Paste 2026 – AB Fourie, M Horta, M Oliveira & S Wilson (eds)

doi:10.36487/ACG_repo/2655_47

Integrating building information modelling and environmental, social and governance strategies for the sustainable management of filtered tailings storage facilities

Thiago Franklin Santos de Almeida [a,*], Thiago Costa Melo [a], Alison Souza Norberto [a], Matheus Lima Barros [a]

[a] *TPF Engenharia, Brazil*

Abstract

The mining industry faces growing expectations to manage environmental, social, and governance (ESG) risks with demonstrable controls and traceability, particularly for filtered tailings storage facilities. This paper proposes an integrated framework in which building information modelling (BIM) provides the digital engineering baseline (geometry, quantities, interfaces and constructability constraints) and advanced work packaging (AWP) translates this baseline into executable work packages with QA/QC hold points, which are then used as structured inputs to hazard identification and risk assessment and failure mode and effects analysis aligned with the Global Industry Standard on Tailings Management (GISTM). BIM requirements were defined for dry-stack layout, drainage and water management systems, and compaction logistics, and models were developed on the Autodesk software to simulate tailings placement and construction sequencing. The BIM-derived elements (e.g. drainage networks, slopes, haul roads and sequencing interfaces) supported failure mode definition and consequence mapping, while AWP enabled control implementation through work-package-level responsibilities, acceptance criteria and inspection gates. For example, drainage segments with low slope and high sedimentation potential were flagged in the model, translated into dedicated installation work package (IWPs) with inspection gates, and linked to water quality monitoring points, reducing the likelihood and consequence of turbidity exceedances. Using this approach, 74 inherent ESG-related risks were identified, predominantly medium and high. After implementing the BIM/AWP-informed controls, high risks decreased from 33 to 1%, while low-risk scenarios increased from 5 to 45%. Key actions included drainage enhancement, revegetation planning, and environmental monitoring linked to model objects and work packages for auditability. The proposed framework advances digital and sustainable management of filtered tailings facilities by explicitly connecting engineering information, execution governance, and ESG risk reduction within a GISTM-compatible structure.

Keywords: *digital engineering, risk assessment, dry stacking, decarbonisation, mine waste governance*

1 Introduction

The mining industry faces significant challenges in adopting sustainable practices, under increasing pressure for responsible management of natural resources and compliance with stringent environmental standards. In this context, filtered tailings storage facilities (FTSFs) are a critical focus for mitigating environmental and social risks, as their design and operation directly affect communities and ecosystems. Recent research indicates that the incorporation of digital technologies, such as building information modelling (BIM) and advanced work packaging (AWP), can optimise the management of these assets and promote safer and more efficient operations (Kivunja & Dalmaris 2020; Hagan et al. 2021).

* Corresponding author. Email address: thiago.almeida@tpfe.com.br

BIM provides modelling and visualisation of complex structures, facilitating spatial simulations that support the planning and execution of mining projects (Azhar 2011). AWP, in turn, organises the scope into integrated work packages, promoting coordination among disciplines, predictability, and productivity control (Construction Industry Institute 2020). Together, BIM and AWP enhance operational efficiency and strengthen the assessment of risks associated with tailings disposal activities, aligning with good practices in governance and social responsibility.

Risk analysis an essential element of sustainability in tailings management and is aligned with the *Global Industry Standard on Tailings Management* (GISTM), which requires an integrated approach that incorporates social and environmental context into decision-making and risk reviews, supported by clear accountabilities, independent review, auditability and transparency mechanisms (GISTM 2021). Nevertheless, some studies lack an integrated approach that encompasses the complete life cycle of tailings, limiting the ability to predict and mitigate incidents.

In the Brazilian context, the regulatory framework for tailings management has evolved significantly since 2019, with the launch of standards such as the National Mining Agency (ANM) Resolution 95/2022, which establishes safety requirements, emergency action plans, and public communication regarding dams (ANM 2022). This advancement has been accompanied by revisions to the National Council for the Environment of Brazil (CONAMA) guidelines and the National Dam Safety Policy, which reinforce the mandatory use of risk analysis methodologies and the integration between structural safety and environmental management (Morrison et al. 2019). Such regulations partially align with the requirements of the GISTM but place additional emphasis on information traceability, technical accountability, and public transparency in the governance of tailings.

Concurrently, the concept of ESG (environmental, social, and governance) has become a benchmark for integrating ESG performance in mining. This approach broadens the scope of corporate sustainability, incorporating performance indicators, non-financial risks, and strategies for environmental and social mitigation (International Council on Mining and Metals [ICMM] 2022; United Nations Environment Programme Finance Initiative [UNEPFI] 2024; Imbrogiano et al., 2025). In the context of tailings storage facilities (TSFs), ESG reinforces the need to incorporate metrics for emissions, energy efficiency, and social responsibility across the life cycle of tailings facilities. Although this applies broadly, this study focuses on FTSFs where the dry-stack configuration and construction logistics (e.g. filtration, hauling, and compaction) create distinct risk pathways and decarbonisation levers that benefit from digital planning and traceability (Environmental Resources Management 2023).

Another central aspect relates to the quantification of greenhouse gas (GHG) emissions during the deposition and operational management of filtered tailings. Within the scope of this study, emissions are assessed specifically for the placement stage of the dry-stack, primarily associated with hauling, spreading, and compaction activities, so that quantification can support targeted mitigation actions. Müller et al. (2019) highlight the importance of continuous monitoring of these emissions to guide reduction and decarbonisation strategies aligned with the United Nations Sustainable Development Goals.

Beyond compliance, ESG risk reduction has a clear value proposition in tailings management. While filtered tailings strategies and stronger governance requirements may increase upfront capex/opex compared with conventional wet disposal, they can help reduce exposure to low-probability, high-consequence events that drive catastrophic losses, long-term liabilities, project delays, loss of social licence to operate, and higher insurance and financing costs. In Brazil, the post-2019 regulatory and market shift has increased the cost and complexity of tailings storage but has also raised expectations for demonstrable safety, transparency, and accountability. Within this context, ESG improvements should be assessed not only as an incremental cost, but as a risk-adjusted benefit that protects people and the environment while strengthening operational continuity and corporate resilience. In this setting, digital traceability (BIM) and execution governance (AWP) provide practical mechanisms to evidence controls and support ESG performance improvements.

