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Challenges in securing final closure of rehabilitated mineral ore stockpiles: a case study of illicit mining impact and long-term maintenance

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Abstract

This case study investigates the persistent challenges in achieving secure mine closure at a remote mineral ore stockpile site in the mountainous Ehlanzeni region, Mpumalanga Province, South Africa – an area known for its greenstone-hosted gold deposits. Despite substantial investment in rehabilitation by The Mining Company (TMC), the site has been repeatedly compromised by illegal mining activities, revealing critical vulnerabilities in post-closure security and monitoring frameworks.

Extensive exploration and bulk sampling were undertaken at the site in the early 1980s, including the excavation of a 2,400-m adit and the deposition of sulphide-rich waste rock on steep ravine slopes. The region's complex topography, wet climate and elevation (~2,000 m above mean sea level) complicated both exploration and subsequent closure efforts. Oxidative weathering of sulphides led to acid rock drainage, culminating in a severe 1989 storm event that discharged heavy metal-laden water into a downstream river system, causing significant ecological damage and legal consequences. A 1991 court order mandated that TMC remediate the site and compensate affected landowners.

In response, TMC implemented a robust rehabilitation strategy, including the encapsulation of contaminated material within a composite-lined cell, adit sealing and long-term water quality monitoring. However, site accessibility limitations and the challenging terrain required unconventional "bucket-and-broom" clean-up methods, and the site's remoteness rendered it increasingly susceptible to illicit activity over time. Recent field inspections and monitoring data indicate that illegal mining operations have breached the containment infrastructure, jeopardised the effectiveness of the original rehabilitation and enabled renewed contaminant mobility.

A comprehensive literature review contextualises this site within a broader trend of escalating illegal mining at abandoned or closed mines, underscoring the need for the mining industry to integrate proactive, risk-based security and surveillance systems into closure designs. This includes physical access controls, stakeholder engagement strategies, ecological maintenance and routine inspections. The case further demonstrates that remote closure sites demand sustained operational readiness, such as road maintenance and fire prevention, to facilitate emergency response and monitoring.

The findings emphasise that closure planning must account for criminal interference as a potential long-term liability, which directly influences regulatory sign-off, closure timelines and budgetary forecasts. Failure to maintain post-closure security not only undermines ecological outcomes but also exposes companies to reputational, financial and legal risks. Accordingly, the study advocates for an evolution in mine closure philosophy – one that regards post-closure vigilance and adaptive security management as indispensable components of responsible mined land stewardship.

Keywords: *final closure risk, illicit mining, closure maintenance, mineral ore, design-for-security*

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1 Introduction

Mine closure has long been approached as a finite engineering task centred on landform stabilisation, contaminant containment and ecological rehabilitation. However, an expanding body of empirical and theoretical research highlights fundamental limitations in this model – particularly its inability to anticipate the complex socio-environmental dynamics that persist beyond the cessation of operations. Post-closure landscapes – particularly in mineral-rich developing regions – are increasingly subject to informal reappropriation and secondary land uses. These include illicit mining, unregulated human settlement and contested land claims, often creating conditions in which criminal networks and extractive opportunism can flourish. Illicit mining refers to unregulated, extra-legal or informal mineral extraction activities that occur outside authorised regulatory frameworks, typically in abandoned or decommissioned mining areas (van Bockstael 2014). Far from being anomalous, such activities are structurally linked to the residual economic potential of mineralised landforms and to the broader socio-economic systems in which these landscapes are embedded (van Alphen 2019; Tibbett 2010). These dynamics pose significant challenges to mine closure, environmental governance and post-mining land-use planning. The persistence of extractive activities post-closure reflects what may be termed a "continuity of economic opportunity", wherein informal actors are drawn to abandoned or inadequately secured sites despite formal cessation of licensed operations (Laurence 2006). This phenomenon directly challenges the prevailing regulatory logic that defines closure as a linear transition – from operation to remediation to relinquishment – by exposing the recursive nature of extractive landscapes and their vulnerability to socio-economic reactivation. Drivers such as poverty, marginalisation and unemployment (Hilson & Potter 2005; Owen & Kemp 2019) further entrench this pattern, suggesting that closure is not merely a technical end state but a complex and enduring socio-ecological negotiation (Laurence 2006).

Illicit mining, often framed as a peripheral or residual issue, is increasingly recognised as a central determinant of closure performance. This form of unsanctioned activity exacerbates contamination risks, compromises engineered containment systems and reintroduces systemic instability into post-closure environments (Dold 2014; Bainton & Holcombe 2018). Moreover, the concept of "social erosion" – defined as the gradual undermining of closure integrity through socio-economic exclusion and informal reoccupation – underscores the inadequacy of closure frameworks that treat human systems as exogenous to technical remediation. As such, the persistence of informal mining activities reveals not only operational vulnerabilities but also conceptual misalignments between closure objectives and post-closure realities. Scientific literature increasingly argues for reframing mine closure within a socio-technical systems perspective – wherein geotechnical, ecological and social factors are interdependent and dynamically evolving (Grant et al. 2016). While earlier closure science focused predominantly on physical stability and contaminant control, the incorporation of long-term social risk and governance into rehabilitation performance assessments must be part of formalised closure planning. In this view, closure readiness cannot be meaningfully declared until both residual contamination and economic opportunity are diminished to the extent that re-entry is neither attractive nor viable. The challenge is not simply one of enforcement or design robustness but of institutional foresight and sustained custodianship.

This paper contributes to the evolving discourse by interrogating the preparedness of closed mining operations to withstand socio-environmental pressures over extended temporal horizons. It synthesises interdisciplinary insights to reveal a persistent gap in closure frameworks: the failure to integrate informal and illicit re-engagement as a predictable outcome rather than a deviation. Within this analytical lens, illicit mining is not a postscript but a defining parameter of closure risk. Consequently, the post-closure phase must be reconceived as a prolonged state of negotiated resilience – requiring adaptive governance, enduring stewardship and a redefinition of closure success that transcends conventional technical endpoints.

1.1 Context of the illicit mining economy

Mining plays a pivotal role in Africa's economic development, with abundant mineral resources like gold, copper, platinum and diamonds contributing significantly to national economies (International Institute for Environment and Development 2017; Ramos et al. 2020). However, mining also creates socio-environmental challenges, notably in the form of illicit mining which is widespread in developing nations due to institutional weaknesses, economic vulnerability, and governance deficits (Hilson & McQuilken 2014; Siegel & Veiga 2009). Illicit artisanal mining in Africa, including "galamsey" (small-scale, often illegal gold mining in Ghana) and "zama zamas" (informal miners operating in abandoned South African gold mines) (Madimu 2024), is common around decommissioned mine sites (Karombo 2025). These areas, once deemed exhausted by formal operators, remain mineralised enough to attract informal miners engaged in high-risk activities such as working in abandoned shafts and tailings facilities (Durrheim et al. 2021).This sector is vast, with 70–80% of artisanal and small-scale mining occurring outside legal frameworks (Bainton & Holcombe 2018; Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development [IGF] 2017). Illicit mining contributes about 20% of the global gold supply but brings serious sustainability risks, including environmental degradation, ecosystem contamination, and safety hazards for miners and local communities (Veiga et al. 2009; Cochrane 2017).

