Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)

doi:10.36487/ACG_repo/2615_76

An outcome-focused framework for legacy mine closure

Freeternity Rusinga [a,*], **Timothy Rohde** [a]

[a] *SGME, Australia*

Abstract

The environmental management of legacy polymetallic mines is frequently complicated by the cumulative impacts of unregulated waste disposal left unattended over many years, exceeding a century in many cases. Unlike modern operations with established closure strategies, derelict sites often present with unmapped shafts, scattered tailings and persistent acid mine drainage (AMD) integrated into local hydrological regimes. In many cases, tailings were placed within watercourse alignments where this presents a significant local and offsite environmental risk. While traditional remediation often prioritises immediate end-of-pipe solutions, this paper proposes an alternative, design-led framework.

By adopting a staged, source-first methodology, the design framework aims to eliminate chemical contamination drivers before the installation of water treatment hydrological infrastructure. Depending on the catchment size draining through these sites, such structures can often represent significant capital investments. Underpinning the framework is the strategic deferment of high-capital hydrological structures pending the results of initial source term removal. If the source removal phase proves effective, large-scale infrastructure may be optimised or excluded entirely, resulting in significant cost savings.

Crucially, the framework adopts a multidisciplinary approach, integrating geochemical considerations with ecological restoration, heritage conservation, Aboriginal representation and local community expectations. The ultimate objective is to provide a defensible engineering pathway for transforming high-risk industrial 'scars' into stable landforms suitable for regional primary production. The case studies presented in this paper were mapped as Capability Class 8 – Extreme limitations, a classification under the New South Wales Land and Soil Capability mapping system that encompasses land generally only able to sustain very low-impact uses, such as nature conservation. By implementing the proposed staged remediation framework, the goal is to stabilise these extreme limitations sufficiently to support a transition towards more productive, yet sustainable, regional outcomes such as agricultural grazing.

Keywords: *legacy mine remediation, acid mine drainage, multidisciplinary design framework, staged remediation, sustainable land use, design-led*

1 Introduction

Legacy sites present complex challenges where historical mineral residues characterised by high concentrations of lead (Pb), zinc (Zn), silver (Ag), arsenic (As) and reactive sulphides were often deposited in riparian zones and unlined shafts. This paper introduces a closure framework underpinned by Integrated Mine Closure and Leading Practice Sustainable Development Program (LPSDP) protocols (Department of Industry, Innovation and Science 2016). Traditional remediation focuses on high-capital end-of-pipe water treatment structures.

In contrast, this design-led framework utilises a staged approach to break the source-pathway-receptor (SPR) linkage by executing primary contaminant source isolation. By prioritising the removal of the source term as the primary chemical driver, the framework challenges the technical necessity for permanent, high-maintenance hydraulic treatment assets. This approach is vital for sites situated in high-value

* Corresponding author. Email address: frusinga@sgme.au

landscapes or areas of traditional significance, where permanent industrial infrastructure may conflict with community expectations or cultural land use practices. Throughout this paper, this design-led philosophy, where primary source-term removal eliminates the need for permanent sediment retention basins, is referred to as the ‘zero-basin’ hypothesis.

2 Literature review: regulatory framework and leading practice standards

The remediation of legacy mine assets requires navigating the regulatory framework to ensure long-term stability and negligible risk to human health and the environment. This section synthesises the primary legislative drivers and industry guidelines that underpin the proposed outcome-focused framework, informed by baseline results from historical assessments at legacy sites, in the Australian context.

2.1 Legislative drivers for legacy remediation

A robust closure strategy must comply with several key statutory instruments in Australia. The *Environmental Planning and Assessment Act 1979* (NSW) (EP&A Act) (Government of New South Wales 1979) provides the primary structure for impact assessment, with public authorities such as the Legacy Mines Program often acting as the determining authority under Division 5.1. Furthermore, the *Protection of the Environment Operations Act 1997* (NSW) (POEO Act) (Government of New South Wales 1997) regulates the handling of contaminated materials, mandating an Environment Protection Licence should soil treatment exceed 30,000 m^3 or the area of disturbance exceed 3 hectares. Assessments informed by this legislation at polymetallic legacy sites have identified high concentrations of Pb, Zn, Ag, and As residues, often deposited in sensitive riparian zones and unlined shafts, necessitating these stringent regulatory triggers.

