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Good acid and metalliferous drainage management begins well before mine closure: a New Zealand example

EJP Sinclair *Bathurst Resources Limited, New Zealand*

P Weber *Mine Waste Management, New Zealand*

Abstract

Bathurst Coal Limited (Bathurst) owns and operates the Canterbury Coal Mine (the Mine), Canterbury New Zealand. The Mine was purchased in 2013, and during acquisition, it was identified that there were legacy issues associated with acid and metalliferous drainage (AMD).

After operational activities started at the site, under the direction of Bathurst, a strategic approach to AMD management was undertaken to address this legacy AMD and also future potential issues. This included a staged response to characterise and schedule materials, assess AMD risks, and implement appropriate engineering controls (prevention minimisation, control and treat) to address these risks. This led to a significant reduction in AMD effects including an improvement in pH and a reduction in acidity loads for the site.

When market and social license issues resulted in the decision to close the Mine in early 2021, the site was well placed to transition to mine closure.

This paper covers the steps undertaken during the operation of the Mine to resolve the legacy AMD issues and minimise AMD impacts associated with ongoing operational activities such that a robust best practicable mine closure plan was possible that will ensure good long-term environmental outcomes with minimal active management requirements.

Keywords: *acid and metalliferous drainage, mine closure, prediction, prevention, legacy, adaptive management*

1 Background – Canterbury Coal Mine

Mining commenced in the Malvern Hills Coalfield in 1872 with over 80 historical mines recorded (predominantly underground). The Canterbury Coal Mine (the Mine), part of this coalfield, was purchased by Bathurst Coal Limited (Bathurst) in 2013. At this point the Mine had been operating as an opencast operation for >10 years (Figure 1) and historical underground mines were also present.

Although mining was small-scale, a significant disturbance footprint had resulted with little consideration for materials management or understanding of acid generating materials.

Figure 1 Canterbury Coal Mine circa 2012 prior to the purchase by Bathurst

Acid and metalliferous drainage (AMD) (pH of ~3.5; Bell & Seale 2004) was first identified at the site in 2003–2004, which led to university research (Alipate 2005; de Boer 2005). de Boer (2005) completed the first waste rock characterisation studies, which included 34 rock samples from the site and identified that:

- Four samples were potentially acid forming (PAF) with a net acid producing potential (NAPP) of 4–280 kg/t $CaCO_3$ equivalent with the remainder being classified as non-acid forming (NAF).
- Some rock samples contained significant acid neutralising capacity (ANC).

These data inferred that the exposed 'main seam' footwall was the primary source of acid runoff, with that coal seam also being the primary target for coal mining. Following these studies, it appears that no detailed waste rock models (delineating PAF and NAF materials) were completed, and little attention was paid to rock placement within waste rock dumps.

The inherited Mine Operations Manual provided little reliable direction on AMD management. The following was noted:

- Inadequate investigations had been carried out to determine the source of the acidity within the mine footprint or lithology (e.g. limited materials characterisation).
- Limited engineering controls to prevent, minimise and control AMD.
- Elevated boron concentrations derived from seepage from overburden.
- Limited testing of mine impacted waters (e.g. limited performance monitoring).
- Small-scale active lime dosing was used to adjust pH in the primary surface water settling pond prior to discharge (which had limited surge capacity for higher intensity rainfall events).

Overall, there was no strategic approach to AMD management, rather a simplistic AMD treatment system was used periodically to neutralise acidic water prior to discharge. Improvement was essential to minimise discharge impacts.

2 AMD management strategy

In 2015–2016 Bathurst initiated its management strategy for AMD to minimise the long-term liability associated with AMD treatment and avoid the risk of non-compliance for site discharges. This strategy incorporated a best practicable approach for AMD management involving prediction, prevention, minimisation, and control & treatment. This was based on international guidance, (e.g. International Network for Acid Prevention 2014) and was imbedded in the sites AMD Management Plan:

- Prediction (characterisation) of AMD, which is critical to understanding the potential and longevity of poor water quality and enables the development of an AMD strategy. Prediction is facilitated by geochemical analysis and interpretations, which forms the basis of a geological-geochemical waste rock block model that characterises and classifies the overburden according to its AMD potential. The output from the model and materials characterisation facilitates a risk-based approach to understand the requirement for engineering controls and enables effective mine planning to achieve the closure objectives.
- The prevention of AMD relates to avoiding sulphide mineral oxidation as much as practicable, by preventing the interaction of the principal constituents of the AMD production process (sulphides, oxygen, and to a lesser extent water) through processes such as encapsulation and compaction.
- Where prevention is not possible, the objective is to minimise the contaminant load reporting to the receiving environment. This often involves minimising the interaction of sulphide oxidation products with water (e.g. run-on water, net percolation).
- Any remaining AMD will be controlled to prevent the release of untreated AMD influenced water to the receiving environment and diverted to a single point for treatment.

Application of this strategy, based on an informed risk assessment, included three stages:

1. Control and treatment of legacy AMD issues immediately.
2. Achievement of longer term improvements in site water quality through prediction, prevention, and minimisation techniques.
3. Development of closure water management that would minimise long-term liabilities.

2.1 Stage 1: control and treatment of legacy AMD

The first task to address legacy issues was to identify and quantify the source of the AMD. Recording sites were selected throughout the Mine and designated ‘CC’ numbers, with CC02_tele being measured with continuous monitoring equipment (Figure 2). Data identified this as the historic Shearers Dump, a legacy landform from the previous mine owner that had numerous AMD seeps (Figure 2). These seeps generated a significant amount of the site’s acidity load (pH 2–3; acidity 800–2,500 g/m^3 $CaCO_3$ equivalent) but were low flow ranging from 0.03–0.06 L/s during dry periods when their effects were most pronounced.

