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

doi:10.36487/ACG_repo/2615_89

Risk-based progressive mine closure in the Amazon

Bruno Guimarães de Oliveira [a,*], Schweyka Holanda [a], Stella Malcher [a], Yorranna Rossy [a], Edson Augusto [a], Vinicius Assis [a]

[a] *Sossego Mine, Vale Base Metals, Brazil*

Abstract

Progressive mine closure in humid tropical environments presents significant challenges due to high rainfall, intense weathering and the potential for acid mine drainage (AMD) generation. These conditions require closure strategies that are responsive to site-specific risk and performance. This paper presents a risk-based framework for progressive mine closure, developed from site geochemical conditions and applied at a large open pit copper–gold operation in the eastern Amazon, Brazil. The approach integrates operational risk classification with long-term hydrogeochemical monitoring to differentiate waste rock facilities according to closure risk and performance. Monitoring results demonstrate clear geochemical distinctions between closure risk classes, supporting the use of proportional, performance-based closure strategies. The case study shows that a risk-driven approach can reduce uncertainty, optimise closure measures, and support defensible progressive relinquishment in high-rainfall tropical mining contexts.

Keywords: *progressive mine closure, hydrogeochemical risk, acid mine drainage (AMD) monitoring*

1 Introduction

Progressive mine closure has become an essential strategy for reducing long-term environmental liabilities and improving closure outcomes in large-scale mining operations. In humid tropical regions such as the Amazon, however, the implementation of progressive closure is challenged by high rainfall, intense weathering and complex hydrogeochemical responses, which increase the risk of acid mine drainage (AMD) and release of dissolved metals if closure measures are inadequately designed or timed (Evangelou & Zhang 1995; Akcil & Koldas 2006).

Waste rock landforms are a critical closure risk in humid tropical mines because lithology, sulphide content and exposure can produce contrasting post-construction geochemical behaviours within the same operation. Risk-based approaches that link monitoring data to closure decisions are therefore needed to avoid over-engineering stable facilities or underestimating risks in more reactive structures.

This paper presents a risk-based methodology for progressive mine closure applied at a large open pit copper–gold operation in the eastern Amazon, Brazil. The approach integrates operational risk classification, long-term hydrogeochemical monitoring and performance-based closure criteria to define closure strategies proportional to risk and defensible to regulators (IBRAM 2013; Sánchez et al. 2013; ICMM 2019).

The framework is evaluated using monitoring data from early progressive closure, with statistical and comparative analyses of pH and dissolved metals used to assess closure performance across risk classes.

* Corresponding author. Email address: bruno.guimaraes8@vale.com

2 Site description and closure risk context

The Sossego Mine, located in southeastern Pará within the Brazilian Amazon, has operated since 2004 and produces chalcopyrite-based copper concentrate with an average copper grade of approximately 30%. Figure 1 shows the location of the Sossego Mine within the regional setting, providing geographic context for the case study.