Considering this overview, this study presents an integrated framework that combines BIM, AWP, and structured ESG risk assessment to support the sustainable development of FTSFs. The framework defines specific modelling requirements, executes digital modelling, and integrates ESG indicators into risk matrices, promoting proactive and transparent management for the mining industry. Section 2 describes the methodology, Section 3 presents results and discussions, and Section 4 offers concluding remarks.

2 Methodology

2.1 Location and general context

The conceptual design of the FTSF will be implemented in the state of Minas Gerais (MG), Brazil. The structure, intended for the deposition of iron mining tailings, will have a total height of approximately 200 m and an estimated volume of 89 Mm^3, distributed between tailings and waste rock. The project is planned to be carried out in stages, with 10 m benches and controlled slopes to ensure geotechnical and operational stability.

The project setting is characterised by complex terrain and multiple environmental receptors typical of mining regions in MG, where seasonal rainfall and surface-water management strongly influence construction logistics and environmental performance. Dry-stack placement requires coordinated hauling, spreading, and compaction operations over staged lifts, which increases the importance of planning, traceability, and control verification at the workface.

The project presents potential social, environmental, and governance impacts due to its proximity to communities, transmission lines, and water bodies. Among the main risks identified are the need for resettlements, land conflicts, property devaluation, and interference with essential infrastructure. These factors underline the importance of integrated, transparent, and preventive management, with a focus on social communication, emergency preparedness interfaces, and continuous monitoring throughout the life cycle of the FTSF. In this context, the ESG risks discussed in this paper are framed as being conditioned by the facility safety envelope: safety-related hazards (e.g. loss of containment or operational incidents during placement) can drive the most severe social and environmental consequences, while governance mechanisms (roles, traceability, disclosure and review) influence the effectiveness of both safety and ESG controls. Safety risks are acknowledged as the broader context; however, this study does not quantify geotechnical stability or failure probability and focuses on ESG risk identification and control effectiveness for the dry-stack placement stage.

2.2 Methodological steps

2.2.1 Constructive sequencing of filtered tailings storage facilities

The methodology adopted in this study combines the constructive sequencing of FTSFs, the integrated application of BIM and AWP platforms, and an ESG risk assessment mapped across the facility life cycle stages. This approach aims to ensure greater technical traceability, operational efficiency, and adherence to applicable sustainability and governance principles in tailings disposal.

The first methodological step consisted of defining the macro stages for the implementation and operation of an FTSF, structured as a sequential flow of technical activities and control activities (QA/QC and operational controls), including inspection/verification gates, monitoring requirements, and acceptance criteria embedded through AWP, according to Figure 1. Although the sequencing spans the full facility life cycle, the ESG risk assessment is performed in detail for the dry-stack placement and operational control stage, while the other stages are used to define interfaces, baseline data needs, and control responsibilities.

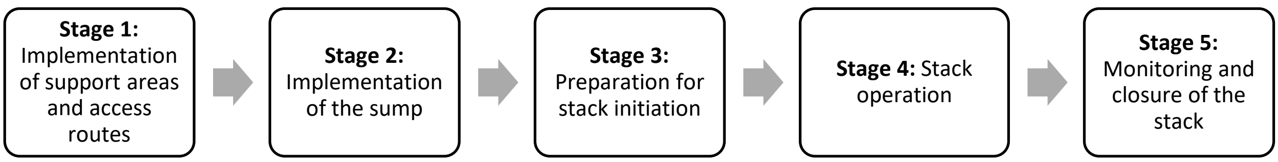

Figure 1 Construction sequencing of filtered tailings storage facilities

The process was structured into 5 macro stages that represent the life cycle of the structure, from implementation to closure. Stage 1 encompasses the establishment of support areas and access routes, ensuring the logistical and operational conditions for the commencement of activities. Stage 2 corresponds to the implementation of sumps and drainage systems, which are fundamental for water management and operational performance of the structure. Stage 3 includes the preparation of the area for the beginning of stacking, including cleaning and foundation treatment activities that establish baseline geotechnical and hydraulic conditions suitable for filtered tailings placement. Detailed evaluation of internal pore-pressure regimes (including perched water tables) is outside the scope of this paper and is addressed in the geotechnical design process. In Stage 4, the operationalisation of the structure occurs, encompassing the disposal and compaction of the tailings, control of the moisture and density of the material, and continuous monitoring of structural and environmental performance. Finally, Stage 5 includes the monitoring and closure of the structure, involving geotechnical and environmental oversight, as well as rehabilitation and revegetation actions in the area.

This sequential structuring allows for a clear and traceable representation of the life cycle of the FTSF, integrating the constructive, operational, and environmental dimensions. The resulting model provides the basis for digital analyses developed through BIM and AWP, as well as for risk and performance studies associated with the subsequent phases of the project.

2.2.2 Building information modelling and advanced work packaging for filtered tailings storage facilities design

The second step integrated BIM and AWP to support planning and execution. BIM models were developed using Autodesk software (primarily Civil 3D) to represent implementation, operation, and closure stages, enabling quantity take-offs and interference checks. In parallel, AWP organised the scope into structured work packages with defined responsibilities, acceptance criteria, and inspection/verification gates. Together, these tools integrated technical, environmental, and operational information, enabling progress visualisation, resource optimisation, and earlier identification of execution and ESG-relevant risks throughout the construction and operational cycle of the FTSF

2.2.3 Integrated environmental, social and governance analysis with stack deployment sequencing

The third step incorporated the evaluation of ESG risks into the digital model and constructive sequencing. This integration allowed for relating risks and mitigation measures to specific phases of the project.

The ESG assessment approach applied to a FTSF is based on widely recognised international frameworks, such as the Global Reporting Initiative (GRI 2021), the Task Force on Climate-related Financial Disclosures (TCFD 2017), and GISTM (2021).

The evaluation process was structured into 3 interdependent phases (Figure 2). The first phase corresponds to the preliminary survey of aspects and impacts (PSAI), dedicated to the acquisition, processing, and organisation of technical and socio-environmental data, as well as its segregation into ESG domains. The second phase (ESG diagnosis) consolidates and deepens the thematic analyses, identifying sensitivities, vulnerabilities, and opportunities, and supporting the development of the risk matrix. The third phase results in the environmental impact control program in tailings disposal structures (EICP-TDS), where mitigation opportunities, control measures, and monitoring indicators are defined.