A passive treatment system was proposed to treat these low flow, high acidity seeps with a mussel shell reactor (MSR) being selected as being suitable (Figure 3). Further details on MSR design and performance are available (Robertson et al. 2017).

In addition to the MSR an active lime ($Ca(OH)_2$) dosing tank and sprinkler irrigation system was established to provide direct neutralisation to the main treatment pond as a contingency for any acidity not treated by the MSR. CC02_tele monitoring data (Tara Stream site discharge) indicated a marked improvement in pH and acidity levels following the installation of the MSR and lime treatment (Figure 4). Further improvements were required to maintain higher pH values consistently. This included refinements to the water management processes and other prevention and minimisation engineering controls.

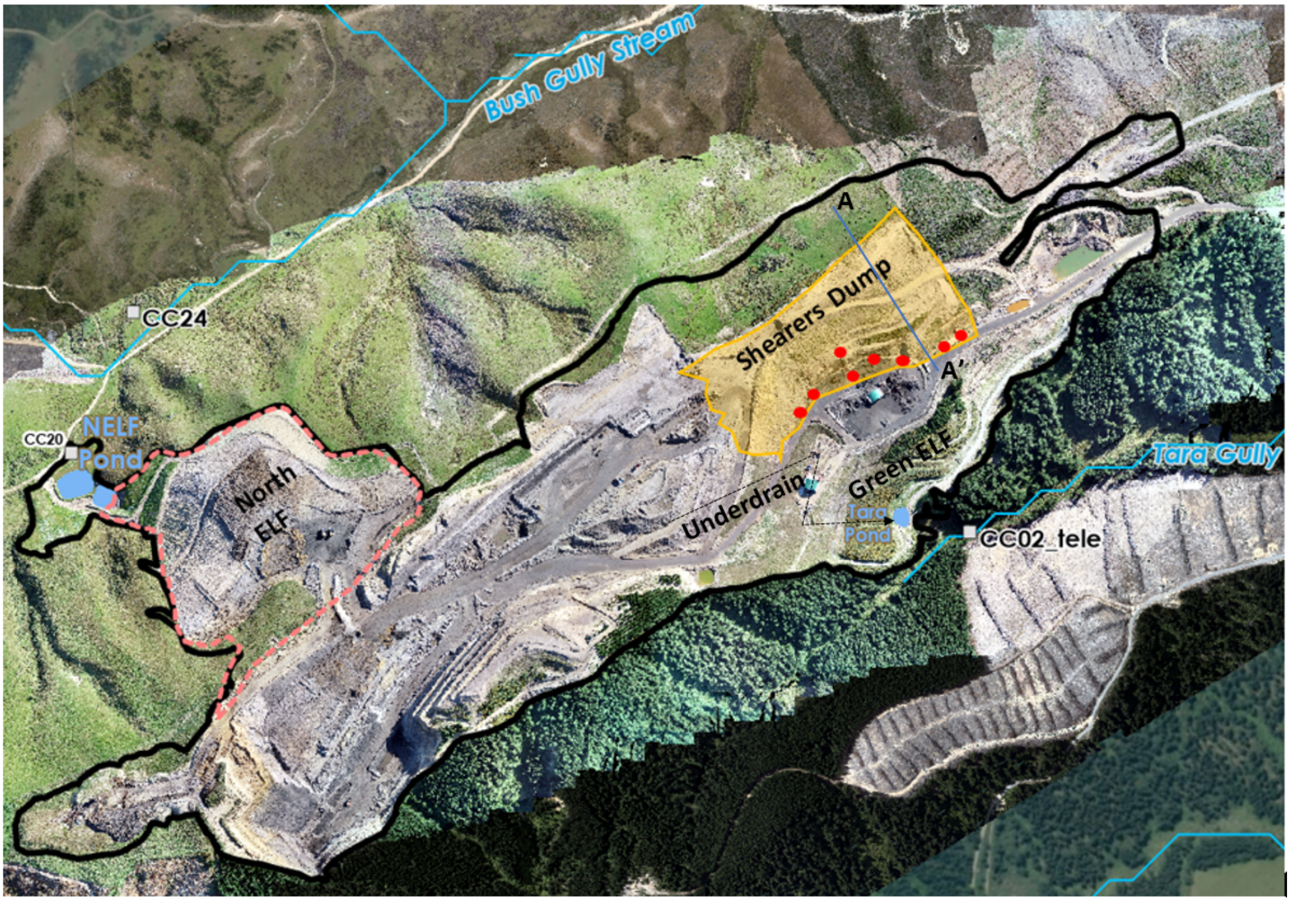

Figure 2 January 2018: Seepage sites associated with the historic Shearer's Dump (red dots). Green engineered landforms (ELF) underdrain and cross-section location (Figure 6) also shown

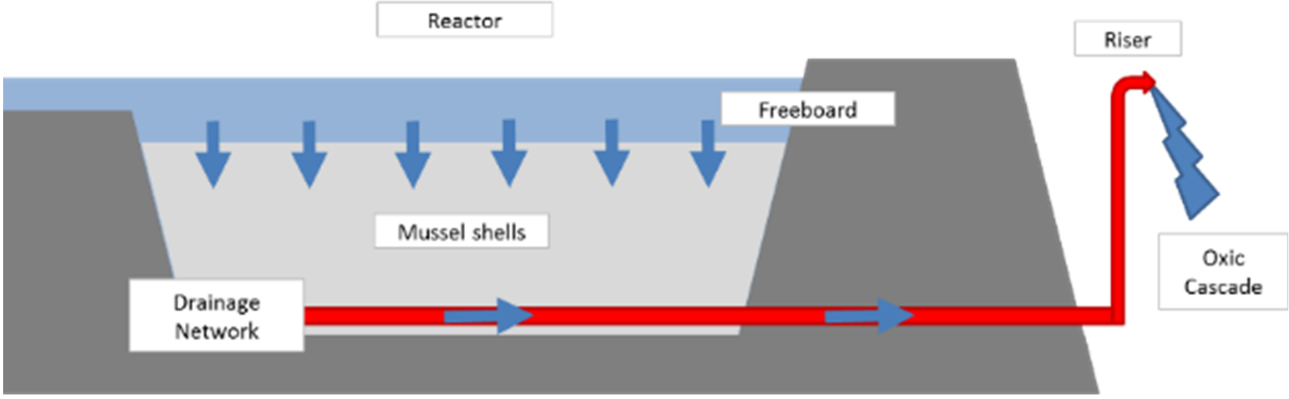

Figure 3 The first mussel shell reactor installed at the Canterbury Coal Mine followed the above basic design