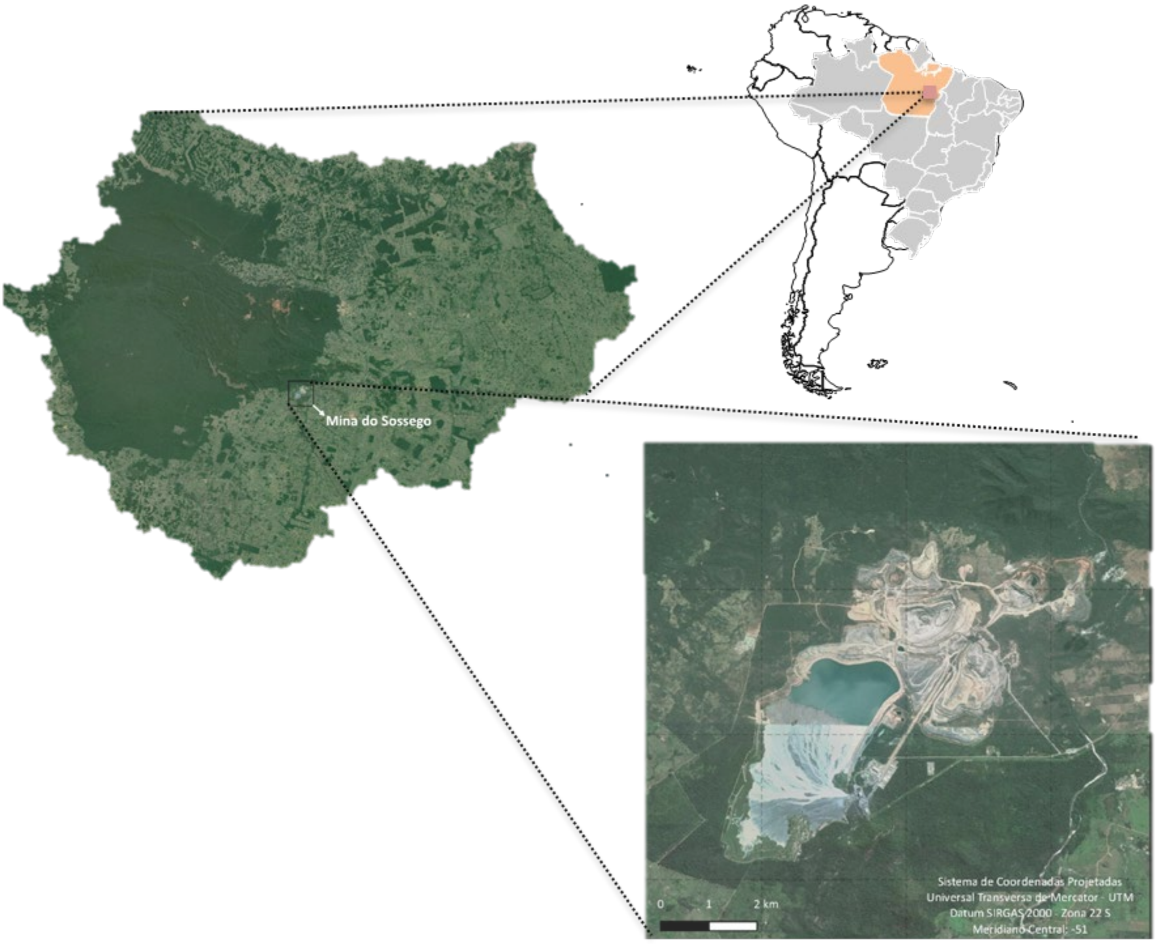


Figure 1 Location of the Sossego Mine

The mine is located in a humid tropical setting with annual rainfall of approximately 1,900 mm, average temperature near 26°C, and high relative humidity, conditions that intensify infiltration, water–rock interaction and sulphide oxidation risk. Figure 2 summarises the local rainfall pattern used to contextualise infiltration conditions and seasonal hydrogeochemical variability.

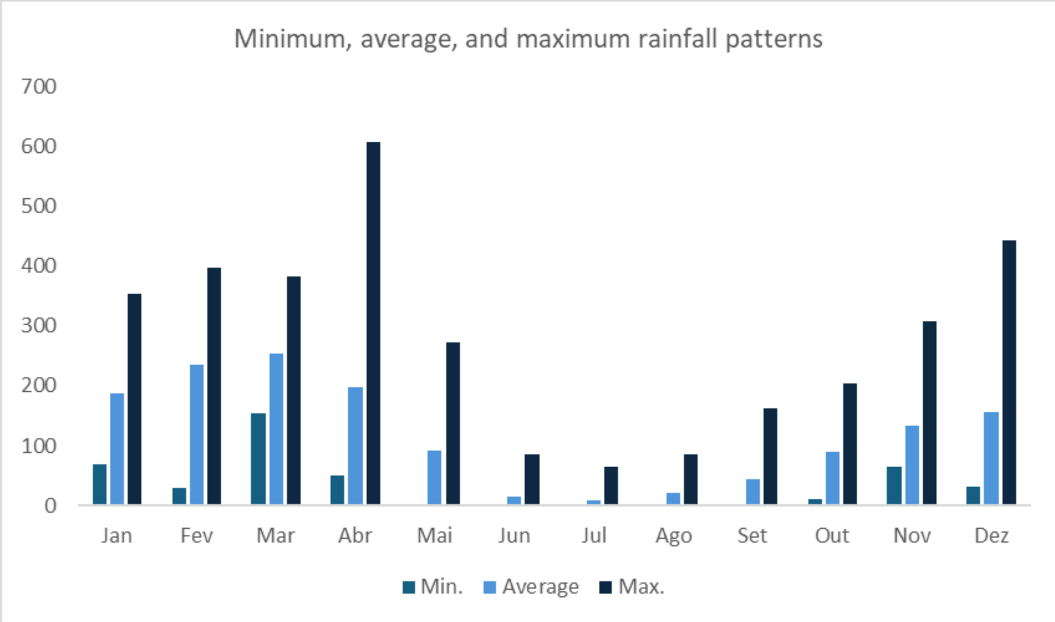


Figure 2 Minimum, average and maximum rainfall patterns at the Sossego Mine

The mining complex comprises 4 open pits and approximately 45 million tonnes of waste distributed across 4 main disposal areas. The Southeast pile contains significant low-grade ore, whereas the Sossego, Southwest and North piles are predominantly waste rock, creating distinct geochemical behaviours that require differentiated closure strategies.

The Southeast pile is therefore geochemically distinct from the predominantly waste rock piles because it contains significant volumes of low-grade ore with higher sulphide and metal contents. For the purposes of this study, the Southeast pile is used as a representative higher hydrogeochemical risk facility and as an indicator of closure considerations applicable to other sulphide-rich or low-grade ore materials.

Monitoring of drainage effluents is essential for environmental compliance, but basal drain monitoring provides a more direct indication of effluents generated within disposal structures and is therefore more suitable for assessing AMD generation, metal leaching behaviour and potential downstream risks.

From a risk-based closure perspective, internal drainage data support the distinction between structures with stable geochemical behaviour suitable for progressive closure and those requiring additional controls for AMD generation or metal release.

At Sossego, basal drain monitoring is used to prioritise areas, define closure solutions and support staged release of structures while allowing management responses to remain aligned with observed hydrogeochemical behaviour.

3 Methodological framework: from monitoring to decision-making

3.1 Geochemical and hydrogeochemical characterisation

Geochemical and mineralogical characterisation identified contrasting hydrogeochemical behaviour between ore and waste rock materials, directly affecting AMD generation and metal leaching potential. Copper concentrations range from 0.3% to more than 1.0% in ore and from 0.01% to 0.3% in waste rock, while nickel ranges from 0.03% to 0.12% in ore and from 0.01% to 0.09% in waste rock. These elements are mainly associated with sulphide phases such as chalcopyrite, bornite, chalcocite/digenite, covellite and millerite, with subordinate malachite in some ore samples (Castro et al. 1999; Lottermoser 2010).

The predominance of chalcopyrite rather than pyrite was initially interpreted as limiting AMD generation, supported by neutralising minerals such as carbonates, chlorite and amphiboles. Neutralisation potential (NP) values of 5–60 kg $CaCO_3$ equivalent per tonne for ore and waste rock reinforced the initial expectation of globally low AMD generation potential.

Acid–base accounting (ABA), including NP, acid potential (AP), the neutralisation potential to acid potential ratio (NP/AP), and net neutralisation potential (NNP), revealed contrasting behaviour between low-grade ore and waste rock materials.