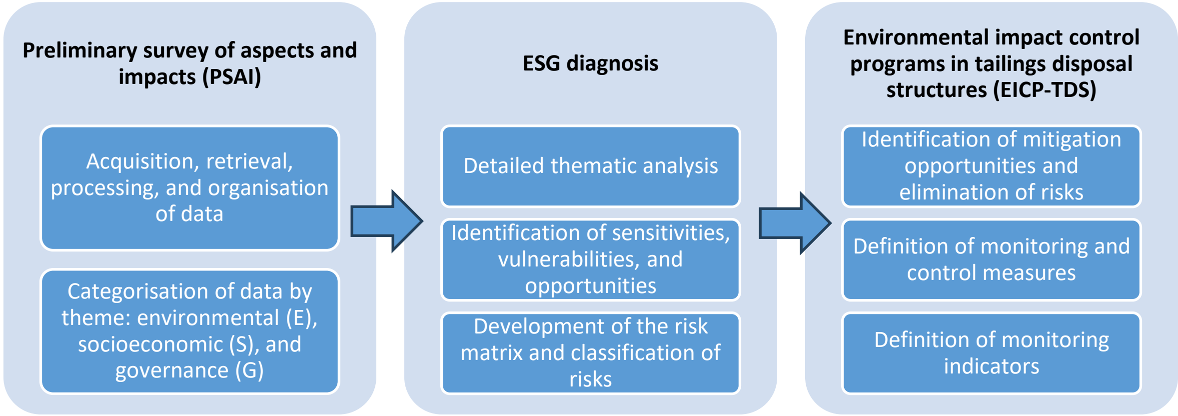

Figure 2 Stages of environmental, social and governance (ESG) analyses for filtered tailings storage facilities

In the context of this approach, it is essential to understand the concepts of risk and consequence, which guide the entire assessment process. According to ABNT (2018), risk is defined as the effect of uncertainty on objectives, which can represent positive or negative deviations from what is expected. Consequences correspond to the potential impacts resulting from undesirable events, such as loss of life, environmental damage, or reputational harm. In this study, consequence severity is classified on a graduated impact scale, and the overall risk rating is determined by combining consequence severity and likelihood of occurrence.

This conceptual framework also considers different levels of risk: inherent risk, understood as that which is naturally associated with an activity or process before the application of any control measures; residual risk, which represents the level of risk remaining after the implementation of mitigation controls; and projected residual risk, which corresponds to the estimated future risk considering the effectiveness of controls and the expected impact of planned corrective actions. The integration of these concepts allows for a comprehensive and dynamic analysis of causes, effects, and control mechanisms, ensuring a systematic, traceable, and coherent approach to risk management within the ESG framework.

The proposed framework aims to systematise the identification, analysis, and prioritisation of risks throughout the implementation and operational stages of the structure, ensuring coherence between technical performance, sustainability, and corporate governance. To achieve this, 2 well-established tools were adapted – the hazard identification and risk assessment (HIRA) and the failure mode and effects analysis (FMEA) – which are complementary instruments for identifying, analysing, and prioritising risks (Staletović 2013; TPF Engenharia 2023; Sukte & Sanjay 2024). The adaptation enabled the identification of hazards and the assessment of risks by considering their potential consequences on health, safety, the environment, and reputation, while the FMEA guided the hierarchical analysis of potential failures within systems, subsystems, and components, considering triggers, root causes, and interrelated effects.

The risk assessment adopted is intentionally semi-quantitative and execution-oriented, designed to support prioritisation and control traceability during dry-stack placement rather than to replace detailed geotechnical stability assessments. Its contribution lies in converting identified threats into auditable controls embedded in work packages and linking these controls to monitoring and review requirements under a GISTM-compatible governance structure.

A distinguishing feature of the proposed framework is the structured reclassification of risk effects through an ESG lens, enabling consistent mapping of consequences to ESG indicators and their linkage to sequencing, controls, and monitoring requirements. This adaptation resulted in the creation of a specific ESG matrix, analogous to the residual risk matrix, capable of measuring impacts on indicators such as biodiversity, vulnerable communities, institutional transparency, corporate reputation, and regulatory compliance.

The severity and likelihood scales were defined through a multidisciplinary calibration workshop that convened specialists from multiple domains to contribute statistical inputs, empirical evidence, and technical judgment for risk categorisation. This multidisciplinary setting of risk criteria constitutes a methodological innovation of the present study, as it strengthens cross-disciplinary coherence, reduces interpretive ambiguity, and improves transparency and traceability in the assignment of ratings. The resulting consequence severity and likelihood scales (reported in the Tables) provide the basis for the HIRA/FMEA scoring procedure and the ESG risk matrix adopted herein. The calibration process was informed by, and adapted from, consequence classification matrices and design criteria presented in Annex 2 of GISTM (GISTM 2021; ICMM 2022; UNEPFI 2024). Integrating these references with workshop-based expert elicitation enabled a structured appraisal of ESG risks across the project life cycle, while explicitly accounting for emissions associated with operational activities.

Within this framework, severity is operationalised via a six-level ordinal scale (very minor, minor, moderate, severe, critical, very critical) applied across 5 ESG-relevant impact dimensions – people, environment, social and human rights, reputational, and financial – each anchored by explicit, dimension-specific parameters. For people, severity escalates from negligible and reversible effects to incapacitating injury and fatality thresholds, culminating in scenarios involving multiple fatalities and explicit linkage to operational-process failures.

For environment, the parameters progress from no impact to low-magnitude localised disturbances manageable with simple controls and no expected legal consequences, advancing to medium/high-magnitude events requiring internal resource mobilisation and regulatory/judicial involvement; recovery-time benchmarks deteriorate from restoration within ~1 week (moderate) to up to 1 year (severe) and up to 3 years (critical), with the highest tier capturing impacts that may not be fully reversible and may trigger restrictive sanctions (e.g. suspension/embargo of operations). For social and human rights, severity is parameterised by remediation feasibility and time horizons (immediate; ≤1 year; ≤3 years; ≤5 years; ≤10 years; >10 years or irreparable), with increasing salience of impacts on indigenous/traditional communities and cultural assets (regional to national/global relevance) and upper tiers explicitly including severe value-chain violations (e.g. forced labour, child labour, trafficking, and child sexual exploitation, including among contractors/subcontractors).