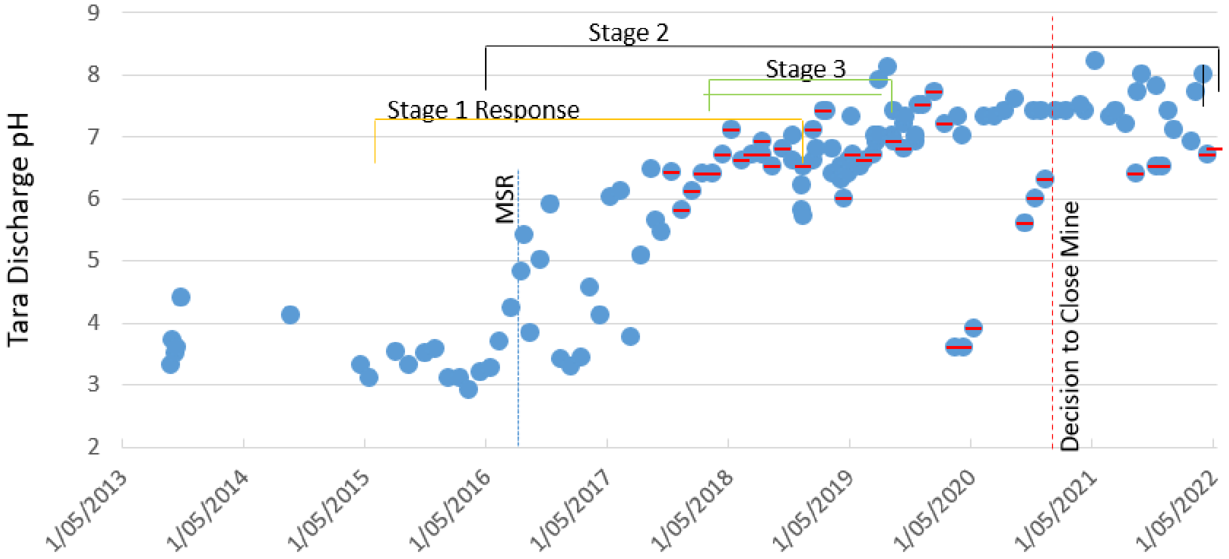

Figure 4 **Tara Stream discharge (CC02_tele) pH. Timeframes shown for each stage. Red dash indicates a background sample taken while no discharge was occurring**

2.2 Stage 2: prediction, prevention, and minimisation techniques

In conjunction with control and treatment of AMD, source control techniques were developed to prevent and minimise the amount of AMD impacted water that required treatment by constructing engineered landforms (ELF) that limit AMD generation. This also coincided with the development of the new ex-pit ELF, the North ELF (Figure 2) and the decision to construct the North ELF using a best practicable approach for AMD management.

The first task was to characterise the overburden using acid base accounting (ABA) methodologies (e.g. AMIRA 2002). Over 600 samples of drillcore were analysed (total and sulphidic sulphur, ANC, paste pH, and net acid generating (NAG) pH). These data were used to classify materials (Figure 5) with regards to AMD risk with the classification including acid neutralising (AN), NAF, low risk potential acid forming (low risk), and PAF.

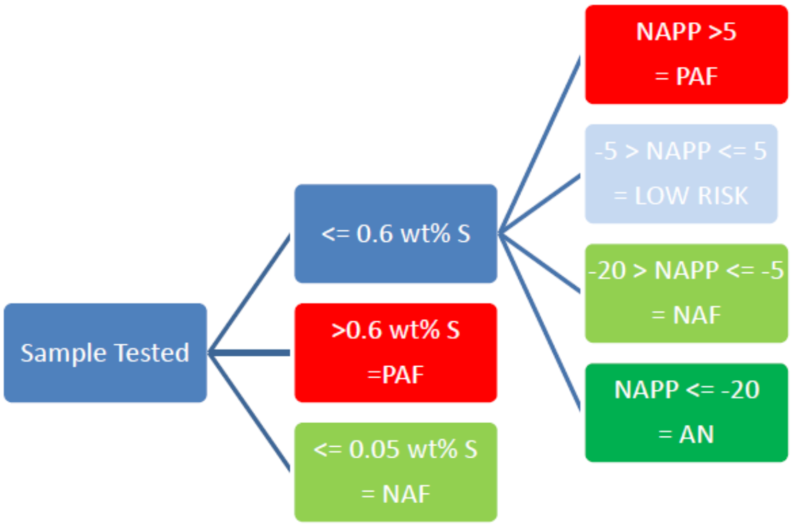

Figure 5 **Canterbury Coal process flow acid base accounting classification scheme**

The AMD materials classification scheme was a significant improvement on the previous system and:

- Reduced samples in an ‘uncertain’ classification category, which was difficult for operational staff to understand and act on.

- Minimised testing requirements.
- Reduced analysis costs – less samples required.
- Simplified modelling processes.

The AMD materials classification scheme and the geology model was used to develop a new AMD waste rock block model (Figure 6) which enabled materials scheduling to be completed. The AMD model shows a greater proportion of PAF rock lies at the top of the sedimentary sequence due to marine influence during deposition.