Figure 3 presents the ABA results for low-grade ore samples, using NP/AP and NNP as screening indicators to support the geochemical basis for material risk classification.

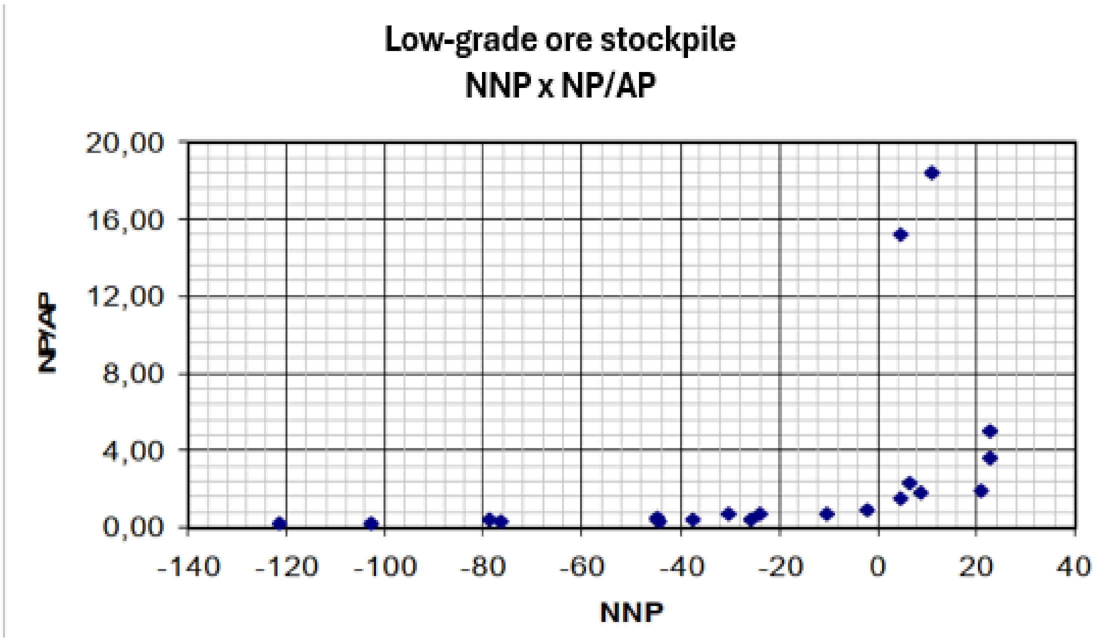
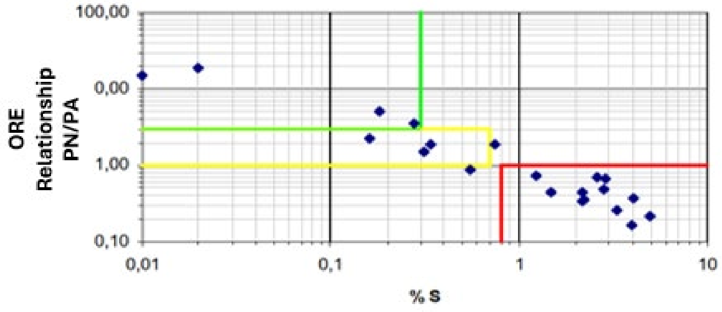


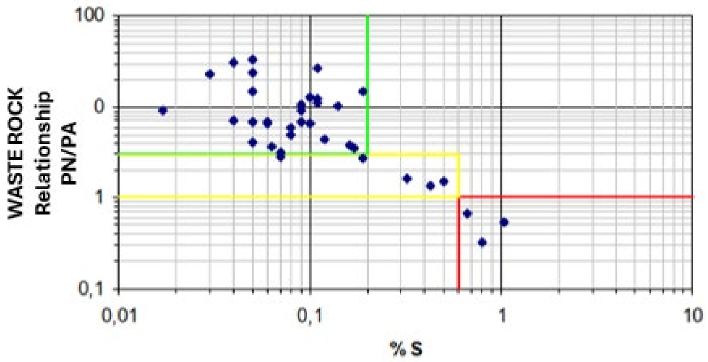
Figure 3 Relationship between neutralisation potential to acid potential ratio and net neutralisation potential for low-grade ore samples from the Southeast pile

Samples collected from the Southeast pile, which contains low-grade ore, exhibited high AMD generation potential, with a predominance of NP/AP values below 1 and NNP values below +20 kg $CaCO_3$ equivalent per tonne, particularly in samples with sulphide contents exceeding 0.8%. The approximately 1:1 relationship between total sulphur and sulphide sulphur indicates that most sulphur is associated with primary sulphide minerals, confirming the availability of reactive phases for oxidation.

In contrast, waste rock pile samples generally showed low AMD generation potential. Approximately 80% of the samples exhibited NP/AP values greater than 3, with sulphide contents predominantly below 0.2%, indicating a strongly net-neutralising geochemical condition. This contrasting behaviour is illustrated by the relationship between NP/AP and sulphide content (Figure 4), in which ore samples cluster predominantly within the higher hydrogeochemical risk field, while waste rock samples display a predominantly stable behaviour.



(a)



(b)

Figure 4 Relationship between NP/AP and sulphide content; (a) Low-grade ore; (b) Waste rock samples from the Southeast pile

Although some samples presented NNP values within the uncertainty range (−20 to +20), the integrated interpretation of the geochemical indicators suggests that waste rock, when considered in isolation, presents a low risk of AMD generation.

Overall, localised low-grade ore and reactive sulphides altered the hydrogeochemical behaviour of specific disposal structures despite initial predictions of low global AMD potential. Predictive characterisation therefore required confirmation through continuous basal drain monitoring, which provides direct evidence of AMD generation and metal leaching and underpins the risk-based progressive closure strategy at Sossego.

