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THE SOUTHERN AFRICAN INSTITUTE OF MINING AND METALLURGY

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CLIMATE CHANGE IN MINING:

Risks, Governance, Sustainability, and Environmental Management

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FOREWORD

On behalf of the Southern African Institute of Mining and Metallurgy (SAIMM), it is my privilege to welcome you to the 2026 Conference on Climate Change in Mining: Risks, Governance, Sustainability, and Environmental Management and to the hospitality of the Glenburn Lodge & Spa, situated within the Cradle of Humankind – a World Heritage Site.

Mining remains a cornerstone of economic development in Southern Africa, yet it is also one of the industries most exposed to the profound challenges of climate change. Rising temperatures, shifting rainfall patterns, water scarcity, and biodiversity loss are no longer distant risks—they are realities reshaping our operations, communities, and responsibilities.

This gathering builds on the success of our inaugural event, reaffirming SAIMM's commitment to fostering dialogue, knowledge exchange, and collaborative solutions. The challenges we face may be complex, but they also present opportunities to reframe mining as a driver of resilience, innovation, and sustainable development.

We encourage all delegates to engage actively, share insights, and forge partnerships that extend beyond this conference. Together, we can ensure that mining not only adapts to climate change but contributes meaningfully to a more sustainable and equitable future.

I trust that the proceedings of this conference will allow you to build the additional perspective that enables you to rise to the challenge of embedding ESG-Sustainability in your professional lives and businesses. I encourage you to participate in the proceedings, debate the issues and enjoy networking with solution-oriented people on this journey to enable environmental and social sustainability in the minerals Industry.

Finally, a heartfelt thank you to the Organising Committee, the SAIMM conferencing team and our willing and generous sponsors, without whom this conference would not have been possible.Take Care and please Stay Safe.

Gordon Smith
Chair: Organising Committee
26 August 2026

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Beyond the design storm: from compliance metrics to adaptive operations for consecutive minor events in dams

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Return water dams at mines are commonly assessed against single-event compliance criteria, typically the 1-in-50 year 24-hour storm, with probable maximum precipitation used as an upper check. Although useful for design verification, these criteria do not adequately represent the operational risk posed by sequences of smaller storms occurring over days to weeks. In practice, spills are often driven by cumulative inflow, antecedent wetness, reduced recovery time between storms, sedimentation and limitations in pumping and operational response.

This paper presents a sequence-based framework for assessing the performance of return water dams and linked tailings storage facilities under consecutive minor rainfall events. The framework uses continuous water balance simulation, rainfall sequencing, antecedent wetness response and climate stress testing to evaluate spill likelihood, time at risk for freeboard exceedance and recovery capacity. A case study based on observed rainfall at a South African mine site is used to illustrate the problem. During January 2026, 831 mm of rainfall was recorded over 11 days, equivalent to about 145% of the local mean annual precipitation. Within this sequence, daily events reached approximately the 5-year to 20-year range, while the 72-hour and 7-day accumulations approached the local 50-year design depths. The findings support a shift from a design storm philosophy towards a design sequence and adaptive operations approach.

INTRODUCTION

Return water dams (RWDs) and tailings storage facilities (TSFs) are often assessed against single-event storm criteria. For mine water systems, this usually means demonstrating adequate storage for a selected design storm, commonly the 1-in-50 year 24-hour event and checking more extreme conditions such as probable maximum precipitation (PMP). These criteria remain useful for benchmarking, but they do not always reflect the way spills occur in practice.

Exceedances are frequently associated with sequences of moderate storms rather than one exceptional event. In such systems, water level depends on cumulative runoff, direct rainfall, return flows from the TSF, pumping capacity, evaporation and the remaining effective storage after sedimentation. Spill risk therefore depends not only on storm magnitude, but also on antecedent wetness, event timing and recovery capacity between storms.

These issues are increasingly relevant under climate variability, where rainfall sequencing, clustering and wet-season timing may change even when long-term annual totals remain broadly similar (IPCC, 2023). This paper examines the limitations of the single design storm approach and proposes a more practical framework based on continuous simulation and adaptive operation.

LIMITATIONS OF SINGLE-EVENT COMPLIANCE

Single-event assessment assumes that the critical system response can be represented by one storm applied to one set of initial conditions. For storage-driven mine water systems, this assumption is limited for three reasons.

First, initial conditions are rarely neutral. Before a wet sequence begins, the catchment, TSF beach and dam may already be wet or partly full. Second, recovery between storms is constrained by pumping, transfer capacity, power supply and maintenance readiness. If storage is not restored, the next event arrives on an elevated level. Third, effective storage changes with time. Sedimentation and operating constraints reduce available live storage and freeboard, sometimes materially.

For these reasons, compliance with a single 24-hour storm criterion does not necessarily imply acceptable seasonal reliability.

METHODOLOGY

A continuous water balance framework was adopted to assess sequence-driven spill risk. The model includes:

- A return water dam with a level-storage relationship
- Direct rainfall and evaporation on ponded areas
- Runoff from mine catchments
- Lagged return inflows from the TSF
- Reclaim and transfer pumping
- Variable pump availability
- Reduction in effective storage due to sedimentation
- Drawdown trigger levels for operational response

At each time step, storage is updated through a standard mass balance:

$$S(t+1) = S(t) + Qin - Qout \qquad [1]$$

where Qin represents runoff, direct rainfall and return flows and Qout represents pumping, evaporation and other losses.

Continuous rainfall series are used rather than one synthetic design storm. Historical records or resampled sequences preserve event depth, seasonality and dry-period structure, allowing assessment of clustered storms and incomplete recovery. Antecedent wetness is represented through dynamic runoff response, while operational scenarios account for pump outages, delayed preparation, loss of standby capacity and reduced live storage.

Climate stress testing is used to assess the effect of altered storm sequencing, shorter dry periods and shifts in wet-season timing. The purpose is not to predict one future climate, but to test system robustness under plausible future sequences.

CASE STUDY: JANUARY 2026 CLUSTERED RAINFALL SEQUENCE

A case study was compiled from rainfall observations at a mine tailings area, supported by comparison with a nearby Department of Water and Sanitation station and a mine site record. Figure 1 shows the cumulative rainfall trends for the three datasets. These are broadly linear over time, indicating that the key hazard in this case is not a major change in long-term annual rainfall totals, but the concentration of rainfall into short-duration wet periods.

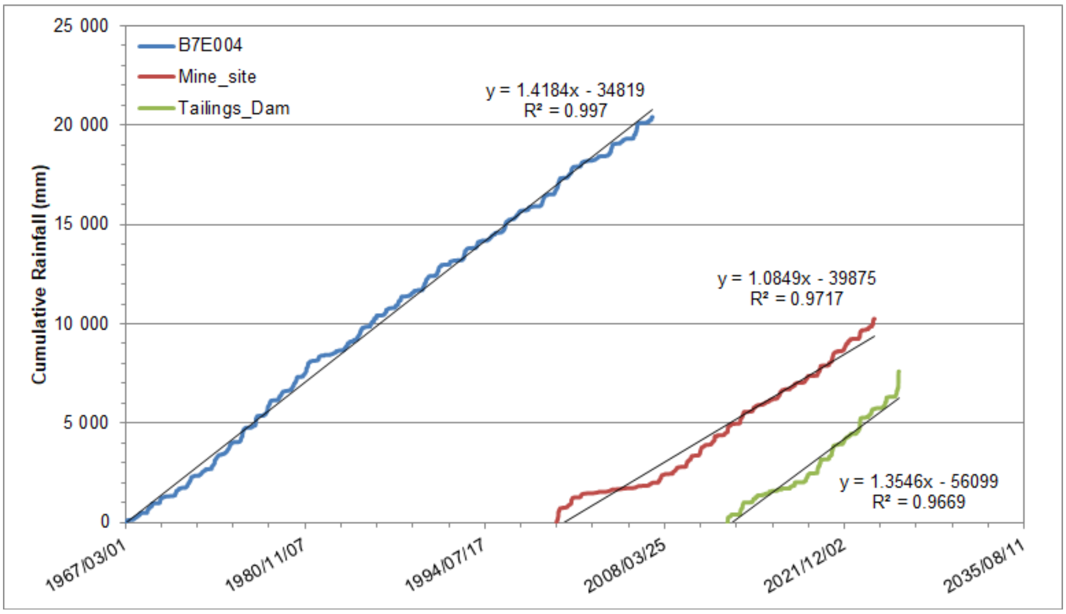

Figure 1. Cumulative rainfall trends for mine site

The derived mean annual precipitation (MAP) values were 510.66 mm for station B7E004, 439.55 mm for the Mine site and 574.28 mm for the Tailings Dam. Design rainfall depths derived for the tailings record are summarised in Table I, and the estimated 24-hour PMP was 522 mm.

Table I: Design rainfall depths for the Tailings Dam dataset

Design storms	LP3	LP3	LP3	LP3
2	79	92	106	138
5	104	144	180	268
10	123	184	236	367
20	137	230	306	503
50	153	299	418	730
100	164	359	521	948
200	175	427	642	1213
500	187	532	837	1655
1 000	196	623	1015	2072
2 475	206	780	1347	2902
5 000	213	901	1605	3546
10 000	221	1021	1859	4181

Rainfall totals from the start of the 2025/2026 hydrological year to the end of January 2026 were 84.5 mm in October, 213 mm in November, 135 mm in December and 831 mm in January, giving a cumulative total of 1263.5 mm by 31 January 2026. Notably, the full January total occurred within 11 days, from 9 to 19 January 2026, as shown in Table II and Figure 2. Figure 2 shows the daily rainfall and cumulative rainfall from 9 to 19 January 2026, compared with the local mean annual precipitation and the 7-day 20-year and 50-year design storm depths for the Tailings Dam dataset.

Table II: Observed daily rainfall during the principal January 2026 wet sequence

Date	Daily rainfall (mm)	Cumulative rainfall (mm)
2026/01/09	9	9
2026/01/10	70	79
2026/01/11	75	154
2026/01/12	100	254
2026/01/13	138	392
2026/01/14	135	527
2026/01/15	125	652
2026/01/16	40	692
2026/01/17	80	772
2026/01/18	50	822
2026/01/19	9	831

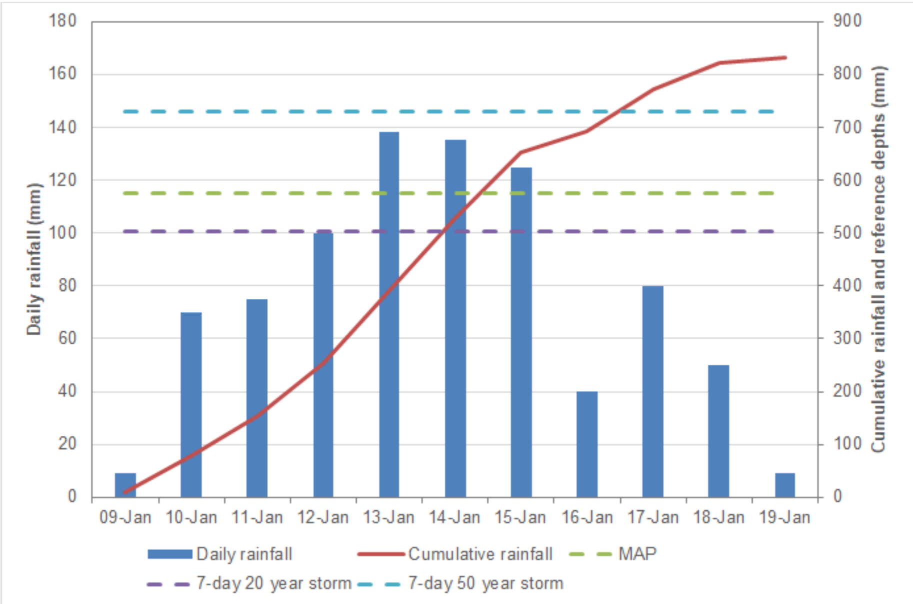

Figure 2. Rainfall comparison during the principal January 2026 wet sequence

The 11-day total of 831 mm is about 45% greater than the local MAP. Several daily totals were also hydrologically significant. The 100 mm recorded on 12 January was close to the 5-year 24-hour storm. The 138 mm on 13 January was approximately equal to the 20-year 24-hour storm. The 135 mm on 14 January fell between the 10-year and 20-year design depths, while 125 mm on 15 January was close to the 10-year 24-hour storm.

Multi-day totals were more severe. The 48-hour total for 13 to 14 January was 273 mm, between the 20-year and 50-year 48-hour design storms. The 72-hour total for 13 to 15 January was 398 mm, between the 20-year and 50-year 72-hour storms and close to the 50-year value of 418 mm. The 7-day totals for 10 to 16 January and 11 to 17 January were 683 mm and 693 mm respectively, both between the 20-year and 50-year 7-day design storms.