The AMD model facilitated mine planning to ensure PAF rock could be segregated and encapsulated to prevent oxidation. The materials schedule also confirmed that the site was net NAF from an ABA perspective, and that if PAF materials were managed in an appropriate manner the risk for AMD impacted drainage would be low.

An ELF construction management plan (CMP) was developed and implemented to ensure overburden and interburden was placed such that the ingress of oxygen was prevented and net percolation through the waste rock was minimised thereby reducing the transport of stored acidity to the receiving environment. This included the following techniques:

- Lift height controlled by paddock dumping followed by dozer levelling, usually 1–2 m lift height.
- After flattening by dozer, trafficking of loaded dump trucks during paddock dumping of the subsequent lift ensures waste rock is well compacted.
- Placement of PAF within the core of the ELF surrounded by NAF.
- When constructing in-pit ELFs, tip heads were not used except during initial pit infill below the pit crest level as there would be no advective draw possible through the ELF toe.
- The development of trigger action response plans (TARPs) in case poor water quality developed (in this instance, a MSR was proposed as part of the adaptive management approach).
- Training was provided to all staff, with supervision, so that the team understood the importance of AMD management and the risks for the business if this was not achieved.

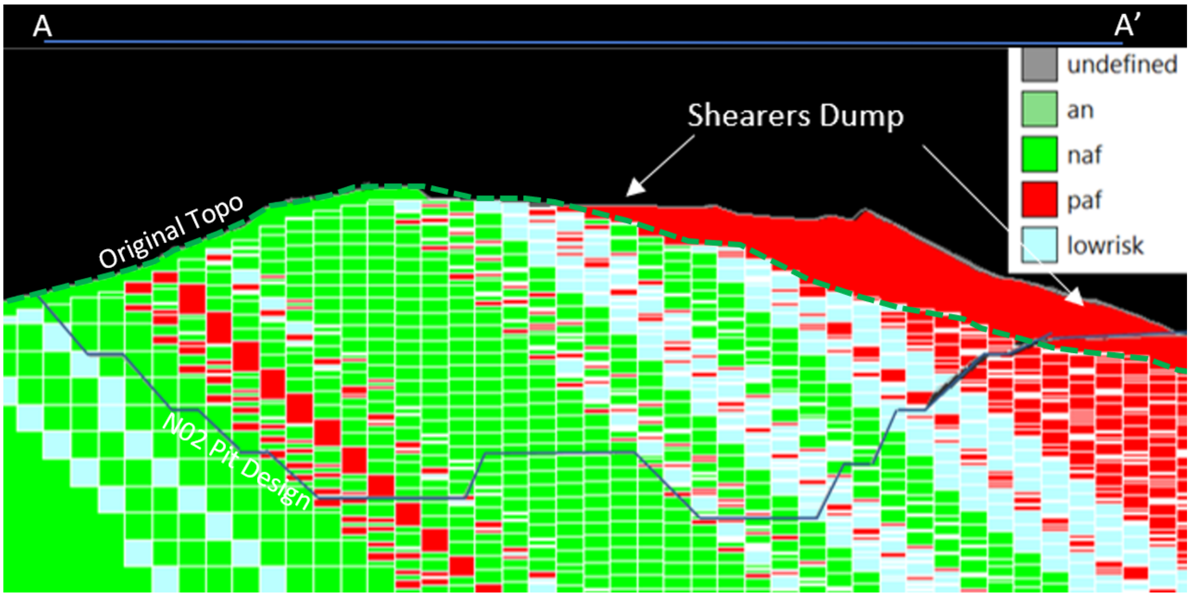

Figure 6 200 m cross-section (A–A') through the acid base accounting block model. Coal blocks report at potentially acid forming (PAF)

The North ELF was constructed from 2017 to 2019 in accordance with the CMP developed through the AMD Management Strategy and AMD Management Plan. As a result of this robust planning and construction process, the resultant water quality was within compliance limits and distinctly better than previous waste rock dumps where PAF management was not addressed. Figure 7 shows the discharge pH from the toe of the North ELF (CC20). No treatment for AMD has been required for the North ELF due to successful construction management.

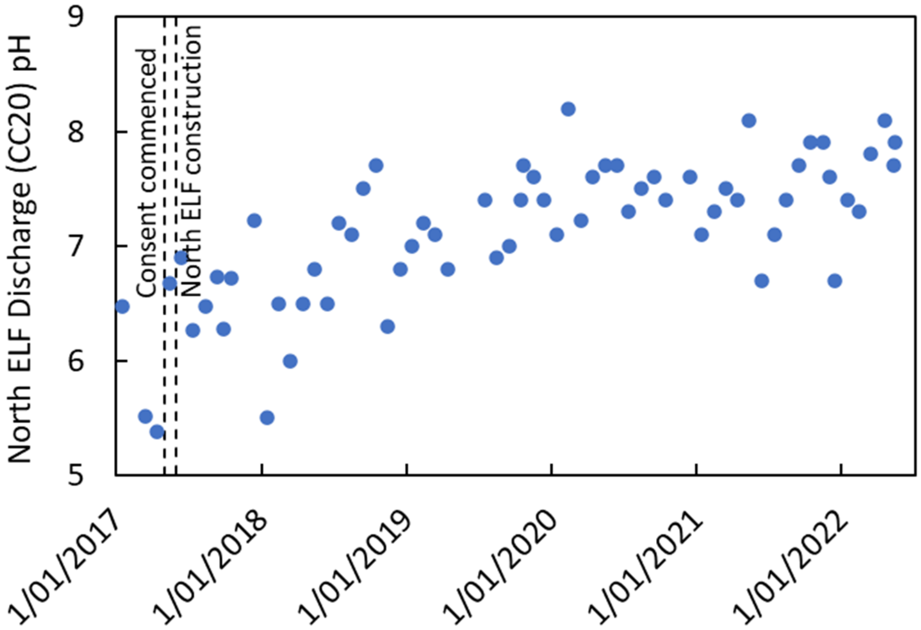

Figure 7 pH at CC20 (North ELF toe Pond 2 discharge point or the pond itself when not discharging)