3.2 Basal drain monitoring program

The Sossego environmental monitoring program supports both compliance and hydrogeochemical risk-based closure decisions, with emphasis on basal drain monitoring and downgradient groundwater wells around disposal structures. Figure 5 identifies the Southeast low-grade ore facility and the Sossego, Southwest and North waste rock facilities, together with the basal drain and groundwater monitoring locations used to support hydrogeochemical assessment.

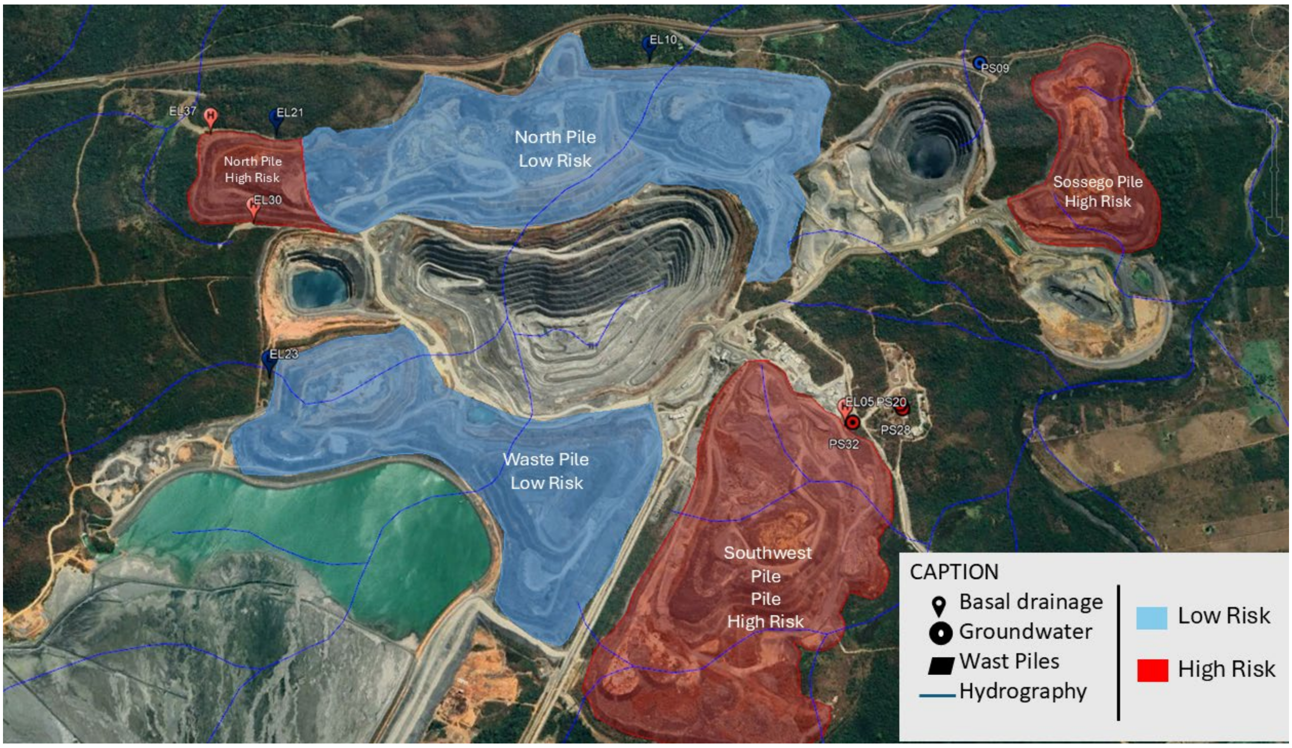


Figure 5 Basal drain and groundwater monitoring points associated with the Southeast, Sossego, Southwest and North disposal facilities

Basal drains from waste rock and ore piles are monitored monthly for key AMD and metal leaching parameters, including pH, dissolved copper, sulphate and other potentially mobilised metals. Some points have uninterrupted records exceeding 10 years, making basal drains the primary indicator of hydrogeochemical performance within disposal structures.

Groundwater monitoring is conducted quarterly and provides a secondary line of evidence for potential downgradient changes in water quality. Interpretation remains dependent on well construction, screened intervals, hydraulic relationship to the disposal facilities, hydrostratigraphic context and seasonal recharge conditions.

In this study, groundwater monitoring wells provide supporting downgradient evidence rather than primary confirmation of AMD generation, attenuation or direct hydraulic connection. Groundwater results are therefore evaluated together with basal drain chemistry and interpreted for well construction, screened interval, hydraulic connection and hydrostratigraphic context, without assuming direct causality between the AMD indicator dataset derived from basal drain monitoring and the groundwater monitoring dataset. Monitoring data support model calibration, validation of predictive assumptions, pile risk classification, risk-proportional engineering solutions, and release decisions for progressive closure.

3.3 Risk-based decision criteria for progressive closure

Integration of geochemical characterisation and monitoring results was used to establish technical guidelines for closure methodologies proportional to each disposal structure's hydrogeochemical risk.

Low hydrogeochemical risk waste rock piles, identified by stable pH and low metal concentrations in basal drains, were directed to simplified closure measures including an approximately 30 cm soil layer, topsoil placement and revegetation with herbaceous species and selected native shrubs and trees. These measures support surface stability, erosion control, infiltration management and ecological recovery.

Structures showing AMD generation or metal leaching in basal drains have not been released for progressive closure; instead, more robust engineering solutions are being evaluated through specialised studies.