Figure 2 provides a practical illustration of the sequence hazard. The cumulative rainfall exceeded the 7-day 20-year design depth by 14 January, exceeded the local mean annual precipitation by 15 January and exceeded the 7-day 50-year design depth by 17 January. These comparisons are used as reference magnitudes rather than directly duration-equivalent thresholds, but they show how quickly the sequence escalated into a severe storage-loading condition. The significance is that the system was exposed to sustained inflow over multiple days with limited opportunity for drawdown, which is the principal mechanism by which return water dams may spill under clustered sub-design events.

DISCUSSION

The paper demonstrates a clear disconnect between single-event compliance metrics and actual operational exposure. The long-term cumulative records do not suggest a dramatic escalation in annual rainfall, yet the January 2026 sequence imposed an exceptional short-term storage demand. The relevant stress mechanism arose well below the 24-hour PMP. Instead, it was produced by repeated daily events in the approximate 5-year to 20-year range, which combined into multi-day totals approaching the local 50-year design depths.

This has practical implications. Adequate performance cannot be inferred solely from successful containment of a nominated 24-hour design storm. For storage-based mine water systems, reliability also depends on pre-wet-season drawdown, available pumping capacity, line condition, power reliability and preservation of live storage.

The case study therefore supports sequence-based planning, especially where RWDs and TSFs operate with limited freeboard, constrained pumping capacity or progressive sedimentation.

RECOMMENDED ADAPTIVE OPERATING FRAMEWORK

A practical adaptive framework for RWDs and TSF-linked water systems should include:

- Seasonal storage targets with lower wet-season operating levels;
- Assessment of pumping and transfer systems based on sustained recovery rate;
- Proactive sediment surveys and silt removal planning;
- Forecast-guided operating triggers for drawdown and storm preparation; and
- Continuous review of storage trends, pump status and near-miss events.

These measures improve reliability by preserving available buffer and recovery capability before and during clustered rainfall.

CONCLUSIONS

Conventional design criteria for return water dams remain useful for compliance and benchmarking, but they do not fully represent the operational risk associated with consecutive minor rainfall events. In many mine water systems, spill risk is controlled by cumulative inflow, antecedent wetness, loss of effective storage and limited recovery capacity between storms.

The case study presented here shows that 831 mm of rainfall was recorded over 11 days in January 2026, equivalent to about 145% of the local MAP. Several daily falls were in the approximate 5-year to 20-year range, while the 48-hour, 72-hour and 7-day accumulations approached the local 50-year design storm magnitudes. Under these conditions, event clustering, wet antecedent conditions and restricted inter-event recovery can be more important than the magnitude of any single storm.

A continuous sequence-based assessment therefore provides a more realistic view of system performance. It captures the effect of rainfall clustering, delayed drawdown, pump outages and sedimentation, all of which can cause freeboard exceedance even where the single-event design criterion is satisfied.

The findings support a shift from a design storm mindset to a design sequence and adaptive operations framework for mine water systems.

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How regional water stewardship can mitigate water stress in mining communities

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Water stress in mining communities arises from intensive abstraction, declining groundwater tables, and contamination from mining influenced water and tailings effluent. Regional water stewardship provides a systems-based approach to mitigate these pressures by embedding mining operations within catchment-scale hydrological planning. Technical interventions include the reuse and treatment of mining-influenced water, integration of closed-loop recycling systems, and deployment of appropriate passive and active treatment technologies to reduce pollutant loads. At the regional level, stewardship frameworks enable coordinated allocation models that balance industrial and agricultural demand with municipal and ecological requirements, supported by hydrological modelling and scenario analysis under climate variability. Collaborative monitoring networks and shared data platforms strengthen transparency, while investment in green infrastructure—such as constructed wetlands and aquifer recharge schemes—enhances resilience. By shifting from site-specific compliance to basin-wide optimisation, regional water stewardship reduces cumulative impacts, secures long-term water availability, and supports sustainable socio-economic development in mining-dependent regions.

INTRODUCTION

Mining is a water-intensive activity that both depends on and influences the quality, quantity and reliability of shared water resources. In mining-dependent regions, water stress is commonly intensified by intensive abstraction, depletion and drawdown of groundwater, contamination from mining influenced water and tailings effluent, and increasing competition between industrial, municipal and ecological water requirements. These pressures are rarely confined to individual mine sites; they accumulate across catchments where multiple users, land uses and hydrological processes interact over time.

Traditional mine water management has often focused on site-level compliance and operational risk reduction. While this approach remains important, it is insufficient where water availability and water quality are shaped by regional abstraction patterns, climate variability, legacy pollution and the needs of surrounding communities. A catchment-scale response is therefore required to understand cumulative impacts, identify shared risks, and align mining operations with broader water security objectives.

Regional water stewardship offers such a response by embedding mine water management within basin-wide planning, governance and decision-making. It promotes coordinated allocation models that balance mine demand with municipal supply, ecological flow requirements and long-term socio-economic development. It also supports the integration of hydrological and hydrogeological modelling, scenario analysis and collaborative monitoring to improve transparency and guide investment under conditions of uncertainty.

At the operational level, stewardship is enabled by technical interventions that reduce freshwater dependence, prevent pollution during both the active and post-closure stages and minimise pollutant loads. These should follow the mine water management hierarchy in the Department of Water and Sanitation's Mine Water Management Best Practice Guidelines which propose a hierarchy of water management approaches, shown on Figure 1:

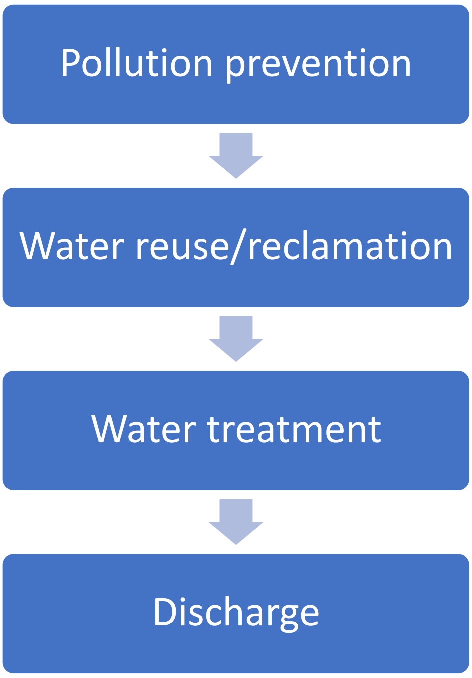

Figure 1. DWS Mine Water Management Hierarchy (Munnik and Pulles, 2009).

Options available include the reuse of mine-affected water, closed-loop recycling systems, passive and active treatment technologies, constructed wetlands, managed natural attenuation and managed aquifer recharge schemes. Mine planning and mine closure planning should also incorporate measures to minimise pollution generation, particularly when looking at long-term impacts. When implemented as part of a regional strategy, these measures can improve resilience by linking engineering controls with catchment-scale water balance requirements.

This paper examines how regional water stewardship can mitigate water stress in mining communities by shifting mine water management from isolated compliance to basin-wide optimisation. The discussion considers the technical, institutional and community dimensions of stewardship, with emphasis on water reuse, treatment, monitoring, allocation planning and green infrastructure as mechanisms for securing long-term water availability while reducing cumulative environmental impacts.

CURRENT SCENARIO

South African Mines and their communities

Water management at South African mines is increasingly shaped by the combined effects of physical water scarcity, declining water quality, legacy pollution and stricter regulatory oversight. Mining operations depend on water for mineral processing, dust suppression, cooling, slurry transport, rehabilitation and domestic uses, yet many mining regions are located in water-stressed catchments where municipal, agricultural, ecological and industrial demands compete for the same resource. This makes mine water management both an operational risk issue and a regional water security concern.

The current scenario is characterised by a move away from conventional end-of-pipe management towards integrated water balance planning, water conservation, pollution prevention and reuse. Active mines are increasingly required to understand site-wide water circuits, separate clean and dirty water systems, contain contaminated runoff, minimise seepage from waste facilities, and maximise recycling before abstracting additional freshwater. However, performance remains uneven across the sector. Modern operations often apply monitoring networks, lined pollution control dams, process-water recycling and treatment systems, while older, abandoned or ownerless mines continue to present significant risks through uncontrolled decant, mining influenced water and deteriorating pollution control infrastructure.

Mining influenced water remains a major regional challenge in coal, gold, platinum and base-metal mining areas. In coalfields, sulfate-rich, acidic and saline mine water can affect surface water and groundwater resources, while gold mining areas are associated with mining influenced water linked to pyrite oxidation and rising underground water levels. In parts of Mpumalanga, Gauteng, KwaZulu-Natal and Limpopo, abandoned workings and decanting mines place pressure on catchment management systems, requiring long-term pumping, treatment, containment or controlled discharge strategies. These conditions demonstrate why water stewardship must extend beyond the mine boundary and consider cumulative impacts at catchment scale.

The primary legislative instrument governing mine water use is the National Water Act, 1998 (Act 36 of 1998). Under the Act, mines must obtain a water use authorisation, typically in the form of a Water Use Licence, for activities such as taking water from a water resource, storing water, impeding or diverting flow, altering the bed or banks of a watercourse, discharging waste or water containing waste, disposing of waste in a manner that may detrimentally impact a water resource, or undertaking controlled activities. Water use licences normally include site-specific conditions relating to abstraction volumes, discharge limits, monitoring, reporting, stormwater management, pollution control infrastructure, rehabilitation and contingency measures.

In addition to the National Water Act, mining operations must comply with regulations dealing specifically with the use of water for mining and related activities aimed at protecting water resources. These requirements generally oblige mines to prevent clean water from becoming polluted, separate clean and dirty water systems, design and maintain pollution control facilities, prevent seepage and uncontrolled discharge, manage residue deposits and stockpiles, and implement measures to protect groundwater and surface water. Water use authorisation applications are also supported by technical information such as hydrological and hydrogeological assessments, water balances, specialist studies, monitoring plans and integrated water and waste management plans. The Department of Water and Sanitation has also published best-practice guidelines for mine water management.

The National Environmental Management Act, 1998 (Act 107 of 1998) (NEMA) provides the broader environmental governance framework and requires environmental authorisation for listed activities, supported by environmental impact assessment processes where applicable. It also embeds the duty of care, pollution prevention, sustainable development and public participation principles that are relevant to mine water management, closure planning and financial provision for rehabilitation and mine closure. The Mineral and Petroleum Resources Development Act, 2002 (Act 28 of 2002) (MPRDA) regulates the granting of mining rights and the issuing of closure certificates, and requires alignment between mining authorisations, environmental management obligations. Since 2014, environmental management on mines has been governed under NEMA, with implementation by the Department of Mineral and Petroleum Resources. Together, these instruments require mines to manage water impacts throughout the mining life cycle, from planning and operation to closure and post-closure.

Recent policy direction reinforces a more proactive and integrated approach. The DWS Mine Water Management Policy promotes mine water management across the full mining life cycle, including liability apportionment, appropriate treatment technologies, continuous improvement, reuse of treated mine water, and specific attention to abandoned and ownerless mines. This policy direction is important because it recognises that mine water impacts are often long-term and may persist beyond the economic life of an operation. It also supports the shift towards beneficial reuse, circular water systems and regional planning, particularly where treated mine water can supplement industrial or municipal supply under appropriate quality controls.

Currently the key impacts on the communities can be summarised as follows:

- **Water insecurity:** Operating mines increase demand on already stressed catchments, reducing the reliability of water available for households, municipalities, agriculture and ecosystems.
- **Declining water quality:** Acid and saline drainage, tailings effluent and contaminated runoff can pollute rivers, wetlands and groundwater used by communities.
- **Health and safety risks:** Where communities rely on untreated surface water, boreholes or informal sources, contamination can increase exposure to metals, acidity, dissolved solids and other pollutants.
- **Livelihood impacts:** Polluted or reduced water supplies affect subsistence farming, livestock, food gardens, small businesses and other water-dependent activities.
- **Higher household costs:** Communities may need to buy water, travel further to collect water, or rely on intermittent municipal supply when local resources become unsafe or unreliable.
- **Loss of trust and social conflict:** Perceived inequity in water allocation, poor communication, and weak transparency around monitoring results can increase conflict between mines, communities and authorities.
- **Long-term legacy burden:** Abandoned and ownerless mines can continue to generate poor quality water and decant long after closure, leaving communities and the state to manage ongoing environmental and financial impacts.
- **Reduced resilience to climate change:** Mining-related water stress compounds drought, extreme rainfall, infrastructure failure and broader catchment degradation, making communities more vulnerable.

The present landscape therefore requires mines to demonstrate not only that water uses are authorised, but that water is used efficiently, pollution is prevented at source, risks are monitored continuously, and residual impacts are financially and technically provided for. In practice, this places growing emphasis on accurate water balances, real-time or routine monitoring, adaptive management, proactive closure planning, stakeholder engagement, transparent reporting and collaboration with catchment institutions, municipalities and neighbouring users. These requirements create a strong basis for regional water stewardship, where individual mine compliance is integrated with shared catchment outcomes.