The conservation of native biota is governed by the *Biodiversity Conservation Act 2016* (NSW) (BC Act) (Government of New South Wales 2016), which may require a species impact statement if significant impacts to threatened species are identified. Baseline studies at regional legacy sites typically identify a range of sensitive ecological receptors, including threatened flora (such as *Eucalyptus* species) and vulnerable woodland birds. Furthermore, specialised habitat utilisation is common, with microbat populations frequently utilising stable subsurface infrastructure like existing mine shafts for roosting and maternity sites. Similarly, the *Fisheries Management Act 1994* (NSW) (FM Act) (Government of New South Wales 1994) manages Key Fish Habitat and requires specific permits for any activities that obstruct fish passage or involve dredging. Historical data indicates that untreated site run-off can transport dissolved metals into distal river systems, potentially impacting receptors.

Non-Aboriginal relics are protected under the *Heritage Act 1977* (NSW) (Heritage Act) (Government of New South Wales 1977), necessitating a Section 140 Excavation Permit for the disturbance of archaeological relics of local significance. Field investigations at legacy mines often reveal significant industrial heritage, including standing mill timbers, corduroy roads and historical poppet heads (also known as a headframe) that must be either conserved or shredded and encapsulated if they act as passive contamination sources. Aboriginal cultural heritage is managed under the *National Parks and Wildlife Act 1974* (NSW) (NPW Act) (Government of New South Wales 1974), requiring rigorous community consultation and, in some instances, an Aboriginal Heritage Impact Permit.

The *Crown Lands Management Act 2016* (NSW) (CLM Act) (Government of New South Wales 2016) authorises remediation on Crown land via departmental agreement, while the *Water Management Act 2000* (NSW) (Government of New South Wales 2000) governs activities on “waterfront land”, defined as the zone within 40 metres of the highest bank of a river. Biosecurity risks, such as the management of priority weeds during earthworks, are addressed under the *Biosecurity Act 2015 (NSW)* (Government of New South Wales 2015).

2.2 Leading practice guidelines

The technical integrity of this framework is aligned with recognised industry standards, including the LPSDP handbooks on mine closure and preventing acid mine drainage (AMD). Water quality validation is benchmarked against Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) (2000) guidelines, and stormwater controls are designed in accordance with the New South Wales (NSW) Department of Housing (2004) guidelines, Managing Urban Stormwater: Soils and Construction (the 'Blue Book'). Technical characterisation at legacy sites often reveals a positive net acid producing potential (NAPP), confirming that the materials are net acid generating and require engineered interventions based on these standards.

Remediation design also integrates the National Environment Protection (Assessment of Site Contamination) Measure 1999 (ASC NEPM) (NEPC 1999, as amended 2013), specifically for establishing Groundwater investigation levels (GILs), Health investigation levels (HILs) and Ecological investigation levels (EILs) to assess site suitability for proposed land uses

At the core of the framework is the mandatory justification of activities against the principles of Ecologically Sustainable Development (ESD) as defined in Section 6(2) of the *Protection of the Environment Administration Act 1991* (NSW) (POEA Act*).* Within this, the Precautionary Principle ensures that a lack of absolute scientific certainty is not used to postpone measures preventing environmental degradation. Inter-generational Equity commits to maintaining the health and diversity of the environment for the benefit of future generations. The maintenance of ecological integrity is established as a fundamental decision-making consideration through the Conservation of Biological Diversity. Finally, Improved Valuation promotes the pursuit of environmental goals through cost-effective engineering and the accurate internalisation of environmental costs, supporting the transformation of industrial 'scars' into stable landforms suitable for regional primary production, such as agricultural grazing.

2.3 Transition to case study methodology

By synthesising these benchmarks it becomes evident that traditional end-of-pipe hydraulic solutions often fail to address the underlying geochemical drivers identified in the literature. The following section applies this multidisciplinary literature to specific regional contexts, utilising the established ANZECC and NEPM triggers as primary success metrics for a staged remediation methodology. This site-specific characterisation serves to demonstrate how primary source isolation can fundamentally alter the long-term infrastructure requirements of a legacy asset. The studies were completed in accordance with Remedial Action Plan (RAP) requirements outlined in the NSW Environment Protection Authority's Consultants reporting on contaminated land guidelines (NSW EPA 2020) and the Guidelines for the NSW Site Auditor Scheme (NSW Environment Protection Authority 2017).

3 Case study application: multi-factor remediation

3.1 Introduction

For confidentiality reasons, the specific sites used for the case studies presented in this paper have not been named. These case studies are based on remediation projects completed by SGME involving legacy mines in NSW. While the lessons learnt and site-specific conditions described are based on regional NSW environments, the key concepts of the framework are broadly applicable to other legacy sites elsewhere, subject to local regulatory requirements.