Engineering alternatives under evaluation include, among others, low-permeability soil encapsulation, bench-scale surface drainage systems designed to minimise meteoric water infiltration, perimeter diversion channels for controlled interception and conveyance of surface run-off, as well as the implementation of sumps and channels associated with passive effluent treatment systems (Skousen et al. 1998).

Passive effluent treatment and source control measures are consistent with established AMD avoidance and remediation guidance (Skousen et al. 1998).

Selective re-mining of higher hydrogeochemical risk materials has been implemented in specific areas to reduce long-term hydrogeochemical liabilities and, where feasible, recover copper through controlled reintroduction into the production process.

This staged approach aligns closure methodologies with observed hydrogeochemical behaviour, prevents premature release of sensitive structures, and follows the APEC Mine Closure Checklist hierarchy, which prioritises risk elimination or minimisation at source before control and treatment measures (APEC 2018).

Figure 6 summarises the mine closure hierarchy used to frame risk-based decision-making for progressive closure.

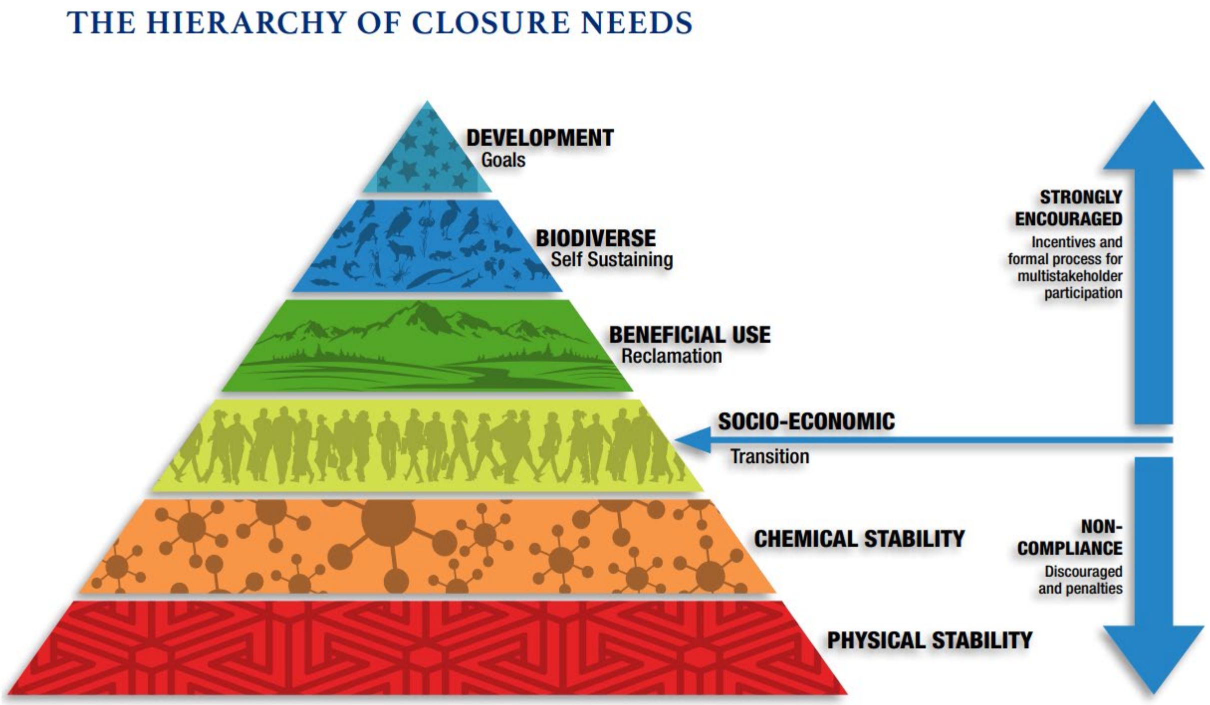


Figure 6 **Mine closure hierarchy according to the APEC Mine Closure Checklist, emphasising risk elimination and minimisation at source**

Accordingly, progressive closure at Sossego is implemented adaptively, grounded in monitoring evidence, risk governance and engineering controls.

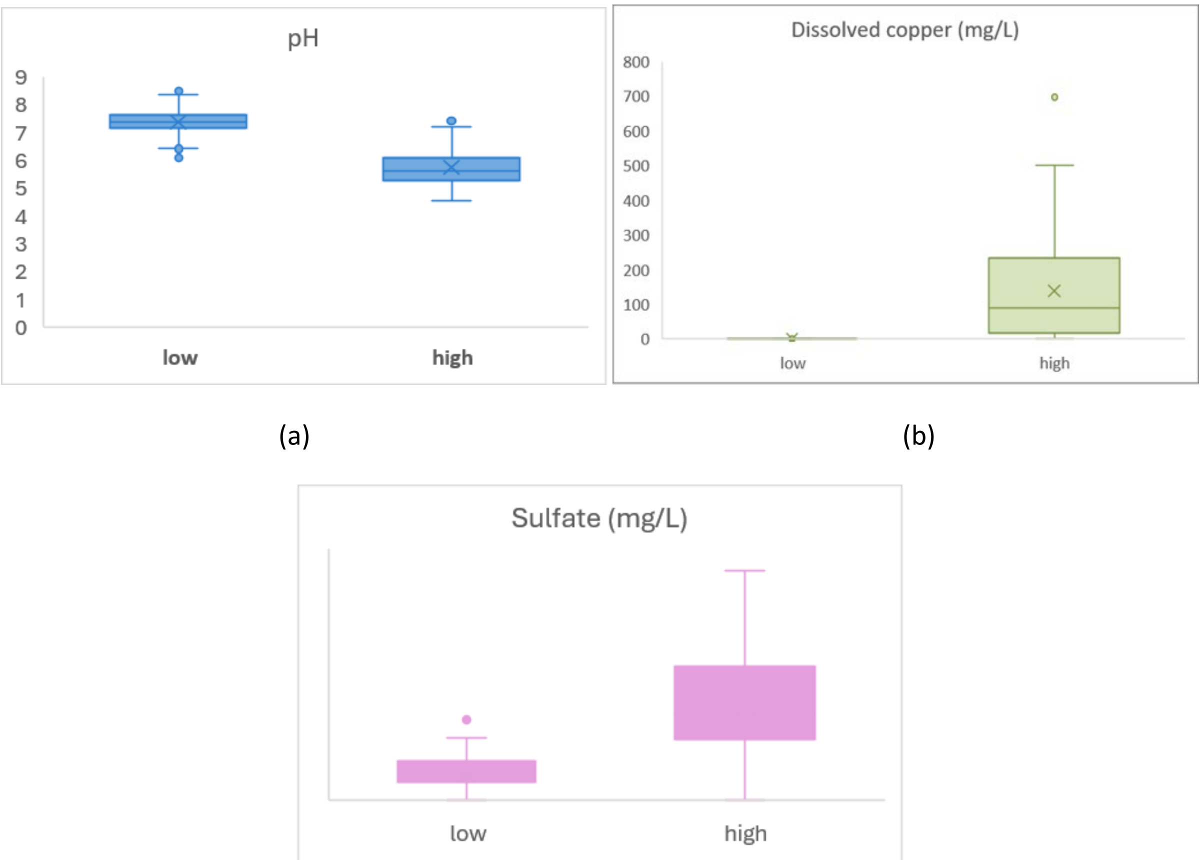
4 Results: monitoring-driven closure performance