Water Stewardship

Current water stewardship in South Africa is developing in response to a water resource system that is already highly allocated, increasingly climate-exposed and constrained by deteriorating water quality and ageing municipal infrastructure. The Department of Water and Sanitation remains the custodian of the country's water resources, while the National Water Resource Strategy sets priorities that include reducing water demand, increasing available supply, improving water quality, strengthening institutions, protecting ecological infrastructure and improving data for decision-making. Within this context, stewardship is increasingly understood as a practical mechanism for moving beyond individual licence compliance towards shared catchment resilience.

In practice, current stewardship is most visible where mines, government, municipalities, catchment institutions and civil-society partners collaborate around shared water risks. The Strategic Water Partners Network has established a Water Stewardship Working Group to promote good practice, shared learning, scalable projects and public-private collaboration. This reflects a broader shift in the sector: water risks are no longer treated only as operational or compliance risks at mine level, but as collective risks that affect downstream users, municipal supply systems, agricultural production, ecosystems and mining-affected communities.

For the mining sector, current stewardship practice is centred on water conservation and demand management (WCDM), water balance optimisation, reuse of process water, treatment of mining-influenced water and improved monitoring. Tools such as the Water Conservation and Water Demand Management Self-Assessment Reporting Tool support standardised reporting of mine water balances, target-setting, fit-for-purpose water use, recycling and reuse. These approaches help mines quantify water demand, identify inefficiencies and demonstrate progressive improvement in water performance. A further feature of the current South African context is the growing recognition of mining-influenced water as a potential supplementary water resource where it can be treated to appropriate quality standards. This is particularly relevant in water-scarce mining regions where treated mine water may support industrial reuse, irrigation or municipal augmentation, provided that regulatory, technical, financial and public-confidence requirements are addressed. Current discussion therefore places strong emphasis on treatment reliability, independent verification, water quality standards, transparent communication and long-term operating responsibility.

Current stewardship practice is also being influenced by international frameworks such as the Alliance for Water Stewardship Standard and the International Council on Mining and Metals (ICMM) water stewardship guidance. These frameworks emphasise site-level water performance, stakeholder-inclusive planning, catchment-based action, governance, transparency and continual improvement. In South Africa, their relevance lies in providing structure for mines to align operational controls with catchment priorities and to demonstrate that water stewardship is embedded in governance, risk management and sustainability reporting.

Despite this progress, current implementation remains uneven. Large and well-resourced mining companies are generally better positioned to invest in digital monitoring, water reuse infrastructure, specialist modelling, assurance systems and collaborative catchment projects. Smaller operations often lack the financial and institutional capacity required for effective stewardship, while legacy mines and abandoned or ownerless mines with no revenue stream ultimately become a burden on the public. In addition, fragmented governance, slow authorisation processes, weak municipal infrastructure, limited data sharing and uncertainty over long-term liabilities can constrain coordinated action.

The current South African stewardship landscape can therefore be described as transitional. The regulatory framework provides the minimum compliance platform, while emerging partnerships, water reuse initiatives, digital monitoring systems and catchment-level planning are beginning to translate stewardship into practical action. However, for stewardship to meaningfully reduce water stress in mining communities, it must become more consistent, measurable and inclusive, with stronger links between mine-level performance, catchment institutions, municipal water security and community participation.

WAY FORWARD

In the South African context, water stewardship is particularly important because water scarcity, uneven spatial distribution of rainfall and increasing rainfall variability, deteriorating water quality and competing demands occur within the same catchments that support mining, municipalities, agriculture, ecosystems and rural livelihoods. The concept extends beyond efficient water use within a mine boundary and requires mining companies to understand their dependence on shared water resources, the impacts of their operations on those resources, and the needs of other users in the catchment.

South Africa’s water governance framework already provides a strong basis for stewardship because the National Water Act recognises water as a public resource that must be protected, used, developed, conserved, managed and controlled in an equitable and sustainable manner. This means that stewardship is not a substitute for compliance; rather, it builds on compliance by encouraging mines to move from meeting licence conditions in isolation towards contributing to broader catchment outcomes, including improved water quality, reduced demand, reuse of treated water and protection of aquatic ecosystems.

At catchment scale, stewardship requires collaboration between mining companies, the Department of Water and Sanitation and other regulators, catchment management institutions, municipalities, communities, agricultural users and conservation stakeholders. Such collaboration is necessary because the consequences of mine water abstraction, seepage, stormwater discharge, tailings storage, mining influenced water and post-closure decant are cumulative and may affect users located far downstream. A stewardship approach therefore places emphasis on shared risk assessment, transparent monitoring, joint planning and coordinated investment in solutions that benefit more than one water user.

For mines, practical stewardship begins with sound operational water management: maintaining accurate water balances, reducing freshwater intake, separating clean and dirty water systems, maximising process-water recycling, preventing uncontrolled discharges and ensuring that pollution control for dams, tailings facilities and residue deposits are designed and operated to protect surface water and groundwater. Closure planning needs to progress in parallel with the entire mining life cycle and should inform operational planning decisions such that long-term risks are identified and mitigated during operations and not left for the closure phase. These site-level measures are essential, but they become more effective when they are aligned with catchment priorities such as water conservation and demand management, climate resilience, ecological infrastructure protection and the beneficial reuse of treated mine water. Early identification and implementation of these risk mitigation measures will also improve the likelihood of closure certification, as well as reducing the required financial provision, both for closure and for post-closure water management.

The National Water Resource Strategy emphasises priorities that are directly aligned with stewardship, including reducing water demand, increasing available supply, improving water quality, managing water under a changing climate, protecting ecological infrastructure, strengthening institutions and improving data for monitoring and decision-making. In mining regions, these priorities translate into the need for water reuse schemes, regional treatment facilities, catchment monitoring networks, managed aquifer recharge, wetland rehabilitation and water offset projects where appropriate.

A South African water stewardship model must also respond to social realities in mining-affected communities. Many communities experience unreliable municipal water supply, poor sanitation infrastructure, limited economic diversification and high exposure to environmental impacts. In this setting, stewardship should not be limited to corporate reporting or technical optimisation; it should include meaningful engagement, accessible water quality information, support for local water security projects, and mechanisms that allow communities to participate in decisions affecting shared water resources. Water must be recognised as an economic enabler, with its availability driving broader development multipliers rather than being treated merely as a tradable commodity.

Accordingly, water stewardship in South African mining should be understood as a progression from compliance to collective action. Compliance provides the legal minimum through water use authorisations, monitoring and pollution prevention duties. In the currently developing regulatory environment, a more proactive approach is needed to ensure compliance in the longer term, and minimise post-closure liabilities, which currently hinder mine closure approvals. Stewardship extends this foundation by using catchment-level data, partnerships and shared investment to reduce cumulative impacts, improve resilience and ensure that mining contributes to equitable and sustainable water outcomes in the regions where it operates.

The following actions provide a practical framework for strengthening water stewardship across the South African mining landscape (summarised in Figure 2).

- **Start with a catchment-level water risk assessment.** Mines should map their full dependence and impact on shared water resources, including abstraction, discharge, groundwater interaction, tailings seepage, mining influenced water, municipal supply risks, ecological requirements and downstream users. This aligns with the ICMM Water Stewardship Framework, which emphasises catchment-based planning, inclusive engagement, transparency and efficient water management. (International Council for Mining and Metals, 2014, 2023)

- **Develop a five-year Water Conservation and Water Demand Management plan.** Each mine should maintain a computerised water balance, identify water-use efficiency indicators, evaluate reduction/reuse/recycling options, cost the options over the life cycle, rank them, and select a practical five-year implementation plan. This follows the Department of Water and Sanitation WC/WDM Guideline for the Mining Sector. [mineralscouncil.org.za]

- **Use standardised reporting tools such as WSART.** The Minerals Council South Africa Water Conservation and Water Demand Management Self-Assessment Reporting Tool can help mines standardise water balances, set targets, assess fit-for-purpose water use, identify reuse and recycling opportunities, and report progress consistently. [mineralscouncilcil.org.za]

- **Prioritise reduction, reuse and recycling before new abstraction.** Mines should reduce freshwater intake through closed-loop circuits, improved leak detection, stormwater separation, dry processing where feasible, tailings water recovery, reuse of process water and treatment of mine-affected water for fit-for-purpose applications.

- **Create regional mine-water reuse schemes.** In water-scarce mining regions, treated mine water should be assessed as a supplementary resource for industrial reuse, dust suppression, irrigation, ecological support or municipal augmentation where quality, reliability, cost recovery and public-health safeguards are in place. South Africa's Mine Water Management Policy supports reuse of treated mine water, including acid mine drainage, and addresses long-term mine-water liabilities. (Department of Water and Sanitation, 2019)

- **Establish shared monitoring networks.** Mines, municipalities, catchment institutions and communities should jointly monitor surface water, groundwater, discharge quality, flow, salinity, metals, pH and ecological indicators. Data should be shared transparently in accessible formats to build trust and support early warning. Long-term preservation of monitoring records is essential to ensure continuity across closure phases and institutional transitions.

- **Make community participation practical, not symbolic.** Community forums should receive plain-language water quality results, maps of risk areas, grievance channels, emergency response procedures and opportunities to influence stewardship priorities. The Alliance for Water Stewardship Standard stresses stakeholder-inclusive action at both site and catchment level. (Alliance for Water Stewardship, 2026)

- **Link stewardship to municipal water security.** Where mining affects or depends on municipal systems, mines should support practical projects such as water-loss reduction, bulk infrastructure maintenance, borehole protection, emergency water supply planning, wastewater reuse and capacity building for local water services. Where mine water treatment plants supplement municipal water supply, the implications of mine closure need to be considered.

- **Plan for closure from the start.** Stewardship must include funded post-closure water treatment, decant prevention, rehabilitation of polluted landforms, long-term monitoring and clear liability arrangements. This is especially important where abandoned and ownerless mines continue to affect communities.

- **Use nature-based and engineered solutions together.** Constructed wetlands, wetland rehabilitation, riparian buffers, erosion control, managed aquifer recharge and ecological infrastructure protection should complement active treatment plants, lined facilities, pumps, telemetry and pollution control dams.

- **Create regional water stewardship platforms.** Mines operating in the same catchment should collaborate with the **Department of Water and Sanitation**, catchment management institutions, municipalities, agriculture, communities and civil society to agree on shared risks, investment priorities, monitoring protocols and drought-response rules. The National Water Resource Strategy III identifies priorities such as reducing demand, increasing supply, improving water quality, protecting ecological infrastructure, strengthening institutions and improving water data. [wisa.org.za]

- **Measure outcomes, not only activities.** Stewardship performance should be tracked through indicators such as reduced freshwater abstraction, increased water reuse, improved discharge compliance, reduced pollutant loads, number of households with improved water security, response time to incidents, community trust measures and catchment water-quality trends. Mine closure outcomes can also be achieved where Social and Labour Plan and Corporate Social Investment projects are more closely aligned with post-mining economic objectives.

Figure 2: Practical water stewardship actions for the South African mining landscape.

RECOMMENDATIONS

Practical water stewardship in the South African mining landscape should move beyond minimum compliance towards coordinated, catchment-based action, as illustrated in Figure 2. This requires mines to maintain accurate water balances, implement five-year water conservation and demand management plans, reduce freshwater abstraction, maximise reuse and recycling, and treat mine-affected water for fit-for-purpose applications. Site-level interventions should be linked to regional platforms through which mines, the Department of Water and Sanitation, catchment institutions, municipalities, communities and other users can jointly assess risks, share monitoring data, prepare for drought and pollution incidents, and invest in solutions that improve both operational resilience and community water security. Stewardship must also extend across the full mining life cycle, including the closure and post-closure phases, to proactively mitigate post-closure risk, enabling the reduction of post-closure liabilities and their associated financial provision. Where abandoned and ownerless mine-water impacts exist, integration with catchment-based initiatives will reduce their environmental and financial impacts on communities and the state.

CONCLUSION

Catchment-scale water stewardship provides a practical pathway for mitigating water stress in mining communities by shifting mine water management from isolated, site-based compliance to coordinated action. In the South African mining landscape, water risks are shaped by the interaction of operational demand, declining water quality, municipal service constraints, climate variability and long-term legacy impacts from abandoned and ownerless mines. These pressures cannot be addressed effectively by individual mines acting alone. They require shared planning, transparent data, joint investment and inclusive governance across mines, municipalities, catchment institutions, regulators and communities.

Effective stewardship should therefore combine sound operational water management with regional collaboration. Accurate water balances reduced freshwater abstraction, reuse and recycling, treatment of mine-affected water, shared monitoring networks and nature-based infrastructure can reduce pressure on scarce water resources while improving water quality and resilience. When these measures are linked to catchment-scale platforms, they create opportunities to align mine performance with municipal water security, ecological protection and the needs of downstream users.

