Verum Group

Assessment of zinc mobilisation from coal mines

The Parliamentary Commissioner for the Environment

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Contents

1. Executive Summary

Zinc occurs as a trace element in overburden rocks disturbed by coal mining. There is little data available on the total concentration of Zn that occurs in these rocks because mining companies and regulators focus on the potential for acid formation from rocks disturbed by mining and the concentrations trace elements including Zn that can be leached from overburden rocks during weathering. Most Zn that can be easily leached from overburden during weathering processes is associated with sulphide minerals, most commonly pyrite.

The total sulphur (S) can be used as a proxy for the pyrite concentration of rocks and this value is variable depending on the geology of the formations that host the coal. We have compiled the total S data for most sets of coal measure rocks where mines are currently active in New Zealand. We have also compiled all available data on weathering tests for these rocks. The total S and weathering test dataset is more abundant for mines that occur in acid forming rocks compared to mines that occur in non acid forming rocks. The amount of Zn that is available to be leached is higher in the acid forming rocks compared to non acid forming rocks.

Based on these data sets and related assumptions we have calculated the total amount of leachable Zn that is moved during overburden handling at coal mines and this value is likely to be about 135 tonnes of Zn per year with a high estimate of 360 tonnes of Zn per year and a low estimate of 30 tonnes per year. The reason for the high uncertainty in this estimate is because the value is derived from two datasets that have high variability, total sulphur and Zn released during weathering tests. In addition, the amount of overburden rock that is moved during mining each year is variable.

Zinc discharged by coal mine sites through mine drainages has been calculated by two methods where possible. At some sites there is sufficient measured stream flow data and Zn concentration data to measure the annual Zn discharge. At other sites there is insufficient data to measure the annual Zn discharge, and at these sites the area of disturbance has been measured and multiplied by the rainfall to develop a conservative annual flow model for the site. The flow model is combined with Zn concentration monitoring data if possible or with Zn concentration data from mines with similar geology.

Using these datasets the total Zn that is discharged to the environment is 35 tonnes ± 15 tonnes per year. Datasets to support this calculation have not been collected with a view to calculation of annual loads of trace elements to the environment and so there is some uncertainty in this estimate. Sources of uncertainty and variability in this estimate relate to changes in concentration with time, variations in rainfall and uncertainty related to dilution or flushing of Zn during high rainfall events.

The dataset for leachable Zn represents an annual snapshot and the value is is directly related to the volume of waste rock that is moved. The amount of Zn that is discharged each year is cumulative and includes areas that have been mined in the last year as well as residual Zn that continues to discharge from parts of the mine that are older than 1 year. Only a portion of the leachable Zn will be discharged at an accelerated rate, because the overburden management measures that mine sites put in place to minimise acid release will also prevent Zn release.

2. Scope and Introduction

2.1 Scope and objective

This report provides an estimated mass balance of Zn disturbed by coal mining operations in New Zealand using best available data. This report integrates Zn concentration data from rocks and catchments, flow volumes for mining impacted streams and the amount of overburden rocks that are moved and rehabilitated during coal mining.

This report calculates national values for:

1. the amount of Zn in coal mine waste rock that is available for leaching
2. the amount of Zn discharged from active coal mine sites into receiving catchments

2.2 Where are New Zealand's coal mines?

Coal is mined throughout New Zealand with different qualities and properties and for different purposes. The main purposes are energy for domestic industry, thermal power generation, coke production for offshore steel making, and domestic steel making. Most active coal mines are located in the Waikato, West Coast, Otago and Southland regions (Figures 1). However, historic mines, inactive/closed mines and unmined coal deposits are located in other parts of New Zealand. This report focuses on discharge of Zn from active mine sites, but a similar study could be completed for historic mine sites. Where these sites have been abandoned (prior to the 1970s), it is likely that there are significant additional discharges of Zn into the environment. Where sites have been rehabilitated and closed additional discharges of Zn are likely to be minimal.

2.3 Where is the Zn associated with coal deposits?

2.3.1 Brief description of coal mining

Coal mines have a stratigraphy that remains relatively consistent at each deposit. The stratigraphy that includes and surrounds coal deposits form in a terrestrial environment and are called coal measures (note the majority of sedimentary rocks form sub-aqueously in lakes or oceans). Coal measures typically include sandstones, mudstones and conglomerates of varying thickness. During open cast mining coal measures that overlie the coal are removed and the coal is mined, the coal measures (and possibly other rocks) that must be removed to extract the coal are called overburden rocks. Typically the overburden rocks are capped by a soil profile and so the mining process usually involves 5 steps:

1. stripping and stockpiling soil
2. removal of overburden to expose coal
3. extraction of coal
4. replacement of overburden into the void after mining
5. reshaping the landform, replacing the topsoil and replanting in accordance with consent conditions

Commonly all steps operate simultaneously at a mine, so steps 1 and 5 and steps 2 and 4 are linked to minimise double handling of material where possible. Underground coal mines have contributed to

New Zealand coal production significantly in the past, but there are currently no active underground coal mines in New Zealand.

