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# Developing a systematic model to rehabilitate key domains of gold mines for environmental sustainability

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## Abstract

*The primary focus of the Mine Rehabilitation Model is to eliminate the acid metalliferous drainage (AMD) released from waste rock dumps (WRDs), reinstate natural biodiversity and ecosystems, ensure a sustainable post-mining land use and ultimately lease relinquishment. The overall strategy is aligned with industry-recognised guidelines, standards with applicable government regulations, integration design methods and innovative technologies, establishing an optimum performance platform for sustainable rehabilitation management.*

*Cosmo Howley Project Area (CHPA) is located 130 km southeast of Darwin, between Adelaide River and Pine Creek. The nearest township is Adelaide River, 50 km to the northwest. The CHPA is operated by Agnico Eagle NT Mining Operations (NTMO).*

*The most significant environmental risk at the CHPA is represented by the WRDs, which are the key source of AMD, impacting on the local creeks and groundwater quality. The issue is unlikely to abate in the foreseeable future unless the AMD source is removed. The ineffective design of the WRDs, limited geochemical characterisation and the highly seasonal tropical rainfall patterns at CHPA compounds the problem with respect to the formulation of a cost-effective, permanent rehabilitation strategy. Longer term, and as part of this mine rehabilitation strategy, NTMO propose to control AMD via oxidation control. This will be achieved by rehandling of waste rock from Howley and Mottrams WRD and placement in-pit in the Cosmo Pit, below the recovery watertable level, which will provide an effective barrier to significant oxygen diffusion.*

*Other environmental risk areas include large dams within the CHPA that store the residue of heavy metal contaminated soil. NTMO adopted biological treatment to ameliorate the acid sulphate soil within these receptors. Naturally occurring biological micro-organisms and plants able to withstand high concentrations of heavy metals can be useful in eradicating hazardous contaminants. This is a process known as bioremediation and is an eco-friendly and efficient method of reclaiming environments contaminated with heavy metals.*

*Biological treatment can be combined with physical processes, such as anionic clay precipitation. The clay binds to metals and other contaminants, which make the toxic metal inactive. Biological treatment can then add nutrient to the soil to promote vegetation growth. A trial treatment investigation was implemented at CHPA to define the best possible physical and biological options for capping to ensure safe remediation of the site as well as potential cropping opportunities for the site after remediation.*

**Keywords:** *acid metalliferous drainage mitigation, wet cap, biological soil amelioration*

## 1 Introduction

The Cosmo Howley Project Area (CHPA) is located 130 km southeast of Darwin, between Adelaide River and Pine Creek. The site is located between the Daley River Catchment to the south and the Adelaide River catchment to the north. Howley Creek subcatchment to the north and northeast of the site is fed by unnamed creeks that drain from the CHPA, ultimately into the Adelaide River 65 km northwest of the CHPA. The mine site is bounded to the north by an elongated ridge that runs from the southwest to the northeast. On the south, landforms consist of a set of discontinuous hills separated by drainage ways.

Site topography has been strongly influenced by mining. Waste rock dumps (WRDs) including the Mottrams, Howley, and Cosmo form topographic irregularities as high as 30 m, and pit lakes up to 80 m deep have been generated from mining activities.

Recent mining has been restricted to underground operations accessed from the Cosmo Pit, with ore hauled offsite for treatment at the Union Reefs Processing Facility. The CHPA mine waste landforms have not been active since 2012, when open pit mining ceased in the Howley and Mottrams open pits. More recently, surface activity at CHPA has been largely focused on care and maintenance operations and in particular the management of acid and metalliferous drainage (AMD) emanating from legacy mine landforms.

Mine rehabilitation planning encompasses post-mining land use goals and rehabilitation objectives, the cessation of operations, identification of stakeholder interests, socio-economic considerations, regulatory requirements, rehabilitation plans, decommissioning of mine infrastructure, rehabilitation of mine disturbed areas, and ultimately, lease relinquishment.

Successful post-mining land use planning occurs prior to rehabilitation and identifies suitable, economically viable, and sustainable measures that recognise complexities and incorporate post-rehabilitation management and monitoring of assets.

The intent of the CHPA rehabilitation works is to:

- Remove mine affected acidic water inventory onsite.
- Remove the volume of problematic waste rock at surface.
- Ensure all potentially acid forming (PAF) material is appropriately contained and performs under the existing conditions to prevent contamination to surface and groundwater.
- Ensure final landscape is stable, safe and non-polluting.
- Ensure soil properties are appropriate to support the vegetation cover in rehabilitation areas.
- Ensure ground cover is appropriate to prevent soil loss and support vegetation growth in rehabilitation areas.
- Ensure vegetation in rehabilitation areas has comparable robustness and functionality to adjacent ecosystems.

## 2 Acid metalliferous drainage

The most significant environmental risk at the CHPA is represented by the WRDs (Figure 1), which are the key source of AMD impacting on the local creeks and groundwater quality. Figure 2 illustrates the interaction between water and oxygen at Mottrams WRD. The key factors causing AMD generation within these dumps include:

- Limited acid neutralising capacity of the waste rock – the inherent acid neutralising capacity (ANC) of the non-acid forming (NAF) rock is generally low and insufficient to buffer sulphide-generated acidity or significantly lag the time before onset of low pH conditions.
- Construction design and/or rehabilitation did not take into consideration the AMD hazard of the waste rock – atmospheric oxygen is readily available within dumps due to the open internal structure and lack of fines in dumps.
- Elevated infiltration rates – oxidation is promoted by convective/advective mechanisms that greatly increase the availability of oxygen in the dump and the mass of sulphide exposed to atmospheric oxygen. Oxidation products that are stored within the dump during dry periods are flushed during the wet season. Because rainfall events can be intense, both coarse and fine seepage pathways within the dump can be flushed, resulting in high AMD volumes and loads.