For mining communities, the value of regional water stewardship lies not only in technical efficiency, but in improved water security, reduced exposure to pollution, stronger trust between stakeholders and better preparedness for droughts, floods and post-closure risks. Stewardship must therefore be measurable, inclusive and sustained beyond the life of individual operations. By embedding water management within regional planning and shared accountability, the mining sector can contribute to more equitable, resilient and sustainable water outcomes for both operations and the communities that depend on the same catchments.

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The role of carbon offsets in decarbonisation strategy development

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To ensure that global warming is limited to 1.5°C above pre-industrial levels, it is critical that companies reach net zero by 2050. Net zero is achieved when the total greenhouse gas emissions produced are equal to the emissions removed from the atmosphere. To reach this goal, companies are tasked with developing a decarbonisation strategy specifically tailored to their organisation considering relevant abatement technologies, implementational enablers and barriers as well as funding considerations. Avoidance of GHG emissions is not always possible and mitigation of GHG emissions can only go so far; therefore, carbon offsets are required for the remaining last bit of emissions. Carbon offsets are mechanisms that allow individuals, companies, or governments to compensate for their greenhouse gas emissions by funding projects that reduce, remove, or avoid an equivalent number of emissions elsewhere. Carbon offsets can stem from projects which entail any of the following activities: leveraging natural processes to remove and store carbon, removing carbon dioxide from the atmosphere, renewable energy and waste management. Offsets can be sourced from international or national markets depending on how they are expected to be used. Offsets can be used for voluntary purposes such as to reach decarbonisation targets, as well as in some cases for regulatory purposes such as to limit carbon tax exposure. When incorporating carbon offsets into a decarbonisation strategy, it is important to note the limitations of offsets with regards to regulations, standards or legislation of the operation's jurisdiction. Offsets are provided with ratings which serve as an indicator for the quality of the offset. This quality rating is based on various factors such as additionality, permanence and transparency of the project or activity generating the offset. Due to misuse of offsets in the past, governments are seeking to introduce legislation to limit the use of offsets for regulatory purposes to only those which fit Article 6 criteria. This will impact the offset market supply as well as the price of offsets. Offset pricing in the free market is very volatile and fluctuates depending on supply and demand; most companies are therefore looking to fixed contracts with regards to procuring offsets. All these factors impact how offsets should be used by companies to reach their decarbonisation goals.

INTRODUCTION

To ensure that global warming is limited to 1.5°C above pre-industrial levels, it is critical that companies reach net zero by 2050. Net zero is achieved when the total greenhouse gas emissions produced are equal to the emissions removed from the atmosphere. Currently, 1300 out of 2000 of the largest revenue publicly traded companies have set a net zero target (NET ZERO TRACKER, 2025). To reach this goal, companies are tasked with developing a decarbonisation strategy specifically tailored to their organisation, considering relevant abatement technologies, implementational enablers and barriers as well as funding considerations. Carbon offsets can form part of a company's decarbonisation strategy to reach net zero.

Carbon offsets represent a reduction or removal of carbon dioxide, or its equivalent in other greenhouse gases, to offset carbon emissions made elsewhere (Romm, Lezak, & Alshamsi, 2025). Carbon offsets are created when a verified project reduces or removes GHG emissions. Such projects fit into one of three broad categories: reducing current emissions from a baseline, avoiding new emissions, or removing CO_2 from the atmosphere (Romm, Lezak, & Alshamsi, 2025). In market-trading terms, a carbon offset represents one metric tonne of carbon dioxide or its equivalent in other greenhouse gases. Carbon projects are monitored and verified by third parties to ensure the emissions reductions are real and measurable. Once verified, the offsets can be sold in carbon markets. Individuals, companies, governments, and organisations can buy carbon offsets to offset their carbon footprint resulting from daily operations or a specific product or service. To date, about 2 gigatonnes of offsets have been issued by the four largest independent mechanisms: American Carbon Registry, Climate Action Reserve, Gold Standard, and Verified Carbon Standard (Romm, Lezak, & Alshamsi, 2025).

METHODOLOGY

The following parameters should generally be considered when developing a decarbonisation strategy which includes offsets:

1. Decarbonisation hierarchy
2. How offsets are to be used
3. Type of carbon offsets to be sourced
4. Issuers of carbon offsets
5. Quality of carbon offsets
6. Carbon offset market
7. Carbon offset procurement
8. Beyond-value chain mitigation
9. Criticism and challenges with offsets

This paper is production-, operation- and regionally-agnostic and does not account for any specific requirements and merely serves as a guide for an approach to offset implementation.

RESULTS

Decarbonisation Hierarchy

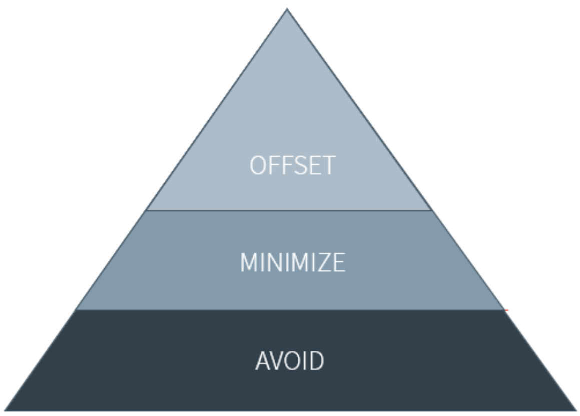

Figure 1. Decarbonisation Hierarchy.

In terms of the decarbonisation hierarchy, avoiding emissions altogether is the most preferred method, where practical. This would entail making design choices which consider the carbon footprint of equipment/technology options. Examples of low carbon design choices include process designs which lower the amount of CO_2 process gas generated, or designs which favour lower fuel usage or less carbon-intensive materials. However, various other considerations will impact design choice such as CAPEX, OPEX and operational constraints. Therefore, there is a limit to how much emissions can practically and economically be avoided just through design.

If emissions cannot be eliminated through design, the next step in the decarbonisation hierarchy is to determine whether emission sources can be minimised/mitigated, whether through energy efficiency, low carbon power, electrification, fuel switching or other technologies such as carbon capture utilisation and storage implementation. Although mitigation can go a long way to decarbonise operations, not all emissions are possible to abate, with residual emissions commonly known as hard-to-abate emissions. For example, the International Copper Association estimates that by 2050, 5% to 15% of emissions compared to a no-action scenario would still be left unabated in the copper value chain due to hard-to-abate emissions (International Copper Association, 2023). Sources of hard-to-abate emissions include non-biogenic portions of fuels and explosives which are typically impractical to directly abate, either from a technical or economic standpoint. Once mitigation measures have been implemented, offsets can be used as decarbonisation strategy for hard-to-abate emissions.

Offsets Use-Cases

Carbon offsets can be used for voluntary purposes or in certain cases, for regulatory purposes. It should be noted that the Science Based Targets initiative (SBTi) recognises that not all GHG emissions can be eliminated and that residual emissions will need to be neutralised to achieve and maintain net zero. SBTi defines neutralisation as measures that companies take to remove carbon from the atmosphere and permanently store it to counterbalance the impact of unabated emissions. However, companies are required to disclose the use of offsets to reach targets and need to report it separately from the carbon inventory. Under the latest SBTi regulations, offsets are not allowed to be used to reach near-term decarbonisation targets. Offsets can be used to neutralise residual emissions of up to 10% of baseline emissions remaining post abatement. A company cannot claim net zero until the long-term science-based target is achieved, and the company has neutralised residual emissions. Additional offsets cannot be used to neutralise more than 10% of baseline emissions but can be used to finance additional climate mitigation beyond science-based emission reduction targets.

A special use case exists where voluntary carbon offsets can be used to reduce carbon compliance costs such as for tax or purchasing allowances. For example, under the Alberta Technology Innovation and Emissions Reduction regulation, operations are given an allowable emission limit and for any emissions above this limit, offsets, performance credits or fund purchases need to be made. In South Africa, there is a carbon tax applicable for certain operations and carbon offsets can be used to limit a company's carbon tax liability. The use of offsets is very region-dependent, with various countries having their own rules with regards to the type and allowable quantity. For example, Chile mandates that only carbon offsets generated in Chile can be used to reduce carbon tax liability. Countries limit the amount of carbon offsets that can be used to reduce carbon compliance for example South Africa (10%), Mexico (10%), China (5%) and Columbia (50%).

Type of carbon offset projects

Carbon offsets can be generated from a variety of different types of projects.

Agriculture, forestry and other land-use

Carbon offsets in the forestry and land-use sector encompass measures such as the acceleration of reforestation programmes, the implementation of comprehensive wildlife-protection protocols, and the proactive engagement of public- and private-sector stakeholders in conservation strategies. As nature-based solutions, these offsets can command premium prices owing to their substantial co-benefits, including biodiversity conservation, enhanced water-resource management and erosion control. Typical project types include afforestation and reforestation, avoided grassland conversion, improved forest management and wetland restoration.

Renewable energy
These projects displace fossil fuels to provide cleaner and more reliable energy in regions where energy access may be limited. This is achieved by implementing renewable technologies such as solar PV, wind farms, small-scale hydro, geothermal, and biogas. Beyond emissions reductions, these projects are often linked with broader goal such as improving air quality and creating jobs. It should be noted that certain carbon offset registries have stopped issuing offsets for this type of project, due to the additionality clause not being met by these projects in some regions.

Energy efficiency
These projects focus on reducing emissions by improving energy efficiency and reducing associated fuel/electricity consumption. Efficiency-focused activities include improved cookstoves, better home insulation, lighting upgrades and streamlined industrial processes in certain cases. These types of projects emphasise practical, measurable energy savings. In many cases, the impact goes beyond emissions abatement; for example, efficient cookstoves also reduce indoor air pollution and improve the general health of affected communities.

Waste handling
These projects are aimed at treating wastes which are a major source of emissions. This includes projects which turn waste streams into climate solutions by capturing methane such as from landfills or converting organic material into usable biogas. These projects tend to deliver co-benefits such as improved sanitation and health.

Livestock and manure management
Manure-management carbon projects on large livestock farms (cattle, swine, buffalo, sheep, goats, poultry) capture greenhouse gases—mainly methane and nitrous oxide—released from animal manure by collecting and pumping it into closed biodigesters. The biodigester traps biogas produced by microbial breakdown; the gas is either flared or, more commonly, converted to heat or electricity. Converting the captured gas to energy also reduces fossil-fuel use, producing additional indirect emissions savings.

Fugitive emissions from industrial gases
These projects are aimed at preventing the release of greenhouse gases from air conditioning and refrigeration systems. These projects can include upgrading valve packing boxes and other upgrades which would lower leaks emerging from valves, flanges, pumps and tanks.

Carbon Offset Issuers
There are various registries which issue carbon offsets, each with their own methodologies and verification standards for issuing carbon offsets. Issuers of voluntary carbon offsets are the United Nations Framework Convention on Climate Change, Verra, Gold Standard, American Carbon Registry and Climate Action Reserve. Verra is the largest global standard with more than 1 billion tCO_2e of offsets issued. The Gold Standard places a stronger focus on projects which have a larger resulting co-benefit.

Quality of Carbon Offsets
Various agencies exist which aims to rate carbon offsets based on project specifics with regards to the criteria listed below. One such agency is the MSCI which rates projects from CCC (low quality) to AAA (high quality). Although voluntary carbon offset registries have different methodologies and verification standards, the following criteria can generally be used to determine the integrity or quality of carbon offsets.

Additionality
Encompasses the environmental and financial aspects that guarantee emissions reductions would not occur without support from carbon offset sales. Factors which impact additionality include whether the

project is financially viable without carbon revenues, if there are regulations or incentives that enforce or encourage the project activity and if there are practices like those implemented by the project in the region (Downey, 2025). Low additionality projects tend to have a very good business case even without generating carbon offsets whereas high additionality projects have no business case without accounting for sale of carbon offsets.

Transparency
Offset projects must provide clear and detailed information about their methodologies, calculations, and verification processes. To achieve transparency, regular monitoring and verification of projects by independent third parties are required. This is to ensure that emission reductions are real and accurately reported. Part of transparency includes having project documentation publicly available to ensure accountability and facilitate scrutiny by stakeholders.

Permanence
This is an indication of the degree of confidence that a particular project will keep carbon emissions out of the atmosphere for a certain amount of time. The best carbon offset projects assure that the carbon they sequester or avoid will remain out of the atmosphere for at least 100 years, which is the benchmark that allows a project to brand itself as 'permanent' (Sylvera, 2022).

Type of Project
The type of project producing carbon offsets also impacts how the issued offsets are viewed. Forestry and land use, large-scale renewables and agriculture projects are considered as higher risk for overestimating emission savings and are less likely to be additional. Small-scale renewables (≤15 MW), energy efficiency and household/community projects are considered medium risk, and fugitive gas destruction can be considered low risk (Trencher, Nick, Carlson, & Johnson, 2024).

Age of Project
Newer carbon offset projects ensure that investments are directed towards recent rather than historical climate actions. Older carbon offset projects are generally viewed as using outdated methodologies and are less likely to be additional (Trencher, Nick, Carlson, & Johnson, 2024).