4.1 Basal drain monitoring results and discussion

Basal drain monitoring provides the primary evidence for assessing hydrogeochemical performance because it directly reflects drainage generated within disposal structures. The analysis uses more than 10 years of monitoring to distinguish persistent patterns between low hydrogeochemical risk and higher hydrogeochemical risk facilities.

4.2 Statistical comparison between low hydrogeochemical risk and higher hydrogeochemical risk structures

Figure 7 presents boxplots of pH, dissolved copper and sulphate in basal drains for low hydrogeochemical risk waste rock structures and higher hydrogeochemical risk structures containing low-grade ore. The boxplots summarise central tendencies, dispersion, variability and extreme values across monitoring records extending up to approximately 10 years.



(a) (b)

(c)

Figure 7 Boxplots of (a) pH; (b) Dissolved copper; (c) Sulphate in basal drains from low hydrogeochemical risk and higher hydrogeochemical risk disposal structures

The pH results differ clearly between risk classes: higher hydrogeochemical risk structures frequently show values below 6 and greater variability, whereas low hydrogeochemical risk basal drains remain predominantly neutral to slightly alkaline, with low dispersion and stable geochemical buffering.

Dissolved copper provides the strongest contrast, with higher hydrogeochemical risk structures showing elevated and highly variable concentrations, including under near-neutral pH. This indicates that copper mobilisation is not controlled only by classic AMD, but also by partial sulphide oxidation and metal complexation mechanisms.

4.2.1 Relationship between dissolved copper and pH

Figure 8 presents the relationship between dissolved copper concentration and pH in basal drain samples from low hydrogeochemical risk and higher hydrogeochemical risk disposal structures.

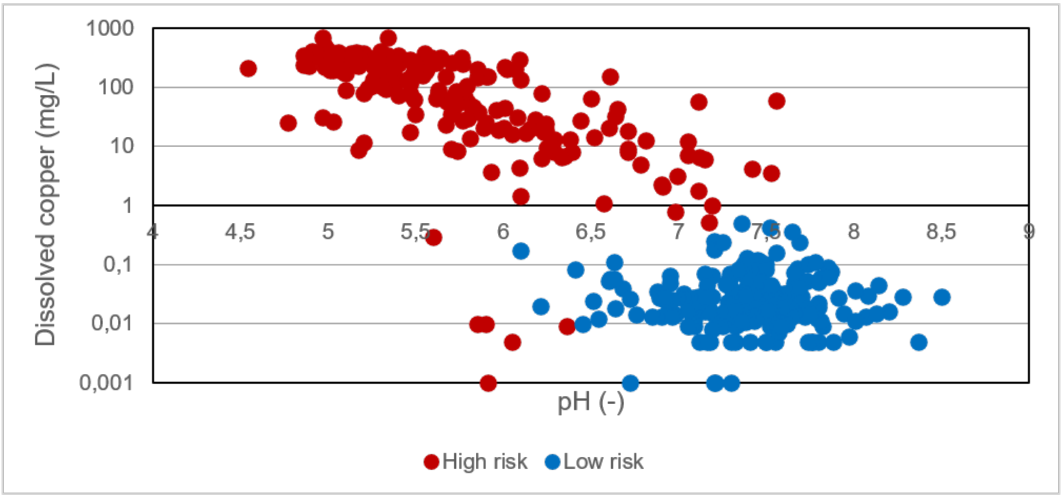


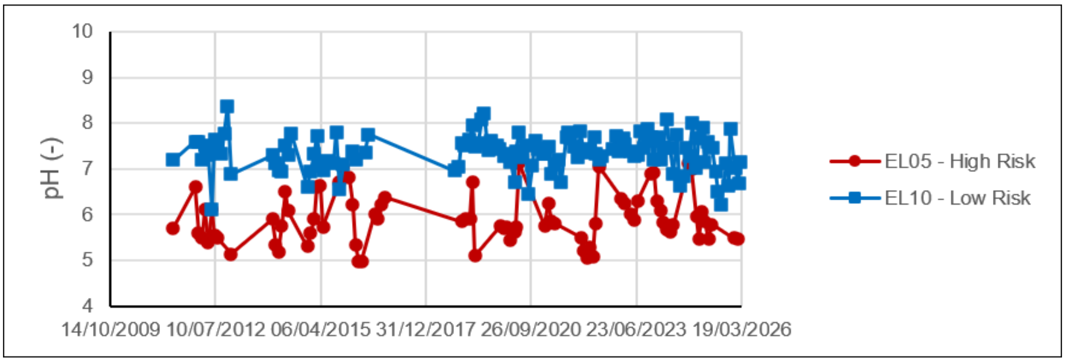
Figure 8 Dissolved copper concentration versus pH in basal drain samples from low hydrogeochemical risk and higher hydrogeochemical risk disposal structures