Reputational impacts are parameterised by the scope and persistence of stakeholder and media engagement, moving from internal containment to regional exposure, then national visibility, and finally national/international crises characterised by sustained media coverage, pressure from authorities/investors/clients/NGOs, market and credit-rating effects, licensing constraints or revocations, and escalation from localised to multi-locality mass demonstrations. The Financial dimension is anchored by quantitative loss bands (<USD 10 million; >USD 10–100 million; >USD 100–300 million; >USD 300 million–1 billion; >USD 1–3 billion; >USD 3 billion).

Complementing consequence severity, likelihood is defined through a 5-tier qualitative–temporal scale that maps expected frequency onto a time-referenced cadence: very remote (not expected), remote (may occur once within one year), unlikely (may occur more than once within one year), likely (may occur monthly), and very likely (may occur weekly). Together, these constructs support a matrix-based assessment in which likelihood is explicitly time-calibrated and severity is dimension-specific, parameter-driven, and empirically grounded – thereby enabling consistent, auditable ESG risk prioritisation across disciplines and life cycle stages.

The baseline data used was consolidated from the PSAI, a structured screening step to identify and catalogue environmental and social aspects, receptors, and interaction pathways relevant to the dry-stack placement stage, integrating technical-environmental information, operational parameters, and GISTM criteria. PSAI outputs were then used to populate the initial hazard list and consequence descriptors adopted in the HIRA/FMEA scoring (International Organization for Standardization 2015; International Finance Corporation 2012; International Association for Impact Assessment 2015). The combination of qualitative and semi-quantitative analyses enabled the assessment of the severity and frequency of risks, ensuring traceability, consistency, and comparability among the results obtained.

Lastly, the methodological approach adopted ensures alignment with principles 1, 3, 4, 5, 6, 10, and 15 of the GISTM (2021), reinforcing governance over critical risks, institutional transparency, and the commitment to sustainability. The result is a robust and strategic technical instrument aimed at prioritising control actions, mitigating impacts, and strengthening the social licence to operate.

Following the PSAI, the ESG diagnosis consolidated and deepened the analyses, scoring each identified risk event by consequence severity and likelihood to position it in the ESG matrix by dimension. The resulting prioritisation informed the EICP-TDS, which defines mitigation measures and associated monitoring indicators for the relevant stages within the scope of this study.

3 Results and discussion

The application of BIM and AWP enabled the development of a detailed 3D model that integrates the terrain model, geological-geotechnical data, topographic registrations of existing constructions, geometric arrangements of layered structures, drainage devices, and instrumentation. The definition of construction work areas facilitated the modelling of the project in alignment with the constructive sequencing, as shown in Figure 3, allowing for the extraction of quantities in a distributed manner over space and time. Mapping this information became the basis for risk analysis, bringing dynamism and confidence to the information obtained from the models.

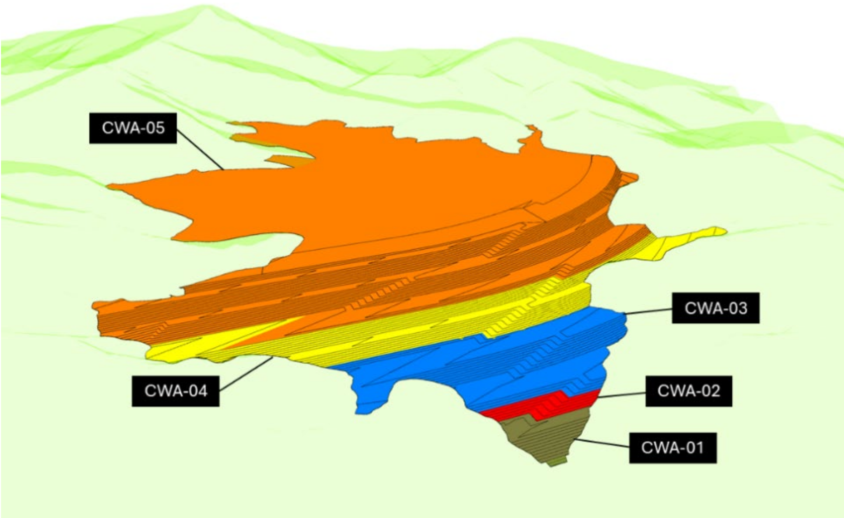

Figure 3 Layers of a filtered tailings storage facility according to the constructive sequencing (CWA = construction work area)

To make the BIM/AWP–ESG linkage explicit, the analysis translated model-based threats into work-package controls and monitoring actions. Examples include the following:

Drainage reaches and sediment control interfaces identified in the model were assigned to dedicated IWPs (Installation Work Package) with inspection/verification gates and linked to downstream water quality monitoring points to reduce turbidity exceedance risk.

Haul-road alignments and stacking traffic routes were modelled to define dust-prone segments and triggering conditions, enabling IWPs (Installation Work Package) with watering/traffic controls and dust monitoring to reduce air quality and community nuisance impacts.

Lift-by-lift placement and compaction logistics were sequenced to define hold points for moisture/density acceptance criteria, supporting consistent placement performance and reducing the likelihood of operational deviations that could amplify environmental and safety consequences. In addition, proximity constraints (communities and critical infrastructure) informed communication and preparedness interfaces by linking work packages to stakeholder notifications, grievance response workflows, and auditable evidence of control execution.

The evaluation of inherent risks allowed for the identification of a set of structural, environmental, and operational causes characterising the initial scenario of exposure to adverse events, with a total of 74 different risks identified. These risks reflected the conditions prior to the adoption of the control measures implemented by the organisation and were predominantly classified as medium (62%) and high (33%), highlighting the relevance of vulnerabilities typical of structures under construction, with only 5% classified as low and no very high risks (0%), as can be seen in Figure 4.