Price
Low priced offsets are assumed to reflect low quality and low additionality (Trencher, Nick, Carlson, & Johnson, 2024).

Co-Benefits
Entails considering the additional environmental and social impacts that a project provides beyond the CO_2e savings. Co-benefits can include various environmental, social and governance parameters such as improved health, job creation, diversity etc. Projects which hold more co-benefits are seen as higher quality and would be higher priced than those with less co-benefits.

Legal & Ethical
Considers whether a project is aligned with local and international laws. Projects which are not certified or compliant with local laws are seen as a risk and have a lower quality than those that do comply.

Delivery Risk
Refers to the risk that a project will not deliver on its CO_2e removal commitments. This can be due to technology limitations, environmental factors or financial constraints. Projects with a high delivery risk are seen as lower quality.

Carbon Offset Market
Carbon offset prices vary greatly within the voluntary market, with nature-based offsets averaging \$7–\$24/tCO_2e, and tech-based removal offsets between \$170–\$500 (Sylvera, 2026). The following five common drivers can explain this volatility in the voluntary carbon market (Senken, 2026)

Removal vs avoidance
Permanent removals (direct air capture, mineralisation, biochar) cost 10 to 80 times more than avoidance (REDD+, peatland restoration) offsets. The cheapest avoidance offset Senken transacts is at $12 and the most expensive durable removal sits above $1,000. This spread is driven entirely by the durability of the storage. Table I provides the current pricing ranges for the different types of projects in the voluntary carbon market.

Table I: Carbon offset pricing range based on durability of storage (Senken, 2026).

Methodology	Price Range ($/tonne)	Removal Type
Direct air capture	450 – 1,000+	Permanent removal
Enhanced rock weathering	350 - 450	Permanent removal
Microbial mineralisation	170 - 200	Permanent removal
Biochar	105 - 200	Permanent removal
Mangrove restoration	50 - 75	Temporary removal
Afforestation, reforestation, revegetation	22 - 50	Temporary removal
Regenerative agriculture	15 - 60	Temporary removal
Improved forest management	25 - 30	Avoidance
Peatland restoration	17 – 90	Avoidance
REDD+	12 – 15	Avoidance

Region of origin
German offsets trade at a 2 to 3 times premium compared to offsets following identical methodologies in lower-cost regions. This difference in locational prices of offsets is largely driven by domestic origin premiums and higher production costs. For example, German biochar offsets trade at $189 to $200 versus Indian biochar at $105/t$CO_2$e and regenerative agriculture at $49 to $60 versus Indian regenerative agriculture at $15 to $27/t$CO_2$e.

Age
Recently issued offsets from 2023 to date, cost 20 to 40% more than those issued from 2018 to 2020, despite following the same methodology. An understood reason for the lower cost associated with these earlier projects, is that they lacked proper additionality. Pre-2018 offsets were verified under earlier standards and have mainly been delisted by ratings agencies. These offsets are rarely transacted by Senken, an end-to-end carbon credit procurement partner, leading to limited information on how they compare.

Certification and rating tier
Verra and Gold Standard certification are seen as the minimum requirements for an offset. The premium tier of offsets is approved by the ICVCM Core Carbon Principles and have a third-party rating from Sylvera, BeZero, or Calyx in the A-band. This combination of additional criteria adds a $5 to $15 per tonne premium to the offset price.

Co-benefits and SDG alignment
Co-benefits add $5 to $20 per tonne in offset pricing. This is the easiest premium to justify in stakeholder communication and the hardest to fake in an assurance review.

Carbon Offset Procurement
Between 2021 and 2023, demand for high-quality carbon removal offsets grew fivefold (Luik, 2026). These numbers include both forward and spot transactions, but they indicate that buyers are starting to prioritise purchasing high-quality carbon offsets. Currently, most offsets on the market are low quality and the few that are high quality are quickly purchased (Probst, *et al.*, 2024). Access to high-quality offsets is thus becoming more competitive. As the market matures, companies looking for high-integrity carbon offsets need to move earlier to secure supply by leveraging carbon offtake agreements. High- quality offsets are generally more expensive than low-quality offsets (Sylvera, 2026). It is

predicted that average carbon offset prices will reach $80-150 per tCO_2e by 2035 without considering projects which tend to carry a premium (Ernest & Young, 2022). By committing to a carbon offtake agreement, a buyer guarantees access to future offsets at pre-agreed prices, effectively shielding their climate strategy from price hikes and potential supply shortages as demand grows (Luik, 2026).

Spot purchase
This carbon offset procurement strategy involves purchasing carbon offsets as and when needed by the organisation and is a once-off transaction. This allows for simple contract administration and a low transaction cost. A large risk with this method, however, is the price uncertainty in the spot market and potential exposure to high prices as the market becomes more constrained. Organisations are also limited in terms of offset quality options, with only those available on the open market being available. Periodic and ongoing procurement is required for spot purchasing procurement strategies.

Forward Contract
This carbon offset procurement strategy involves purchasing a predetermined number of offsets for a short-medium period, namely, about 3-5 years. This allows for price certainty in the medium term and decouples the offset price from market movements. It is also likely that the price paid for each offset is lower than that on the spot market. A large risk with this method, however, is the uncertainty regarding offset volumes available for purchase post-contract. This contract strategy also comes with higher transaction costs.

Long-term Offtake
This carbon offset procurement strategy involves purchasing a predetermined number of offsets over a long term, namely, about 10-15 years. This allows buyers to provide input during the development of the project and reduces the competition for securing the produced offsets. A large risk with this method, however, is the exposure to the project development risks. There is also an added risk of the project coming online after the specified methodology has been replaced or the project becomes ineligible for offset generation. This offtake agreement comes with increased costs stemming from due diligence requirements.

Own Projects
This entails developing a high-quality carbon project to generate carbon offsets for internal use. This allows for greater control of generating the offsets and ensuring the quality criteria is met. A large barrier for this method, however, is the high capital investment required for developing the project. Project development risks could also exist if a company lacks experience in executing offset-generating project types. A possible opportunity would be generating excess offsets which could be an additional revenue stream for the organisation.

Beyond-value chain mitigation
Beyond value chain mitigation (BVCM) is sometimes confused with carbon offsetting; however, the two play different roles in a company's decarbonisation strategy. BVCM is a mechanism through which companies can accelerate the global net zero transformation by going above and beyond their science-based targets. BVCM is defined as "mitigation action or investments that fall outside a company's value chain, including activities that avoid or reduce GHG emissions, or remove and store GHGs from the atmosphere" (Science Based Targets, 2024). An important distinction is that BVCMs do not impact an organisation's scope 1,2 or 3 reported emissions and do not count towards meeting their targets. The business case for BVCMs will depend on the region, market and industry in which the company operates and will be influenced by the extent to which the company is impacted by physical climate change events. Businesses must also consider the associated changes in policy, financial markets, consumer markets, society and technology to ensure that their BVCM activities have the necessary impact. Currently there is a gap between the committed levels of climate mitigation and what is needed to achieve the 1.5°C target (Science Based Targets, 2024). BVCMs can act as a bridge to address this gap by providing financing for scaling innovative climate solutions for net zero.

Criticisms and challenges

The voluntary carbon market faces several challenges with implementation of offsets as well as the perception of offsets.

Over-crediting

Over-crediting refers to projects being granted more carbon offsets than what is truly reduced or removed. Over-crediting claims have plagued the voluntary carbon market for the past two decades, with various studies citing over-crediting claims for a variety of different projects; notably for improved forest management, cookstoves replacement and avoided and reduced deforestation projects (Romm, Lezak, & Alshamsi, 2025). A 2024 analysis of 65 relevant studies covering 972 million tonnes of CO_2e found that at least 812 million offsets are unlikely to represent true emissions reductions (Probst, *et al.*, 2024).

This number is also on the low end, given that the study did not consider several key issues, such as double accounting, impermanence, nor did they include several studies that indicate integrity issues with project types. The high number of over-crediting cases call into question the efficacy of using carbon offsets to claim carbon reductions.

Greenwashing

Greenwashing refers to when companies or people make claims regarding sustainability which are untrue or misleading. Using the voluntary carbon market for greenwashing can occur in one of two ways. The first way involves inflating carbon offsets' role in mitigation and includes statements of products or services having no carbon footprint without disclosing the use of offsets. The second way involves inflating the positive effects from carbon offsets and includes making statements claiming high quality of offsets, when those purchased are known to be of low quality. Greenwashing poses reputational, litigation and regulatory risks to all those participating in the carbon market. Greenwashing allegations are being pursued by environmental non-government organisations. By 2024, more than 140 cases of greenwashing had been filed (Igini, 2024).

Impact on Mitigation

A common view of carbon offsets is that companies are using it to delay taking real emission mitigation actions. This can be true if companies are over-reliant on carbon offsets to reach targets and do not go through the process of mitigating emissions themselves. Most commonly this is made possible by cheap, low-quality offsets which can be secured at a lower price than that of mitigation activities. However, regulations are beginning to come online which limit the quantity of carbon offsets that can be used to reduce regulatory exposures from carbon emissions and will force organisations to decarbonise or incur penalties.

Social Risk

Forestry offset projects risk infringing on the rights of indigenous and local communities. Examples include allegations of displaced communities in Peru, indigenous ways of life being harmed in Kenya, and the government of Zimbabwe arguing that the state is not benefiting from offset projects on its soil (Gabbatiss, 2023). Forestry projects need to ensure that benefits are equitably distributed to indigenous communities and local populations, as historical concerns about displacement and unfair distribution of resources persist. These projects require obtaining free and informed consent, prior to the project developing and would need to address potential negative impacts on biodiversity and ecosystem services.

CONCLUSION

To reach net zero emissions by 2050, companies need to prioritise emission avoidance and mitigation as far as possible at their own operations. Companies can then consider using carbon offsets to address the gap to net zero for hard-to-abate emissions only. Carbon offsets can come from a variety of different projects. Companies should focus on securing high-quality offsets which are additional, have high permanence and are transparent. Due to the price volatility in the spot market, offsets should be secured from contract agreements and spot market prices should be avoided, where possible. Internal offset generating projects can be considered by an organisation if the offset verification and project development risks can be mitigated or accepted. In regions where companies are greatly exposed to physical climate change threats, they can look at integrating BVCMs in their decarbonisation framework. When using carbon offsets, companies need to be diligent and cautious with decarbonisation claims to avoid greenwashing risks which can leave them vulnerable to litigation and reputational damages.

In conclusion the role of carbon offsets in decarbonisation strategy development should be seen as a last resort measure, and only to be used after there are no avoidance or mitigation options left to consider. If incorporating carbon offsets into a decarbonisation strategy it is important to define the quality and type of offsets which will be sourced to meet the company's goals, since this will impact the cost of implementing the decarbonisation strategy as well as the effectiveness of the strategy.

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De-risking mining investments for a low-carbon future: Climate finance strategies in emerging markets

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Emerging-market mining jurisdictions supply a dominant share of the critical minerals required for the global energy transition. Climate-related risks, including carbon pricing, water stress, extreme weather variability, and transition-policy uncertainty, increasingly distort project cash flows and elevate investor risk premiums. This study applies panel data econometric modelling and Monte Carlo simulation to a dataset of ten mining operations across five emerging-market jurisdictions over the period 2021 to 2024, using publicly available audited annual reports and climate disclosure data. The panel regression identifies country risk premium as the statistically dominant driver of the weighted average cost of capital, with a coefficient of 0.628 ($p < 0.001$, within-$R^2 = 0.91$). All variance inflation factors are below 5.0, confirming the absence of problematic collinearity. An alternative specification excluding tdhe country risk premium reduces the within-R^2 to 0.36 and produces a significant carbon exposure coefficient, confirming that the country risk premium absorbs — rather than suppresses — climate risk variation through the sovereign risk transmission channel. The Monte Carlo simulation demonstrates that stacking three climate finance instruments — green bond refinancing, development finance institution concessional first-loss tranches, and public-private partnership risk-sharing guarantees — produces a mean cost of capital reduction of 23.1% at the base calibration. Sensitivity analysis confirms the result is robust: across the full range of calibration assumptions tested, the WACC reduction ranges from 17.7% to 27.9%, consistently exceeding the study's initial estimate. A taxonomy gap in current development finance institution eligibility frameworks is identified, enabling climate finance instruments to reduce the cost of capital for fossil fuel operations within inadequate carbon pricing regimes. The paper provides an empirically grounded and fully replicable framework for aligning mining capital allocation with sustainability imperatives.

Keywords: blended finance; cost of capital; emerging markets; green bonds; mining investment; Monte Carlo simulation; country risk premium; climate finance

KEY FINDINGS FOR PRACTITIONERS

What this paper finds — in plain terms

1. Country risk, not project-level climate risk, is what drives up mining investment costs in emerging markets. A sovereign default — like Ghana's in 2022 — raises financing costs for every mine in that country, regardless of how well-managed or low-emission that mine is.