The economic impact of illicit mining is significant (Ramos et al. 2020). In 2022, over 435 metric tonnes of gold were smuggled out of Africa, depriving governments of tax revenues and weakening state sovereignty (Karombo 2025; IGF 2017). This trade is often linked to transnational criminal syndicates and corrupt officials, which further complicates enforcement efforts (Organisation for Economic Co-operation and Development 2022). From a social perspective, illicit mining often exhibits organised and structured characteristics, emerging as an adaptive livelihood strategy in response to persistent unemployment and economic marginalisation rather than being driven solely by criminal intent (Madimu 2024; Hilson & Potter 2005). Similar illicit mining patterns are seen outside Africa (United Nations Environment Programme [UNEP] 2019). In Brazil, artisanal miners have reoccupied many closed industrial sites due to disrupted livelihoods (Cochrane 2017). In Indonesia's Jambi Province, communities engage in environmentally harmful mining despite recognising its long-term ecological and health consequences (Wibowo et al. 2022). These cases, and many more throughout the developing world, underscore the failure of traditional mine closure frameworks, which often ignore the social need for access to post-mining lands. Communities increasingly view decommissioned mines as economic opportunities rather than abandoned sites (UNEP 2019), challenging the finality of closure and highlighting the need for socio-political considerations in land-use planning (Bainton & Holcombe 2018; O'Faircheallaigh 2013).

The persistence of illicit mining reflects deeper tensions between misaligned mine closure regulations and closure timelines, lack of economic development, land use needs and environmental sustainability. Addressing these challenges requires an integrated approach that includes not only technical mine closure strategies but also social integration, accelerated access to land and community resilience in post-mining landscapes (Lèbre et al. 2020; Owen & Kemp 2019; UNEP 2019).

1.2 Deterioration of illicit mined land

Illicit mining challenges traditional security protocol and now contributes significantly to environmental and social degradation, impacting land stability and community wellbeing. Often utilising rudimentary methods, these operations contaminate soil, air and water with heavy metals like mercury, arsenic, lead and cadmium during gold amalgamation and ore roasting, or via tailings run-off due to inadequate containment (Ehrmann & Abdel-Maksoud 2023; Veiga et al. 2006). These pollutants accumulate in groundwater and river systems, posing acute and chronic health risks to local populations (Azcue et al. 2022). Several studies link exposure at historic and abandoned Ghanian mines to elevated mercury levels in river sediments to neurological disorders and developmental delays in communities (Donkor et al. 2006; Hilson, 2019), while lead and arsenic exposure near illicit mining sites in the Democratic Republic of the Congo and South Africa has caused gastrointestinal and respiratory illnesses (Nkulu et al. 2018).

Beyond health impacts, environmental degradation exacerbates socio-psychological challenges. The destruction of agricultural land and contamination of water resources erode livelihoods and cultural identity, leading to displacement and despair (O'Faircheallaigh 2013). These losses contribute to cycles of poverty, unemployment, substance abuse and youth disenfranchisement, undermining social cohesion (Hilson & McQuilken 2014; Cochrane & Lemos 2016). Affected communities often face a future of limited opportunities, deepening psychological trauma and hopelessness (Fraser et al. 2020). Addressing these issues requires integrated interventions that tackle both environmental and socio-economic vulnerabilities.

The involvement of organised criminal groups further exacerbates illicit mining, particularly in South Africa's Witwatersrand Basin. These syndicates exploit poorly secured or abandoned mining sites, fostering lawlessness characterised by violence, extortion and forced labour (Madimu 2024; IGF 2017). Migrant miners often work in overcrowded, dangerous conditions with limited access to healthcare and sanitation, exposing themselves to respiratory diseases such as silicosis, tuberculosis and chronic obstructive pulmonary disease (Naidoo et al. 2006; Pillay et al. 2020). These operations transform mining from economic activity into survival, with miners vulnerable to exploitation and coercion by criminal syndicates (Van Bockstael 2014).

The environmental and social consequences of illicit mining undermine sustainable mine closure goals. Traditional closure processes focus on technical site rehabilitation, often overlooking the socio-political factors enabling illicit mining (Gunningham & Sinclair 2017). Without proactive custodianship, effective law enforcement and viable post-mining land uses, rehabilitated sites risk becoming contested spaces marked by continued extraction and pollution (Owen & Kemp 2019; Cochrane & Lemos 2016). This highlights the need for a paradigm shift in mine closure that integrates environmental remediation with social renewal and coordinated law enforcement to prevent illicit mining recurrence (O'Faircheallaigh 2013).

Effective closure strategies must address the interconnected issues of pollution, poverty and criminality. Integrating environmental restoration, social support and governance reforms can mitigate the long-term risks of illicit mining, safeguarding both ecological and social system stability (Owen & Kemp 2019; Bainton & Holcombe 2018).

1.3 Closure readiness for continual illicit mining

The vulnerabilities of landscapes unprepared for "social erosion", if unaddressed, could undermine closure outcomes and reinforce cycles of environmental degradation and informal extraction (Hilson & McQuilken 2014; Cochrane & Lemos 2016). Therefore, from a sustainability perspective, under-designed landscapes and abandoned and unmaintained sites may present the perpetuation of ecological harm necessitating reforms that pro-actively engage the social context of land-use, social equity and environmental resilience (Gunningham & Sinclair 2017; Siegel & Veiga 2009; Owen & Kemp 2019). Moreover, post-closure vandalism, equipment theft and unauthorised extraction degrade rehabilitated landscapes, lead to environmental non-compliance and increase corporate liability (Kemp & Owen 2020). Tailings facilities are particularly vulnerable, serving as both pollution hotspots and targets for mineral theft, with risks of acid mine drainage and metal leaching (Hilson 2017; Kefeni et al. 2017, Park et al. 2019). Mine closure must therefore be approached not as a terminal event but as an ongoing, multidimensional process that integrates both technical and social elements (Van Zyl et al. 2023). Effective closure strategies require more than environmental rehabilitation – they must promote social reintegration and adopt adaptive, context-specific land management practices (Bainton & Holcombe 2018; International Council on Mining and Metals [ICMM] 2022). Productive post-closure land uses, including agroforestry, renewable energy and formalised small-scale mining, can align ecological restoration with socio-economic development, thereby reducing the recurrence of illicit mining (O'Faircheallaigh 2013; UNEP 2019; Owen & Kemp 2019).

Protracted closure processes heighten tension between companies and regulators, especially where closure delays lead to extended liabilities and unresolved compliance issues. Companies face ongoing costs from maintenance, security and monitoring which, combined with regulatory disputes, can result in financial penalties and reputational damage (Kemp & Owen 2020). These pressures highlight the need for proactive, integrated closure strategies that anticipate and address long-term operational, environmental and governance risks.