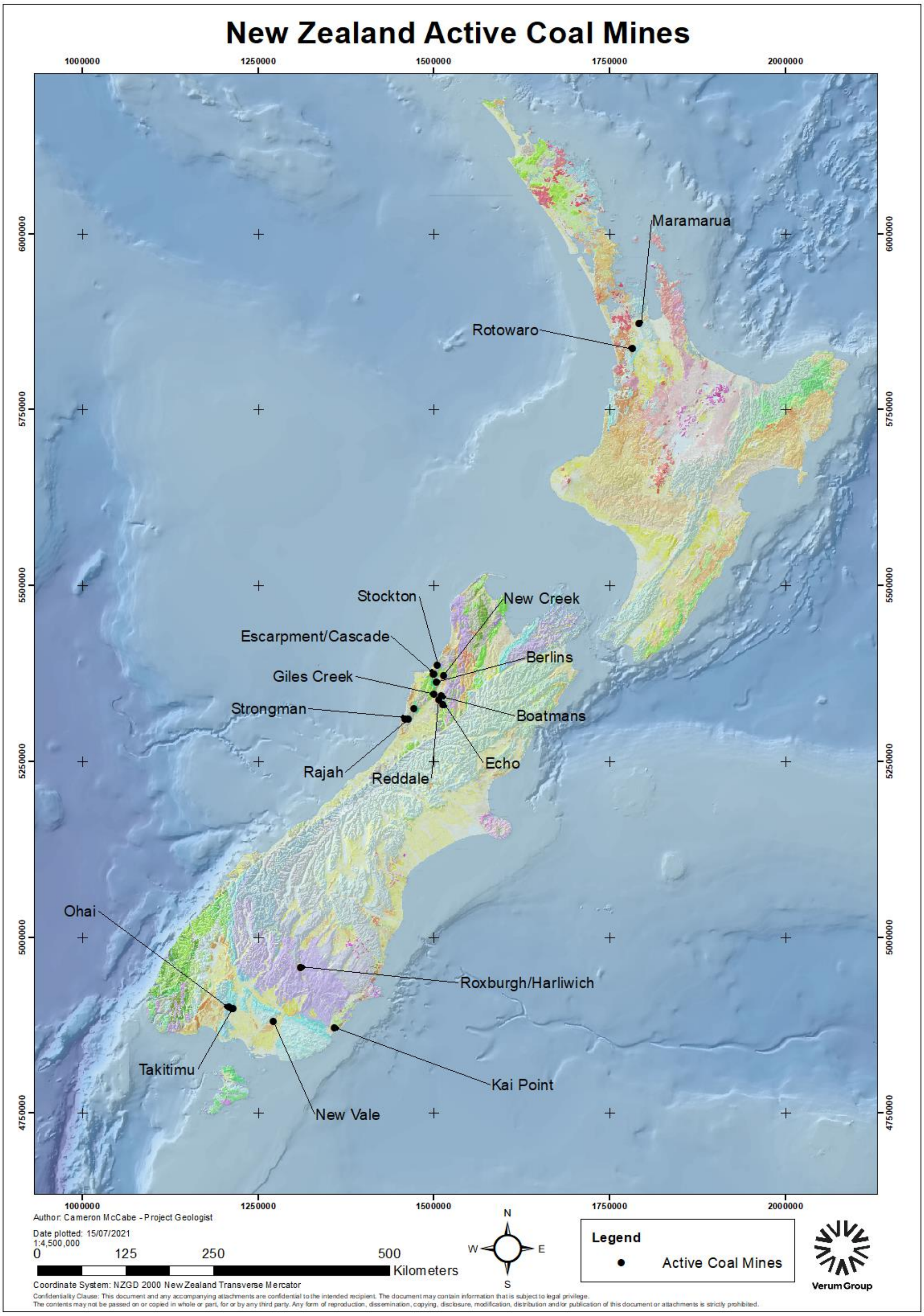

Figure 1. Locations of active coal mines in New Zealand plotted on 1:1,000,000 scale Geological map of New Zealand (GNS Science).

2.3.2 How does Zn get into mine drainages?

Zinc and other trace elements occur naturally in overburden rocks that are removed to access coal. The disturbance of in situ rock for mining can increase the rate of weathering processes. In general, there are two possible outcomes for weathering of overburden at coal mines depending on the mineralogy of the rocks. One outcome is neutral mine drainage where the pH is circum neutral and acidity is low and the other outcome is acid mine drainage where the pH is low and the acidity is high so, coal mine drainage chemistry is bimodal (Pope, Newman et al. 2010).

Neutral mine drainages (NMD) form when weathering of overburden rocks produce alkalinity and drainage from mine impacted areas have circum-neutral pH, 6-8. The concentrations of dissolved components in NMD can fall within background values for local surface water, or concentrations of dissolved components, including trace elements like Zn, can be elevated compared to local surface waters.

Acid mine drainages (AMD) form when weathering of the overburden rocks produce acid and drainages from mine impacted areas have low pH, 3-5. The reactions that form acid are controlled by redox chemical processes and usually release elevated concentrations of trace elements including Zn. The products of these redox reactions can catalyse further acid forming reactions and this can lead to rapid acidification of surface waters at mine sites.

2.3.3 How do mines assess and manage drainages?

In general data sets collected at mine sites are not for the purpose of calculation of annual loads of different dissolved components into the environment. Instead the datasets collected at mine sites are for the purpose of prediction and management of mine drainage chemistry to meet compliance criteria. Identification of methods most useful to predict and manage mine drainage chemistry has been a focus of global research for the last 40 years and several international practise modules have been developed for the minerals sector by the International Network for Acid Prevention (INAP). Science quality for emerging mine water science is led by the International Mine Water Association (IMWA, publishers of Mine Water and the Environment) and other peer reviewed journals where research findings have been published such as Applied Geochemistry, Science of the total Environment and Chemical Geology. In New Zealand, research into mine drainage prediction and management has been led by CMER (Centre for Minerals Environmental Research, www.cmer.nz), and is often published in the New Zealand Journal of Geology and Geophysics. Work by this team culminated in 2018 with the release and publication of the Mine Environment Lifecycle Guides (Cavanagh, Pope et al. 2018).

In general, the outcomes of these research projects and many related mining industry led studies (locally and globally) provide:

- a geochemical testing framework for mines to complete ahead of mining
- a range of overburden management, surface water management and rehabilitation options to deliver the best outcomes for mine drainage quality
- a range of treatment options for mine sites to meet surface water quality targets
- advice on broader aspects of minerals sector environmental best practise

Mines then adapt their operations to allow for local climate and geology and use prediction, management and treatment to deliver discharges to the environment that meet consent conditions.

Consent conditions are usually based on an acceptable departure from background values supported by ecotoxicology studies (eg, Champeau and Cavanagh 2010).

2.3.4 Geology of New Zealand's coal mines

Coal is mined in New Zealand from seven main geological formations and these can be used to link the types of mine drainage chemistry that occur at the mines (Pope, Weber et al. 2010) (Table 1) including the potential for enriched concentrations of trace elements such as Zn.

Table 1. Geological formations that host New Zealand active coal mines

Geological Formation	Age	Region	Mines or resource	Production tonnes (2019) or status
Waikato Coal Measures		Waikato	Rotowaro Mine	652 300
			Maramarua Mine	246 144
Brunner Coal Measures		West Coast	Stockton Mine	1 041 958
			Echo Mine	59 979
			New Creek Mine	10 455
			Reefton Mine	51 705
			Berlins Mine	7 489
Paparoa Coal Measures		West Coast	Strongman Mine	55 430
			Rajah Mine	158 553
Rotokohu Coal Measures		West Coast	Giles Creek Mine	137 760
Taratu Formation		Otago	Kai Point Mine	No data
Gore Lignite Measures		Southland	Newvale Mine	No data
Morley Coal Measures		Southland	Wairaki Mine	32 220
			Takitimu Mine	118 904

Production at mines varies annually as demand for product of various quality and properties rises and falls or as supply contracts or offtake arrangements are completed and re-negotiated. There are several other mines where production is low/paused, including: Escarpment (West Coast, not producing), Harliwich (Otago, not producing), or are going through closure, Malvern Hills (Canterbury), Cascade (West Coast), and Spring Creek (West Coast). In addition, there is one resource currently negotiating consent, Te Kuha (West Coast). Escarpment Mine and the Te Kuha resource have been through resource consent processes in the last decade and have geochemical datasets that are used in this report.

2.3.5 Mineralogical control and mobility of Zn in coal mine environments

There has been limited study of the total Zn concentration in coal measures rocks. However, there have been case studies which show nickel (Ni) in Brunner Coal Measures rocks (below detection to about 30ppm) is slightly less than average crustal abundance (about 80ppm) and that Ni is found mostly in sulphide minerals (de Joux and Moore 2005, Weber, Skinner et al. 2006). Subsequent studies of mine drainages and leachate from geochemical testing indicate there is an association between Ni and Zn (Black, Trumm et al. 2005, Pope, Newman et al. 2010, Pope, Christenson et al. 2018). Zn has a similar crustal abundance to Ni and by extrapolation it is likely that Zn is mostly associated with sulphide minerals (pyrite) in Brunner Coal Measures rocks and likely other coal measures rocks. This interpretation does not rule out that Zn might also be associated with other mineral types including carbonates, silicates and oxides.

It is significant that Zn is likely to be associated with pyrite because this mineral is relatively reactive during weathering and trace elements associated with pyrite will be among the first released to surface water under natural conditions and at mine sites where weathering processes are accelerated by disturbance of large volumes of overburden rocks.

The interpretation that Zn is likely to be associated with reactive minerals such as pyrite in coal measures rocks is supported by long term weathering studies of rocks that are disturbed by mining (Pope and Weber 2013) (Figure 2) and other studies of mine drainage chemistry (Pope and Trumm 2014, Pope, Christenson et al. 2018).