2. Combining three instruments — a green bond, a development bank first-loss guarantee, and a public-private risk-sharing arrangement — reduces the cost of capital by 23% on average. No single instrument achieves more than a fraction of this. The combination is what matters.

3. This makes a material difference for the operations that supply the copper, platinum, and gold required for the energy transition. Freeport-McMoRan's Grasberg copper mine moves from a 29% probability of viable returns to 48% under the combined structure.

4. Climate finance instruments alone cannot rescue fundamentally uneconomic operations. Where costs exceed revenues regardless of financing, revenue-side solutions — offtake guarantees, royalty restructuring — are the necessary complement.
5. Current development bank eligibility rules have a gap: a coal mine operating under an inadequate carbon tax can access the same instruments designed to fund clean infrastructure. Taxonomy alignment is not optional — it is the policy fix this finding demands.

INTRODUCTION

The global energy transition is structurally dependent on emerging-market mining jurisdictions. The International Energy Agency (IEA) estimates that demand for critical minerals — including lithium, cobalt, copper, nickel, and platinum group metals — will increase between two and six times by 2040 under net-zero scenarios, with the majority of production concentrated in Sub-Saharan Africa, Latin America, and South-East Asia (IEA, 2023). Yet the capital required to develop, sustain, and decarbonise these operations is increasingly constrained by the same climate agenda driving mineral demand. Carbon pricing exposure, water stress, transition policy uncertainty, and the progressive tightening of environmental, social, and governance (ESG) disclosure standards are introducing new risk dimensions into project economics that conventional financing structures were not designed to absorb.

The financial consequences are measurable. Emerging-market mining operations face weighted average costs of capital (WACC) that consistently and significantly exceed global benchmarks, driven by country risk premiums (CRP) that compound equity risk in the jurisdictions where most critical mineral production is located (Damodaran, 2025). In Sub-Saharan Africa, cost of capital in energy and infrastructure sectors is estimated at 11% or above, compared with approximately 5% in Western Europe — a differential that directly suppresses project net present value (NPV), elevates hurdle rates beyond the reach of marginal deposits, and concentrates investment in a diminishing pool of tier-one assets (Calcaterra et al., 2024; Dato et al., 2025). Climate-related risks exacerbate this premium further: carbon pricing imposes direct operating cost increases on emissions-intensive operations, while physical climate risks introduce stochastic shocks to cash flows not adequately captured by conventional discounted cash flow models (Tsavdaroglou et al., 2019).

The literature offers two distinct but inadequately integrated responses. The first is the expansion of climate finance instruments — green bonds, blended finance structures, and public-private partnership (PPP) risk-sharing mechanisms — as tools for mobilising private capital into climate-aligned infrastructure in emerging markets (Convergence, 2025; OECD, 2025). The second is the development of more sophisticated quantitative frameworks for embedding climate risk into project valuation (Espinoza et al., 2022). These two bodies of work have largely proceeded in parallel. This paper bridges that gap.

We apply panel data econometric modelling and Monte Carlo simulation to a dataset of ten emerging-market mining operations across five jurisdictions — South Africa, Ghana, the Democratic Republic of Congo (DRC), Indonesia, and Brazil — over the period 2021 to 2024. The paper makes three contributions to the mineral economics literature: it provides the first cross-jurisdictional panel quantification of climate risk's effect on mining project WACC; it demonstrates that instrument stacking — rather than any single mechanism — produces material cost of capital reductions, with a mean panel reduction of 23.1% at base calibration (range: 17.7%–27.9% across sensitivity scenarios); and it provides a fully replicable framework using publicly available data.

LITERATURE REVIEW

Climate risk in mining finance

The financial consequences of climate change for mining operations are transmitted through two distinct pathways: physical risks arising from direct climate impacts on operational conditions, and transition risks arising from policy, regulatory, and market adjustments associated with the low-carbon transition (UNEP FI, 2024). Water stress is particularly material: mining is among the most water-intensive industrial activities and a significant proportion of global mineral production is concentrated in water-scarce regions (UNEP FI, 2024). Tsavdaroglou et al. (2019) demonstrate that mining companies face a major knowledge gap regarding the financial quantification of climate change costs.

South Africa's carbon tax — the only operational carbon pricing instrument on the African continent — escalated from R159 per tonne of carbon dioxide equivalent (CO_2e) in 2019 to R236 per tonne as of 2025, with the National Treasury targeting USD 30 per tonne by 2030 and USD 120 per tonne by 2050 (Climate Action Tracker, 2025). Globally, carbon pricing revenues exceeded USD 100 billion for the first time in 2023 (World Bank, 2024). Fliegel (2025) demonstrates that transition risk quantification remains methodologically contested, with inter-database divergence in emissions estimates limiting the reliability of firm-level risk assessments across listed companies. Fu, Li and Zhang (2024) demonstrate empirically that higher ESG performance in mining companies reduces financial risk, while Brucato, Mereu and Zanetti (2024) find that ESG-rated mining companies do not automatically face lower debt costs, challenging the assumption that disclosure compliance alone reduces the cost of capital.

The social and governance dimensions of ESG risk compound the financial transmission channels examined in this paper. Social licence to operate — the degree of community and stakeholder acceptance of a mining operation — is increasingly priced by institutional investors and lenders as a distinct risk category (UNEP FI, 2024). Operations facing community opposition, land rights disputes, or inadequate benefit-sharing arrangements face higher cost of capital through risk premiums attached to social licence uncertainty, regardless of their carbon profile. Similarly, governance quality in the operating jurisdiction — the rule of law, regulatory predictability, corruption risk, and enforceability of contracts — is a material component of the country risk premium that this paper identifies as the dominant transmission channel for climate risk. The finding that CRP drives WACC variation is therefore not merely a financial finding; it is a governance and social licence finding, because CRP aggregates the institutional and social risk environment in which mining operations are conducted.

Blended finance, green bonds, and climate finance mechanisms

Blended finance — defined by the Organisation for Economic Co-operation and Development (OECD) as the strategic use of development finance to mobilise additional commercial capital toward sustainable development — has emerged as the primary institutional mechanism for de-risking private investment in high-risk jurisdictions (OECD, 2025). Convergence (2025) reports that blended finance deal flow in 2024 totalled USD 18 billion across 123 transactions, with climate-related deals representing 49% of volume and 62% of total financing value.

A systematic review of 70 empirical studies on green bond pricing published up to 2025 finds a consistent negative green premium of −12.44 basis points on average across global markets, with the effect modest in isolation (Negi, Jaiswal and Rekunenko, 2025). Zhang, Li and Liu (2021) identify three channels through which green bond issuance reduces corporate cost of capital: reduced information asymmetry, improved security liquidity, and lower perceived issuer risk. Calcaterra et al. (2024) quantify the cost of capital differential between Sub-Saharan Africa and Western Europe in the energy sector at approximately 300 to 600 basis points, and demonstrate that convergence of this differential would unlock nearly 100 GW of additional installed renewable capacity in the region by 2050. Dato et al. (2025), projecting WACC across 48 African countries, confirm that the cost of equity in Africa is on average nearly double that of debt, amplifying the proportional impact of equity risk-reducing instruments on WACC.

WACC estimation in emerging markets

Damodaran (2025) provides the methodological foundation for country risk premium estimation, arguing that for natural resource companies, country risk exposure should be measured using production weights rather than revenue weights or domicile of incorporation. Applied to our panel jurisdictions, these premiums produce WACC estimates ranging from 7.5% to 16.8% before climate risk adjustment, consistent with the broader literature (Calcaterra et al., 2024; Dato et al., 2025). Espinoza et al. (2022) propose a decoupled net present value framework that separates climate risk cash flows from operational cash flows and prices them at the risk-free rate, making the value of climate adaptation investments explicit. The combination of panel regression with Monte Carlo simulation has been applied in the mining investment literature (Cardozo, Alipour and Liang, 2022) but not previously to a cross-jurisdictional emerging-market panel designed to isolate the effect of climate finance instrument choice on WACC and project economics.

METHODOLOGY

Research design

We employ a two-stage research design combining panel data econometrics and Monte Carlo simulation. The first stage uses panel regression to establish the empirical relationship between climate risk exposures and project-level WACC across ten emerging-market mining operations over 2021 to 2024. The second stage uses Monte Carlo simulation to model probability distributions of project outcomes under two financing scenarios: a conventional financing baseline (Scenario A) and an integrated climate finance structure (Scenario B). Sensitivity analysis on the key calibration parameters of Scenario B is conducted to assess the robustness of results to uncertainty in instrument pricing assumptions.

WACC construction

For each operation-year observation, WACC is constructed using the standard weighted average formulation:

$$WACC = (E/V) \times Re + (D/V) \times Rd \times (1 - Tc) \quad [1]$$

The cost of equity uses the Damodaran extended Capital Asset Pricing Model:

$$Re = Rf + \beta \times (ERP + CRP) \quad [2]$$

where Rf is the ten-year US Treasury yield, β is the equity beta estimated from trailing 52-week returns, ERP is Damodaran's mature market equity risk premium, and CRP is the production-weighted country risk premium for the operating jurisdiction (Damodaran, 2025). The cost of debt is estimated from the yield on each company's outstanding senior unsecured bonds, sourced from annual report disclosures. Where bond yields are unavailable, the weighted average interest rate on drawn facilities from financial statement notes is used.

Panel regression specification

The primary econometric model is a two-way fixed effects panel regression:

$$WACCit = a + \beta_1 CarbonExposureit + \beta_2 WaterStressit + \beta_3 OperationalShockit + \beta_4 CRPit + \beta_5 CapitalStructureit + \mu i + \lambda t + \varepsilon it \quad [3]$$

CarbonExposure is each operation's scope 1 emissions intensity (tCO_2e per tonne of ore processed) multiplied by the applicable jurisdiction carbon price; WaterStress is a binary indicator from the WRI Aqueduct Water Risk Atlas version 4.0; OperationalShock is climate-related lost production days from CDP disclosures; CRP is the annual Damodaran estimate; and CapitalStructure is net debt to enterprise value. μi and λt represent firm and year fixed effects respectively. All regressions use Driscoll–Kraay standard errors robust to heteroscedasticity, autocorrelation, and cross-sectional dependence (Driscoll and Kraay, 1998; Hoechle, 2007). The choice between fixed and random effects is confirmed using the Hausman (1978) test.

Multicollinearity is assessed through variance inflation factors (VIF) computed on both the raw regressors and the within-transformed (demeaned) regressors. All VIF values are below 5.0 (raw) and below 2.0 (demeaned), confirming the absence of problematic collinearity. The Pearson correlation between CarbonExposure and CRP is 0.70, which is the largest pairwise correlation in the regressor matrix; however, after within-group transformation this reduces substantially, and the VIF for CarbonExposure in the demeaned specification is 1.84 — well within acceptable bounds. An alternative specification excluding CRP is estimated to distinguish collinear absorption from independent climate risk effects (see Results).

It is worth noting that CRP occupies a structurally distinct role in this specification: it is both a direct component of WACC construction (Equation 2) and a key explanatory variable in the regression model. This dual role means that part of the regression's explanatory power is definitional rather than purely empirical, and the resulting coefficient should not be read as evidence of an independent causal channel running from CRP to WACC. Rather, it reflects the mechanical transmission of sovereign risk into financing costs through the WACC formula itself, with the regression estimating how strongly that transmission manifests across the panel. This structural relationship does not compromise the validity of the collinearity diagnostics or the alternative specification reported above, but it does bound how the coefficient should be interpreted, a point revisited in the Results section.

Monte Carlo simulation design

We implement 10,000 iterations per operation-scenario, modelling ten-year project NPV and internal rate of return (IRR) under both financing scenarios. Scenario A uses each operation's 2024 observed WACC. Scenario B stacks three instruments: green bond refinancing of 40% of the debt stack at the empirically validated greenium of –12.44 basis points (Negi, Jaiswal and Rekunenko, 2025); a DFI concessional first-loss tranche of 15% of total capital at 6.70% reducing the effective CRP by 150 basis points; and a PPP risk-sharing guarantee reducing CRP by a further 80 basis points in high-risk jurisdictions (DRC, Ghana, Argentina) or 40 basis points elsewhere, calibrated from IFC and AfDB deal structures (IFC, 2022).

The DFI CRP reduction of 150 basis points is calibrated from the IFC Working Group's documented range of 100–200 basis points for first-loss guarantees in Sub-Saharan Africa and Latin America (IFC, 2022). The PPP guarantee reduction of 80 basis points in high-risk jurisdictions reflects the MIGA political risk insurance pricing benchmark. Both assumptions are subjected to sensitivity analysis: the DFI reduction is varied from 50 to 250 basis points and the PPP reduction is varied proportionally, producing five scenarios ranging from –50% to +50% of base calibration. Commodity prices are drawn from lognormal distributions parameterised from ten-year historical series; carbon cost trajectories from triangular distributions bounded by current policy rates and 2030 targets; water stress events as Bernoulli trials calibrated from CDP-disclosed frequencies.