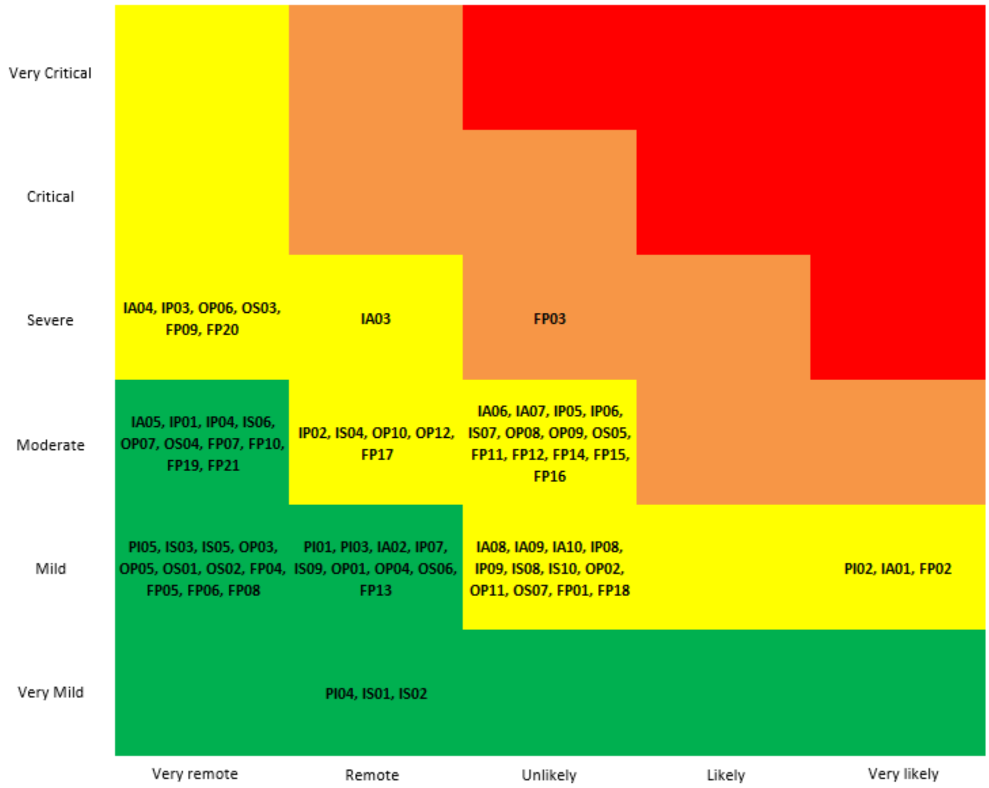

Figure 4 Projected residual risk matrix

The main causes associated with the inherent risks were concentrated in natural and operational factors, with emphasis on:

- intense rainfall events and insufficient drainage, which exacerbate erosive processes and geotechnical instabilities
- intensive use of diesel-powered machinery, resulting in significant GHG emissions
- modifications to vegetation cover and natural drainage due to soil movement and access construction
- visual and landscape impacts, affecting social perception and land valuation
- interference with neighbouring communities related to changes in access, rural occupations, and territorial dynamics
- absence of structured contingency plans, hampering rapid responses to anomalies, extreme rains, or seismic events
- hypothetical scenarios of internal rupture or construction failures, associated with saturation of masses and inadequate management of surface water.

These causes express the multifactorial nature of risk in mining, involving interdependent geotechnical, environmental, and social dimensions.

Following the implementation of control measures already practiced by the organisation, a significant reduction in the probability and severity of risks was observed, with a general reclassification of events to moderate and low levels. Among the main mitigated causes are:

- improvements in the surface and internal drainage systems, enhancing structural stability
- revegetation of exposed areas, reducing erosion and sedimentation
- installation of barriers and stabilised slopes, which limited the risk of landslides
- implementation of environmental and geotechnical monitoring systems, enhancing operational control
- adoption of practices for controlling particulate emissions, decreasing atmospheric and climatic impacts
- strengthening communication with local communities, mitigating social and reputational risks.

The result of these actions translated into a reduction of high risks from 33 to 1%, with a significant increase in the low-risk category from 5 to 45% and complete elimination of the 'very high' class (Figure 5). This quantitative change confirms the effectiveness of existing controls and the maturity of the organisation's management practices.

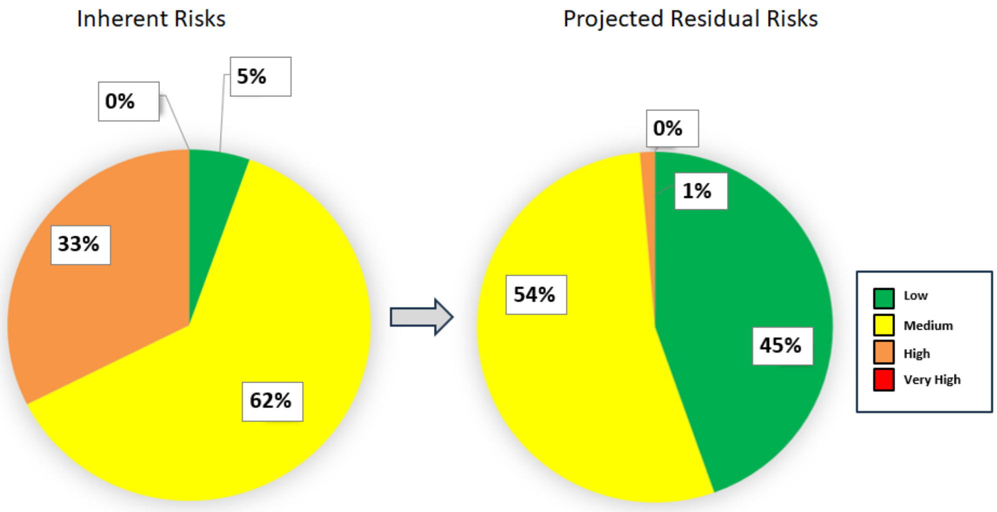

Figure 5 Comparison of inherent risks and projected residual risks

However, some residual risks remained relevant after existing controls, primarily associated with extreme rainfall, drainage underperformance, and placement/construction deviations that can challenge stability under adverse conditions. Although the frequency of these events has been reduced, the residual severity remains classified as severe, particularly in the environment and people domains, due to the potential to challenge the stability of the structure under extreme conditions and the physical integrity of workers and neighbouring communities. This does not negate the risk-reduction rationale of adopting a filtered tailings strategy. FTSFs are widely selected because they can reduce the likelihood of certain catastrophic failure mechanisms typical of conventional water-retaining TSFs, thereby shifting the overall risk profile. However, risk is not eliminated: severe consequences may still arise under low-probability scenarios driven by extreme hydrometeorological loading, drainage underperformance, or operational deviations during dry-stack placement and operations. In this study, the residual 'severe' classification reflects the potential consequence magnitude in the people and environment domains, which is consistent with a conservative tailings risk governance approach and reinforces the need for layered controls and emergency preparedness.