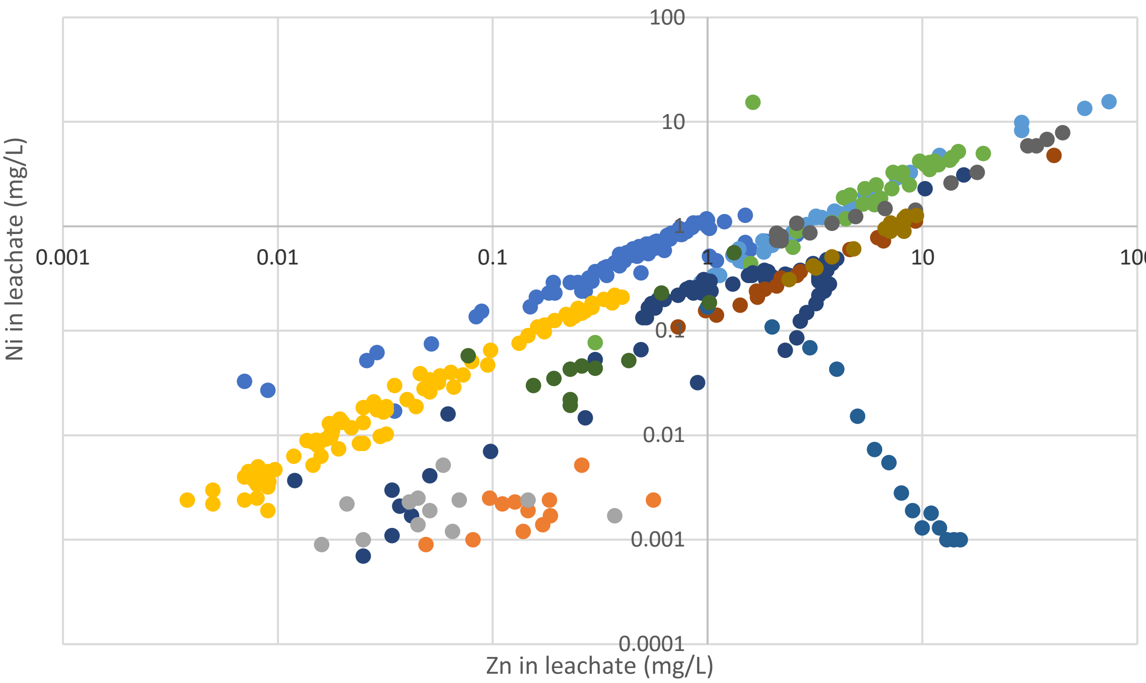

Figure 2: Zn and Ni concentrations in leachate from weathering tests indicate that there is typically a strong relationship between leachable Zn and Ni. Each colour indicates a difference leaching column.

The weathering tests that are used by the minerals sector involve placing known mass of rock crushed to 4mm in a buchner funnel (column) and leaching the rocks (usuall over several years) with water at a rate that is similar to annual rainfall. The chemistry of the leachate is tested and mass balanced so that the total amount of leached components can be calculated. Usually these tests have weathering conditions further simulated by regular watering, diurnal temperature variations to encourage capillary processes. Often these tests are conducted with a specific purpose for example

- identification of rocks that might be useful for capping,
- to investigate additives to prevent acid forming reactions
- to deliver a worst case scenario mine drainage chemistry to use for water treatment planning.

Mining operations minimise release of reactive components in their overburden through various management strategies. Management practices include

- segregation and sealing off the most reactive rocks based on geochemical testing,
- minimising infiltration of oxygenated water with capping materials or compaction,

- construction of engineered landforms where oxygen is excluded
- addition of alkaline materials to prevent acid formation

All of these practices are in use at mine sites throughout New Zealand where appropriate.

3. Methods

3.1 Approach to Zn in overburden at coal mines

There is not widespread data on the concentrations of trace elements such as Zn in coal measures rocks. In general, the minerals sector (mining companies and regulators), take the view that the total trace element concentrations are not likely to be useful in managing the environmental impacts of mining. Instead, leachable trace element concentrations, including Zn, are determined through simulated weathering tests on representative samples of overburden rocks. This approach is in line with global minerals sector environmental management practices.

Our approach is to calculate the leachable concentration of Zn in overburden rocks and use this value to assess the amount of Zn that might be available under normal weathering processes to the wider environment as mining disturbs rocks surrounding coal. For this calculation, we make the following underpinning assumptions:

1. The available Zn concentration is related to the reactive sulphide content of the rocks (mostly pyrite). This approach implies that:
   - Other minerals that might contain Zn are relatively unreactive during weathering (silicates and oxides)
   - Or, other minerals such as soluble salts that might contain Zn are not abundant in coal measures
2. The total S concentration of overburden rocks can be used as a proxy for the pyrite concentration. This assumes that:
   - Sulphur in other forms in overburden rocks is negligible including
     - S in organic material
     - S in sulphate minerals
   - The weathering of other reactive minerals that might contain Zn such as carbonates only release significant Zn when pyrite oxidises, causing acidic conditions that favour carbonate dissolution. Under circum-neutral conditions carbonate minerals are relatively un-reactive.

Using these assumptions, the total S concentration of overburden rocks can be linked to the leachable Zn concentration that is found through weathering tests on overburden rocks. The total S concentration in overburden rocks is assessed because the S concentration is also related to the potential for rocks to produce acid mine drainage (AMD). Both mining companies and regulators assess the potential for acid mine drainage as part of environmental management at mine sites. In some mining regions there is sufficient historic mine drainage information to assess the potential for AMD by analogy to other sites and so at some sites where there is a history of mine drainage that does not cause significant downstream impacts, geochemical testing of overburden ahead of mining is minimal.

3.1.1 Brunner Coal Measures

The most complete dataset of total S concentrations and weathering tests occurs at mines hosted in the Brunner Coal Measures because this geological formation has the potential to form AMD, whereas other geological formations that host coal mines typically form NMD (neutral mine drainage).

The total S concentration of Brunner Coal Measures rocks ranges from a high of 12.6% to less than detection (0.01%) with a median value of 0.21% (Figure 3A & B). This is based on analysis of 642 samples from all mined areas in the Brunner Coal Measures, some of these samples are not selected to be representative, but are selected to identify worst case scenario rocks for overburden management processes.

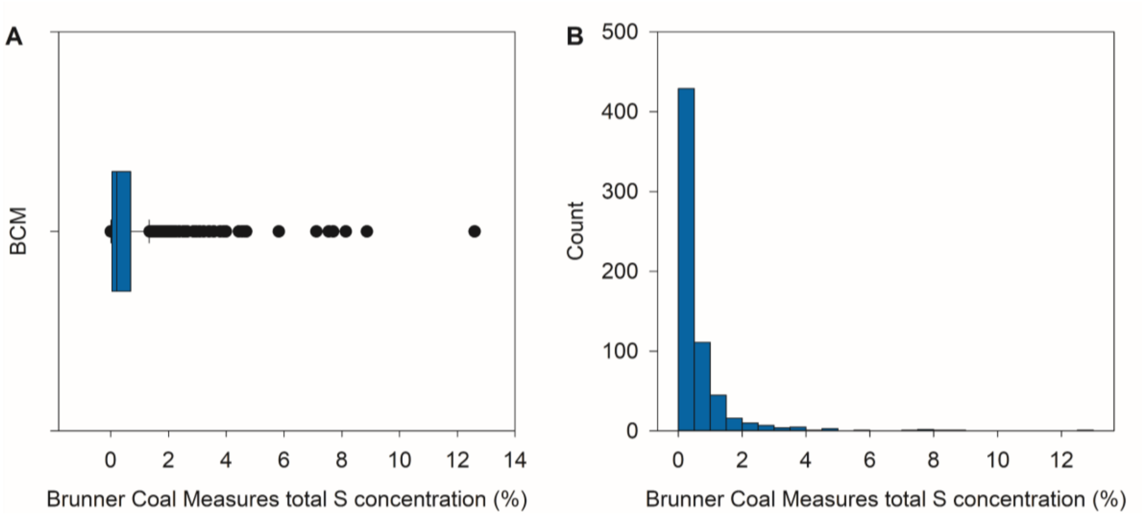

Figure 3. Total Sulphur data for the Brunner Coal Measures, n=642, $\mu_{1/2}$=0.21% ($\mu_{1/2}$=median) A) Box and whisker plot of sulfur distribution. The box indicates the upper and low quartiles of the dataset with the central line the median value. The whiskers indicate the 10^{th} and 90^{th} percentile values with outliers indicated by dots. B) Frequency distribution histogram of sulfur data.