Continuous post-closure monitoring – both technological and social – is essential. It not only supports environmental performance but also deters unauthorised activities and signals active governance, mitigating risks such as pollution reactivation and geotechnical instability (Prayitno et al. 2025). To meet evolving closure challenges, companies must embed alternative metrics such as security, governance and social renewal into early-stage planning, ensuring that post-mining landscapes foster ecological recovery and community resilience. Where illicit mining is entrenched, mining companies should now reconceptualise closure as a long-term and comprehensive risk management process. Traditionally focused on physical stabilisation and revegetation, closure plans will now have to incorporate security and land-use planning into closure designs to prevent illegal mining, ore theft and infrastructure sabotage (Parbhakar-Fox & Baumgartner 2023). Security is increasingly viewed not merely as protection but as a strategic element of sustainable closure, supporting environmental outcomes and community safety (Cochrane & Lemos 2016).

1.4 Engineering and closure management imperatives within the illicit mining economy

Illicit mining at closed and legacy mine sites presents a persistent and complex challenge for mine closure engineers, especially in jurisdictions with weak governance, socio-economic instability and limited regulatory enforcement. These activities – ranging from ore theft to unauthorised access to tailings storage facilities – compromise landform stability, damage infrastructure and trigger pollution sources such as acid mine drainage (Park et al. 2019). This undermines closure objectives, threatens environmental and community health, and creates long-term liabilities often excluded from traditional closure designs (Durrheim et al. 2021; Owen & Kemp 2019).

Conventional closure approaches emphasise physical rehabilitation, such as reshaping landscapes, revegetation and water quality management. However, they often fail to address the socio-economic drivers of illicit mining. In contexts marked by poverty and unemployment, residual mineral resources at abandoned sites attract illicit miners who exploit tailings and waste rock dumps (WRDs), intensifying degradation and corporate risk (Cochrane 2017; Hilson & Potter 2005; Veiga et al. 2009).

To mitigate these risks, engineers must embed security-informed design elements into closure strategies. While technical interventions like armoured capping, hostile landscaping and tamper-resistant infrastructure are valuable, they are insufficient alone. In regions with limited state capacity, these technical measures are often rendered ineffective without complementary social and governance responses. The absence of long-term monitoring systems and adequate funding further increases site vulnerability (Lottermoser 2010; ICMM 2022).

Adaptive mine closure frameworks offer a critical pathway forward. These frameworks must treat closure as an ongoing process requiring continual engagement and risk reassessment. Engineers should design for long-term custodianship, including active land management and continuous environmental and social monitoring. This ensures responsiveness to evolving threats – both human and ecological – and promotes inclusive governance involving mining companies, regulators and affected communities (Laurence 2006; Bainton & Holcombe 2018).

Security and risk-informed design are essential pillars of such adaptive approaches. Illicit mining, equipment theft and resource pilfering can destabilise rehabilitated landforms, reactivate contamination, and escalate maintenance and remediation costs. Proactive integration of robust monitoring, security infrastructure and community co-management from the outset of closure planning is crucial to pre-emptively manage these risks (Parbhakar-Fox & Baumgartner 2023; ICMM 2022).

Failure to address illicit mining in closure planning can lead to significant unplanned financial liabilities. Reactivated pollution sources and accelerated site degradation often necessitate costly re-intervention, while reputational damage may follow non-compliance or conflict with affected communities (Owen & Kemp 2019).

Transitioning to resilience-based closure design that incorporates technical robustness, long-term stewardship and socio-political awareness enables more durable and socially responsible outcomes. The dynamics presented by illicit mining compel a paradigm shift in mine closure engineering. Engineers must move beyond compliance-driven rehabilitation and adopt adaptive, risk-informed frameworks that balance technical, environmental and socio-political imperatives. Through collaborative design and inclusive governance, closure strategies can foster secure, sustainable and community-aligned post-mining landscapes.

2 Study background

2.1 Study site

The study area is located within the mountainous Barberton Mountain Land in the Ehlanzeni District, approximately 50 km east of Mbombela in Mpumalanga Province, South Africa (Figure 1). Geologically, it forms part of the Archean Barberton Greenstone Belt, renowned for greenstone-hosted gold and associated metalliferous mineralisation. The region lies along the eastern escarpment of the Drakensberg and shares a border with Eswatini, featuring a complex topography of rugged ridges, deeply incised valleys and steep elevation gradients. Altitudes range from below 600 m in the western valleys to over 1,800 m on the escarpment peaks, with a mean elevation of ~1,200 m. This terrain supports a range of microclimatic zones within a broadly subtropical climate classified as Region NT by the South African Weather Bureau.

Annual precipitation is highly variable and topographically controlled, ranging from ~600 mm in lower valleys to > 1,200 mm on elevated eastern slopes. Rainfall is markedly seasonal, concentrated in the austral summer (October–March), driven by moist easterly airflows from the Indian Ocean and enhanced by orographic uplift. Frequent summer thunderstorms produce high-intensity, short-duration rainfall events that generate rapid surface run-off, localised erosion and sediment mobilisation, with implications for landscape evolution and catchment hydrology. Mean annual temperatures range from 18–22°C in low-lying areas to 12–16°C at higher altitudes.

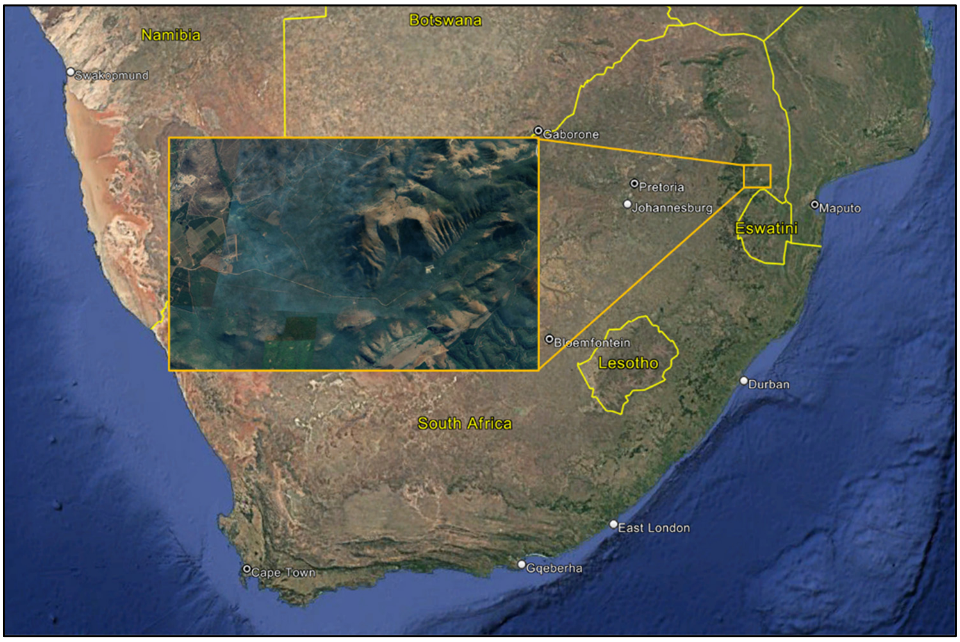

Figure 1 Study area location

Winter (May–August) brings significant diurnal temperature variation, with night-time temperatures frequently falling below 5°C at elevation. Frost is rare but may occur in sheltered microclimates. Relative humidity is highest in summer due to increased cloud cover and rainfall, declining in winter and contributing to seasonal shifts in evapotranspiration and vegetation dynamics.