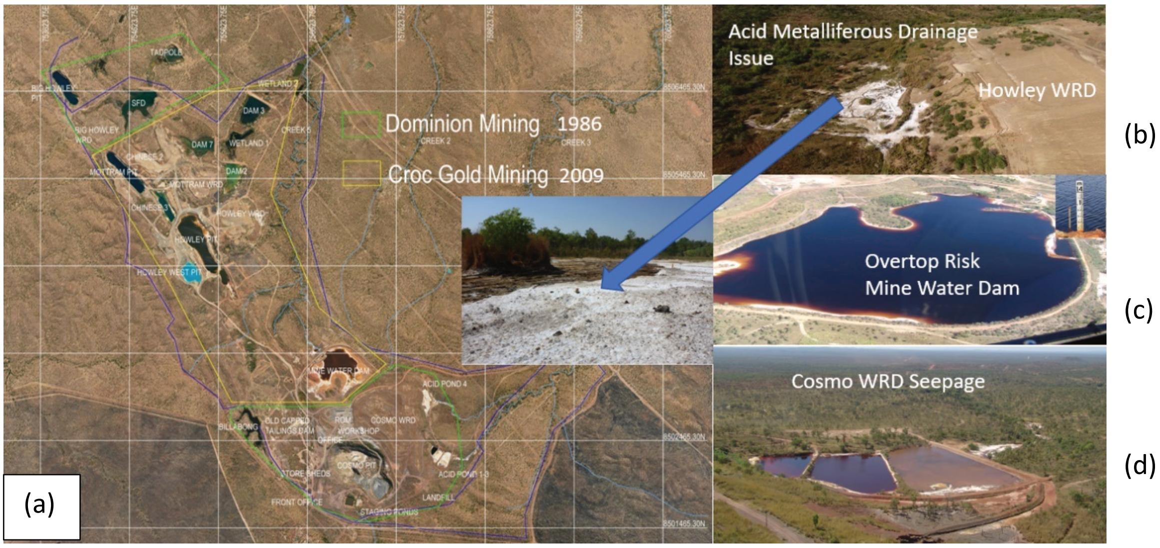

**Figure 1** (a) Cosmo Howley Project Area acid and metalliferous drainage; (b) Howley waste rock dump; (c) Mine Water Dam; (d) Cosmo waste rock dump seepage

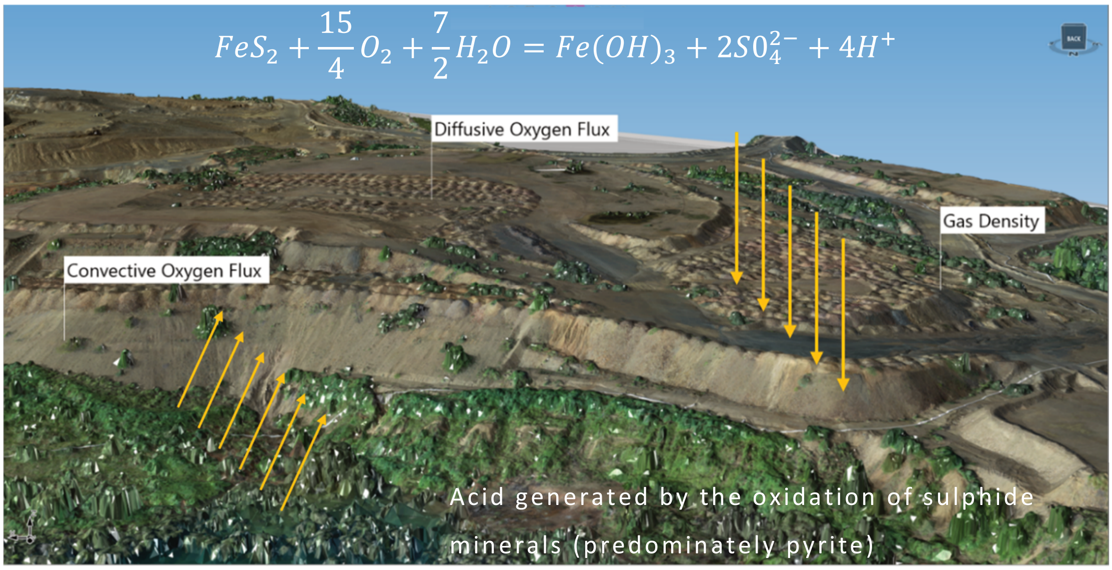
$$FeS_2 + \frac{15}{4}O_2 + \frac{7}{2}H_2O = Fe(OH)_3 + 2SO_4^{2-} + 4H^+$$

**Figure 2** Cosmo Howley Project Area Mottrams waste rock dump interaction with water and oxygen flux

The AMD problem is unlikely to abate in the foreseeable future unless the AMD source is removed or encapsulated. The ineffective design of the WRDs, limited geochemical characterisation and the highly seasonal tropical rainfall pattern compounds the problem with respect to the formulation of a cost-effective, long-term rehabilitation strategy.

Agnico Eagle NTMO undertook the following activities to develop a total ecosystem approach to the mine rehabilitation strategy for the AMD at CHPA.