2.3 Stage 3: closure water management strategies

The performance monitoring for the North ELF showed that the AMD management approach and engineering controls were effective, enabling closure objectives to be achieved for that catchment. By mid-2018, results in the Tara catchment were also vastly improved due to AMD treatment (Figure 4) but the elimination of AMD had not been addressed. In 2018–2019 the historic Shearers Dump was removed, re-handled, and placed within the Water Tank pit and Frew Hill ELF in accordance with the AMD Management Plan using the engineering controls: scheduling, encapsulation and compaction.

This approach was successful with site runoff now reporting to the treatment pond as circum-neutral pH (Figure 4), moving from a regime of constant AMD treatment (MSR, lime dosing) to occasional lime dosing to buffer pH to 7.5–8 pH to aid Zn removal. Boron remained elevated and was not removed by pH correction.

3 Mine closure

3.1 Mine closure strategy and risk assessment

A new mine closure and rehabilitation strategy was developed for the mine once early closure was initiated, and a broad-brush risk assessment undertaken to identify key closure risks, with an aim to enable handover of the site to landowners and allow pre-mining land use activities of farming and production forestry to recommence with minimal ongoing AMD management requirements.

Closure required rebuilding the materials schedule, mine planning, final landform design and design of final water management structures that needed to meet agreed closure objectives. Mine closure stages included:

- **Operational mining phase** – scheduled mining through to June 2021 with placement of overburden to create the agreed closure landforms. Active treatment methodologies to remain in place.
- **Operational and active closure phase** – Final landform construction involving bulk earthworks, placement of topsoil, revegetation and removal of infrastructure features used during mining.

Surface water is managed through the creation of a small settling and containment pond called the N02 Pit Pond and discharged via pumping from the N02 Pit Pond with periodic active lime dosing as required.

- **Post-closure phase** – Adaptive management of mine impacted waters and passive MSR treatment technologies supported by performance monitoring and TARPs.

The risk assessments identified two key mine domains that required additional management to achieve successful closure of the site:

- Green ELF underdrain (CC02 underdrain, Figure 4) – which is elevated in Al, B, Fe, Mn, Ni, and Zn.
- N02 Pit Pond (Figure 8) – which is within the final pit and in the Tara catchment.

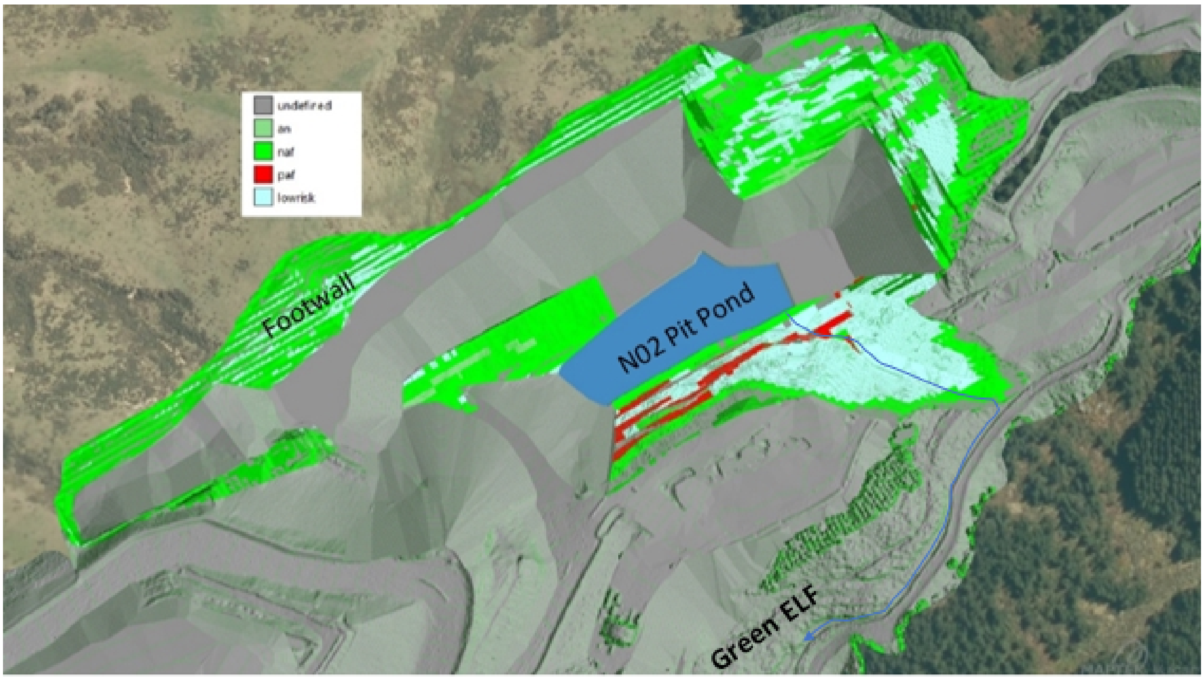

Figure 8 Plan showing ABA classification of in situ rock under only shallow cover within the final landform. N02 Pit Pond and outflow drain to Tara shown

3.2 Materials management

The waste rock block model was used to ensure PAF materials were placed within ELFs in the appropriate manner. Where possible all PAF highwall exposure were covered with NAF, although the rock exposed in the footwall (Figure 8) could not be covered due to the shortened mine life, the exposed footwall rock is NAF.