The dissolved copper–pH relationship further differentiates low hydrogeochemical risk and higher hydrogeochemical risk disposal structures. Low hydrogeochemical risk structures maintain consistently low copper concentrations under neutral to slightly alkaline pH, whereas higher hydrogeochemical risk structures show broader pH ranges and substantially higher copper concentrations.

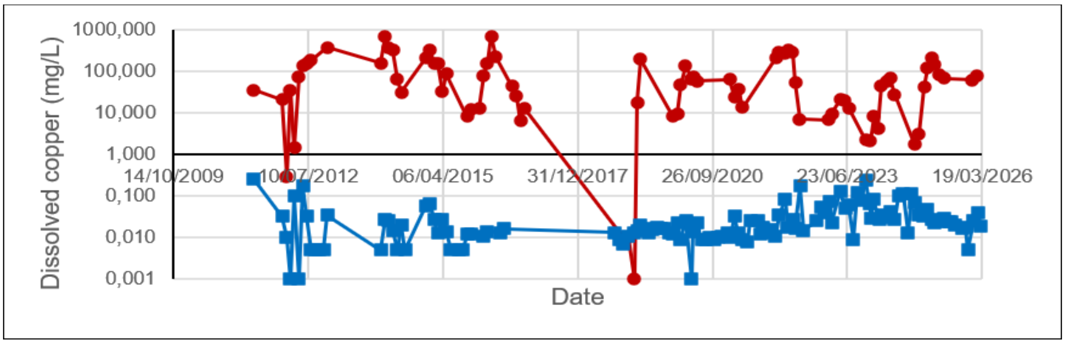
Elevated copper under near-neutral conditions suggests partial sulphide oxidation, copper complexation or soluble secondary copper phases, reinforcing the need for differentiated closure controls and the use of basal drain monitoring as a key decision-making tool.

4.2.2 Temporal trends in basal drain chemistry

Figure 9 presents long-term time-series of pH and dissolved copper concentrations in representative basal drains from low hydrogeochemical risk and higher hydrogeochemical risk disposal structures.



(a)



(b)

Figure 9 Long-term trends in representative basal drains from low hydrogeochemical risk and higher hydrogeochemical risk disposal structures; (a) pH; (b) Dissolved copper

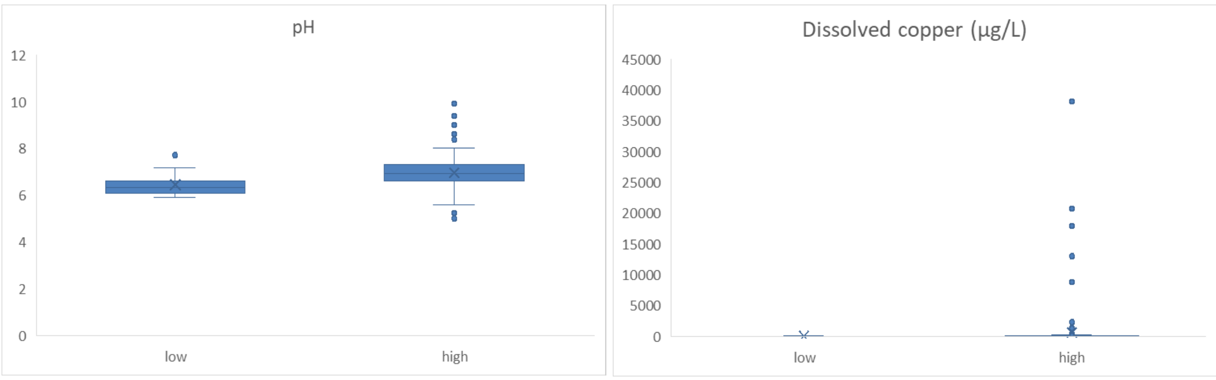
Temporal trends in pH and dissolved copper concentrations support the hydrogeochemical risk classification adopted in this study. Low hydrogeochemical risk structures show stable pH conditions and consistently low dissolved copper concentrations throughout the monitoring record, indicating persistent geochemical stability and limited AMD generation and metal leaching potential.

By contrast, higher hydrogeochemical risk structures exhibit greater temporal variability and elevated dissolved copper peaks, consistent with more active sulphide oxidation and metal mobilisation. These persistent differences confirm the value of basal drain monitoring as a key line of evidence for distinguishing structures suitable for simplified closure from those requiring additional engineering controls.

4.2.3 Groundwater quality performance

Groundwater monitoring results indicate predominantly neutral to slightly alkaline conditions across the evaluated wells. Low hydrogeochemical risk wells, such as PS09, remained stable, typically between pH 6.0 and 7.5, while wells associated with higher hydrogeochemical risk structures (PS20, PS26, PS28 and PS32) also remained mostly neutral, with occasional variations linked to hydrological or operational events. Based on the available monitoring wells, no persistent downgradient acidification trend was observed; however, interpretation remains dependent on well construction, screened interval and the hydrostratigraphic unit monitored.