Additionally, persistent risk drivers were identified, recurring across multiple stages of the facility and therefore requiring continuous management. These include hydrometeorological loading and water management challenges (infiltration, water overload, and transient saturation), drainage underperformance, erosion and loss of vegetation cover, and operational deviations during placement. Because these drivers can manifest repeatedly over time, they are managed through permanent monitoring, defined trigger/action response protocols, and periodic review of drainage, erosion control, and operational procedures, as consolidated in the EICP-TDS programs. They are managed through permanent monitoring, defined trigger/action response protocols, and periodic review of drainage, erosion control, and operational procedures, aiming to reduce risk to a level as low as reasonably practicable consistent with GISTM risk-reduction expectations (e.g. requirements 4.7, 5.4 and 5.7, GISTM 2021).

Thus, the diagnosis of this phase highlights that, while existing organisational controls have materially reduced inherent risks, causes linked to climatic and geotechnical dynamics persist, and their complete mitigation requires the adoption of complementary measures. Such measures were subsequently consolidated and detailed in the EICP-TDS, which strengthens the organisation's capacity to prevent and respond to high-consequence ESG scenarios by integrating controls for environmental performance (e.g. water, erosion and monitoring), social preparedness and communication, and governance mechanisms (roles, traceability and periodic review), particularly under instability conditions and extreme climatic events.

The subsequent analysis of the causes associated with the projected risks confirmed that, although the previously implemented engineering and management actions have significantly reduced the likelihood of events occurring, certain causes maintained elevated final severity, requiring the development of new programs and mitigation strategies. Among the main causes associated with projected risks, the following were highlighted:

- Extreme rainfall events exceeding design values, causing water overload, geotechnical instability, and surface erosion.
- Localised deficiencies in drainage and containment systems that could compromise hydraulic functionality and the safety of the structure.
- Seismic acceleration above design parameters, representing a potential risk of structural instability in critical scenarios.
- Construction failures and progressive degradation of operational components, associated with the lack of redundancy in support structures.
- Loss of vegetation cover and alteration of environmental quality, related to erosive processes and inadequate management of exposed areas.
- Social and reputational risks resulting from the perception of insecurity among neighbouring communities and the potential for cumulative impacts on the surroundings.

These causes were concentrated in risks classified as medium (54%) and in 1% of high risks, with the 'very high' categories remaining non-existent, indicating that the main challenge lay in reducing residual severity and consolidating manageable risks. Based on the remaining projected risks, Table 1 summarises the prevention, control, and mitigation plans defined within the EICP-TDS and their objectives.

Table 1 Plans objectives

Prevention, control and mitigation plans	Objective
Monitoring, action and response plan for geotechnical instability conditions	Establish continuous criteria for assessing filtered tailings storage facility stability and define actions in the event of structural anomalies
Climate change mitigation and adaptation plan	Based on the greenhouse gas (GHG) protocol and the national climate adaptation plan (PNA), aiming to reduce GHG emissions and strengthen resilience to extreme climate events
Environmental quality maintenance plan	Focusing on the water and air compartments, based on CONAMA Resolutions No. 357/2005 (CONAMA 2005), No. 420/2009 (CONAMA 2009), and No. 491/2018 (CONAMA 2018)
Emergency preparedness and response plan	Structured according to *Global Industry Standard on Tailings Management* principles, with guidelines for preparation and response in disruption scenarios or critical events
Seismic response plan	Based on ABNT NBR 8681 (ABNT 2003) and 15421 (ABNT 2006) standards, for monitoring and acting in geodynamic events with the potential to compromise the structure
Action plan for updating regulations and legislation	Ensure continuous alignment with federal, state and corporate regulatory frameworks, and promote the timely updating of management instruments in the face of legal changes

Based on these findings, the EICP-TDS structured a set of integrated mitigation and control programs developed according to national and international standards, including the GISTM, ABNT NBR standards 8681 (ABNT 2003) and 15421 (ABNT 2006), the national climate adaptation plan (Ministério do Meio Ambiente 2016), CONAMA Resolutions No. 357/2005 (CONAMA 2005), No. 420/2009 (CONAMA 2009), and No. 491/2018 (CONAMA 2018) and the GHG protocol guidelines (FGV EAESP n.d.). These programs were designed to address the remaining critical causes, operating in a coordinated manner across the ESG domains.

The association between the projected risks and the developed programs can be summarised as follows:

- The first and most comprehensive axis of action was the geotechnical instability monitoring, action, and response plan (RSB and RCE), addressing risks related to structural instability, construction/placement deviations, and water overload conditions. These risks are associated with structural instability, construction failures, and water overload, conditions that could jeopardise the safety of the FTSF and the integrity of its operational structures. Engineering design robustness and conservative criteria constitute the primary risk-reduction layer (e.g. staged construction controls, drainage and erosion protection, and design redundancy where applicable). The monitoring, trigger/action levels and response protocols defined in this program are implemented as an additional defence-in-depth layer to manage residual risk, rather than a substitute for engineered controls. The program establishes continuous stability evaluation criteria, defines geotechnical instrumentation parameters, response protocols for anomalies, and periodic structural safety reporting, with the aim of ensuring the physical and functional reliability of the structure.