3.2 Site environmental context

These case study areas in NSW typically experience a mean annual rainfall of approximately 895 mm, with the most significant rainfall events frequently occurring in November. Summer temperatures often reach a mean maximum of 27°C, while winter minimums can drop to approximately −1.0°C. Topography is generally characterised by undulating rocky hills and rises, with elevations ranging between roughly 750 and

830 mAHD. The drainage systems for these sites often dissect the landscape via ephemeral drainage lines reporting to regional river systems. Geologically, these sites are dominated by granite geology, specifically undifferentiated Permian granite, which hosts the complex polymetallic mineralisation targeted by historical mining.

3.3 Typical site layout and conceptual site model

The layout of these sites reflects typical historical mining practices, featuring several distinct domains. These typically include processing areas situated near main shafts, scattered waste rock dumps and tailings piles often deposited in unlined riparian zones. The formulation of the site-specific conceptual site model (CSM) was informed by an integration of geochemical, hydrogeological, ecological and heritage technical studies to define the critical nexus of risks within these layouts.

The primary contamination sources are identified as historical Pb, Zn, Ag and As residues. Migration pathways are dominated by advective transport via surface water run-off, infiltration and seepage into drainage lines. A critical hydrogeological pathway exists through vertical mine shafts which serve as preferential flow paths or 'conduits', allowing contaminated surface water to bypass natural soil attenuation and directly enter deep groundwater aquifers. Furthermore, mechanical transport of contaminants occurs via wind-blown dust and the erosion of sodic and dispersive soils where existing controls are ineffective. Receptors at risk include aquatic ecosystems, groundwater resources, humans, livestock and endemic plants.

These complex interactions are visualised in the pictorial CSM diagram in Figure 1, which illustrates the link between legacy sources and sensitive regional environments. Construction works for water treatment hydrological infrastructure in such an environment will inevitably require expensive blasting, which drives the capital cost very high, further justifying the source-first methodology advocated in this paper.