Data indicated that the life-of-mine materials movement was dominated by NAF materials (Figure 9), which supports the analysis that at closure the overall NAPP for all materials moved was negative (-4.9 kg/t $CaCO_3$ equivalent). During mine closure earthworks there was a greater proportion of low risk materials moved and lesser NAF (Figure 9).

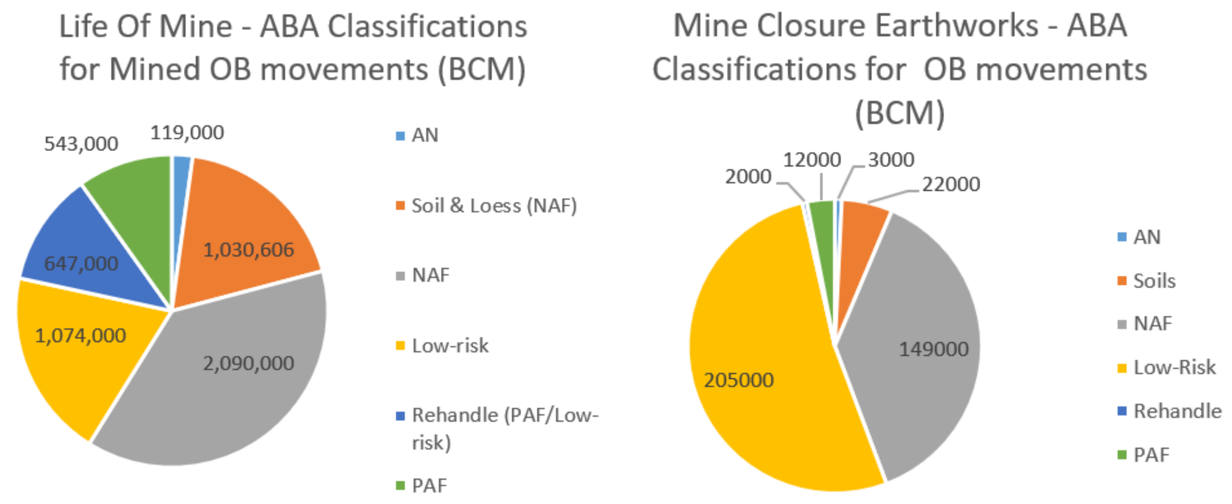

Figure 9 Materials balance

3.3 Closure water quality

Closure planning required an assessment of long-term water quality and flow rates to understand what water management activities (treatment, dilution) would be required in the post-closure phase. A study was undertaken to confirm the most suitable approach to minimise long-term treatment liabilities.

Water quality data indicated the key contaminants of concern were Al, Fe, Mn, Ni, and Zn, which were associated with AMD, and boron, which is found in the sedimentary rocks at the site. The study identified the need for a small MSR to passively treat water emanating from the CC02 underdrain for AMD contaminants that included Al, Fe, Ni, Zn and Mn. It was identified that boron would not be removed by the MSR treatment and diluting flows would be required.

Water quality data for the CC02 underdrain from the Green ELF (Figure 10) showed the following trends:

- Decreasing flow rates due to mining in the catchment and the removal of underground workings (and their associated seepage).
- Relatively consistent Mn, Zn, and SO_4 concentrations, but decreasing loads due to decreasing flows.
- Decreasing acidity and Fe concentrations (and loads).
- An increase in boron concentrations in the last couple of years.

Water quality expectations using an analogue model were developed for the N02 Pit Pond, which was an important management feature for closure, providing the diluting flows for the elevated boron from the CC02 underdrain. Empirical data from other mine domains (e.g. North ELF, CC20 monitoring site) were used to estimate N02 Pit Pond water quality at closure.

The design triggers for Tara MSR maintenance were expected to be sludge accumulation at or below the mussel shell layer surface therefore decreasing treatment capacity and resulting in untreated water potentially spilling from the MSR, or exhaustion of the mussel shell ANC. Therefore, the MSR design focused on Fe and acidity loads as these inputs control the expected maintenance frequency.

Two sets of calculations estimating the effect of sludge accumulation on maintenance requirements were undertaken. These calculations considered sludge layer accumulation increasing driving head requirements leading to decreasing treatment capacity and mussel shell substrate exhaustion due to shell ($CaCO_3$) dissolution for acidity (primarily Fe) neutralisation by hydrolysis. The design concentrations of Fe, and acidity and a design flow rate were used in these calculations and resulted in expectations for maintenance frequencies of 10–20 years. As can be seen in Figure 10, the design concentrations and flow rate has significantly higher than levels recorded from mid-2020 to 2022 and are therefore considered conservative.