The region supports a diverse ecological mosaic including savanna, montane grasslands and patches of Afromontane forest, shaped by the interplay of climatic gradients, elevation and ancient geology. Soils are typically shallow and heterogeneous, influenced by intense weathering and mineral-rich parent materials. Land use reflects the area's physical and socio-economic complexity. Conservation areas such as the Barberton Makhonjwa Mountains World Heritage Site and Songimvelo Nature Reserve dominate the uplands. Subsistence agriculture and communal livestock grazing occur in the lower valleys, often on marginal lands. Commercial irrigated agriculture – mainly citrus, sugarcane and subtropical fruit – is concentrated along river corridors. Commercial forestry (*Eucalyptus* and *Pinus*) occupies moist escarpment slopes, while mining, both industrial and artisanal, remains economically important. Urban development is limited, with the town of Barberton serving as the primary population centre.

2.2 Case study background

2.2.1 Rehabilitation and closure interventions pre-2000 (phase 1 and 2)

The study site was initially developed by TMC in 1977 on the upper slopes of a steep ravine within a mixed forestry-agricultural landscape. Exploration intensified in the mid-1980s, including adit excavation into a gold-bearing orebody. Waste rock was deposited on a steep slope above a non-perennial stream without containment or erosion control. By 1988 the orebody was deemed uneconomic, and the site was abandoned without rehabilitation. The uncontained waste led to the rapid downslope transport of mineralised material while severe acid rock drainage and metal leaching (ARDML) degraded water quality and caused ecological damage, particularly on the adjacent agricultural land and the downstream Lodge Dam. Investigations identified the waste rock as the primary ARDML source, with minor contributions from adit seepage. Geochemical assessments confirmed pyrite (FeS_2) oxidation – facilitated by sulphate-reducing and iron-oxidising bacteria under toxic and moist conditions – generated sulphuric acid. This acidic leachate mobilised Fe and Zn, with pH ≤ 3 waters reacting with circum-neutral stream water (pH 6–7), precipitating ferric hydroxide ("yellow boy") while soluble metals persisted downstream. Continual fish kills and riparian vegetation loss prompted landowner complaints in November 1987, and the Inspector of Mines recommended immediate remediation activities. This was the commencement of almost 40 years of closure activities.

TMC rapidly removed waste rock from the stream but a high-intensity rainfall event on 9 November 1989 caused renewed waste ore disposal and ARDML impacts, revealing the inadequacy of initial interventions. After this event, TMC implemented a comprehensive and encompassing closure strategy at substantial cost, with the first engineering and closure design emphasising source isolation and hydrological risk control. The main priority was rehabilitation of the ARDML sources as follows: (1) the adit where the waste rock originated from was plugged and sealed with rock; (2) the entire waste rock source was relocated 1.7 km upslope with machinery and customised elevator systems to a purpose-built engineered depository on elevated terrain placed specifically on the watershed divide to reduce run-off exposure; and (3) the entire footprint was cleaned up and revegetated.

Following the initial large-scale rehabilitation undertaken by TMC in 1999, all waste rock material was systematically removed from the ravine using a manual "bucket-and-broom" methodology. This process entailed complete extraction, transport, consolidation and an engineered capping over the depository of the mineralised waste at the designated low-risk location. The depository featured a multi-layered barrier system comprising: a compacted bentonite base, an overlying high-density polyethylene (HDPE) geomembrane and earth bunds for structural integrity. The capping system was designed to promote slope stability, reduce erosion and significantly limit infiltration, thereby interrupting the ARDML generation pathway. The entire facility was covered by a composite liner which included an HDPE liner with geotextile protection, and a layer of topsoil, and was vegetated. The borehole monitoring network was installed and the project progress report submitted to the regulator. A schematic illustration of the containment structure is presented in Figure 2.

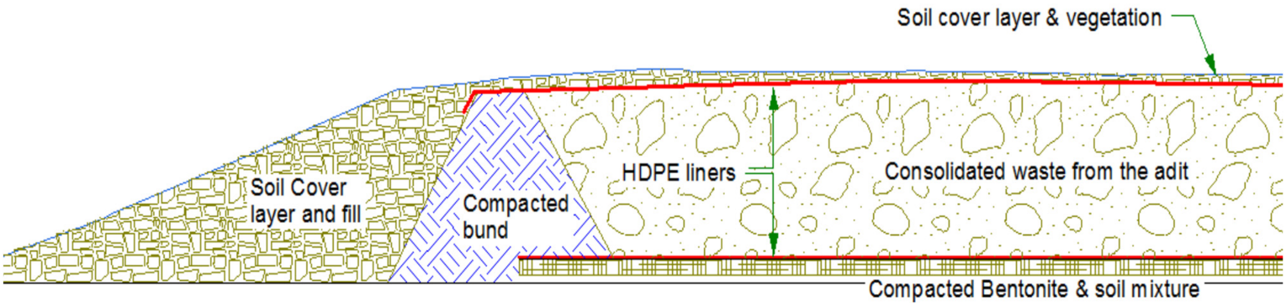

Figure 2 Schematic cross-section indicating the 1999 design of the discard material depository

Table 1 presents a chronological timeline for the rehabilitation and closure effort between 1987–2000.

Table 1 Project timeline and actions for the period 1987–2000

Date/year	Closure activity
November 1987	Complaints were made by farmers about water quality reduction in the river and dam. TMC commenced initial rehabilitation actions by removing waste rock sources
9 November 1989	Heavy rains occurred. The Farmers Union complained about fish and riparian vegetation dying within the dam and along the non-perennial stream downstream of the adit. Complaints from landowners and severe negative media coverage followed. Comprehensive water sampling and a testing program by the mine initiated remediation work to clear the stream of pollution and contain pollution from the waste rock deposit
1990	Detailed remedial plans were developed by TMC and approved by landowners and regulators. Remediation work ceased due to complaints from landowners. The Department (Dept) of Water informed TMC of impending legal proceedings for failing to observe Water Act requirements, waste rock deposit proximity to a water course and river pollution contributing to fish mortalities
1991	TMC was served with a summons for water pollution and the court ordered it to compensate the landowners for the resulting damages. Following payment, the landowners released all claims against TMC The mine removed contaminant-generating waste from the ravine and relocated it 1.7 km away from the adit, where it was consolidated according to a detailed engineered design. The facility included an engineered liner, capping system and a soil cover – all implemented at an exorbitant cost
1992	Final Closure Site Visit 1 – TMC applied for a closure certificate after remediation actions were completed. The closure certificate was not granted due to the Water Regulator's dissatisfaction with water quality downstream of the waste rock deposit and the need for cut-off drains to prevent soil erosion. The Minerals Dept requested a full report on all monitoring data after completion of the closure works. TMC continued with water monitoring
1993–1999	Water quality and toxicity were monitored at regular intervals
1999	TMC consulted with the Depts of Water and Minerals, as well as the landowners, on further requirements for obtaining a closure certificate. The Minerals Dept agreed to grant closure if landowners and the Water Dept were satisfied with remedial work. Once the adit was sealed, the Water Dept required proof that no pollution was leaving the site. Two more water sampling runs were completed and an improvement in water toxicity test results continued

Post-construction environmental monitoring from 1999 onwards indicated a sustained and marked improvement in downstream water quality, with reduced metal concentrations and the recovery of aquatic and riparian ecosystems. These outcomes supported TMC's case for initiating the closure certification processes, subject to ongoing performance verification.