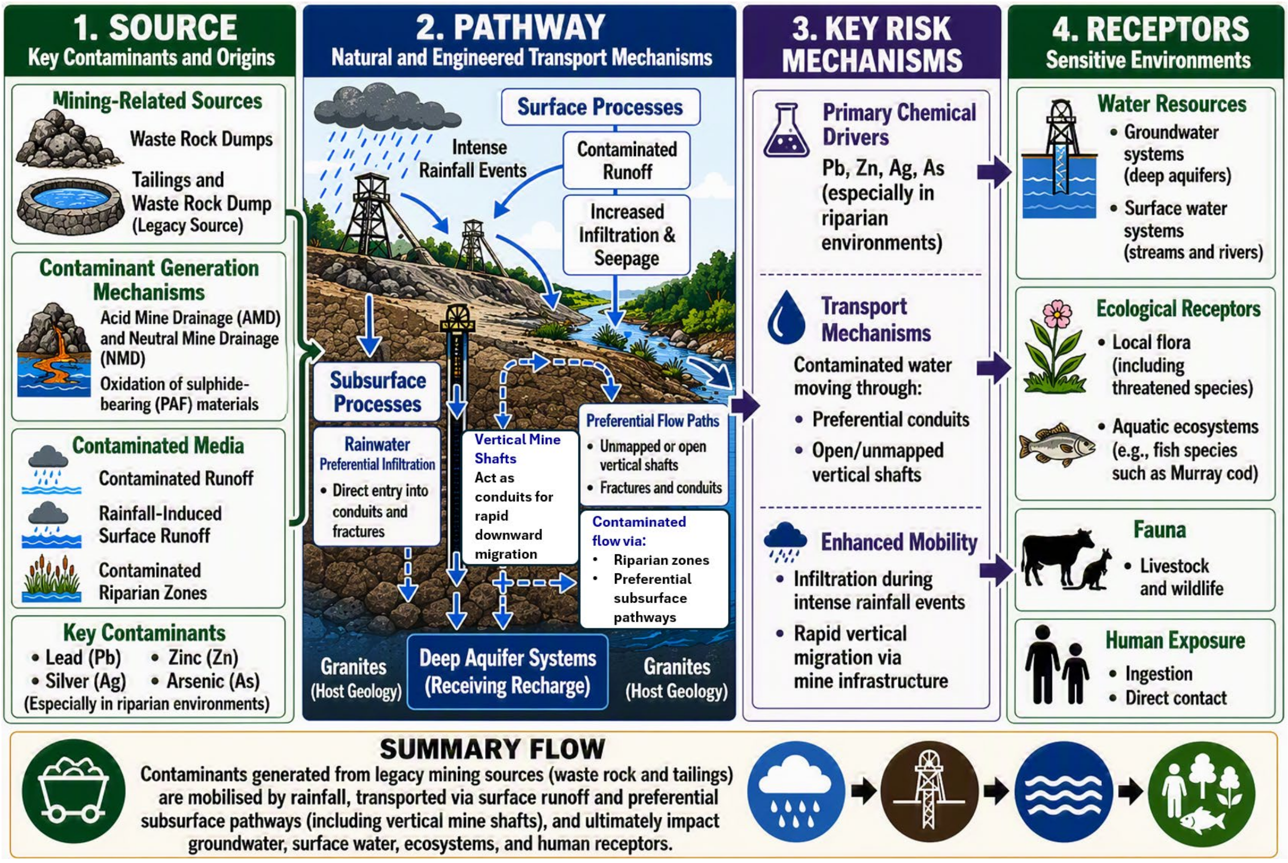

Figure 1 Conceptual site model illustrating source-pathway-receptor linkages and key risk mechanisms in a legacy mine setting

3.4 Methodology

The characterisation and remediation design for the legacy mine site utilised a multidisciplinary approach, integrating drone-based remote sensing, in situ geochemical screening and geotechnical modelling to address complex polymetallic contamination by operationalising the leading practice standards and regulatory frameworks established in the literature review. High-resolution topographic data and a digital twin of the legacy landform were established through unmanned aerial vehicle (UAV) flyovers. The resulting drone photogrammetric data was processed using DJI Terra mapping software to generate a 3D model for volumetric estimates, allowing for precise quantification of the ‘source’ components identified in the CSM. Surface flow paths and sub-catchment areas reporting to proposed infrastructure locations were defined using CatchmentSIM topographic processing software, which utilised a 5 m-resolution digital elevation model (DEM) and high-density point cloud data. This spatial analysis directly informed the mapping of advective transport ‘pathways’ defined in the CSM, such as surface run-off and erosion into drainage lines.

A tiered sampling regime was implemented to delineate potentially acid forming (PAF) domains from non-acid forming (NAF) materials, adhering to NEPM guidelines for managing contaminated land. This began with real-time elemental analysis conducted via a handheld X-ray fluorescence (XRF) analyser across strategic locations to define the lateral extent of Pb, Zn, Ag and As contamination. Laboratory validation involved standard acid-base accounting (ABA) to determine NAPP and net acid generation (NAG) pH. Samples were classified as PAF or PAF-low capacity (LC), based on specific sulphur percentages and pH thresholds, to identify the chemical drivers of the site based on criteria of the Department of Industry, Science, Energy and Resources (DISER) and the Department of Foreign Affairs and Trade (DFAT) (DISER & DFAT, 2016) (see Table 1). Aqueous chemistry for surface and groundwater was analysed for dissolved metals via laboratory testing and benchmarked against ANZECC & ARMCANZ (2000) 95% protection triggers and Australian Drinking Water Guidelines (National Health and Medical Research Council & Natural Resource Management Ministerial Council [NHMRC & NRMMC] 2011) to assess risks to ecological and human ‘receptors’.

Table 1 Acid mine drainage potential screening criteria (DISER & DFAT, 2016)

Classification	NAPP (kilograms of sulphuric acid per tonne [kg H_2SO_4/t])	NAG pH
PAF	>10	< 4.5
PAF-low capacity	0–10	< 4.5
NAF	Negative	≥ 4.5
Acid consuming	<100	≥ 4.5
Uncertain	Positive	≥ 4.5
	Negative	≥ 4.5

Notes: NAPP - net acid producing potential; NAG - net acid generation; PAF – potentially acid forming; NAF - non-acid forming

The staged framework necessitated complex hydrological simulations to quantify predicted sediment reduction and test the ‘zero-basin’ hypothesis Stormwater quality modelling was conducted using the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (eWater 2014) to quantify total suspended solids (TSS) and associated contaminant loads from disturbed areas. These results informed the sizing of sediment basins according to the Blue Book (Landcom 2004) standards and Managing Urban Stormwater: Volume 2E – Mines and Quarries (Department of Environment and Climate Change [DECC] 2008), with spillways engineered to withstand a 50-year time-of-concentration event.