## 3 Integration design and business model

A long-term collaborative approach can be adopted to appropriately manage cumulative impacts where required. This leads to positive relationships with internal and external stakeholders and improved reputation for the company and the industry. Strategy risks typically require a company to look beyond the mine gate to consider current and future risks at a regional scale.

Agnico Eagle NTMO developed an integration management process to validate rehabilitation design for waste material reduction projects based on the economic viability, environmental data analysis and multiple line of evidence and created collaborative working environments, ensuring transparency in the decision-making process, and ensuring all stakeholders are aligned with the targets and goals throughout the development process.

A marginal abatement study was established to validate proposals for pollution reduction projects based on economic viability and development of long-term implementation strategies to maximise return on investment.

The primary outcome of this marginal abatement study was to stabilise and prevent further degradation of AMD waste material by containing contamination using a wet cap model along with the Howley WRDs to Cosmo option, using a Capex three-year model (Figure 3).

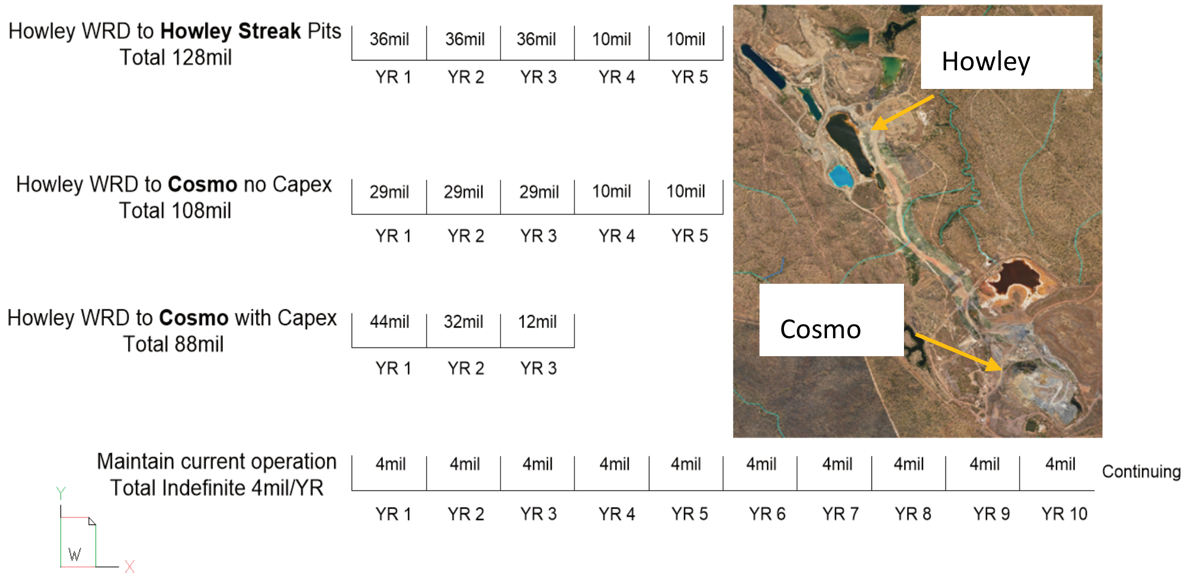

**Figure 3 Cosmo Howley Project Area rehabilitation business model**

This significant financial commitment to the Northern Territory strongly supports the corporate model, which recognises that implementing responsible environmental practices is critical to future success. The CHPA rehabilitation business model aims at integrating environmental, social and economic considerations. It is also aimed at the fostering of mutually beneficial environmental partnerships with our communities through communication and engagement of community stakeholders. Ultimately, the long-term rehabilitation plan is to return as much of the site the pastoral estate and demonstrate an overall commitment to being a model corporate citizen in the Northern Territory.

Howley WRDs to Cosmo Pit with Capex is the best outcome out of all four options with minimum future water treatment, optimised waste haulage, lowest carbon footprint, reduces high-risk liabilities in early stages, no mineral resource sterilised and the project becoming a low management site.

# 4 Cosmo Pit wet cap

## 4.1 Pit lake modelling

Longer term, and as part of this mine rehabilitation strategy, NTMO propose to control AMD via oxidation control – that is, isolation of pyritic materials from oxygen. This will be achieved by rehandling of waste rock from Howley WRDs and placement in-pit in the Cosmo Pit, below the recovery watertable level. Water is an effective barrier to significant oxygen diffusion.

A qualified environmental consultancy, namely Lorax from Canada, was appointed to undertake a feasibility study of Cosmo Pit wet cap, including:

- Investigation of current computer simulation for 1D-transport and inverse geochemical calculations.
- Reviewing the modelling inputs and implications for closure planning.
- Predicting pit lake water column properties using a coupled mixing and geochemical speciation model.
- Developing a conceptual model for pit lake formation in the backfilled pit, including inputs from the following sources:
    - Short term: Release of soluble metals and acidity associated with the flushing of waste material surfaces.
    - Long term: diffusive loading from waste rock porewater into overlying water column. Suboxia will develop within waste rock porewaters, with long-term porewater conditions governed by suboxic redox processes (e.g. reductive dissolution of Fe oxide phases). Pit wall runoff may be associated with overland runoff that enters the pit, direct precipitation to pit walls, and groundwater inputs that enter the pit above the pit lake surface.