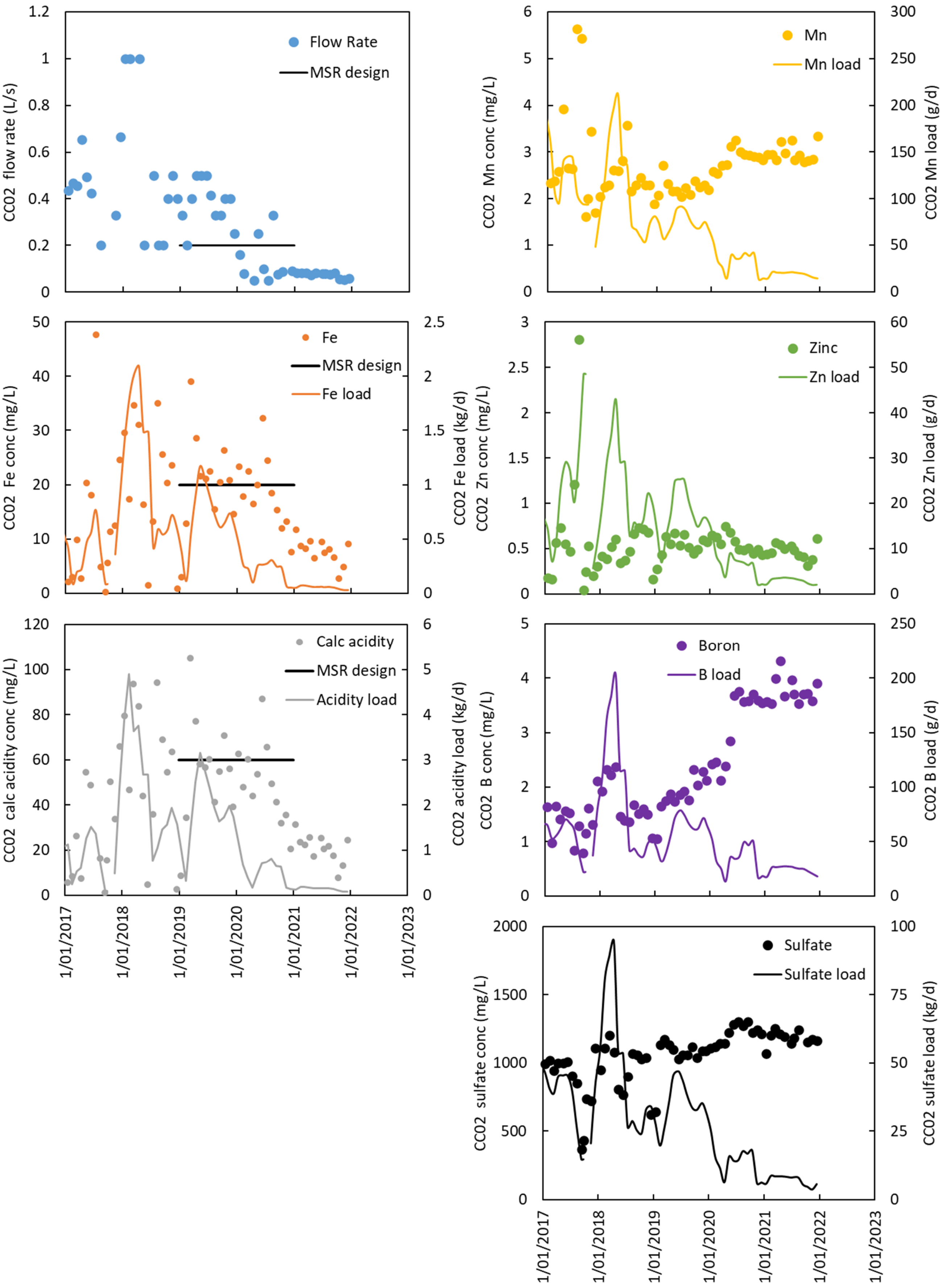

Figure 10 Contaminants of concern as measured from CC02 underdrain

3.4 Adaptive management

Adaptive Management will be used for mine closure activities at the Mine where uncertainty exists for key AMD related risks (Weber 2021). Adaptive management is a recognised management option under the Resource Management Act (RMA) (e.g. Leckie 2017). Effective adaptive management is supported by understanding the nature and duration of possible events that could occur, monitoring these events, and then having options in place should there be variance from the expected condition. This requires:

- Understanding the risks.
- Monitoring (as early warning, i.e. performance monitoring).
- Variance planning.
- Trigger Action Response Plans (TARPS).

A number of TARPS have been developed for the water treatment system for both active closure and post-closure phases. This includes TARPs for:

- Water quality and triggers for when management may be required.
- Water quantity and triggers when additional management may be required for dilution.
- MSR treatment performance.

The MSR passive treatment system and the N02 Pit Pond diluting flows are key aspects of the long-term AMD treatment system, designed to minimise longer term liabilities.

3.5 Closure treatment systems

The lower portion of the Green ELF was constructed prior to Bathurst involvement at the site, with the upper portion completed using the AMD management plans outlined. The CC02 underdrain drains historic underground workings (and the adjacent hill behind workings) and also collects seepages through the Green ELF. The CC02 underdrain flows continuously with very low flows of around 0.05–0.08 L/s. A small passive treatment is required to treat discharge from the CC02 underdrain for some metals, but only minor acidity as drainage is circum-neutral pH. Its location is shown in Figure 11.