More than 30 long term weathering tests have been carried out on Brunner Coal Measures with the leaching process conducted for 1 to 6 years with continuous monitoring that includes physiochemical properties of leachate (for example pH and electrical conductivity) and concentrations of major chemical components and trace elements in leachate. Many of the weathering tests were established to identify specific aspects of mine drainage chemistry or management of acidity.

We have selected 3 columns that were commissioned to deliver leachate chemistry that might be expected on a mine site. The columns have total S values of 0.33, 1.14 and 1.47 %, all higher than the median total S concentration. The weathering tests were terminated before all available Zn was released (Figure 4). In general, the concentration of Zn in leachate decreased with time and can be fitted with an exponential decay curve (Figure 5). We have extrapolated the leachate data out until the Zn leachate concentration is projected to be 0.01mg/L, the maximum value reported in natural streams that drain Brunner Coal Measures (Pope, Newman et al. 2010).

Based on this analysis, three estimates of the leachable Zn concentration for Brunner Coal Measures Rocks can be made. These is a low estimate of 0.0015 kg/t, a best estimate of 0.02 kg/t and a high estimate of 0.057 kg/t.

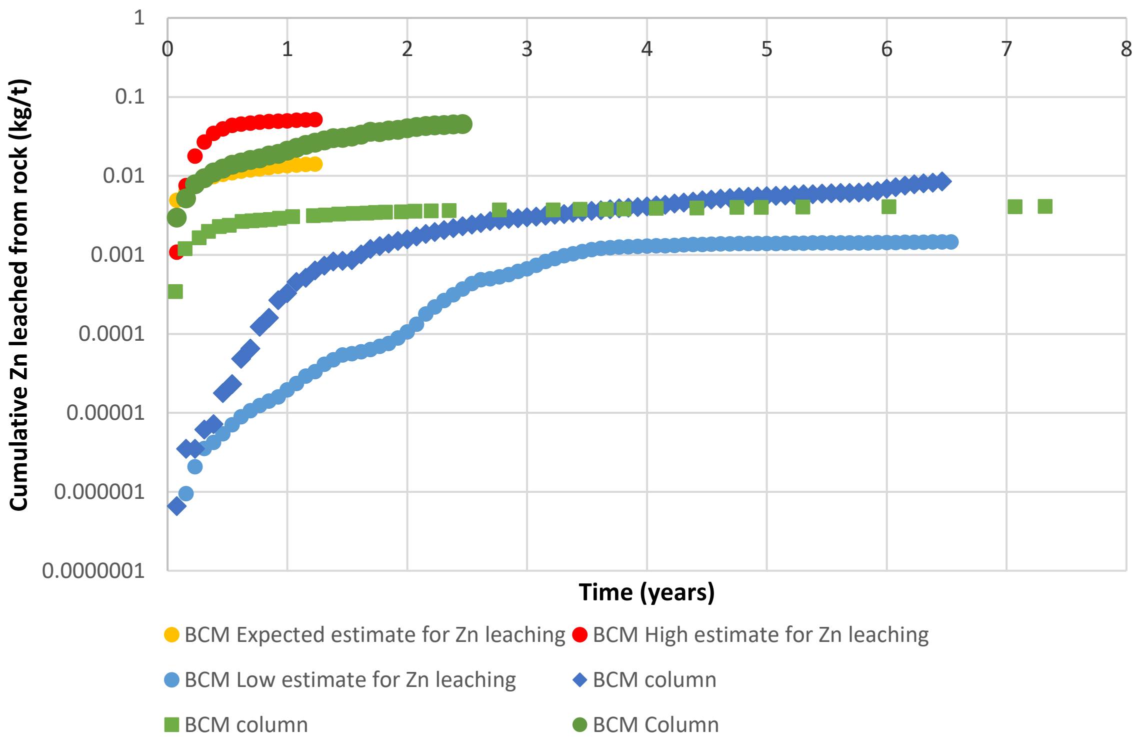

Figure 4. Examples of cumulative Zn released during weathering tests of Brunner Coal Measures.

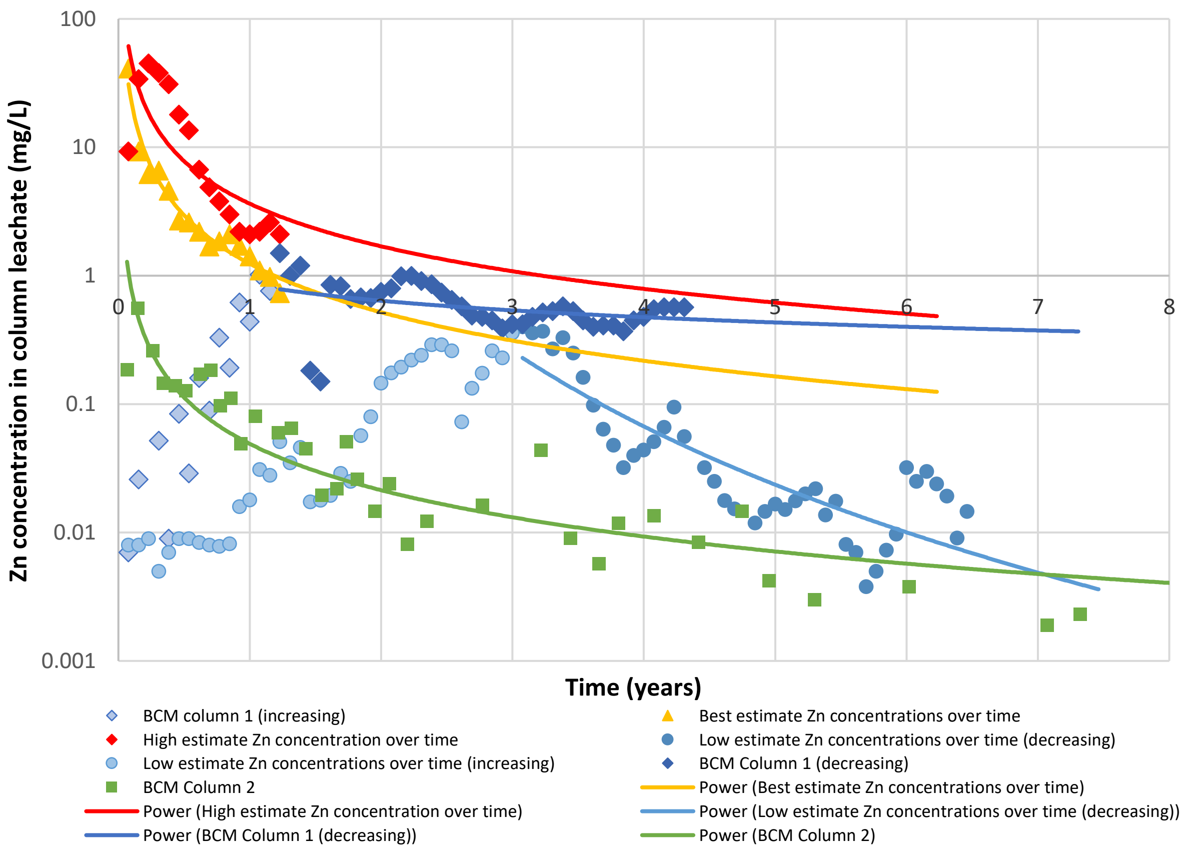

Figure 5. Examples of decay curves fitted to concentration data in leachate from Brunner Coal Measures generated during weathering tests.