Pit lake modelling was conducted using a one-dimensional hydrodynamic and water quality model that predicted the vertical distribution of temperature, salinity, density, and other water quality variables in pit lakes. In addition, the model incorporated non-conservative removal mechanisms, including oxygen consumption, denitrification and metal scavenging from the surface layer associated with the settling of inorganic and biogenic particles. The results indicated 5 m of wet cap water column was the minimum depth of water and 10 m of wet cap would produce the ultimate results showing in Figure 4.

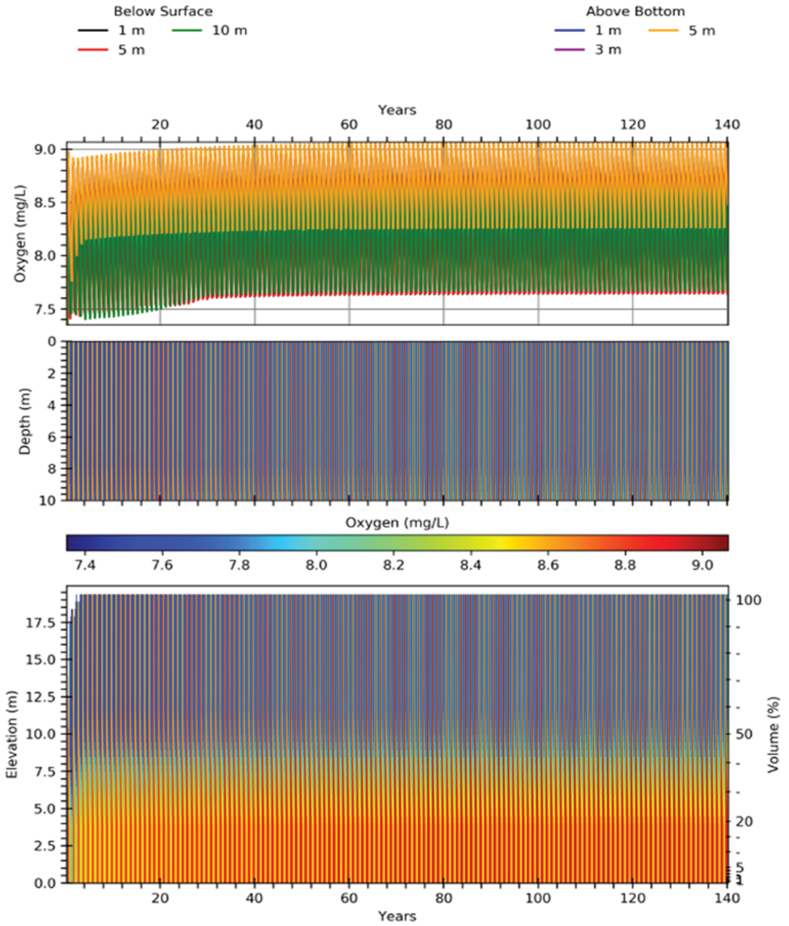

**Figure 4** 1D-transport and inverse geochemical calculations (Lorax Environmental Services Ltd. 2021)

## 4.2 Wet cap design concept

It was anticipated that the PAF fill could be separated into three zones by the compacted NAF layer and wet cap (Figure 5). Due to the nature of the formation and field monitoring, groundwater flow is expected to be minimal. The NAF layer and the wet cap were predicted to minimise the oxidation of the PAF material, and when the formation pressure comes into balance, the PAF material will remain quite stable.

Reducing infiltration by compaction of the backfill material to reduce permeability is essential to minimise the diffusion and hence reduce the AMD volume and load. To construct an effective wet cap to perform oxidation control effectively, generally a NAF sealing layer (with compacted fine-grained material) and a minimum 5 m water depth would be required to reduce the diffusive flux.

For an ideal (hypothetical) scenario, a 50 cm thick layer of non-PAF waste would be sufficient to afford an adequate diffusion barrier. However, given the practical limitations relating to the operation of heavy machinery, as well as to some degree of blending that will inevitably occur upon backfill placement, a minimum thickness of 1.0 to 1.5 m was recommended.