Data sources and replicability

All financial data are sourced from annual reports filed with the JSE, NYSE, ASX, and TSX. CDP responses are publicly accessible at data.cdp.net. Country risk premiums are sourced from Damodaran's annual data files at pages.stern.nyu.edu/~adamodar. Water stress classifications are from WRI Aqueduct version 4.0. Carbon prices are from the World Bank Carbon Pricing Dashboard (World Bank, 2024). The complete dataset, variable definitions, and simulation code are provided as supplementary material. The random number seed is set to 42 for full reproducibility.

DATA

Panel composition

The panel comprises ten publicly listed mining operations across five emerging-market jurisdictions, observed over four fiscal years 2021 to 2024, yielding a balanced panel of 40 operation-year observations. The study period provides four complete fiscal years of post-COVID data for all operations including Thungela Resources (JSE-listed June 2021), and captures South Africa's carbon tax escalation from R159 to R236 per tonne CO_2e, the COP26 and COP27 ESG disclosure tightening, and the IEA critical minerals demand acceleration.

Table I. Panel composition, primary commodity, and data sources

Operation	Jurisdiction	Commodity	Primary data sources
Sibanye-Stillwater SA PGMs	South Africa	PGMs	JSE / CDP / Damodaran
Anglo American Platinum	South Africa	PGMs	JSE / CDP / Damodaran
Thungela Resources	South Africa	Thermal coal	JSE / CDP / Damodaran
Gold Fields (Tarkwa/Damang)	Ghana	Gold	JSE/NYSE / CDP / Damodaran
AngloGold Ashanti (Iduapriem)	Ghana	Gold	JSE/NYSE / CDP / Damodaran
Newmont (Ahafo)	Ghana	Gold	NYSE / CDP / Damodaran
Barrick Gold (Kibali JV)	DRC	Gold	NYSE / CDP / Damodaran
Newmont (Cerro Negro)	Argentina	Gold	NYSE / CDP / Damodaran
Freeport-McMoRan (Grasberg)	Indonesia	Copper/gold	NYSE / CDP / Damodaran
Vale (Carajás)	Brazil	Iron ore	B3/NYSE / CDP / Damodaran

Variables

The primary dependent variable is WACC, constructed using equations [1] and [2]. CarbonExposure is the product of each operation's disclosed scope 1 emissions intensity and the applicable jurisdiction carbon price; the World Bank Social Cost of Carbon is applied as a shadow price where no direct carbon tax applies (Espinoza et al., 2022). Water stress is sourced from WRI Aqueduct version 4.0; operations with a score above 3.0 receive a binary indicator of one. OperationalShock is measured as climate-related lost production days from CDP disclosures. Annual CRP values are taken from Damodaran's January update files, ranging from 1.87% (Indonesia, 2023) to 11.66% (Ghana, 2023, post-sovereign default).

Data limitations

Four limitations warrant acknowledgement. The panel of 40 observations limits statistical power; this is an inherent constraint of data availability for operations with complete public climate disclosures over the study period, and is addressed by supplementing regression with Monte Carlo simulation and sensitivity analysis. CDP disclosures are voluntary and self-reported, mitigated by cross-referencing with sustainability report data. WACC construction for the DRC observation carries higher estimation uncertainty due to thin sovereign CDS data, addressed through sensitivity analysis on the CRP assumption. NPV and IRR estimates derived from annual report carrying values are approximations rather than project-specific valuations. On the question of external validity, the ten operations were selected to maximise jurisdictional and commodity coverage across the investable universe of emerging-market operations with complete public disclosures; the framework is generalisable to any operation for which the required public data are available.

RESULTS

Panel WACC and descriptive statistics

Table II presents the constructed WACC for each operation-year observation under Scenario A. The panel exhibits substantial cross-jurisdictional dispersion, ranging from 7.51% (Sibanye-Stillwater, 2021) to 16.75% (Newmont Cerro Negro, 2023). The panel mean WACC under Scenario A is 11.88%, consistent with the broader emerging-market infrastructure finance literature (Calcaterra et al., 2024; Dato et al., 2025). Ghana operations experienced the most severe intra-panel volatility: Gold Fields rose from 7.90% in 2021 to 14.69% in 2023, a 476 basis point increase driven by Ghana's sovereign default in December 2022 and the consequent CRP escalation from 5.20% to 11.66%.

Table II. Constructed WACC, Scenario A (%), 2021–2024

Operation	Jurisdiction	2021	2022	2023	2024
Sibanye-Stillwater SA PGMs	South Africa	7.51	10.40	11.39	10.81
Anglo American Platinum	South Africa	7.67	10.62	11.63	11.24
Thungela Resources	South Africa	12.19	14.86	16.03	14.81
Gold Fields (Tarkwa/Damang)	Ghana	7.90	12.75	14.69	13.10
AngloGold Ashanti (Iduapriem)	Ghana	8.39	13.25	15.63	13.53
Newmont (Ahafo)	Ghana	7.57	12.05	13.89	12.09
Barrick Gold (Kibali JV)	DRC	10.34	13.59	14.07	13.86
Newmont (Cerro Negro)	Argentina	11.01	16.09	16.75	13.79
Freeport-McMoRan (Grasberg)	Indonesia	8.49	10.89	10.70	10.71
Vale (Carajás)	Brazil	8.61	11.26	10.65	10.20
Panel mean		**8.97**	**12.58**	**13.54**	**11.81**

Panel regression results and collinearity diagnostics

Table III presents the two-way fixed effects regression results alongside the collinearity diagnostics requested by reviewers. All VIF values are below 5.0 in the raw specification and below 2.0 in the within-transformed specification, confirming that multicollinearity does not compromise the regression estimates.

The within R^2 of 0.91 is high but interpretable: CRP is both a regressor and a direct input to the WACC construction formula (through equation [2]), so a strong within-group relationship between CRP variation and WACC variation is structurally expected. The R^2 is not inflated by overfitting; it reflects the mathematical architecture of the WACC model interacting with genuine CRP variation across the panel. Because CRP is embedded in the WACC calculation itself, part of the observed explanatory power reflects this structural relationship. Consequently, the estimated coefficient should be interpreted primarily as evidence of the transmission channel through which sovereign risk affects financing costs rather than as an independent causal estimate.

The dominant and statistically significant regressor is CRP, with a coefficient of 0.628 ($p < 0.001$): a one percentage point increase in the jurisdiction CRP is associated with a 0.628 percentage point increase in WACC. The coefficients on CarbonExposure (0.317), WaterStress (−0.193), and OperationalShock (0.011) are in the expected direction but do not achieve conventional significance, reflecting collinear absorption rather than irrelevance — a distinction confirmed by the alternative specification in Table III Panel B.

Table III. Panel A: Two-way fixed effects regression results. Panel B: Collinearity diagnostics. Panel C: Alternative specification (CRP excluded).

Panel A: Primary specification — two-way fixed effects (firm + year)					
Variable	**Coefficient**	**Std error**	**t-statistic**	**p-value**	**Sig.**
Carbon exposure	0.3168	7.2022	0.044	0.965	
Water stress	–0.1929	0.1803	–1.070	0.296	
Operational shock (days)	0.0114	0.0119	0.956	0.349	
Country risk premium	0.6280	0.0540	11.634	0.000	***
Capital structure (D/V)	2.0451	2.0121	1.016	0.320	
*N = 40; within R^2 = 0.91; two-way fixed effects (firm + year); Driscoll–Kraay standard errors. *** $p < 0.01$*					
Panel B: Collinearity diagnostics					
Variable	**VIF (raw)**	**VIF (demeaned)**	**Corr. with CRP**		
Carbon exposure	3.84	1.84	0.702		
Water stress	1.82	1.55	0.008		
Operational shock (days)	1.63	1.58	0.123		
Country risk premium	3.27	1.61	1.000		
Capital structure (D/V)	1.17	1.62	0.244		
All VIF values < 5.0 (raw) and < 2.0 (demeaned). Conventional threshold for concern: VIF > 10. Carbon exposure and CRP are correlated (r = 0.70) in levels but this does not produce problematic collinearity after within-group transformation.					
Panel C: Alternative specification — climate variables only (CRP excluded); within R^2 = 0.36					
Variable	**Coefficient**	**Std error**	**t-statistic**	**p-value**	**Sig.**
Carbon exposure	50.547	15.078	3.352	0.003	***
Water stress	0.006	0.469	0.013	0.990	
Operational shock (days)	–0.030	0.030	–1.008	0.323	
Capital structure (D/V)	1.655	5.262	0.315	0.756	
When CRP is excluded, carbon exposure achieves significance (p = 0.003) and the within R^2 falls from 0.91 to 0.36, confirming that CRP absorbs — rather than suppresses — the climate risk signal. Carbon exposure has an independent effect on WACC that is channelled through the sovereign risk assessment process.					

Scenario B WACC outcomes

Table IV presents the WACC reduction under the integrated climate finance structure. The three stacked instruments produce a mean panel WACC reduction of 2.74 percentage points, equivalent to 23.1% of the Scenario A baseline, with a range of 21.0% to 27.6% across all 40 operation-year observations. The DFI concessional first-loss tranche is the primary driver, contributing 150 to 230 basis points of effective CRP reduction; the green bond component contributes approximately 5 basis points; and the PPP guarantee provides the remainder. The non-additive interaction — whereby the first-loss tranche changes the residual equity risk profile such that the PPP guarantee prices more favourably — is the key mechanism distinguishing instrument stacking from sequential deployment.

Table IV. WACC comparison, Scenario A vs. Scenario B (2024 base year)

Operation	WACC Scenario A	WACC Scenario B	Reduction (pp)	Reduction (%)
Sibanye-Stillwater SA PGMs	10.81%	8.37%	2.44	22.5%
Anglo American Platinum	11.24%	8.79%	2.45	21.8%
Thungela Resources	14.81%	11.06%	3.75	25.3%
Gold Fields (Tarkwa/Damang)	13.10%	10.22%	2.88	22.0%
AngloGold Ashanti (Iduapriem)	13.53%	10.47%	3.06	22.6%
Newmont (Ahafo)	12.09%	9.40%	2.69	22.3%
Barrick Gold (Kibali JV)	13.86%	10.79%	3.08	22.2%
Newmont (Cerro Negro)	13.79%	10.90%	2.90	21.0%
Freeport-McMoRan (Grasberg)	10.71%	8.23%	2.48	23.2%
Vale (Carajás)	10.20%	7.85%	2.36	23.1%
Panel mean	**11.81%**	**9.61%**	**2.20**	**22.1%**

Sensitivity analysis

Table V presents the sensitivity analysis of the Scenario B WACC reduction to the key calibration assumptions. The DFI first-loss CRP reduction and PPP guarantee CRP reduction are varied simultaneously from –50% to +50% of their base case values, generating five scenarios. In all cases the panel mean WACC reduction exceeds the 15% lower bound identified in the initial hypothesis. At the most conservative assumption — DFI reduction of 75 basis points and PPP reduction of 40 basis points for high-risk jurisdictions — the mean panel WACC reduction is 17.7%, confirming the robustness of the directional finding. The base case result of 23.1% sits at the midpoint of the tested range (17.7% to 27.9%).

Table V. Sensitivity analysis: Scenario B WACC reduction under alternative instrument calibration assumptions

Scenario	DFI (bps)	PPP high (bps)	WACC_A	WACC_B	Δ pp	Δ % (WACC reduction)
Conservative (–50% of base)	75	40	11.88%	9.78%	2.10	17.7%
Moderate (–25% of base)	112	60	11.88%	9.45%	2.42	20.4%
Base case	**150**	**80**	**11.88%**	**9.14%**	**2.74**	**23.1%**
Optimistic (+25% of base)	188	100	11.88%	8.84%	3.03	25.5%
Aggressive (+50% of base)	225	120	11.88%	8.56%	3.32	27.9%

Scenario	DFI (bps)	PPP high (bps)	WACC_A	WACC_B	Δ pp	Δ % (WACC reduction)
DFI = development finance institution first-loss CRP reduction. PPP high = PPP guarantee CRP reduction for high-risk jurisdictions (DRC, Ghana, Argentina). WACC_A = 11.88% in all scenarios (unchanged). Base case marked in grey.						

Monte Carlo simulation results

Table VI presents the Monte Carlo simulation results. The 10,000-iteration simulation reveals two structurally distinct operation clusters. The first — Sibanye-Stillwater, Anglo American Platinum, and Thungela Resources — exhibits strongly positive mean NPV under both scenarios. Sibanye-Stillwater's mean NPV improves from USD 3,093 million (Scenario A) to USD 3,919 million (Scenario B), an improvement of USD 826 million or 26.7%.