3.1.2 Paparoa Coal Measures

There is a dataset of 95 analyses of total S data in the Paparoa Coal Measures. Mines that are developed in Paparoa Coal Measures on the West Coast of the South Island seek to demonstrate that they are unlikely to create AMD (because the acidic issues related to Brunner Coal Measures are well known). Collection of total S data and other tests typically show a clear difference in overburden chemistry from the Brunner Coal Measures.

The total S concentration of Paparoa Coal Measures ranges from a high of 0.45%S to <0.01%S with a median value of 0.02%S (Figure 6A & B). This is based on analysis of 95 samples, mostly from the Greymouth Coalfield and Te Kuha resource

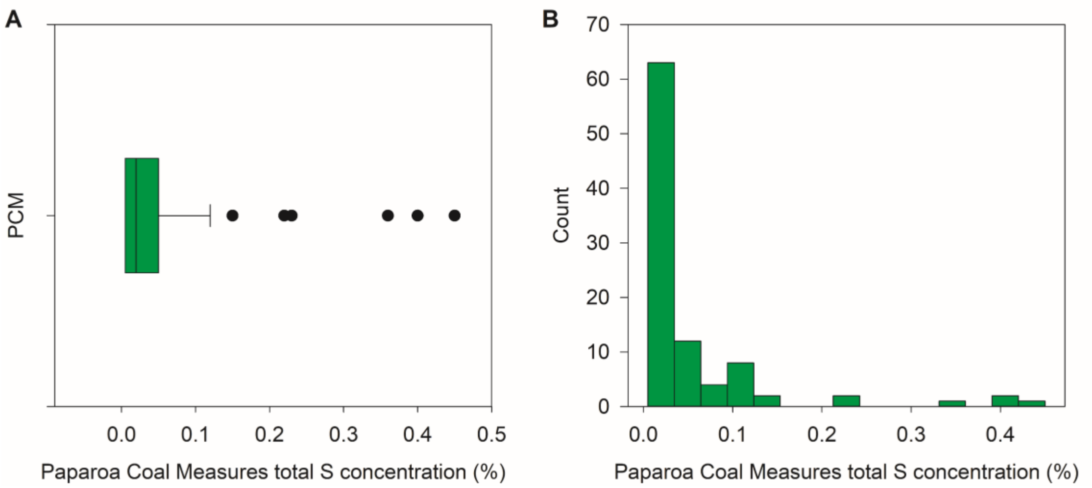

Figure 6. Total Sulphur data for the Paparoa Coal Measures, n=95, $\mu_{1/2}$=0.02%. Description of box and whisker plot and histogram as for Figure 3.

Two long term column leach tests have been carried out on the Paparoa Coal Measures for about seven years. There are only two leach tests completed on the Paparoa Coal Measures because other geochemical testing indicates that rocks from this formation will not release acid. Historically, once AMD is ruled out, mine environmental management practise focuses on sediment control. Historically, tests on the potential for leaching of elevated concentrations of trace elements in NMD was generally not completed. However, modern consent applications to establish mining permits generally include such geochemical test work. The only new mine proposed to disturb Paparoa Coal Measures is the development of the Te Kuha resource. All other operations in the Paparoa Coal Measures operate in mining licences granted prior to current resource consent practices

Based on analysis of leach columns for the Paparoa Coal Measures and similar processes to those used for the Brunner Coal Measures above, the total leachable Zn content of these coal measures is 0.9 – 1.5 g/t (Figures 7 and 8).

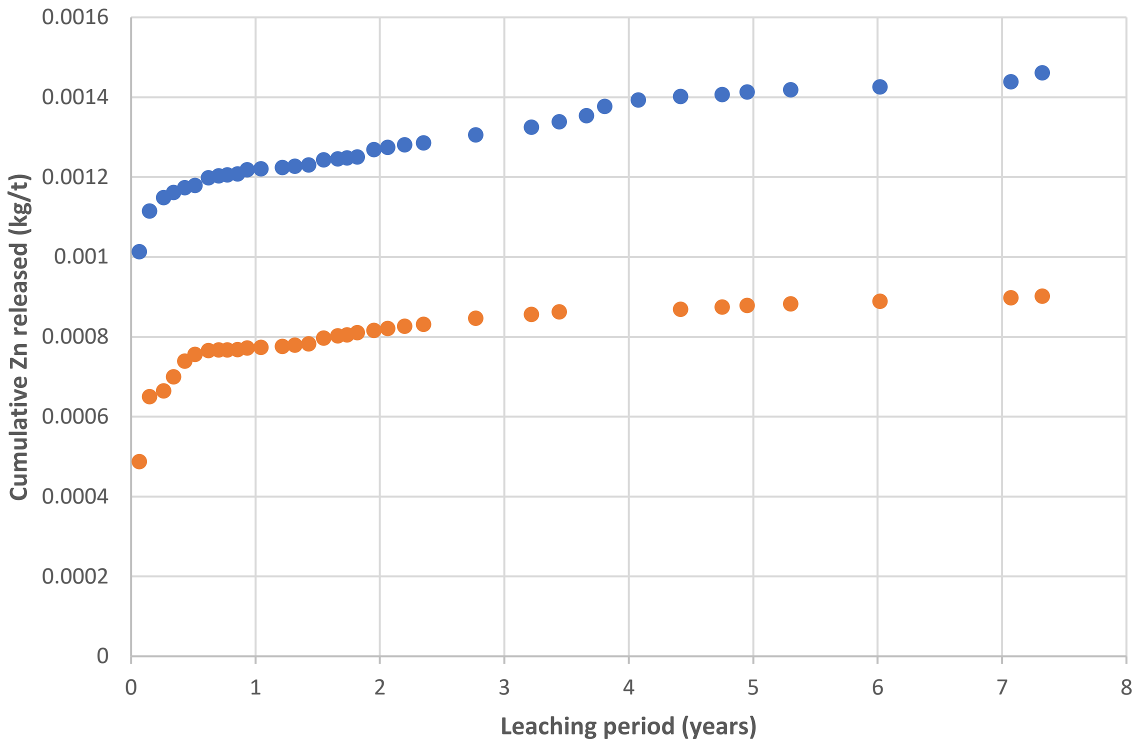

Figure 7. Cumulative Zn released during weathering tests of Paparoa Coal Measures.