However, in subsequent years, routine monitoring detected episodic increases in downstream metal concentrations. These findings suggested that the integrity of the encapsulation system had been compromised. Investigations revealed that the remote location of the containment facility made it susceptible to unauthorised access. Repeated incursions by illegal artisanal miners resulted in excavation and disturbance of the engineered depository in pursuit of residual ore. These intrusions caused structural breaches to the HDPE liners and capping system, re-exposing sulphidic waste rock to atmospheric and hydrological conditions conducive to renewed ARD generation.

The resultant reactivation of contaminant leaching necessitated multiple emergency remediation interventions by TMC, including the reinstallation of geomembrane barriers and reconstruction of protective covers. The cover across the facility was repaired and capped with a second HDPE and geotextile liner, overlain with vegetated growth medium to promote slope stability, reduce erosion and limit infiltration, thereby disrupting ARDML generation pathways.

Despite these efforts, the lack of enforceable security measures and the informal nature of the artisanal mining activity have delayed the closure process and the closure strategy with another costly re-rehabilitation process.

2.2.2 Rehabilitation and closure actions after 2000 (phase 3 and 4)

Despite the comprehensiveness of the rather complete intervention, the Water Regulator issued a formal notice on 26 September 2000 declining closure certification. Cited reasons included persistent aquatic toxicity near the site, episodic stream pH fluctuations adjacent to the former waste rock deposit and the failure to achieve a demonstrably stable post-mining stream system. A 10-year monitoring program was requested by the interested and affected parties (I&APs) and the regulators. In response to the post-10-year water monitoring records, and the newly enacted mine closure and water protection requirements, TMC requested approval for a closure application. The closure site visit revealed that extensive criminal damage by illegal artisanal miners had resulted in a breach of the engineered cover system and water management features, leading to stormwater ingress and overtopping of polluted water – with subsequent damage to the ecosystem. This situation necessitated the full re-rehabilitation to meet closure application standards. TMC embarked on a third complete closure effort in 2012 and decided to implement a zero-risk and complete landscape rehabilitation and closure process. A comprehensive closure strategy that aimed to establish a physically, chemically and ecologically stable post-mining landscape was agreed on to address specific concerns raised by I&APs about future water pollution and to convince the regulator to award a closure certificate.

For this project the entire exploration site was divided into functional zones, including the waste rock containment facility, the original adit footprint, the ravine and stream corridor, the borrow pit, the adit structure and access roads – each targeted with site-specific engineering and ecological interventions. Roads constructed during earlier prospecting lacked adequate drainage and were retrofitted with stormwater diversion berms and outlets to reduce erosion. Inspection of the adit confirmed its stability, with no groundwater ingress or recent human activity, and natural vegetation was re-establishing. Below the adit, where historical waste had been removed, slope stability was achieved, although vegetation was sparse due to rocky terrain and poor soil development. Importing topsoil was deemed unsustainable. In the ravine and stream, downstream water quality had improved significantly, with chemical analyses confirming reductions in contaminant concentrations. The large borrow area where topsoil was sourced was reshaped, ameliorated and vegetated, while the adit was permanently sealed using a reinforced concrete plug fitted with a breather pipe for pressure and seepage monitoring. The plug was anchored into competent rock and backfilled with coarse waste to prevent re-entry. The adit entrance was further stabilised with earth plugs and revegetation. All disturbed areas were subjected to soil amelioration using scientifically prescribed inputs (e.g. lime, composted manure, fertiliser), then ripped, scarified and seeded with a mixture of native grasses.

Rehabilitation of the WRD site included the removal of contaminated soil and mature invasive trees, followed by re-capping using a 1.5 mm HDPE liner, protected by A10 geotextile, and covered with a 500 mm-thick, well-graded soil cover layer and growth medium. Indigenous grasses were reintroduced to stabilise the cover and reduce erosion potential. The waste facility was reprofiled with contour berms and low-gradient stormwater channels to control run-off. Figure 3 presents the design layout for the second rehabilitation intervention.

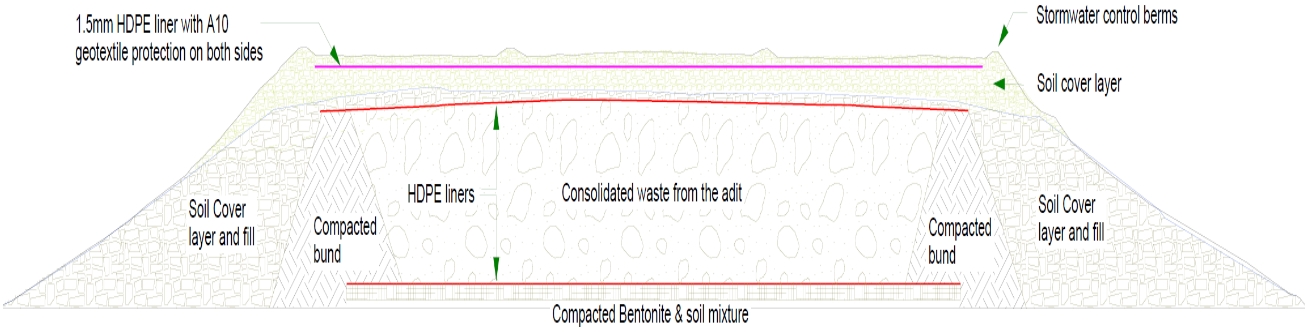

Figure 3 Schematic cross-section indicating the design of the discard material depository constructed in 2012

Upon completion of physical works, an active aftercare and monitoring phase commenced. This included structured surveillance of erosion dynamics, vegetation cover establishment, water quality and infrastructure performance, supported by site access control measures. A formal monitoring and maintenance plan was implemented to demonstrate the long-term effectiveness of the rehabilitation. By the end of 2012 all physical interventions were completed and the landowner expressed formal support for the closure application. However, the Water Regulator mandated a 10-year monitoring period with demonstrable aquatic ecosystem recovery and water quality compliance before closure certification could be considered. Table 2 outlines the project timeline for 2000–2025.