Subsurface stability and material suitability for the engineered containment cell were verified through a geotechnical investigation involving soil profiles logged using a handheld auger to a depth of 3.0 m to assess depth to weathered granite. Potential borrow materials were subjected to falling head permeability tests and standard compaction tests to determine standard maximum dry density (SMDD). The containment cell design incorporates a multibarrier system utilising a geosynthetic clay liner (GCL) and a perforated 200 mm high-density polyethylene (HDPE) leachate collection pipe system to provide a long-term hydraulic and geochemical barrier between the contaminant source and groundwater receptors.

Environmental and heritage safeguards were integrated into the methodology to protect sensitive receptors, applying the Precautionary Principle for biological diversity conservation *Environment Protection and Biodiversity Conservation Act 1999 (Cth)* (EPBC Act) (Government of Australia 1999**)**. Identification of hollow-bearing trees was conducted through ground-based visual assessments using high-magnification binoculars. To protect identified heritage features, such as standing mill timbers and corduroy roads, a 2.0 m exclusion buffer was established via high-precision survey markers, mandating manual excavation within these zones to preserve the historical integrity of the industrial landscape.

3.5 Land and soil capability mapping

A critical component of this characterisation is the assessment of the land's inherent capacity to sustain various uses without degradation. The framework utilises Sharing and Enabling Environmental Data (SEED) Land and Soil Capability (LSC) Mapping for NSW (NSW Government 2022), which operates on an 8-class system where values represent a decreasing capability of the land to sustain land use.

The case study areas presented in this paper are mapped as Capability Class 8 – Extreme limitations, which constitutes the most restrictive classification. Land in this category is characterised by significant physical and chemical constraints, often exacerbated at legacy sites by historical surface contamination, and is generally restricted to very low-impact land uses such as nature conservation.

By integrating this mapping into the CSM, the framework establishes a defensible baseline for remediation goals. Rather than attempting to achieve residential-grade soil standards that may be geochemically or economically unattainable, the framework focuses on stabilising these Capability Class 8 industrial scars to a point where they can safely support a transition to limited regional primary production, such as agricultural grazing. This alignment ensures that the remediation effort is proportional to the land's capability and consistent with regional stakeholder expectations.

3.6 Results and discussion

The application of the multidisciplinary methodology confirmed significant polymetallic contamination and provided a definitive baseline for the staged remediation framework. Surface water quality assessments identified that local drainage lines were moderately to highly acidic, with dissolved metal concentrations for aluminium (Al), As, cadmium (Cd), copper (Cu), iron (Fe), Pb, manganese (Mn) and Zn frequently exceeding ANZECC & ARMCANZ (2000) 95% protection triggers and health-based guidelines. Notably, downstream sampling in the receiving river system revealed elevated dissolved Pb exceeding health guideline values (0.002 mg/L) and Zn exceeding protection triggers (0.044 mg/L), confirming the 'pathway' and 'receptor' risk linkages established in the CSM. Groundwater analysis further supported these findings, showing impacts from neutral mine drainage (NMD) characterised by neutral to alkaline pH but elevated concentrations of dissolved As, Cd, Mn, selenium (Se) and Zn.

Geochemical characterisation of the 'source' components delineated approximately 16,000 m^3 of PAF materials. In situ XRF screening and laboratory ABA revealed that approximately 63% of analysed site samples possessed a positive NAPP and a NAG pH $\leq$ 4.5, indicating they are net acid generating. Total metal concentrations for As, Pb and Zn significantly exceeded NEPM, HIL-C and EIL across multiple domains. Furthermore, approximately 83% of samples exhibited an Electrochemical Stability Index (ESI) below 0.05, identifying the soils as highly dispersive and prone to severe erosion.

Hydrological and geotechnical simulations validated the feasibility of the engineered containment strategy while highlighting the massive scale of required infrastructure. MUSIC modelling and Blue Book calculations determined that to achieve an 88% reduction in TSS, a total basin storage volume of approximately 33,000 m^3 would be required. The proposed design includes 4 significant structures (dams 1 to 4) within the tributaries across the site where the mining occurred. Existing dams 1 and 2 are located in series within the same tributary, while dam 3 (proposed) is situated in a second tributary. Dam 4 (proposed) is positioned furthest downstream, below the confluence of these 2 tributaries.

The requirement for these extensive hydrological assets, combined with the site's challenging granite geology, which would necessitate expensive blasting for construction, results in a huge capital cost. This significant financial burden necessitates the outcome-focused staged approach adopted for the project.

To evaluate the validity of the zero-basin hypothesis, a comparative assessment of the remediation scenarios and their corresponding basin requirements was compiled, as presented in Table 1.