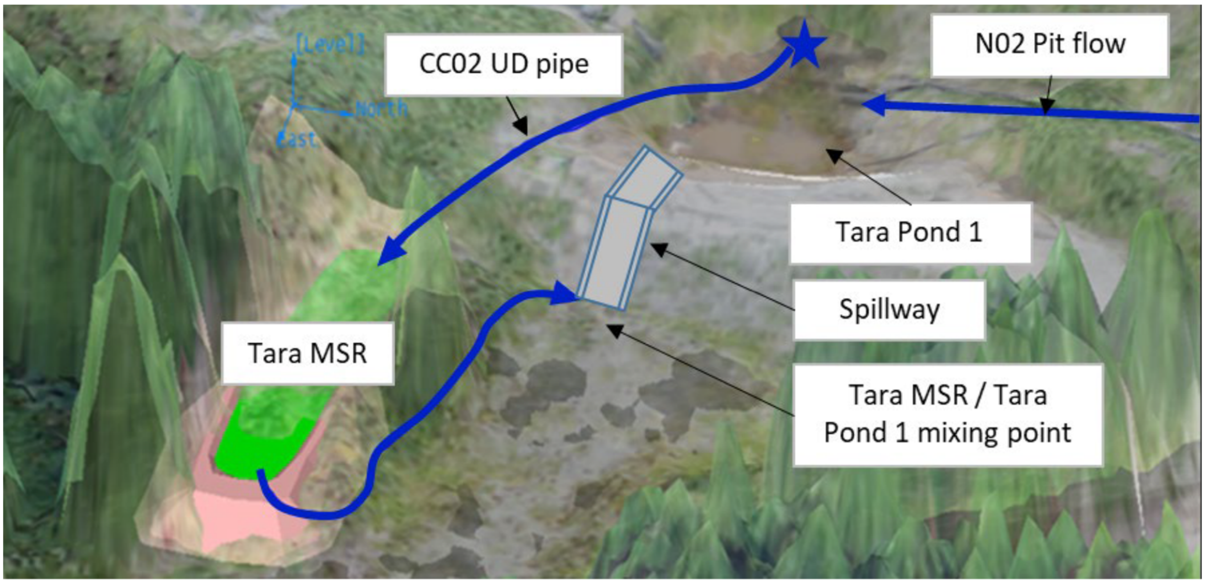

Figure 11 Mussel shell reactor (MSR) passive treatment system design

Underdrain water is collected by a pipe inserted (and sealed to limit oxygen ingress back into the ELF) directly into the CC02 underdrain. This prevents surface water flows (potentially elevated in sediment) entering the

Tara MSR through the post-closure period when revegetation is establishing. The Tara MSR will target treatment including:

- Removal of Fe (which is potentially in the ferrous (Fe^{2+}) speciation) by aeration (in standing water on the surface of the MSR), hydrolysis to form insoluble $Fe(OH)_3$ precipitates, and filtration through the mussel shell media.
- Removal of Zn and partial removal of Mn through either co-precipitation/adsorption to Fe precipitates or direct precipitation to form insoluble Zn precipitates.

The design of the down flow MSR (e.g. Figure 3) consists of:

- Installing an underdrain network at the base of a sump measuring 24 m long by 5 m wide.
- Filling of the sump with a 1 m deep layer of mussel shells resulting in a shell layer surface area of 94 m^2 at the top and a shell volume of 53 m^3.
- A water column depth above the shells of up to 0.5 m (including freeboard) to provide driving head and hold up to 58 m^3 of untreated water.
- Design capacity to enable regular sludge removal as required (monitored by stage height logger).

Early trials confirmed that the MSR would not reduce boron concentrations. To manage the elevated B concentrations during the active closure phase, the effluent from the MSR will be diluted with clean water from the sites potable water supply (up to 0.2 L/s) to ensure compliance with boron water quality limits. Post-closure, the dilution is expected to derive from decanting flows from N02 Pit Pond, which has been designed to provide 0.48 L/s.

4 Progress

At the time of preparing this paper the operational phase of mine closure is nearing completion, with only 2.2 ha of topsoil/revegetation (seeding) remaining of the total site footprint of 59 ha (Figure 12). A number of drains remain to be lined to ensure erosion prevention meets closure criteria. Water quality being measured in the N02 Pit Pond are already showing comparable levels of AMD contaminants to analogue models used to predict water quality at closure.

Figure 12 Site view showing final rehabilitation efforts and the N02 Pit Pond area

The Tara MSR is currently going through its commissioning phase. During commissioning effluent water is returned to the site surface water system via pumps. Four months of water quality data has been recorded to ensure the system is working as-designed and that contaminant concentrations are low achieving closure water quality criteria. Once commissioning is complete a potable water source will be used to dilute the MSR effluent to ensure boron is compliant with water quality objectives.

Table 1 summarises the MSR data acquired during the commissioning phase. Results show that the MSR is removing >98% of Fe, Ni, Zn, and acidity. Removal of Mn is >85%, far higher than the 33% observed during earlier site trails. The MSR is also removing 25% of SO_4, which again exceeds expectations of the MSR.

Table 1 Expected mussel shell reactor (MSR) inflow and expected removal (MSR model) versus actual MSR commissioning data

	Median CC02 historic	Design performance (% removal)	Median MSR influent	Median MSR effluent	Median MSR performance (% removal)
Flow rate (L/s)	0.08		0.056	0.045	
pH	6.4		6.3	7.3	
Electrical conductivity (mS/m)			110	129	
Manual DO (mg/L)			4.41	0.48	
Manual DO (%)			62.95	5.1	
Calc acidity (mg/L $CaCO_3$)	54.3	98%	14.6	0.1	99%
Sulphate (mg/L)	1,130		522	391	25%
Al (mg/L)	0.005		0.005	0.003	40%
Fe (mg/L)	20.4	98%	5.3	0.05	99%
Ni (mg/L)	0.089	83%	0.039	0.0008	98%
Zn (mg/L)	0.55	88%	2.03	0.004	99.8%
As (mg/L)			< 0.001	0.007	
B (mg/L)	2.3		1.4	1.4	negligible
Cd (mg/L)			< 0.0002	< 0.0002	
Ca (mg/L)	235	-25%	118	169	-43%
Cr (mg/L)			< 0.001	0.001	negligible
Co (mg/L)			0.0319	< 0.0005	
Cu (mg/L)			< 0.0005	< 0.0005	
Pb (mg/L)			< 0.0005	< 0.0005	
Mg (mg/L)	115		53.8	49.5	negligible
Mn (mg/L)	2.6	33%	1.76	0.24	86%
Hg (mg/L)			< 0.0005	< 0.0005	
Total hardness (mg/L)	1,047	-13%	516	621	-20%

5 Expected outcomes of mine closure

Current performance monitoring data are showing that the Canterbury Coal Mine is heading towards a successful mine closure process that meets the expectations of its AMD strategy for the site which includes:

1. Control and treatment of legacy AMD issues immediately.
2. Achievement of longer term improvements in site water quality through prediction, prevention, and minimisation techniques.
3. Development of closure water management that would minimise long-term liabilities.

Results suggests, the ability to return the site to pre-mining activities (production forestry and farming) with effect of acidic rock drainage being eliminated and only minor passive treatment being required. Performance monitoring will be required to confirm that all systems are working effectively, but should decrease in intensity with time, concurrent with decreasing uncertainty and risk such that the site can be handed back to landowners.

Acknowledgement

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