Table 2 Project timeline and actions for the years 2000–2025

Date/year	Closure activity
2000	The mining entity applied for a closure certificate. The Water Department (Dept) declined the closure certificate due to water toxicity concerns, pH fluctuations and unstable stream flows
2000 to 2004	Water quality and toxicity were monitored at regular intervals, with substantial improvements demonstrated. The Water Dept required another 10 years of data before the mining entity could apply for closure
2004 to 2011	Water quality and the toxicity of the dam and stream were monitored at regular intervals. Water quality deterioration was noticed in late 2011. The Final Closure Site Visit 2 was attended by the management committee. The cover had been damaged again by illegal miners (and needed urgent assessment and repair), oxidising mine waste was causing localised pollution and vegetation die-off, the soil cover layer was thin, there was a lack of stormwater control structures aimed at preventing concentrated run-off visible on the waste rock dump (WRD). Erosion of the side slopes had occurred. *Eucalyptus* and other invader tree species on the perimeter of the WRD presented liner damage risk

Date/year	Closure activity
2012	To ensure renewed closure compliance, TMC had to execute yet another detailed rehabilitation and closure plan to mitigate all the outstanding issues. The mine consulted with the Dept Mineral Resources, Dept Water Affairs the landowners concerning the proposed rehabilitation plan, which was agreed on by all I&APs and consequently implemented Water course – The vegetation had re-established and previous damage was not visible. The downstream water quality significantly improved to meet the regulatory standards. Rehabilitation of all identified disturbed areas was completed by December 2012. A monitoring and maintenance plan was compiled. The landowner indicated that he was satisfied with the remedial work conducted and would be willing to sign an approval letter, if he was still satisfied, at the end of 2014, after the two-year monitoring and maintenance (if required) plan was completed
2014	Care and maintenance were undertaken around the dump. This included removal of regrown *Eucalyptus* trees on and around the dump perimeter and borrow pit, construction of additional stormwater control structures on the roads where signs of light scouring were visible, the addition of fertiliser and organic material on a few minor patches with slightly sparse vegetation growth, removal and burying of polluted material previously unattended to , and re-profiling of the dump's northern slope to a lower gradient to ensure regrowth of the vegetation
2022	Final Closure Site Visit 3 – The management committee attended a closure sign-off visit. It was observed that the WRD cover liner had been substantially damaged by illegal miners, resulting in the exposure of oxidising mine waste. This needed urgent assessment and repair. The exposed waste beneath the damaged liner was contributing to polluted run-off during storm events, which was being washed onto the surrounding natural ground, causing localised contamination and vegetation die-off. Additional concerns included the thin soil cover layer, the absence of adequate stormwater control structures and the need for chemical analysis of the growth medium to assess its suitability for vegetation. The WRD had been placed in a good position on a watershed, with minimal risk of erosion of the toe line due to stormwater run-off from the surrounding area
2024	Final Closure Site Visit 4 – The WRD cover is repaired again at exorbitant cost, the damaged liner is rewelded at six locations and topsoil is replaced. A complete reseeding effort is carried out. Invasive plant species are removed across the site. Rehabilitation of all identified disturbed areas is completed by December 2024. The monitoring and maintenance plan was continued, and soil and water samples were collected for this study
2025	The northern slope of the WRD was breached and risk to geotechnical stability was imminent. The liner placed over the WRD had been damaged again by illegal miners and needed urgent assessment and repair. The exposed mine waste below the damaged liner was oxidising. This time the slope on the northern side was exposed and presented a real risk for structural failure and environmental contamination. No action has been taken yet

For completeness of the case study, the results for the soil and water chemistry from samples within the WRD (above and below the liner system) is included for reference purposes. The samples were collected in December 2024 to evaluate the potential sustained risk of environmental contamination from this site. The testing methodology used is included in the tables and the threshold risk values is also included as per the South African Soil and Water Screening Values (2014). Table 3 presents the median results from five readings from each sampling point both above and below the liner. From the data it is evident that the acidic soil and elevated heavy metals still present significant long-term contamination risk. The waste still clearly presents significant contamination risk if the material is to be exposed to oxidation processes.

Table 3 Median water results (analyses in mg ℓ^{-1} unless specified otherwise) and median soil results (analyses in mg kg^{-1} unless specified otherwise)

Water results (semi-quantitative Inductively coupled plasma mass spectrometry) (n.t. denotes not tested; n.a. denotes not applicable)			Soil results (ammonium acetate extract) standard ammonium acetate extraction procedure (Handbook of Standard Soil Testing Methods – Method 8 [Klute 1986])							
	Result	Threshold	Control sample	Above geofabric	Above liner 1	Below liner 1	Side slope	Seep line	Dump toe	Threshold
pH value @ 25°C	3	5.5–7.5	4	4	4	3	n.t.	6	5	5.5–7.5
Electrical conductivity in mS/m @ 25°C	1,185	> 20–350	12	94	15	390	n.t.	15	14	> 20–350
Total dissolved solids @ 180°C	21,740	> 450–3,500	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total alkalinity as $CaCO_3$	< 5	> 120–200	n.a.	n.a.	n.a.	n.a.	n.a.	n.a	n.a	2,000
Sulphate as SO_4	14,808	500	6	809	46	2,896	n.t.	16	21	4,000
Sodium	9	> 60–200	14	6	7	2	n.t.	11	3	100
Organic carbon	n.t.	n.t.	0	1	0	0	n.t.	1	1	2

Water results (semi-quantitative ICP scan)			Soil results (total metals from acid digestion method and plant available metals (PAM) NH_4NO_4 method)											
Result	Result	Threshold	Control sample		Above geofabric		Above liner 1		Below liner 1		Side slope	Seep line	Dump toe	Plant toxicity threshold
			Total	PAM	Total	PAM	Total	PAM	Total	PAM	Total	PAM	PAM	
Al	637	5	16,110	76	19,460	216	17,485	93	12,610	193	15,103	0	2	> 5
As	0.11	0.1	5	0	77	0	95	0	100	0	58	0	0	> 5–10
Ba	n.t.	n.a.	51	5	300	1	55	1	4,563	1	30	1	5	> 500–1000
Cd	n.t.	n.a.	0	0	0	0	1	0	4	1	0	0	0	> 1
Cr	1	0.1	35	0	181	0	132	0	61	0	130	0	0	> 5–10
Cu	22	0.2	3	0	22	2	86	2	307	10	14	0	0	> 20–30
Fe	3,135	5	6,567	1	41,356	0	31,673	0	43,004	302	29,826	6	1	> 500
Mn	232	0.02	127	12	106	3	132	26	128	46	194	2	7	> 300–500
Ni	5	0.2	106	0	35	0	47	1	22	1	23	0	0	> 10–50
P	0	0.2	54	0	97	0	97	0	95	0	109	0	0	> 200–300
Pb	n.t.	n.a.	8	0	19	0	48	1	643	0	6	0	0	> 100
V	0.059	0.1	5	0	38	0	39	0	13	0	25	0	0	> 1–10
Zn	1,161	1	8	0	44	21	130	7	1,315	293	18	7	1	> 100–300