Table 2 Comparative remediation scenarios and basin infrastructure requirements

Scenario	Predicted contaminant/sediment load	Basin volume requirement
Existing conditions	38,300 kg/yr TSS (source) → 22,500 kg/yr (residual)	33,000 m^3 (required for standard 85% urban target alignment if untreated)
Source removal only (Stage 1 verification)	Targeting 0% net acid producing potential via isolation of 16,000 m3 PAF	0 m^3 (testing the zero-basin hypothesis over a 2–3-year monitoring window)
Source removal + basins (Stage 2 if required)	4,610 kg/yr TSS residual (88% total catchment reduction)	Optimised or excluded entirely depending on Stage 1 water quality validation

Notes: TSS - Total suspended solids; PAF - Potentially acid forming

Modelling results were extracted from the point equivalent to the outlet of proposed dam 4 within the model for the existing case and the iterated design. The results show the flow (ML) and TSS (kg/yr) generated from all catchments to the location (source) and the values flowing from the outlet of the sediment dam (or the same location in the existing case) (residual). The existing scenario (with dams 1 and 2 in their current configuration) reduces 35% of all flows and 41% of all TSS generated in the catchment

The post-development scenario with additional dams reduces 73% of all flows and 88% of all sediment compared to having no sediment dams in place. The existing sediment dams (1 and 2) provide a limited degree of treatment as evidenced by comparisons between source flow and source TSS and residual flow and residual TSS within the existing scenario (Table 3). Under the existing case, the sediment dams present reduce flows and TSS from 77.8 ML/yr and 38,300 kg/yr to 50.6 ML/yr and 22,500 kg/yr, respectively. This provides a 35% reduction in flow and a 41% reduction in TSS.

With the upgrades proposed to the water management system, the residual load for TSS decreases from 22,500 kg/yr in the existing case to 4,610 kg/yr in the post-development scenario. Likewise, the residual load for flow decreases from 50.6 to 20.3 ML/yr. Thus, installation of the sediment dams will reduce sediment and flow by 79.5 and 60%, respectively, compared to the existing case. Stormwater quality targets for urban areas require that TSS values are reduced by 85%. This applies to the percentage reduction from source to residual TSS values within the post-development model. As shown in Table 2, the proposed basin set-up achieves an 88% reduction compared to having no sediment dams in place at all, thus achieving the stormwater quality target.

However, as mentioned above, the costs of the dam construction are excessive. The clean-up rehabilitation measures include seeding. A reassessment of the modelling would be required if the monitoring for this staged approach indicates low improvements.

Table 3 Modelling results from the Model for Urban Stormwater Improvement Conceptualisation

Parameter	Existing scenario	Post development	Reduction (%)
Source flow	77.8	77.8	
Residual flow	50.6	20.3	60%
% Reduction	35%	73%	
Source TSS (kg/yr)	38,300	38,300	
Residual TSS (kg/yr)	22,500	4,610	79.5%
% Reduction	41%	88%	

Notes: TSS - Total suspended solids

By implementing Stage 1: Contamination Management first, focusing on the excavation and physical isolation of the primary chemical drivers, the project seeks to test the zero-basin hypothesis. If subsequent monitoring over a 2- to 3-year period verifies that source removal has effectively neutralised the pollutant load, the high-capital Stage 2 structures may be optimised or excluded entirely, potentially resulting in substantial cost savings while still meeting the ultimate remediation objectives.

3.7 Construction staging

The remediation project is structured into 3 distinct phases designed to prioritise high-impact contamination management and provide a defensible empirical basis for the optimisation of capital-intensive hydrological infrastructure.

Stage 1 focuses on contamination management through the physical isolation of chemical drivers to break the SPR linkage. This primary phase involves excavation works targeting approximately 16,000 m^3 of identified PAF, PAF-LC, and uncertain (UC) materials across strategic domains. These excavated materials are consolidated within a new containment cell lined with GCL and finished with a multibarrier capping system to prevent rainfall infiltration and isolate contaminants from deep groundwater.

Following completion of the Stage 1 clean-up, an intermediate monitoring and performance verification stage is implemented for a period of 2 to 3 years. This phase serves as the philosophical and technical basis for the framework by testing the zero-basin hypothesis, which posits that the effective removal of the contaminant source may render high-capital sediment dams technically unnecessary. During this time, systematic surface water and groundwater monitoring is conducted to ensure that contaminant concentrations, specifically lead and zinc, remain consistently below established protection trigger values.

