal and sulphate distribution indicates that sulphate may be used as a cost-effective reconnaissance tool for acid drainage assessment.

Surface waters impacted by acid producing abandoned mines generally contain metal pollutants about ten times higher than the ANZECC (1992) values for aquatic environments. Point and diffuse sources of acid drainage are likely to affect environmental base flows in catchments heavily impacted by a base metal mining history.

Low pH/high sulphate/high metal waters are commonly sourced from abandoned mines with high NAPP materials. Carbonate-hosted base-metal mines are generally high acid producers, mainly because of the restricted availability of acid neutralisation from the host rock.

Many base metal abandoned mine sites contain large deposits of reactive waste rocks and tailings that have high concentrations of trace metals. Surface waters from such sites are generally high metal/high sulphate types. Downstream impact from mass loading of these reactive waste rocks and tailings during major flood events is a serious threat to the receiving environment.

Because of the reconnaissance nature of this survey, the information provided in this report and accompanying maps is intended to serve only as a preliminary guide to addressing management and remediation strategies of the acid drainage pollution problems.

RECOMMENDATIONS

Lack of sulphur analyses in the ROCKCHEM database was a major constraint in geochemical characterisation of acid-forming rocks from abandoned mine sites. A routine sulphur analysis in all samples from geological and geochemical investigations will allow quick assessment of the potential acid-forming nature of host rocks in an area.

Hydrochemical assessment of acid drainage requires analysis of specific parameters not always measured in routine water quality analyses carried out for

environmental monitoring of aquatic ecosystems. More extensive surface water and groundwater sampling and analysis needs to be carried out for accurate delineation of catchment areas impacted by acid drainage from abandoned mines.

Site-specific hydrogeochemical characterisation of potential acid-producing abandoned mines needs to be carried out in quantitative assessment of point and diffuse sources of acid drainage and downstream impact from metal contaminant mass loading. Such a characterisation is important in effective implementation of remediation methods.

The impact on water quality from residual pollutants, such as mercury and cyanide, from past ore processing waste materials at many of the abandoned gold mining sites in northeast Tasmania has not been assessed. These deserve independent study in tandem with acid drainage investigations.

The hydrogeochemical data on the inventory of acid-forming abandoned mines is incomplete. Systematic environmental assessments of all the potential and actual acid-producing sites needs to be carried out to enable the selection of priority sites for detailed characterisation and remediation options.

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