Figure 10 presents groundwater geochemistry downgradient of the disposal structures, providing the subsurface monitoring context for comparison with basal drain results.



(a) (b)

Figure 10 Groundwater geochemistry downgradient of disposal structures grouped by closure risk; (a) pH; (b) Dissolved copper

Groundwater results therefore provide complementary downgradient evidence rather than direct confirmation of hydraulic connection or attenuation. Although sulphide oxidation is evident within specific disposal structures from basal drain chemistry, the available groundwater wells have not shown persistent increasing trends in acidity or dissolved copper downgradient of the monitored facilities.

Dissolved copper concentrations in groundwater were generally much lower than those measured in basal drains, with most dissolved copper concentrations reported in the microgram per litre (µg/L) range. Isolated elevated copper episodes occurred in downgradient wells associated with higher-risk structures, but these did not form persistent increasing trends. Lower groundwater concentrations may reflect dilution, adsorption, precipitation or limited hydraulic connection between screened intervals and seepage pathways, but the available data do not support assigning a single controlling mechanism.

Overall, groundwater monitoring provides complementary downgradient evidence, while basal drain monitoring remains the primary indicator of AMD generation and metal leaching within disposal structures.

4.2.4 Implications for risk-based progressive closure

Statistical and temporal analyses confirm that basal drain monitoring effectively distinguishes the hydrogeochemical performance of low hydrogeochemical risk and higher hydrogeochemical risk disposal structures.

Low hydrogeochemical risk structures, characterised by stable pH, low dissolved metals and limited temporal variability, are suitable for simplified closure, whereas higher hydrogeochemical risk structures require continued monitoring and more robust closure controls before release.

More than 10 years of monitoring support the identification of persistent performance patterns; however, final release should still depend on stability through representative wet and dry seasons, absence of increasing trends in pH, dissolved copper and sulphate, and regulator agreement on acceptable residual risk.

This evidence-based approach reinforces monitoring as a governance tool for mine closure in environmentally sensitive regions.

5 Progressive closure performance

Post-closure performance was assessed using basal drainage indicators, particularly pH stability and dissolved metal concentrations.

Low hydrogeochemical risk waste rock facilities show near-neutral pH and low dissolved metal concentrations after closure interventions, consistent with low sulphide content, sufficient acid-neutralising capacity, soil cover and revegetation. Higher hydrogeochemical risk facilities show greater drainage variability and require continued monitoring and more conservative closure strategies.

Although monitoring remains at an early post-closure stage, observed trends support adaptive closure management under humid tropical conditions.

While monitoring records exceeding 10 years provide a strong basis for identifying recurring hydrogeochemical behaviour and persistent performance trends, long-term closure confidence should not rely solely on monitoring duration. Instead, closure release should be supported by sustained performance through representative wet and dry climatic cycles, absence of increasing trends in key indicators such as pH, dissolved copper and sulphate, and agreement with regulators on acceptable residual risk levels. Continued monitoring therefore remains an important component of progressive closure governance and long-term performance verification.

5.1 Implications for liability reduction and future planning

Progressive closure at Sossego reduces environmental liabilities by separating geochemically stable low hydrogeochemical risk areas from higher hydrogeochemical risk structures requiring greater engineering focus.

Release criteria supported by basal drain monitoring provide a defensible basis for practical closure decisions in environmentally sensitive settings such as the Amazon.

Between 2021 and 2024, progressive closure interventions covered approximately 44.90 ha, with successful revegetation progress observed in the treated areas. Representative examples are shown in Figure 11.

(a) (b)

Figure 11 Revegetation progress after progressive closure interventions; (a) Southwest waste rock pile; (b) North waste rock pile

6 Conclusion

This study demonstrates that integrating operational risk classification with hydrogeochemical monitoring can support progressive mine closure in humid tropical environments such as the eastern Amazon.

Low hydrogeochemical risk facilities generated seepage with more stable pH and consistently lower dissolved metal concentrations than higher hydrogeochemical risk facilities, supporting proportional closure strategies based on observed environmental risk.

By linking monitoring performance to closure risk classification, the framework provides a practical and defensible basis for progressive relinquishment and is transferable to other tropical or high-rainfall mining operations requiring risk-informed closure planning.

References

Akcil, A & Koldas, S 2006, 'Acid mine drainage (AMD): Causes, treatment, and case studies', *Journal of Cleaner Production*, vol. 14, no. 12–13, pp. 1139–1145.

Asia-Pacific Economic Cooperation (APEC) 2018, *Mine Closure Checklist for Governments*, APEC Secretariat.

Castro, AC, Moore, F & Oyarzun, R 1999, 'Geochemical characterization of acid mine drainage at the abandoned Lo Aguirre Mine, central Chile', *Environmental Geology*, vol. 37, no. 3, pp. 217–227.

Evangelou, VP & Zhang, YL 1995, 'A review: pyrite oxidation mechanisms and acid mine drainage prevention', *Critical Reviews in Environmental Science and Technology*, vol. 25, no. 2, pp. 141–199.

International Council on Mining and Metals (ICMM) 2019, *Integrated Mine Closure: Good Practice Guide*, London.

Lottermoser, BG 2010, *Mine Wastes: Characterization, Treatment and Environmental Impacts*, 3rd edn, Springer, Berlin.

Sánchez, LE, Silva-Sánchez, SS & Neri, A C 2013, Guide for Mine Closure Planning Brasília, Brazil: Instituto Brasileiro de Mineração (IBRAM).

Skousen, J, Rose, A, Geidel, G, Foreman, J, Evans, R & Hellier, W 1998, *Handbook of Technologies for Avoidance and Remediation of Acid Mine Drainage,* National Mine Land Reclamation Center, West Virginia University, Morgantown.