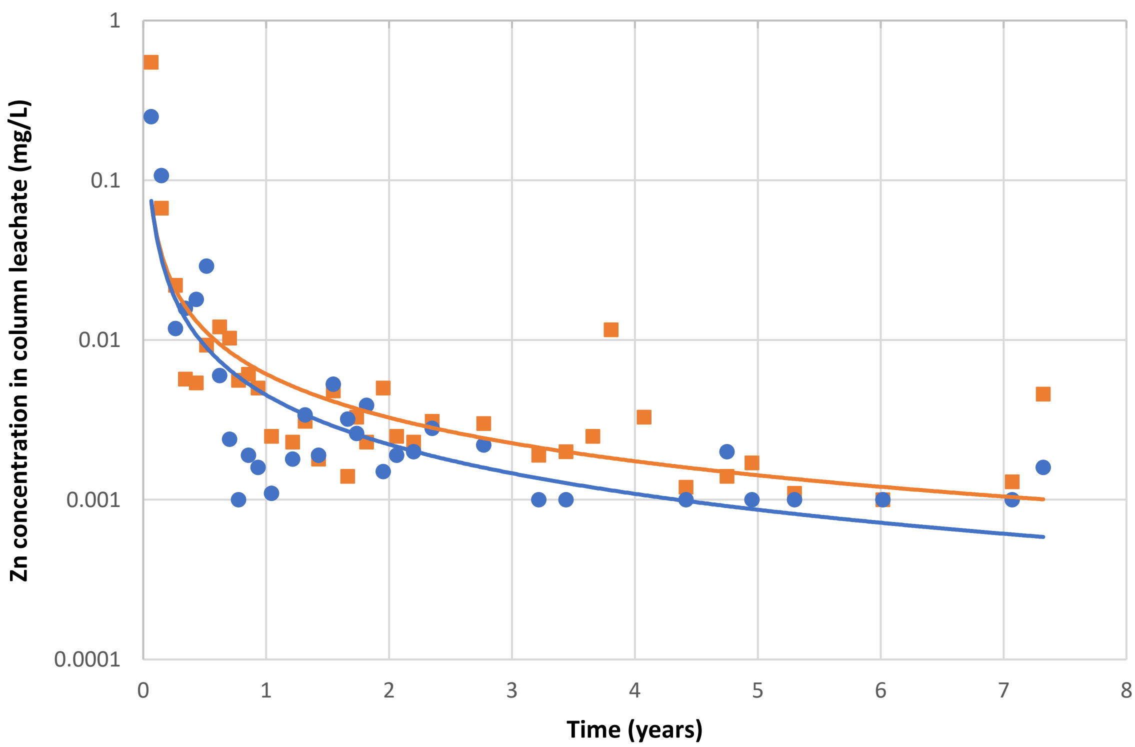

Figure 8. Examples of decay curves fitted to concentration data in leachate from Paparoa Coal Measures generated during weathering tests.

3.1.3 Gore Lignite Measures

There 81 analyses of total S concentration in the Gore Lignite Measures (Figure 9) that indicates a range between <0.01 and 5.29 % with a median value of 0.05 %. Although the total S data for the Gore Lignite Measures are higher than for the Paparoa Coal Measures, Gore Lignite Measures produce neutral mine drainage (Craw, Mulliner et al. 2008).

No data on weathering tests could be located for the Gore Lignite Measures but the concentration of Zn in mine drainages is low at mines where data is available (Craw, Mulliner et al. 2008). So the Zn concentration available to be leached from the Gore Lignite Measures is assumed to be similar to the Paparoa Coal Measures estimated at 0.9 – 1.5 g/t.

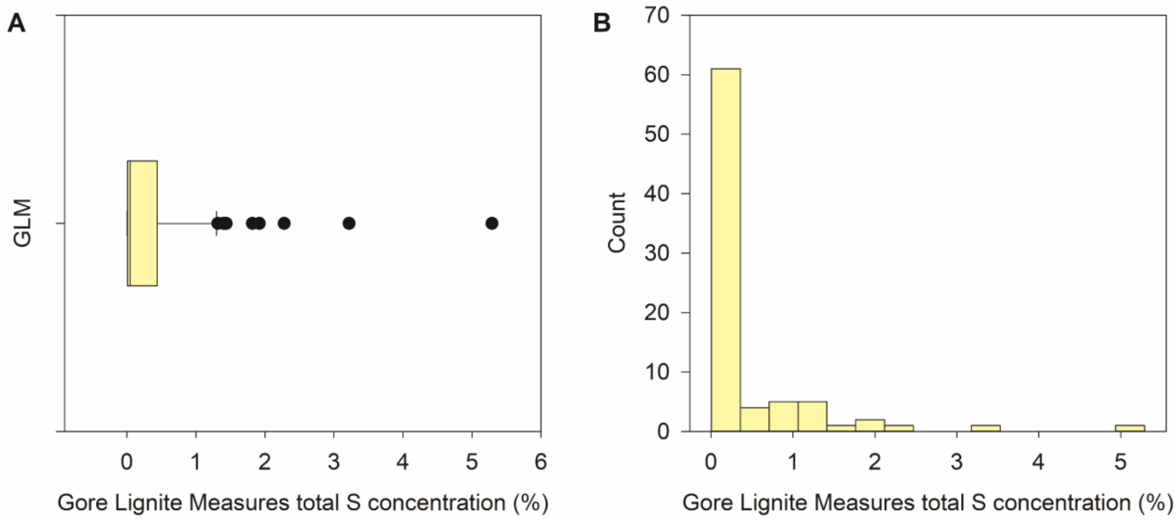

Figure 9. Total Sulphur data for the Gore Lignite Measures, n=81, $\mu_{1/2}$=0.05%. Description of box and whisker plot and histogram as for Figure 3.

3.1.4 Morley Coal Measures

There is a small dataset of 15 analyses total S data available for the Morley Coal Measures that indicate the total S concentration ranges between <0.01 and 0.22% with a median value of 0.05% (Figure 10). Morley coal measures produce neutral mine drainage with low Zn concentrations (Craw, Mulliner et al. 2008). No data on weathering tests could be located for the Gore Lignite Measures and the leachable Zn concentration is assumed to be similar to the Paparoa Coal Measures estimated at 0.9 – 1.5 g/t.

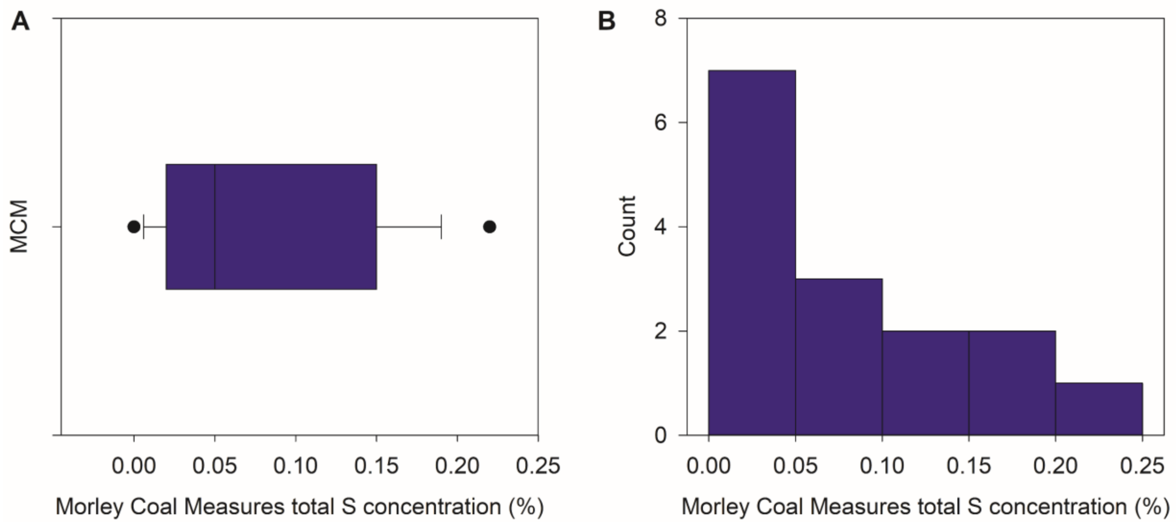

Figure 10. Total Sulphur data for the Morley Coal Measures, n=15, $\mu_{1/2}$=0.05%. Description of box and whisker plot and histogram as for Figure 3.

3.1.5 Waikato Coal Measures.

There is a small dataset of total S available for Waikato Coal Measures (Campbell, Lindsay et al. 2001). The values of total S range from below detection to 0.04% and this indicates a low pyrite content and likely a low leachable Zn concentration for these coal measures.

In the Waikato coal field there are other geological formations that might be disturbed by mining that have higher total S concentrations, however, these are managed to minimise oxidation and release of acid and trace elements (Lindsay, Campbell et al. 2002).

Data from weathering tests on the Waikato Coal Measures or other overlying rocks have not been located and probably have not been completed.