Thungela Resources warrants specific discussion. Its mean IRR of 181.2% under Scenario A — the highest in the panel — reflects the extraordinary profitability of thermal coal at price levels prevailing over the 2022 to 2024 calibration period. This is the paper's most policy-consequential empirical finding: the operation with the highest climate transition risk in the panel generates the highest returns under conventional financing. The mechanism is transparent: South Africa's carbon tax at its current effective rate of USD 11.80 per tonne is insufficient to eliminate the private return advantage of thermal coal at prevailing prices. The Scenario B improvement of USD 416 million demonstrates that current DFI eligibility frameworks, without binding Paris-aligned taxonomy criteria, can in principle extend these instruments to fossil fuel operations.

The second cluster demonstrates the most significant policy-relevant transformation. Barrick Kibali moves from 34.5% to 66.6% probability of positive NPV (Δ +32.1 percentage points); Newmont Cerro Negro from 6.0% to 21.1% (Δ +15.1 pp); Freeport Grasberg from 29.4% to 48.2% (Δ +18.9 pp); and Vale Carajás from 30.0% to 47.0% (Δ +17.0 pp). The three Ghana operations show negative mean NPV under both scenarios, establishing that a WACC reduction alone is insufficient to achieve viability where project economics are fundamentally depressed.

Table VI. Monte Carlo simulation results, Scenarios A and B (2024 base year, 10,000 iterations)

Operation	NPV_A (USD m)	NPV_B (USD m)	ΔNPV	P(+NPV) A	P(+NPV) B	Δ pp	P(IRR>h) A	P(IRR>h) B
Sibanye-Stillwater SA PGMs	3,093	3,919	+826	99.3%	99.8%	+0.5	98.8%	99.5%
Anglo American Platinum	5,711	7,264	+1,553	99.5%	99.9%	+0.4	99.5%	99.8%
Thungela Resources	1,782	2,198	+416	100%	100%	0.0	100%	100%
Gold Fields (Tarkwa/Damang)	–705	–594	+111	0.1%	0.5%	+0.4	0.9%	1.2%
AngloGold Ashanti (Iduapriem)	–1,110	–1,148	–38	0.0%	0.0%	0.0	n/a	n/a
Newmont (Ahafo)	–1,178	–1,105	+73	0.0%	0.0%	0.0	0.0%	0.0%
Barrick Gold (Kibali JV)	–44	+58	+101	34.5%	66.6%	+32.1	31.5%	50.1%

Operation	NPV_A (USD m)	NPV_B (USD m)	ΔNPV	P(+NPV) A	P(+NPV) B	Δ pp	P(IRR>h) A	P(IRR>h) B
Newmont (Cerro Negro)	–133	–74	+59	6.0%	21.1%	+15.1	15.8%	27.0%
Freeport-McMoRan (Grasberg)	–1,180	–5	+1,175	29.4%	48.2%	+18.9	31.9%	41.0%
Vale (Carajás)	–2,070	–167	+1,903	30.0%	47.0%	+17.0	45.2%	54.2%
P(IRR>h) = probability of IRR exceeding the disclosed or proxied hurdle rate. NPV in USD millions. Δ pp = percentage point change in probability.								

DISCUSSION

The instrument stacking mechanism

The mean WACC reduction of 23.1% exceeds the 15% to 20% estimate posited in the abstract and provides evidence that instrument stacking may produce financial effects materially larger than the sum of individual instrument contributions within the sampled operations and calibration assumptions. The sensitivity analysis confirms this finding is robust: even at the most conservative calibration tested — DFI first-loss guarantee of 75 basis points and PPP reduction of 40 basis points — the mean panel WACC reduction is 17.7%, above the study's lower-bound estimate. The directionality and order of magnitude of the result are insensitive to plausible variation in the calibration assumptions; what changes across scenarios is the precise magnitude, not the conclusion.

Country risk as the dominant transmission channel

The regression's identification of CRP as the statistically dominant driver (coefficient 0.628, $p < 0.001$) requires careful interpretation in light of the alternative specification results. When CRP is excluded from the regression, the carbon exposure coefficient rises from an insignificant 0.317 to a highly significant 50.547 ($p = 0.003$) and the within R^2 falls from 0.91 to 0.36. This pattern confirms that CRP absorbs the climate risk variation in the primary specification — the insignificance of climate variables in the full model reflects collinear absorption through the sovereign risk channel, not the absence of a climate risk effect. Carbon exposure has an economically meaningful and statistically identifiable effect on WACC; it operates through the sovereign risk assessment process rather than through an independent project-level channel that survives CRP control.

The Ghana finding illustrates the mechanism at its starkest. The 2022 sovereign default increased the WACC of every mining operation in Ghana by 400 to 600 basis points regardless of individual operation ESG performance or carbon intensity. Gold Fields Tarkwa is a technically well-managed, declining-emissions operation; its 2023 WACC of 14.69% was not a reflection of its own climate performance but of Ghana's sovereign risk profile following fiscal mismanagement and IMF intervention. This finding extends Calcaterra et al. (2024) and directly supports the conclusion that sovereign-level climate governance — credible carbon pricing, just energy transition partnerships, fiscal sustainability — is a prerequisite for project-level climate finance deployment, not a complement to it.

The ESG dimensions: environment, social licence, and governance

This paper has focused on the environmental and financial dimensions of ESG risk, where the data and quantitative framework are most tractable. Two further dimensions warrant acknowledgement. The social licence to operate — the degree of community and stakeholder acceptance of a mining operation — is increasingly recognised as a cost-of-capital risk factor independent of financial metrics, as institutional investors apply social risk premia to operations facing community opposition or inadequate benefit-sharing arrangements (UNEP FI, 2024). The CRP itself partially captures social licence risk at the sovereign level, as countries with weaker governance, higher inequality, and more contested resource rights systematically carry higher default risk premiums. Future research should disaggregate the CRP into its governance and social risk components to identify which aspects of sovereign risk are most amenable to targeted intervention.

The governance dimension is most directly implicated in the taxonomy gap finding. The finding that Thungela Resources — a thermal coal operation — shows the highest IRR in the panel and would benefit from Scenario B instrument stacking under current DFI eligibility rules is a governance failure before it is a financial finding. The absence of binding climate taxonomy alignment in DFI frameworks reflects a governance gap in the institutional architecture of climate finance: without enforceable eligibility criteria, the instruments designed to accelerate the energy transition can in principle reduce the cost of capital for the very operations the transition is designed to displace. Addressing this gap is a governance imperative, not merely a policy preference.

The Thungela finding and the taxonomy gap

Thungela's mean IRR of 181.2% under Scenario A is a precise quantitative expression of the structural misalignment between private investment returns and the social cost of continued fossil fuel production at current carbon price levels. South Africa's carbon tax at USD 11.80 per tonne reduces Thungela's earnings before interest, taxes, depreciation, and amortisation by a measurable but non-prohibitive amount. The National Treasury's own escalation trajectory — USD 30 per tonne by 2030 and USD 120 per tonne by 2050 — would transform this economics; the model does not assert that high coal returns will persist. What the Scenario B result demonstrates is that at the current rate, the DFI instrument stack would improve Thungela's returns by USD 416 million — a direct consequence of the taxonomy gap between current DFI eligibility rules and Paris alignment.

The viability threshold and the limits of finance

The results establish a quantitative threshold below which cost-of-capital reduction alone is insufficient to achieve project viability. For operations near the economic threshold — Kibali at USD –44 million, Cerro Negro at USD –133 million — a WACC reduction of approximately 300 basis points is sufficient to shift mean NPV to positive territory and increase the probability of positive NPV by 15 to 32 percentage points. For operations substantially below viability — the three Ghana gold operations — the WACC reduction improves but cannot rescue project economics. The sensitivity analysis confirms this finding is stable: the Ghana operations remain NPV-negative across all five calibration scenarios tested. This distinction has a direct implication for DFI deployment: blended finance instruments are most efficiently deployed where the project economics are near the viability threshold and the barrier to investment is genuinely the cost of capital. Operations below the threshold require revenue-side mechanisms — offtake guarantees, royalty restructuring, concessional debt for cost base improvement — as the necessary complement to any cost-of-capital reduction.

Critical minerals and the capital allocation imperative

The cross-commodity dimension reveals that the operations producing critical minerals for the energy transition — platinum group metals for hydrogen fuel cells and autocatalysts, and copper essential to electrification — show among the largest absolute NPV improvements under Scenario B. Freeport Grasberg's mean NPV improves by USD 1,175 million with its probability of positive NPV increasing by 18.9 percentage points, directly quantifying the potential of climate finance instruments to unlock copper production capacity in a jurisdiction the IEA identifies as critical to the energy transition timeline (IEA, 2023). Critical minerals policy and climate finance policy are currently designed in separate institutional silos; this paper's results suggest the intersection is precisely where the most significant financing gap exists and where integrated policy design would produce the highest return.

CONCLUSIONS

We applied panel data econometrics and Monte Carlo simulation to a dataset of ten emerging-market mining operations across five jurisdictions over 2021 to 2024, quantifying the cost of capital reduction achievable through climate finance instrument stacking and its effect on project NPV, IRR, and investment viability.

The panel regression confirms CRP as the statistically dominant driver of WACC variation (coefficient 0.628, $p < 0.001$, $R^2 = 0.91$). All VIF values are below 5.0, confirming the absence of problematic multicollinearity. The alternative specification excluding CRP produces a significant carbon exposure coefficient ($p = 0.003$) and an R^2 of 0.36, confirming that CRP absorbs climate risk variation through the sovereign risk channel rather than suppressing an independent climate risk effect. The transmission of climate risk through sovereign risk assessments — rather than through project-level cash flows — redirects policy attention from project-level risk mitigation toward sovereign-level climate governance as the primary lever for reducing mining investment costs in emerging markets.

The integrated climate finance structure produces a mean WACC reduction of 23.1% at base calibration. Sensitivity analysis across five calibration scenarios demonstrates that the result is robust: the WACC reduction ranges from 17.7% (most conservative) to 27.9% (most optimistic), consistently exceeding the study's initial estimate. Instrument stacking, not any single mechanism, is what achieves these reductions.

Three policy recommendations follow. Development finance institutions should structure climate finance as integrated instrument packages, recognising that stacking interaction effects produce WACC reductions materially larger than individual instrument contributions. Sovereign-level climate governance — credible carbon pricing escalation, just energy transition partnerships, fiscal sustainability — should be recognised as a prerequisite for project-level climate finance deployment. The findings support consideration of stronger Paris-aligned eligibility criteria within DFI taxonomy frameworks to reduce the possibility that climate-finance instruments unintentionally subsidise high-emission assets. The Thungela finding quantifies the cost of inaction on this third recommendation: without taxonomy alignment, climate finance instruments designed to accelerate the energy transition can reduce the cost of capital for the very operations the transition is designed to displace.

Three limitations and research directions follow. The panel of 40 observations, inherent to data availability constraints, limits statistical power; future work should extend the panel as CDP coverage expands to smaller operations. The social licence and governance dimensions of ESG risk — which this paper conceptually addresses but does not quantify — represent a direct extension opportunity, particularly in disaggregating the CRP into its governance, social risk, and climate risk components. Finally, empirical validation of the Scenario B instrument parameters against actual closed blended finance transactions would strengthen the precision of the cost-of-capital reduction estimates as Convergence's deal database expands.

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Olebogeng Tefo Sentsho is the Founder and Chief Executive Officer of Morton Energy Partners (MEP), a transition finance advisory practice focused on unlocking bankable climate finance for African mining and industrial decarbonisation. Under the Morton Energy Partners brand, she has developed CLOVR™, a structured finance platform built around the Carbon-adjusted Lending Opportunity Framework (CLOF™), which reprices sovereign and project-level risk to route bankable transition deals to lenders, development finance institutions (DFIs), and insurers operating across Sub-Saharan Africa.

She is also a PhD candidate in the School of Mining Engineering at the University of the Witwatersrand, where her research examines mineral economics and the intersection of climate finance, carbon-backed valuation, and sovereign risk in resource-dependent economies. She holds an LLB from Wits, and her academic work is thematically aligned with, though conducted independently of, her commercial practice at MEP, giving her a vantage point that bridges rigorous financial-economic research with deal-level structuring experience. Her recent research includes work on financing mineral decarbonisation through climate bonds and carbon-backed valuation as a new asset class for mining, as well as a framework for sovereign wealth fund climate bond issuance in extractive economies.

This scholarship informs her advisory work at MEP, where she has led the development of buy-side and sell-side transaction materials for mining and PGM assets, and has structured investor engagement for CLOVR™ with capital-structuring partners across the DFI and institutional investor landscape. Beyond her advisory and academic work, she is the author of *Mines Create Economies*, a mining entrepreneurship textbook set in Africa that follows a fictional character through the full mine lifecycle, written to build practical financial and commercial literacy among students and early-career professionals entering the mining sector.

Tefo's work sits at the intersection of African mining, structured finance, and climate policy, with a consistent focus on building proprietary frameworks that formalise how sovereign and project risk is priced, structured, and de-risked for climate-aligned capital. She brings to the ESGS Conference a practitioner's perspective on how transition finance instruments can be structured to accelerate decarbonisation in mining without inadvertently subsidising high-emission assets — a theme central to her ongoing research and advisory practice.