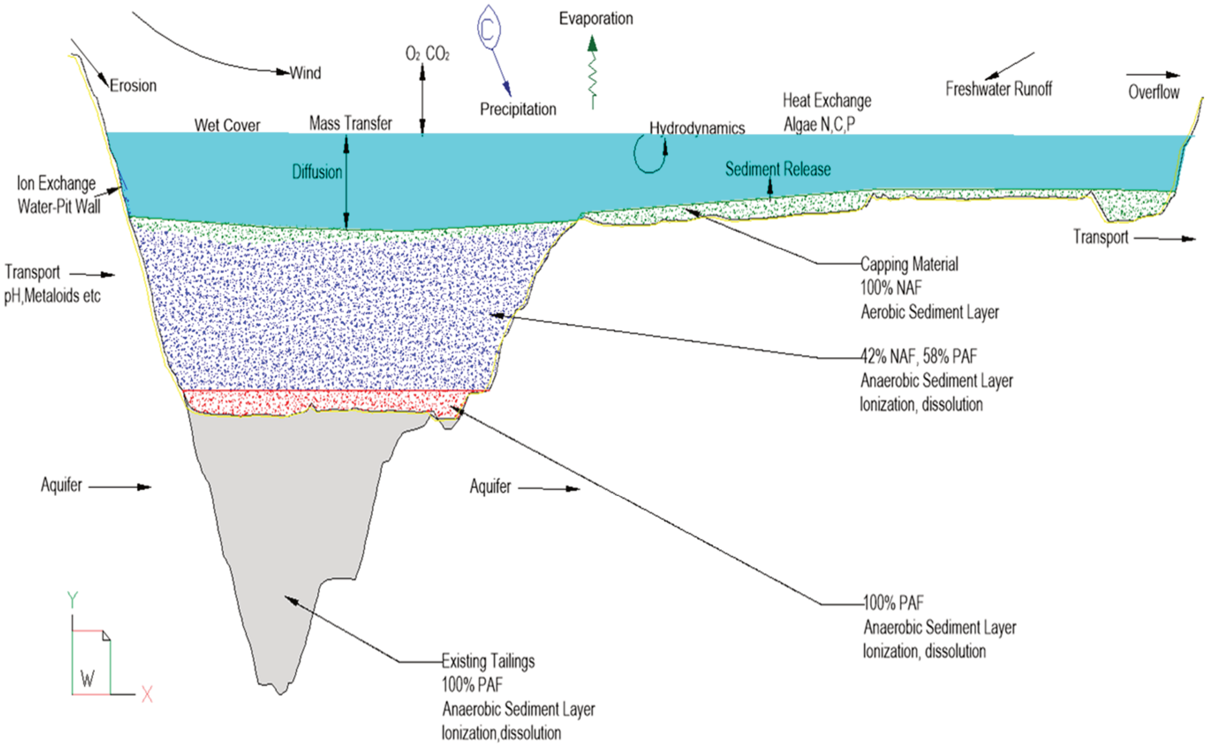

**Figure 5 Cosmo Pit wet cap concept layout**

## 4.3 Water treatment

Cosmo wet cap consists of treated water from existing acidic water pits and dams. The treatment method involves the use of quicklime (CaO) and inline dosing infrastructure to treat Howley Pit acidic water as required during the transfer into Howley West Pit prior to final discharge to Cosmo Pit for the wet cap (Figures 6 and 7). Figures 8 and 9 illustrate pre- and post-backfilling of Cosmo Pit, respectively. Laboratory trials and actual treatment trials onsite determined that inline treatment rates of 1.8–2.4 g/l of CaO are adequate to produce a pH between 8.2 and 9, low metal concentrations (almost Australia and New Zealand Guidelines for Fresh and Marine Water Quality [ANZECC 2000] 95%) and electrical conductivity of between 3,500 to 4,000 µs/cm after 48 hours detention time. Refer to Table 1 for summarised water quality results from 2019 to 2022.

Figure 6 Quicklime inline dosing setup

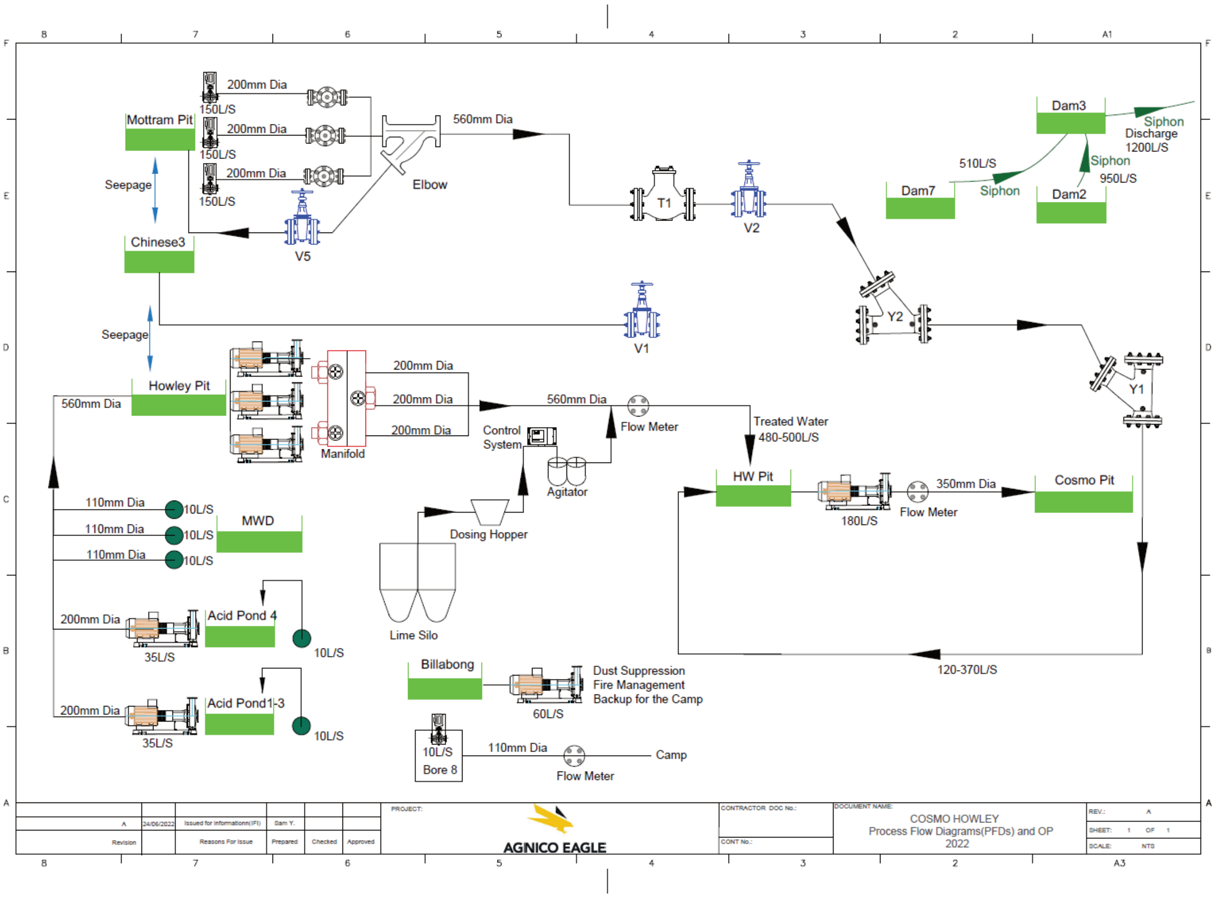

Figure 7 Cosmo Pit wet cap water treatment schematic

Figure 8 Cosmo Pit pre-backfill

Figure 9 Cosmo Pit post-backfill (wet cap is ongoing)