The pH (3–4) of both the water and soil remain a major concern. Soil pH (H_2O) values ranged from 2.5 to 5.2, with the lowest readings found on and below the discard, indicating highly acidic conditions that can mobilise metals and inhibit vegetation growth. Several heavy metals exceeded soil screening value (SSV) thresholds, posing direct risks to ecological and human health. Lead (Pb) levels ranged from 5.73 to 687.83 mg kg^{-1}, with all samples above the SSV1 limit. Zinc (Zn) reached up to 2,483.87 mg kg^{-1}, with all below-liner samples exceeding threshold values. Arsenic (As) ranged from 5.25 to 132.54 mg kg^{-1}, with all but the reference point exceeding thresholds. Copper (Cu) (3.03–645.33 mg kg^{-1}) exceeded SSV1 in samples from the seep line and toe of the dump. Nickel (Ni) also exceeded SSV1 at the reference point, ranging from 13.03 to 106.18 mg kg^{-1}. These concentrations indicate risk of leaching and long-term environmental impact if the waste is not strictly contained. Data from the soil cover soil confirms that a viable growth medium which can sustain long-term vegetation growth has been achieved and if the capping layer remains uncontaminated, the cover could sustainably protect the structure.

Water sample results confirmed the presence of acid mine drainage, with a pH of 2.5 and electrical conductivity of 1,185 mg L^{-1}, indicating elevated salinity. Several metals in water – Zn, Fe, Al, Mn, Co, Cd, Se, U and Cr – exceeded target water quality ranges, posing serious risks to aquatic life and potential groundwater contamination.

The presence of multiple constituents of potential concern above or near risk thresholds – and their increased mobility under acidic conditions – underscore the importance of the robustness of the engineered liners and sustainable erosion-control measures. Figure 4 presents a visual summary of the "re-rehabilitation" project illustrating the challenge of management and surveillance of remote sites. The original successfully rehabilitated landscape has become a renewed source of ARD (Table 3) due to the damage to the infrastructure from the continued illicit mining activities.

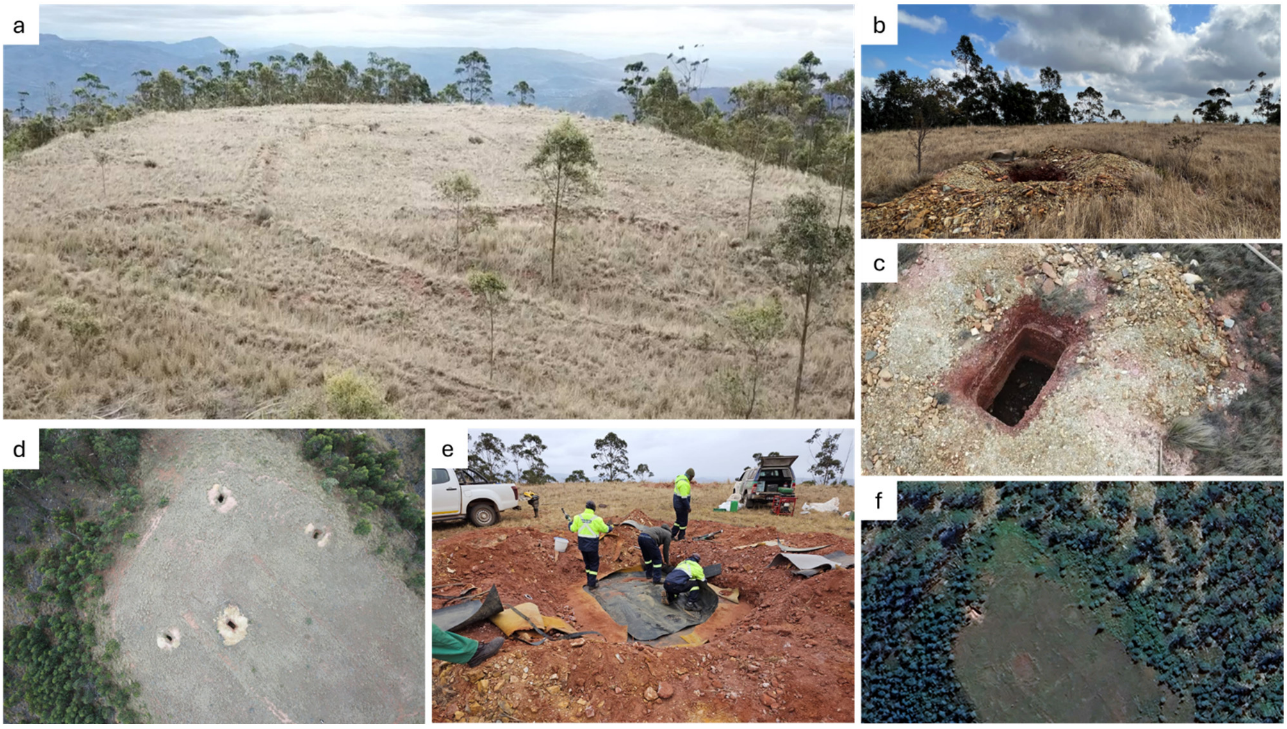

Figure 4 (a) Originally rehabilitated site; (b) Damage to the revegetated cover; (c) Arial view of trenching indicating the cover thickness as well as the ARD formation; (d) Arial view of diggings and water entry points; (e) Reparations; (f) New structural damage to the containment wall after 2024

Given the continual risk of damage to the depository and the associated long-term contamination potential, the viability of the current risk mitigation strategy should perhaps be reconsidered, as more illicit activities continued after the 2024 interventions. The complete removal of the depository to more secure locations should be investigated as a more sustainable option for final closure.

3 Closure responsibility amidst illicit mining activity

The case study presented represents a classic example of countless rehabilitated mine sites which are under siege from illicit mining. Empirical evidence from African case studies (Hilson 2017) confirms that rehabilitated infrastructure – mine dumps, tailings facilities and sealed shafts – is routinely compromised. Criminal elements (either impoverished local communities or syndicates) damage engineered cover systems, disturb contaminated sediments and interrupt ecosystem recovery. These actions, as demonstrated, result in groundwater contamination, air pollution and ecological regression, requiring costly re-rehabilitation, emergency containment and public health interventions. The mining entity remains liable for such remedial actions, irrespective of compliance with relinquishment criteria.

As in other mining countries, South Africa's legislative framework imposes strict, long-term environmental responsibilities on mining operations. The South African National Environmental Management Act (NEMA), Act 107 of 1998 (South Africa 1998), mandates in Section 28 a "duty of care" for any person whose actions have, or may cause, environmental degradation. This duty is not extinguished by mine closure and is not a waver against after-closure liabilities. Section 43 of NEMA, as amended by the *National Environmental Management Laws Amendment Act (NEMLA) 25 of 2014* (South Africa 2014), further clarifies that liability for residual or latent environmental impacts may persist beyond closure certification – especially when risks were foreseeable. The *Mineral and Petroleum Resources Development Act (MPRDA),* Act 28 of 2002 (South Africa 2002), requires the submission and approval of environmental management programs and financial provisioning for closure. The *Financial Provisioning Regulations* (GNR.1147/2015) under NEMA (South Africa 2017) (amended in 2022) compel mining right holders to set aside funds for rehabilitation and post-closure care. However, these instruments do not explicitly account for third-party criminal interference, creating significant gaps in post-closure liability forecasting.