Based on analysis similar non acid forming coal measures (the Paparoa Coal Measures) the leachable content of Zn is estimated at 0.9 – 1.5 g/t.

3.1.6 Other rocks disturbed by Coal Mining

There is a total S concentration data for the Taratu Formation (Figure 11) but no weathering tests for this formation. Taratu formation has acid forming rocks similar to the Brunner Coal Measures. A case study within the Taratu formation at the closed Wangaloa Mine indicate that localised acid mine drainage can form with elevated Zn concentrations (Black, Trumm et al. 2005), however, overall the drainage from this site was less acidic than the Brunner Coal Measures sites on the West Coast of the South Island. Reliable data on dissolved concentrations of Zn for mines operating in the Taratu Formation have not been identified for this study. Based on the total S data and case study, the leachabe Zn is assumed to be similar to the Brunner Coal Measures between 0.0015 and 0.057 kg/t with likely best value of 0.02kg/t.

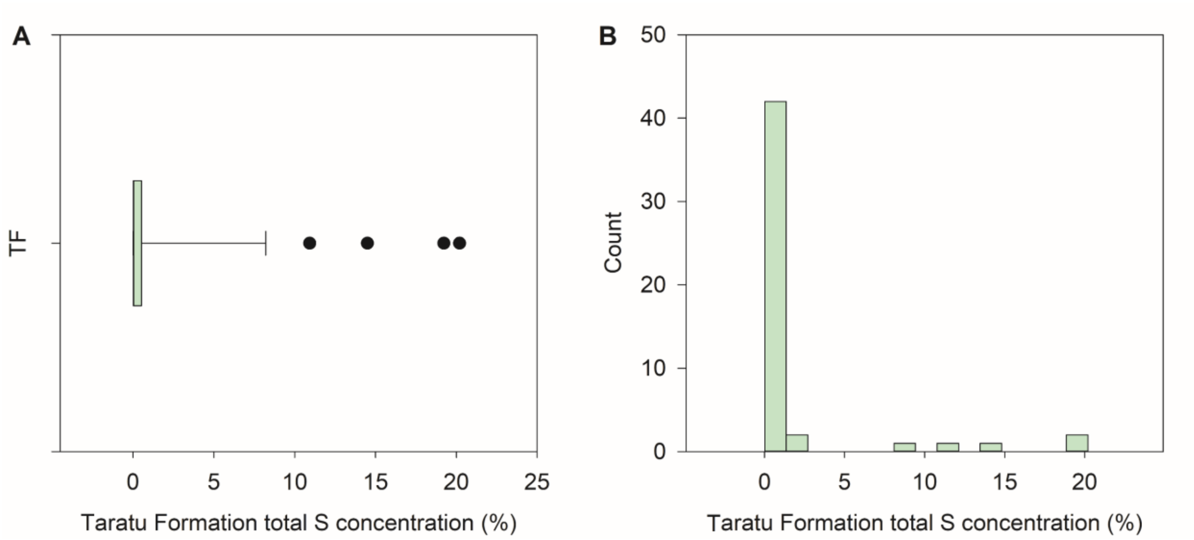

Figure 11. Total Sulphur data for the Taratu Formation, n=52, $\mu_{1/2}$=0.25%. Description of box and whisker plot and histogram as for Figure 3.

No data on total S or weathering tests for the Rotokohu Coal Measures have been identified through the literature review completed for this study. Acid mine drainage does not occur at this site, and so it is assumed that the available Zn is similar to the Paparoa Coal Measures estimated at 0.9 – 1.5 g/t

There is total S data available for the Te Kuiti Group (Waikato) rocks (0.19 – 0.36%S) and the Kaiata Formation (West Coast, 1.3 – 3.3 %) however, the volumes of these rocks disturbed by mining operations could not be established within the timeframe available for this report. The Kaiata Mudstone rocks contribute to the leachable Zn in overburden materials that are disturbed but are not included in calculations.

3.2 Approach to measuring Zn in surface water discharged by coal mines

3.2.1 Zn Concentrations

Zn concentrations in surface waters at mine sites have been collected from current monitoring data where this has been made available by mine operators. If monitoring data is not available, then a literature search has been completed to obtain Zn concentration data from academic papers, conference publications or student theses. Where no published data are available, Zn concentrations are completed by analogy to sites with similar geology.

Monitoring data from mine sites is the most reliable source of concentration data because mean data can be used to manage variability in the concentration data with time, whereas results published in other sources usually relate to samples collected on a single occasion.

Zn concentrations that have been used for calculations are generally from sites downstream of water management and water treatment systems where these systems are in place so that the total load of Zn exported from mine sites to the wider environment is calculated. Where downstream drainages have significant dilution from catchment area outside the mine footprint, concentrations from on site drainage has been used which may overestimate the average concentration from these sites. Higher concentrations of Zn are often reported within mine drainages in the literature because these published studies often focus on chemical or microbial processes at mine drainage seeps rather than collection of a stream sample that is appropriate for calculation of the Zn load from a site.

3.2.2 Surface water flows

Flow data have been derived by two methods where possible. At some sites there are sufficient flow records to measure total stream flows from the site including variations in flow related to rainfall events. Complete and mine site wide flow measurement datasets are not common at coal mine sites because these systems must be designed to manage about 2 orders of magnitude change in flow during high rainfall events and because consent conditions are related to discharge concentrations rather than annual load calculations for dissolved components. More commonly regular flow measurements are made along with regular concentration sampling but not with a view to mass balancing stream flow on an annual basis. Where these datasets are available the median annual flow has been multiplied by the mean Zn concentration to calculate the annual load of Zn to the environment. Median values for flow are favoured as the most appropriate statistical measure because short duration extreme flow events skew other statistical measures (such as the mean) to unrepresentatively high annual flow values. The relationship between concentrations of dissolved components in mine drainages and rainfall events is complex. From some studies there is evidence that little dilution occurs, and as flow increases mine drainage chemistry remains relatively constant (Trumm, Pope et al. 2016, Jewiss, Craw et al. 2020). There is also evidence that higher rainfall events can lead to flushing of and increased concentrations of dissolved components in mine impacted drainages (Fairgray, Webster-Brown et al. 2020). Finally, there is also evidence that dilution of dissolved components can occur related to very high flow events (Davies, Weber et al. 2011, Davies, Weber et al. 2011). Therefore, detailed site-specific information would be required to fully interpret the impact of high rainfall events on the load of Zn leaving a site on an annual basis and this data is not typically available with respect to trace element concentrations such as zinc.

Where flow data measured at a mine site are insufficient to provide a measure of median annual discharge or flow data are not available, the area of disturbance has been multiplied by the average annual rainfall to provide an estimate of the surface flows from these mine sites. The area and rainfall method provides a relatively good approximation of annual flow volumes from upland catchments where mines commonly occur (Pope et al unpublished data). The most significant uncertainties present in deriving annual flow from rainfall and area relate to evapotranspiration and infiltration of rainfall into groundwater systems, these factors are not commonly measured and are site specific.

3.2.3 Summary

The load of Zn that is discharged to the environment by coal mines is calculated from:

1. The concentration of Zn in mine impacted drainages downstream from treatment systems. This concentration could come from the following sources depending on the availability of data
    - Regular monitoring data
    - Occasional grab samples
    - By analogy to sites with similar geology
2. The annualised flow of streams discharging from mine sites. The flow data could come from the following sources
    - Near continuous measurement of discharge from mine sites that encompass the range of flow conditions in mine drainages
    - Regular flow data measured at sites at the same time as monitoring samples are collected
    - An estimate based on the disturbed area at the mine site and the average annual rainfall

The key uncertainties in these calculations are that concentration of Zn in surface waters at mine sites varies with time (depending on weathering rates, mine operations and dilution processes) and that the annualised flow rate in the streams is not uniform each year depending on rainfall.