**Table 1 Acidic water treatment results**

| Field | Pre-treatment median (2019–2022) | Post-treatment median (2019–2022) |
|---|---|---|
| EC (µS/cm) | 5,910 | 4,149 |
| TDS | 3,344 | 2,671 |
| Salinity | 2.9 | 2.2 |
| pH | 2.9 | 7.9 |
| Acidity as $CaCO_3$ (mg/L) | 1,100 | 5 |
| Aluminium-dissolved (µg/L) | 140,000 | 195 |
| Arsenic-dissolved (µg/L) | 12.5 | 1 |
| Cadmium-dissolved (µg/L) | 13 | 0.1 |
| Chromium-dissolved (µg/L) | 19 | 1 |
| Cobalt-dissolved (µg/L) | 3,000 | 11 |
| Copper-dissolved (µg/L) | 2,500 | 1 |
| Iron-dissolved (µg/L) | 21,000 | 10 |
| Lead-dissolved (µg/L) | 29 | 1 |
| Manganese-dissolved (µg/L) | 44,000 | 500 |
| Nickel-dissolved (µg/L) | 3,500 | 4.5 |
| Sulphate (mg/L) | 5,000 | 3,100 |
| Zinc-dissolved (µg/L) | 2,200 | 3 |

# 5 Contaminated rehabilitation material

Another environmental risk incorporated into the Mine Rehabilitation Model is contaminated soils and other materials available for rehabilitation activities. A treatment investigation was trialled at CHPA to develop the best possible physical and biological options for capping and final land use options, after remediation.

## 5.1 CH2 Pit dry cap

Naturally occurring biological micro-organisms and plants able to withstand high concentrations of heavy metals can be useful in eradicating hazardous contaminants. This is a process known as bioremediation and is an eco-friendly and efficient method of reclaiming environments contaminated with heavy metals.

Biological treatment can be combined with physical processes, such as anionic clay precipitation. The clay binds to metals and other contaminants, which make the toxic metal inactive. Biological treatment can then add nutrients to the soil to promote vegetation growth.

A trial treatment investigation occurred at NTMO’s CH2 Pit in 2020; test results on available capping material are outlined in Table 2.

**Table 2 Capping material soil chemistry**

| **Soil texture** | **Clay loam** |
|---|---|
| pH | 4.5–5.6 |
| Phosphorous (mg/kg) | 280 |
| Calcium (mg/kg) | 460 |
| Magnesium (mg/kg) | 5,600 |
| Sodium (mg/kg) | 30 |
| Aluminium (mg/kg) | 9,900 |
| Potassium (mg/kg) | 3,200 |
| Exchangeable Ca (mEq/100 g) | 1.4 |
| Exchangeable K (mEq/100 g) | 0.2 |
| Exchangeable Mg (mEq/100 g) | 7 |
| Exchangeable Na (mEq/100 g) | 0.1 |
| CEC (mEq/100 g) | 8.6 |
| ESP (%) | 1 |
| Mg:Ca ratio | 5 |
| % Total organic carbon | 3 |
| % Organic matter | 5 |

The screen material test results highlighted that the Mg:Ca ratio is high, indicating the screen material would present a very serious waterlogging issue. The material would be an appropriate material for a sealing layer; however, it was not considered suitable for top cover.

The screen material is slightly acidic with high aluminium concentrations, which can be toxic to vegetation. It was proposed that the pH be increased to 6.5–7.5 using agricultural lime with a treatment rate between 2 and 4 kg/m$^3$. Dolomite was not considered for treatment due to the high magnesium ratio and because it is less beneficial as a soil ameliorant. The trial treatment investigation determined that to mitigate the issue where topsoil and subsoil is sodic (ESP>6% or Ca:Mg<0.1), agricultural lime should be spread over the soil at the suggested rate if the pH<6.5; if the pH>6.5, gypsum should be applied.

The results also indicate that the cation exchange capacity of the screen material is low as 12 mEq/100 g is considered moderate, which has adequate nutrient-holding capacity. Total organic carbon below 5% indicates the screened material needs to be treated using lime, gypsum and other organic matter to improve overall condition for successful vegetation growth. Previous revegetation success is illustrated in Figure 10.

To address these issues, the final rehabilitation program included hydro-seeding and hydro-mulching, which utilised plant fibre material mulching which, when applied in conjunction with Biotic Soil Media (applied between 5 and 10 t/ha), increased overall organic carbon. Biotic Soil Media utilises a combination of recycled thermally refined bark and wood fibres, with a proprietary blend of biopolymers, biochar, seaweed extract, humic acid, endomycorrhizae and a high concentration of beneficial soil bacteria.

Adding beneficial bacteria (*Trichoderma* and *Bacillus*) into the hydro-mulch blend will:

- Rebuild tired and worn soils through remineralisation.
- Build critical levels of many trace elements.
- Increase soil carbon levels for energy, water and nutrient-holding capacity.