Progress to Stage 2, involving sediment and water management, is contingent upon the empirical results of the performance verification phase. If monitoring data confirms that run-off is non-polluting and the site clean-up was effective, these high-cost structures may be optimised or excluded entirely to provide significant capital savings. Should a verified risk persist, Stage 2 will proceed with the installation of the proposed major water management infrastructure.

3.8 Clean-up and staging criteria

To determine if the Stage 1 clean-up has successfully severed the SPR linkage, the framework utilises specific geochemical and water quality validation metrics. If these predefined acceptance criteria are met during the 2- to 3-year monitoring phase, the high-capital Stage 2 sediment dams may be optimised or excluded entirely, supporting the zero-basin hypothesis.

Geochemical validation targets the primary objective of reducing the risk of transporting acidity, dissolved metals, metalloids and sulphate to surface run-off and groundwater. The metrics for validating that the PAF material has been effectively isolated include a targeted NAPP of < = 0 kg H_2SO_4/t to ensure no residual acid-generating capacity. Success is further defined by a NAG pH targeted at ≥ 4.5 and a NAG acidity targeted at ≤ 1 kg H_2SO_4/t. To ensure a non-acidic surface environment suitable for vegetation establishment, the paste pH is targeted at ≥ 5.5, while electrical conductivity (EC) is targeted at ≤ 2,000 µS/cm to manage salinity constraints on plant growth and support the return to agricultural grazing land.

Success is also measured by the quality of the run-off reporting to the local aquatic system, utilising ANZECC & ARMCANZ (2000) 95% species protection triggers for fresh water as the primary benchmark. Under these criteria, Pb must remain below 0.0034 mg/L, and Zn must remain below 0.008 mg/L. Additionally, as is targeted at 0.013 mg/L, and Cd at 0.0002 mg/L.

The intermediate stage monitoring program serves as the mechanism for verifying these metrics through a comprehensive validation sampling and analytical quality plan. This includes periodic leachate testing of metals and sulphate every 6 months for 3 years to confirm stability; if concentrations remain below triggers, testing may be ceased. Systematic groundwater monitoring is also conducted upstream and downstream to assess the effectiveness of the encapsulation cell liner in isolating PAF material from the aquifer. If these metrics demonstrate that the run-off is no longer contributing a significant contaminant load, the project transitions to sustainable landform transformation without the need for additional Stage 2 hydrological infrastructure.

3.9 Land rehabilitation and landform transformation

Following the completion of excavation activities, disturbed areas are backfilled to establish a free-draining profile shaped specifically to reduce surface flow velocities. In instances where onsite verification testing confirms that residual PAF material remains at the base of an excavation, a multibarrier sealing approach is implemented. This engineering control consists of a low-permeability clay layer with a hydraulic conductivity of $k \leq 1 \times 10^{-9}$ m/s to isolate the reactive surface, protected by a non-woven geotextile to prevent the washout of fines. Above this, a layer of angular rock armour is placed to protect the seal from high-flow lotic events within drainage lines. A specific growth medium composed of gypsum-treated soil is incorporated within the rock matrix of the armour layer to promote the establishment of stable vegetation while maintaining the structural integrity and continuity of the underlying clay encapsulation. This combined layer facilitates surface stabilisation and reduces the exchangeable sodium percentage (ESP) to below a target of 6% while excluding deep-rooted species that could compromise the multibarrier system.

Complementing the riparian restoration, a ‘farm dam concept’ is utilised to transform borrow pits into functional agricultural assets by engineering them as excavated dams located entirely below the natural ground surface. This design eliminates the technical requirement for engineered embankments while providing a beneficial end use for the landholder. To ensure the safety of livestock and the long-term structural stability of the landform, the side slopes of these pits are strictly restricted to a maximum gradient of 1V:3H. This integrated approach allows for the sourcing of necessary construction materials while fulfilling landholder expectations that resulting excavations remain suitable for regional primary production. Final validation of these transformed landforms requires a post-works survey to confirm free-draining characteristics and a formal statement from a suitably qualified person certifying that the site is suitable for the proposed end use of agricultural grazing.

4 Conclusion

The outcome-focused framework presented in this paper provides a multidisciplinary and defensible engineering pathway for the closure of complex legacy polymetallic mines. By transitioning away from traditional end-of-pipe water treatment philosophies, this design-led approach addresses the root cause of environmental degradation through primary contaminant source isolation. The characterisation of the case study areas confirmed that historical residues high in lead, zinc, silver and arsenic act as persistent chemical drivers within sensitive riparian zones. The integration of high-resolution remote sensing, digital twin modelling and tiered geochemical screening allowed for the quantification of approximately 16,000 m^3 of potentially acid forming (PAF) material, providing the necessary data to break the source-pathway-receptor linkage.