- In parallel, risks associated with intense rainfall events, water overload, and drainage underperformance underpinned the climate change mitigation and adaptation plan (PMGEE and PAR). This program aims to strengthen the project's water and climate resilience through the redesign of drainage systems, increasing surface and groundwater discharge capacity, and integrating real-time rainfall models to support decision-making. The plan also aligns with corporate decarbonisation and climate adaptation targets, connecting the project to commitments for emission neutrality and sustainable water resource management
- In the environmental domain, risks related to erosion, loss of vegetation cover, and deterioration of water and air quality guided the creation of the environmental quality maintenance plan (PMQA). This program focuses on the preservation of environmental compartments such as soil, water, and air, with actions aimed at controlling erosive processes, managing vegetation, and continuously monitoring physical, chemical, and biological parameters, in accordance with CONAMA Resolutions No. 357/2005 (CONAMA 2005), No. 420/2009 (CONAMA 2009), and No. 491/2018 (CONAMA 2018). The PMQA plays a vital role in maintaining ecological stability and complying with legal and corporate sustainability requirements.
- The identification of risks associated with dynamic loading, vibrations, and seismic accelerations exceeding project specifications resulted in the formulation of the seismic response and geodynamic change conditions plan (PMCAS). This plan is implemented as a defence-in-depth measure that complements robust design criteria aligned with applicable Brazilian standards and consistent with GISTM expectations for risk governance. It is not intended to substitute engineered design conservatism. The PMCAS defines protocols for seismic monitoring and dynamic stability verification, utilising instrumentation such as accelerometers and piezometers, and establishes immediate response actions in accordance with ABNT NBR 8681 (ABNT 2003) and 15421 (ABNT 2006), which address structures subjected to dynamic loads and abnormal geodynamic conditions.
- Risks directly associated with the physical safety of individuals and the operational integrity of the structure informed the emergency preparedness and response plan (PPRE/PAE). Structured in accordance with GISTM principles, this plan defines a set of alert, evacuation, communication, and institutional coordination protocols, involving communities, public agencies, and civil protection. The central proposal is to ensure a rapid and coordinated response to any emergency scenario, prioritising the protection of human life and minimising socio-environmental impacts.

To synthesise the linkage between residual risk drivers and the proposed programmes, Table 2 summarises the EICP-TDS programs, their primary risk focus, implementation stage, and associated ESG domains.

Finally, acknowledging the cross-cutting nature of risks associated with regulatory lag and the need for technical and regulatory updates, the action plan for the updating of normative standards and legislation (PAGMNL) was established. This plan ensures the continuous alignment of environmental, social, and safety management instruments with federal, state, and corporate legal frameworks, as well as promoting periodic reviews in line with best industry practices and international compliance and governance standards.

Table 2 Programs and associated risks

Program	Primary risk drivers	Typology	Program implementation stage	Associated aspect
RSB and RCE	Instability mechanisms, water overload, placement deviations	Geotechnical instability	Implantation	Environmental, Social and governance
PMGEE/PAR	Extreme rainfall, drainage underperformance, water overload	Extreme weather events and drainage	Pre-implantation	Environmental, Social and governance
PMQA	Erosion, vegetation loss, water/air quality deterioration	Environmental quality	Implantation	Environmental
PMCAS	Seismic/dynamic loading exceedance	Earthquakes and dynamic overload	Implantation	Environmental, Social and governance
PPRE/PAE	People safety, emergency response	People safety and emergency response	Implantation	Social and governance
PAGMNL	Regulatory change, compliance and governance gaps	Governance and legal compliance	Pre-implantation	Governance

RSB and RCE = geotechnical instability monitoring, action, and response plan; PMGEE/PAR = climate change mitigation and adaptation plan; PMQA = environmental quality maintenance plan; PMCAS = seismic response and geodynamic change conditions plan; PPRE/PAE = emergency preparedness and response plan; PAGMNL = action plan for the updating of normative standards and legislation

Together, the 6 programs comprise an integrated ESG risk management system that articulates technical, environmental, social, and institutional dimensions. The association between projected risks and control programmes highlights the methodological maturity and innovative character of the adopted approach, transforming risk diagnostics into concrete, measurable, and auditable operational actions.

The implementation of these programs has promoted a significant reconfiguration of the project's risk profile. Following the application of the proposed measures, high risks were eliminated, low risks increased to 47%, and medium risks decreased to 53%, with the 'very high' categories remaining non-existent. This redistribution evidences the effectiveness of the mitigation programs and the advancement towards a scenario of manageable and controlled residual risks.

The structuring of these programs thus represented a methodological and institutional advancement. By integrating geotechnical, environmental, and social analyses into a single ESG matrix, the EICP-TDS expanded the traditional scope of risk management and introduced the measurement of reputational and governance risks as a central evaluation dimension. This pioneering approach allowed for the technical and auditable quantification of the impact of control measures on social perceptions of safety, institutional transparency, and corporate sustainability.

Therefore, the analysis of projected risks and the implementation of control programs demonstrate that the adopted methodology not only mitigated operational and structural risks but also consolidated an integrated ESG risk management model that supports continuous improvement through periodic review, performance monitoring, and the systematic update of controls and risk ratings. The result is a more robust and adaptive control system aligned with corporate commitments to decarbonisation, safety, and socio-environmental responsibility.

4 Conclusion

This study demonstrates that the integration of BIM, AWP, and ESG risk assessments constitutes an effective approach for the sustainable development and operation of FTSFs. The proposed methodology allowed a reduction rework during the design and planning stages, as well as improved predictability of construction deliveries, as evidenced by digital simulations and work-package control. These results reinforce the potential of digital tools to enhance operational efficiency and to support safety and risk governance across key stages of FTSF development and operation, particularly during dry-stack placement and operational control.

The combined application of BIM and AWP approaches enabled the construction of a parametric three-dimensional model of the structures, integrating geotechnical, hydrological, and operational information. This integration facilitated the early identification of interferences and the optimisation of field resources, supporting reductions in mobilisation and assembly time compared to traditional planning processes.

The incorporation of ESG criteria into risk analysis and operational planning contributed to increased traceability and transparency in decision-making processes. The cross-analysis of technical data and ESG indicators allowed for the identification of 11 critical aspects distributed across the ESG dimensions, with mitigation measures prioritised according to the ABNT NBR IEC 31010:2021 methodology (ABNT 2021) and the GISTM (2021) guidelines. This result illustrates that digital integration supports a more proactive and preventive risk management approach, helping to manage exposure to non-compliance events and strengthening corporate governance.

Overall, the developed framework represents a step forward towards a digital, integrated, and sustainable management of tailings disposal structures, uniting technical rigour, innovation, and socio-environmental responsibility. It is recommended that future studies quantify efficiency gains in different geotechnical and climatic contexts, as well as integrate measurable ESG-related metrics into monitoring and review workflows, in near real time for instrumented environmental parameters (e.g. rainfall, pore pressures, seepage/drainage performance, water quality and dust) and in short review cycles for social and governance metrics (e.g. grievance response time, engagement actions, auditability/traceability of controls and compliance status), to support a continuous improvement cycle in the management of FTSFs.