- Increase the ability for plants and turf to resist pest and disease attack.
- Improve biological activity in the soil, promoting availability of both target and other tied-up nutrients in the soil.

(a) (b)

**Figure 10 CH2 pit; (a) Dry cap; (b) Revegetation**

## 5.2 Bioremediation for acid mine drainage contaminated soil

The Mine Water Dam (MWD) is one of the receptors to store large quantities of heavy metal contaminated water at the Cosmo site. Rehabilitation planning is essential to state-based regulatory approvals and mine closure. As a condition of approval, the MWD has been progressively remediated, including dewatering, water treatment and acidic material removal. The remaining projects include decommissioning the dam wall, reshaping, residue soil remediation and revegetation. The final capping is required to be safe, stable and non-polluting. Testing of the soil material within the MWD embankment confirms that it is suitable for capping the contaminants stored within the old MWD. See Figure 11 for the location of the MWD and Figure 12 for acid-based accounting results from embankment material testing. Figure 13 illustrates the initial success of a bio-treatment trial.

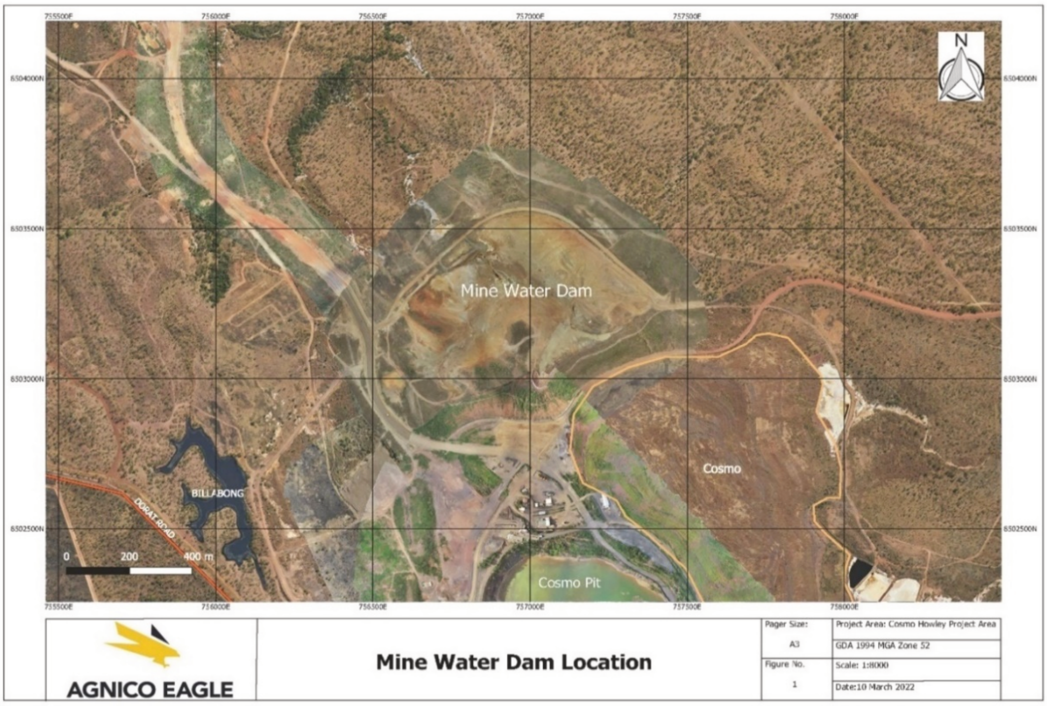

**Figure 11 Mine Water Dam site location**

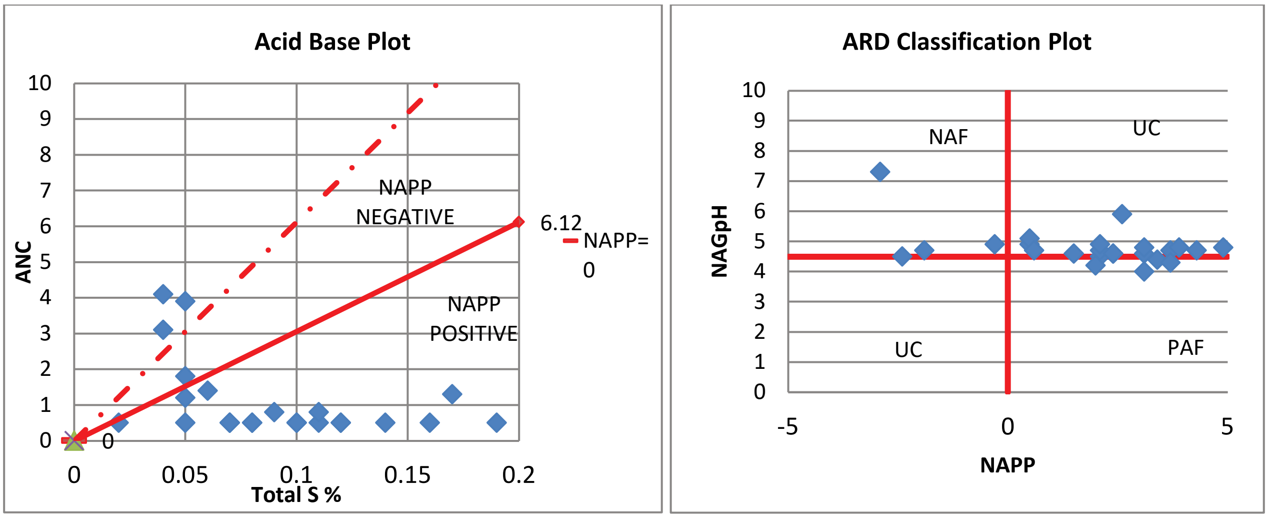

Figure 12 Mine Water Dam floor acid base accounting results (29 samples)

Figure 13 Acid and metalliferous drainage contaminated soil bio-treatment trial

The objective of this study was to investigate and identify the most efficient and effective application rate of cattle manure and seeding options, as well as possible physical mechanisms such as lime treatment rate, to bioremediate a heavy metal contaminated dam. Trials were conducted to evaluate efficacy and speed of remediation, identify which organisms can work in harmony with others and the ideal mixed treatment recipe.