The massive scale of required hydrological infrastructure identified in the results, totalling approximately 33,000 m^3 of basin storage, highlights the prohibitive capital costs associated with permanent water management in challenging granite geologies. This financial reality necessitates the staged construction framework proposed, which utilises an intermediate monitoring phase to test the 'zero-basin' hypothesis. By verifying if source term removal effectively neutralises the pollutant load reporting to distal river systems, the framework allows for the strategic optimisation or complete exclusion of high-capital hydraulic assets.

Ultimately, the successful execution of the Stage 1 clean-up, governed by rigorous geochemical validation and Australian and New Zealand Environment and Conservation Council surface water protection triggers, supports the transformation of industrial 'scars' into stable landforms. The implementation of the 'farm dam concept' and multibarrier sealing for residual PAF ensures that the final topography is safe, non-polluting and supportive of regional primary production. This outcome-focused framework demonstrates that by prioritising source removal and multidisciplinary integration, legacy mine sites can be transitioned into sustainable assets suitable for agricultural grazing and meeting local community expectations.

Acknowledgement

Funding and logistical support for the case studies presented in this paper were provided by a state government Legacy Mines Program. The authors would like to thank the project managers and field teams whose data collection and site assessments were fundamental to the project outcomes.

References

ANZECC & ARMCANZ 2000, *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*.

Australian New Zealand Minerals and Energy Council & Minerals Council of Australia 2000, *Strategic Framework for Mine Closure*, Australia, Canberra.

Commonwealth of Australia 2015, *Biosecurity Act 2015*, Australia.

DECC 2008, Managing Urban Stormwater: *Soils and Construction* – Volume 2E: Mines and Quarries, Department of Environment and Climate Change, Sydney.

Department of Industry, Innovation and Science 2016, *Leading Practice Sustainable Development Program (LPSDP): Handbooks on Preventing AMD and Mine Closure*, Australia.

DISER & DFAT 2016, *Preventing Acid and Metalliferous Drainage: Leading Practice Sustainable Development Program for the Mining Industry*, Department of Industry, Science, Energy and Resources and Department of Foreign Affairs and Trade.

eWater 2014, *MUSIC (Model for Urban Stormwater Improvement Conceptualisation)*, version 6, Canberra.

Government of Australia 1999, *Environment Protection and Biodiversity Conservation Act 1999* (Cth), Canberra.

Government of New South Wales 1974, *National Parks and Wildlife Act 1974*, Sydney.

Government of New South Wales 1977, *Heritage Act 1977*, Sydney.

Government of New South Wales 1979, *Environmental Planning and Assessment Act 1979*, Sydney.

Government of New South Wales 1991, *Protection of the Environment Administration Act 1991*, Sydney.

Government of New South Wales 1994, *Fisheries Management Act 1994*, Sydney.

Government of New South Wales 1997, *Protection of the Environment Operations Act 1997*, Sydney.

Government of New South Wales 2000, *Water Management Act 2000*, Sydney.

Government of New South Wales 2015, *Biosecurity Act 2015,* Sydney.

Government of New South Wales 2016, *Biodiversity Conservation Act 2016*, Sydney.

Government of New South Wales 2016, *Crown Lands Management Act 2016*, Sydney.

Government of New South Wales Environment Protection Authority 2017, *Contaminated Land Management: Guidelines for the NSW Site Auditor Scheme*, 3rd edn, Sydney.

Government of New South Wales Environment Protection Authority 2020, Consultants reporting on contaminated land – contaminated land guidelines, NSW Environment Protection Authority, Sydney.

Landcom 2004, *Managing Urban Stormwater: Soils and Construction (The "Blue Book")*, volume 1, 4th edn.

National Environment Protection Council (NEPC) 1999, *National Environment Protection (Assessment of Site Contamination) Measure 1999* (as amended 2013), Commonwealth of Australia, Canberra.

NHMRC & NRMMC 2011, *Australian Drinking Water Guidelines Paper 6 National Water Quality Management Strategy, National Health and Medical Research Council, Natural Resource Management Ministerial Council*, Commonwealth of Australia, Canberra.

NSW Government 2022, *SEED (Sharing and Enabling Environmental Data) Map*, viewed October 2022, https://geo.seed.nsw.gov.au/Public_Viewer/index.html?viewer=Public_Viewer&locale=en-AU