3.3 Natural Zn discharged in un-mined coal measures areas

Natural Zn concentrations from Brunner Coal Measures rocks are likely to be elevated compared to Zn concentrations from other rock types. Natural Zn concentrations in streams that drain both Brunner and Paparoa Coal Measures rocks around the Te Kuha resource are usually more than an order of magnitude lower than average concentrations in mine drainages and range from about 0.001 to 0.006mg/L (Dutton and Pope 2015). There is sufficient flow and concentration data to calculate annual background Zn discharge from Brunner Coal Measures for the Te Kuha area and with collation of additional background data this could be extrapolated to provide an estimate of the amount of Zn discharged by natural weathering of Coal Measures. The natural weathering of Zn from Brunner Coal Measures rocks is likely to be naturally higher than other rock types. These calculations are beyond the scope of this report.

3.4 Controls on data availability for this report

Monitoring data from major coal mine sites has been contributed by mining companies. In general the companies have compliance monitoring that is required to be reported regularly for consent purposes as well as internal monitoring that enables management of mine drainages on site. Typically, neither of these types of data is ideal for measuring the annual load of dissolved components, such as Zn, discharged into the wider environment but are adequate for compliance and operational purposes. This is because consent conditions are generally set for a specific concentration of a dissolved component (or physiochemical property such as pH) that is thought to be acceptable based on eco-toxicology assessment or based on assessment of background conditions in the catchments receiving the discharge. Once a compliance concentration is set, a monitoring regime is established to check discharge concentrations, but not measuring annual loads of dissolved components into the wider environment.

There is considerable complexity in the range and type of compliance regimes that operate at coal mine sites related to legislation and regulations that predate the Resource Management Act (1991) and transitional arrangements used after the RMA was implemented (PCE 2009). For old mine consent arrangements (~established earlier than the 1990s) the monitoring parameters that determine compliance with consent conditions might be quite brief, such as pH and turbidity and with relatively wide tolerances. At these sites additional monitoring and compliance conditions may have been added with time and these could include measurement and monitoring of additional dissolved or particulate components including Zn. However, there is no national approach to replacing outdated monitoring regimes, and instead, site-specific factors determine which parameters are added to monitoring regimes for compliance related to consent. Site-specific factors that impact compliance monitoring decisions could include

- Public concern
- Changes of operational or water management processes within the mine
- The presence of un-controlled historic mine drainage entering a catchment
- Local ecotoxicology surveys (eg, Champeau and Cavanagh 2010)
- Site-specific water quality issues that have been identified during monitoring but after initial consent
- The approach of different regional authorities for triggering a change in consent conditions

Mine consents that have been issued recently or applied for recently include conditions on dissolved concentrations for a more complete set of water quality parameters including trace elements such as Zn. In general, the modern consent conditions are based on geochemical testing of the rocks that will be disturbed by mining (which typically highlight Zn) and detailed background chemical surveys of the receiving environment prior to mining.

In summary, the amount and availability of data to calculate an annual load of Zn from coal mine sites is variable depending on the consenting history and monitoring program for each site. Our approach is to use the best available datasets from sites where Zn discharge to the environment can be measured using flow and concentration data, and compare these values to values derived using an area and rainfall calculation. We have established a relationship between the two methods of calculation, and extrapolated this relationship to sites where the only possible method for calculaton of Zn discharge is to use area and rainfall.

In addition, the time and budget for this report are limited and there may be datasets available that have not been included in the final calculations. The authors have prioritised obtaining the best underpinning data sets to extrapolate across the coal mining sector in New Zealand rather than try to obtain site specific datasets from small operations where Zn contributions to the environment are likely to be lower and highly uncertain.

3.5 Summary of key assumptions and sources of uncertainty and variability

3.5.1 Zn in overburden

The amount of available Zn in overburden rocks as calculated rests on two key assumptions;

1. Most leachable Zn occurs in pyrite and is related to total S in the overburden rocks
2. The median total S value for overburden is the best value to use for calculation of available Zn

The key uncertainties are

1. Zn released in geochemical weathering tests of rocks with values of total S close to the median value are best to use for available Zn concentrations. Tests on these rocks are relatively sparse in the dataset due to the lesser potential to generate acid mine drainage relative to high sulfur rocks. The amount of Zn released in these weathering tests is quite variable in magnitude and release rate, and is partially determined by the length of time for which the weathering test is completed.
2. For rock types where weathering tests are not available tests from the most similar rock type are extrapolated. This places reliance on 2 weathering tests completed on the Paparoa Coal measures to represent likely available Zn concentrations in other coal measures formations where total S is low.

The key variable in this calculation is the tonnage of overburden moved in any year depending on mining rates, thicknesses of overburden and demand for production at each mine.

3.5.2 Zn in surface water

Zinc discharged from coal mine sites in water have been calculated two ways.

1. Where flow and concentration data are adequate these data have been combined to calculate a load. Uncertainties include

- Variation in concentration with time. We have statistically processed as much data as possible to minimise this this source of variability, usually monthly or weekly monitoring data. In addition, case studies indicate variable response of concentrations to high rainfall; dilution, flushing or conservative bahaviour of the Zn concentration are all possible.
- Flow data is likely to be relatively reliable for sites. We have used median flow values to characterise stream flow.

2. Where flow and concentration data are not available, an area rainfall method has been applied. The area rainfall method was also applied to sites where flow measurements were available and a scaling factor was developed to apply to sites where area and rainfall was the only calculation method. Uncertainties include
    - Site specific variations in infiltration of rainwater to groundwater have not been included.
    - Validity of extrapolation of concentrations from other geolocically similar sites to sites where this data is not available

4. Results

4.1 Zn content in overburden rocks

The total Zn content in overburden rocks has not been calculated because there is insufficient data to measure this parameter adequately. The leachable Zn content in overburden rocks has been calculated by relationships that have been established between the total S content in overburden rocks and the Zn released during weathering tests on overburden rocks. For Brunner Coal Measures rocks, where there have been many weathering tests, there is significant variability in the amount of Zn that is mobilised by weathering. There is a limited dataset of weathering tests to base leachable Zn concentrations on rocks from other coal measures. The reason for the inconsistent availability of datasets for this calculation is that mine sites have been established under different consenting regimes over the last ~40 years. Historically weathering tests have only been completed to predict leachate quality of acid forming rocks. Only recently consented mines have complete geochemical testing of all rock types that will be disturbed by mining.

The total amount of leachable Zn that is moved with overburden is likely to be about 135 tonnes of Zn per year with a high estimate of 360 tonnes of Zn per year and a low estimate of 30 tonnes per year.

The leachable Zn is a snapshot of total Zn moved in overburden each year. Most of the leachable Zn that is moved in overburden each year remains in the overburden storage facilities because the overburen management processes are designed to prevent oxidation of pyrite (and related acid formation) and therefore these measures will also prevent release of Zn.

4.2 Zn discharged through mine impacted drainages

The amount of Zn discharged to the environment by coal mines has been calculated through a combination of measured flows from sites and measured concentrations of Zn in drainages. Where data on flow and concentration data are insufficient to develop a measured load model for Zn release, analogous site data, nearest weather station rainfall, and area of disturbance are used to estimate the load model. The rainfall and area calculations indicate that there is slight over estimation of Zn load calculated by this method compared to sites where measured data has also been collected and so an appropriate scaling factor has been applied to sites where the rainfall and area are the only option for calculation of the Zn load.

The total quantity of Zn discharged to the environment by coal mining is 35 tonnes ± 15 tonnes per year.

The quantity of Zn discharged to the environment is a number that includes Zn from across entire mine sites that have been undergoing cumulative disturbances for the duration of the mine life.

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