This dynamic fundamentally challenges the closure paradigm. The assumption that expenditure ceases upon certificate issuance is no longer tenable in jurisdictions with persistent governance deficits and systemic criminality. Liability becomes effectively indefinite, raising concerns about fairness and the enforceability of environmental statutes. Mining companies are, in effect, underwriting state failures to secure closed mine land – a situation at odds with the original intent of the "polluter pays" principle.

Legal precedent is emerging whereby criminal acts are considered partially foreseeable. This raises a critical contradiction at the heart of mine closure planning: the assumption that closure expenditure will cease following the achievement of regulatory relinquishment criteria is increasingly unfeasible. The continued liability for damages inflicted post-closure implies an indefinite cost burden on private entities. Yet, as the "polluter pays" principle – enshrined in international and domestic law – is stretched to account for damages caused by criminals, it begins to blur into a scenario where mining companies are underwriting the failings of the state to ensure law and order. Yet, the absence of legal clarity regarding liability for third-party criminality is generating significant financial and operational risk. Companies may adopt risk-averse behaviours such as delaying closure certificate applications, over-investing in unsustainable security measures or withdrawing from high-risk jurisdictions, thereby undermining both environmental remediation and socio-economic transition objectives.

Regulatory authorities are pressing for the integration of vulnerability mitigation strategies within mine closure and post-closure designs. Co-management approaches with local communities and participatory land-use planning after closure are consistent with global frameworks like the ICMM's *Integrated Mine Closure: Good Practice Guide* (ICMM 2022) and the UN Sustainable Development Goals (SDGs), which emphasise resilience, inclusivity and long-term sustainability.

The policy gap reveals an urgent need for shared accountability mechanisms. Without reforms to redistribute risk – possibly through state-backed post-closure funds, community compacts or adaptive legal instruments – the sustainability of mine closure remains compromised. Future mine closure strategies must integrate criminal risk resilience as a core planning principle, not an ancillary concern.

4 Bridging the gap: theft-proof closure design

Since illicit mining risks pose a critical post-closure threat to the integrity of rehabilitated landscapes, engineers and environmental managers must now move beyond environmental compliance to develop resilient closure strategies that account for “social erosion solutions” or landscape protection. This challenge necessitates the emergence of a new domain within closure science and engineering – one that acknowledges the interplay between socio-economic conditions, criminal enterprise and post-mining land design. Illicit mining represents a rapidly escalating post-closure threat to rehabilitated mine sites by compromising the physical integrity and ecological function of engineered landscapes, leading to slope failures, re-exposure of contaminants, infrastructure degradation and the uncontrolled discharge of pollutants. The remedial works that follow – ranging from re-rehabilitation and containment interventions to public health responses – remain the legal and financial responsibility of the original mining entity. This reality invalidates the prevailing assumption that closure liabilities conclude with the issuance of closure certificates upon meeting relinquishment criteria. The recurrence of post-closure damage to previously certified sites renders the notion of a fixed end point in closure expenditure technically implausible. Consequently, closure cost models and financial provisioning mechanisms must be recalibrated to internalise long-tail liabilities and the likelihood of post-closure rework.

This challenge necessitates the emergence of a new domain within closure science and engineering – one that acknowledges the interplay between socio-economic conditions, criminal enterprise and post-mining land governance. Proactive planning, institutional reform and integrated socio-technical design are key to ensuring sustainable closure outcomes and mitigating long-tail liabilities. Closure engineering must therefore transition from compliance-driven design towards functionally resilient, intrusion-resistant landscapes. The first line of defence lies in earthworks design. Landforms should eliminate features that offer re-mining opportunities by sealing or recontouring pits, erasing ore-associated geomorphologies and burying enriched residues beneath inert capping layers. Material selection and compaction protocols must further reduce excavation potential and ensure long-term geotechnical stability. Hydrological control is equally critical. Engineered drainage systems must prevent pooling or seepage that could facilitate informal ore processing. Subsurface drains should be concealed and armoured, while above-ground channels are designed to resist both erosion and manipulation. Concurrently, biophysical engineering can provide a passive yet effective security layer. Rapidly establishing, deep-rooted vegetation stabilises slopes, obscures the landscape from opportunistic access and reduces visual indicators of prior mineralisation. Nature-based solutions such as stability and accessibility management systems, as well as phytostabilisation of contaminants, can further render targeted illicit areas unworkable or unappealing for illegal operations.

Beyond physical design, technological integration is essential. The deployment of distributed sensor networks enables real-time monitoring of ground disturbances and unauthorised access. Data from these networks can feed into geospatial models to simulate risk zones and inform adaptive management. Coupled with drone surveillance and satellite-based change detection, these tools allow for rapid response and targeted intervention before large-scale damage occurs.

In this evolving context, mine closure engineers must reconceptualise closure as a dynamic, risk-informed process extending beyond final landform construction. By engineering post-mining environments to pre-emptively deter intrusion, absorb disruption, and recover ecological and structural function after impact, closure becomes not just a technical outcome but a long-term operational strategy. Sustainable closure, underpinned by socio-technical landscape design, is thus not only a regulatory goal but a critical defence mechanism against the financial, legal and environmental consequences of post-mining illicit activity.

5 Conclusion

Illicit mining at closed mine sites presents a systemic risk that traditional closure frameworks are not equipped to manage. Despite full compliance with environmental and engineering obligations, post-closure criminal activity continues to undermine site integrity, reintroducing environmental harm and reactivating corporate liabilities. This case study from South Africa highlights the need for a paradigm shift in mine closure thinking.

This challenge necessitates the emergence of a new domain within closure science and engineering – one that integrates socio-economic dynamics, criminal enterprise and post-mining governance into closure planning. Closure is no longer a finite task; it is a long-term, risk-managed process. Engineering must now include intrusion-resistant landforms, passive surveillance systems and closure designs that eliminate re-mining potential while maintaining environmental function. At the same time, mining companies must acknowledge that illicit activity often reflects broader socio-political tensions. Closure strategies must therefore include community-based monitoring, livelihood alternatives, and coordinated partnerships with law enforcement and civil society. The evolution of South African regulations to require post-closure security provisioning and stakeholder engagement is a positive step – but further institutional alignment is essential.

A new closure model must enable risk transfer through insurance or superfund mechanisms, clarify legal distinctions between negligence and third-party crime, and embed socio-technical co-governance as standard practice. Only by integrating environmental security with social legitimacy can closure outcomes be sustained. The mine closure industry must now act – redefining sustainability success criteria within the context of long-term stability and the resilience of rehabilitated landscapes – but in real-world conditions. Anything less will leave mining companies vulnerable to unending closure costs, regulatory scrutiny and claims, and undermine public trust in the sector's ability to deliver safe, sustainable and just post-mining futures.

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