As seen in Table 3, the material is slightly acidic with high aluminium and iron concentrations, which can be toxic to vegetation.

The available nitrite and nitrate as N is low at 0.1–0.7 mg/kg compared to the optimal range of 40–60 mg/kg. Total organic carbon below 0.5% indicates the material needs to be improved by adding lime, cattle manure and beneficial bacteria to improve the overall condition for successful vegetation growth.

To address these issues, the site will be ripped 300 mm depth, then cattle manure will be applied at 100 t/ha. Then fertiliser (150 kg/ha), biotic media (1.5–5 t/ha) will be applied via hydro-seeding and hydro-mulching.

The Bonded Fibre Matrix hydro mulch recommended for rehab contains microbial Leonardite combined with Pro-Tech Stimulate, containing active bacteria to carry mineral trace elements from plant surfaces into plant tissues. Key ingredients in high-quality fertilisers are added, such as *Trichoderma herzlianism*, *Trichoderma* *lignorum*, *Trichoderma koningii*, *Bacillus subtilis*, kelp, fish emulsions and carbon fulvic humates. Applications at specific plant growth stages can be used as a production tool for maximising the plant's productive capacity. This blend has been delicately handled to ensure the full benefit of a nutrition catalyst to enhance ion transfer and their enhancement of cell wall permeability.

**Table 3 Sediment test results**

| | **Unit** | **Dam embankment[1] Median value** | **MWD floor[2] Median value** | **MWD floor[3] Median value** | **Cattle manure[4]** | **Optimal range** |
|---|---|---|---|---|---|---|
| **Acid sulphate soils** | | | | | | |
| Net acid production potential (NAPP) | kg H2SO4/t | −2.2 | 2.6 | 6.7 | – | – |
| NAG pH (OX) | pH Unit | 6.7 | 4.7 | 3.9 | – | – |
| ANC as H2SO4 | kg H2SO4 equiv./t | 2.6 | 0.5 | 0.5 | – | – |
| Sulphur – Total as S (LECO) | % | 0.01 | 0.1 | 0.26 | – | – |
| Electrical conductivity (saturated paste) | µS/cm | 133 | 2,430 | 1,580 | 420 | 100–250 |
| Moisture content | % | 7.6 | 6.5 | 12.3 | 80 | – |
| **ED093S: Soluble major cations** | | | | | | |
| Calcium | mg/kg | 10 | 80 | 190 | 6,800 | 1,100–3,300 |
| Magnesium | mg/kg | 10 | 290 | 380 | 3,000 | 200–480 |
| Sodium | mg/kg | 20 | 20 | 10 | 200 | 50–72 |
| Potassium | mg/kg | 25 | 90 | 10 | 5,500 | 110–140 |
| **EG005(ED093) T: Total metals by ICP-AES** | | | | | | |
| Aluminium | mg/kg | 7,285 | 5,720 | 6,640 | 630 | 9–45 |
| Cobalt | mg/kg | 8 | 10 | 7 | 3 | – |
| Copper | mg/kg | 29 | 66 | 178 | 15 | 0.6–2 |
| Iron | mg/kg | 28,750 | 22,500 | 44,200 | 2,700 | 33–60 |
| Lead | mg/kg | 11 | 20 | 10 | 3 | – |
| Manganese | mg/kg | 123 | 125 | 119 | 400 | 6–12 |
| Nickel | mg/kg | 8.5 | 16 | 12 | 3 | – |
| Zinc | mg/kg | 20 | 14 | 16 | 130 | 2–10 |
| **Ammonia, nitrate, phosphorus, chloride, total carbon** | | | | | | |
| Total nitrogen as N | mg/kg | 170 | 130 | 240 | 16,000 | 200–300 |
| Total phosphorus as P | mg/kg | 102.5 | 98 | 246 | 3,900 | 50–200 |
| Total carbon | % | 0.24 | 0.16 | 0.29 | TOC 310,000 mg/kg | 2–3 |

Notes: [1]46 samples. [2]29 samples Oct 2022. [3]29 samples Feb 2022. [4]3 samples.

# 6 Conclusion

The mine closure completion target was successfully achieved by both wet cap and bioremediation strategies, which were aimed at returning the disturbed mining areas to modified natural ecosystems that:

1. Have no residual hazards or contamination of the environment exceeding relevant standards and guidelines relating to human and livestock health.
2. Enable the land to be returned to a viable post-mining land use.
3. Are consistent with the surrounding landforms where possible and exhibit surface stability adequate to retain the integrity of the landform design.
4. Support vegetation communities comparable with the surrounding environment and a low maintenance management regime. The mined environment is managed to reduce any significant impacts to the surrounding environment, including surface and groundwater resources identified as having beneficial uses.

# References

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