References

ABNT 2003, *ABNT NBR 8681: Ações e Segurança nas Estruturas – Procedimento (Actions and Safety in Structures – Procedure)*, Brazilian Association of Technical Standards, Rio de Janeiro.

ABNT 2006, *ABNT NBR 15421: Projeto de Estruturas Resistentes a Aismos – Procedimento (Design of Earthquake-Resistant Structures – Procedure)*, Brazilian Association of Technical Standards, Rio de Janeiro.

ABNT 2018, *ABNT NBR ISO 31000:2018 – Risk management – Guidelines, Brazilian Association of Technical Standards*, Rio de Janeiro.

ABNT 2021, *ABNT NBR IEC 31010:2021 – Gestão de Riscos – Técnicas de Avaliação de Riscos (Risk Management – Risk Assessment Techniques)*, Brazilian Association of Technical Standards, Rio de Janeiro.

ANM 2022, *ANM Resolution No. 95, of 7 February 2022*, National Mining Agency, Brasília.

Azhar, S 2011, 'Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry', *Leadership and Management in Engineering*, vol. 11, no. 3, pp. 241–252, https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127

CONAMA 2005, *Resolution No. 357, of 17 March 2005*, National Council for the Environment, Brasília.

CONAMA 2009, *Resolution No. 420, of 28 December 2009*, National Council for the Environment, Brasília.

CONAMA 2018, *Resolution No. 491, of 19 December 2018*, National Council for the Environment, Brasília.

Construction Industry Institute 2020, *AWP education framework (Version 1.0)*, AWP Education & Outreach Subcommittee.

Environmental Resources Management 2023, *Sustainability Report 2023*, viewed 8 February 2026, https://www.erm.com/globalassets/sr2023/erm-sustainability-report-2023.pdf

FGV EAESP n.d., *Programa Brasileiro GHG Protocol (Brazilian GHG Protocol Program)*, viewed 23 May 2025, https://eaesp.fgv.br/centros/centro-estudos-sustentabilidade/projetos/programa-brasileiro-ghg-protocol

Global Reporting Initiative 2021, *GRI Standards*, viewed 8 February 2026, https://www.globalreporting.org/standards/

Global Tailings Review, International Council on Mining and Metals, United Nations Environment Programme & Principles for Responsible Investment 2021, *Global Industry Standard on Tailings Management*, viewed 8 February 2026, https://globaltailingsreview.org/wp-content/uploads/2020/08/global-industry-standard_EN.pdf

Hagan, A, Munoz, A & Kivunja, C 2021, 'Implementing advanced work packaging in the mining industry: challenges and solutions', *Journal of Mining Science*, vol. 57, no. 6, pp. 1124–1142, https://doi.org/10.1134/S1062739121060010

Imbrogiano, J P, Schaltegger, S & Boiral, O 2025, 'Management responses to climate change: an analysis of scholarly recommendations', *Sustainable Development*, vol. 33, no. 5, pp. 6680–6692.

International Association for Impact Assessment 2015, *Social Impact Assessment: Guidance for Assessing and Managing the Social Impacts of Projects*, viewed 8 February 2026, https://iaia.org/wp-content/uploads/2025/03/Social-Impact-Assessment-Guidance-for-Assessing-and-Managing-the-Social-Impacts-of-Projects.pdf

International Council on Mining and Metals 2022, *Conformance protocols for the Global Industry Standard on Tailings Management*, London, viewed 8 February 2026, https://www.icmm.com/en-gb/our-principles/tailings/tailings-conformance-protocols

International Finance Corporation 2012, *Performance Standard 1: Assessment and Management of Environmental and Social Risks and Impacts*, viewed 8 February 2026, https://www.ifc.org/en/insights-reports/2012/ifc-performance-standard-1

International Organization for Standardization 2015, *ISO 14001:2015 — Environmental Management Systems — Requirements with Guidance for Use*, Geneva.

Kivunja, C & Dalmaris, P 2020, 'Digital technologies in mining: Revolutionizing the industry for a sustainable future', *Journal of Cleaner Production*, vol. 258, p. 120892, https://doi.org/10.1016/j.jclepro.2020.120892

Ministério do Meio Ambiente 2016, *Plano Nacional de Adaptação à Mudança do Clima – PNA (National Adaptation Plan to Climate Change – PNA)*, viewed 23 may 2025, https://bibliotecadigital.gestao.gov.br/handle/123456789/1012

Morrison, TH, Adger, WN, Brown, K, Lemos, MC, Huitema, D, Phelps, J, Evans, L, Cohen, P, Song, AM, Turner, R, Quinn, T & Hughes, TP 2019, 'The black box of power in polycentric environmental governance', *Global Environmental Change*, vol. 57, p. 101934, https://doi.org/10.1016/j.gloenvcha.2019.101934

Müller, S, Schmeichel, K & Winkler, T 2019, 'Assessment of greenhouse gas emissions in mining operations: a case study of selected mining processes', *Resources Policy*, vol. 60, pp. 511–519, https://doi.org/10.1016/j.resourpol.2018.11.006

Staletović, N 2013, 'Methods for risk management of mining excavator through FMEA and FMECA', *Mining and Metallurgy Engineering*, viewed 8 February 2026, https://www.academia.edu/28356316

Sukte, NB & Sanjay, M 2024, 'Hazard identification and risk analysis (HIRA) in mining industry', *International Journal of Research and Analytical Reviews*, vol. 11, no. 1, pp. 29–41, viewed 8 February 2026, https://ijrar.org/papers/IJRAR24A3324.pdf

Task Force on Climate-related Financial Disclosures 2017, *Recommendations of the Task Force on Climate-related Financial Disclosures: Final Report, Financial Stability Board*, viewed 8 February 2026, https://www.fsb-tcfd.org/publications/final-recommendations-report/

TPF Engenharia 2023, *Aplicação da Metodologia HIRA em Projetos de Mineração (Application of the HIRA Methodology in Mining Projects)*, viewed 8 February 2026, https://www.tpfengenharia.com.br/case/aplicacao-da-metodologia-hira-em-projetos-de-mineracao

United Nations Environment Programme Finance Initiative 2024, *2024 Climate Risk Landscape Report*, viewed 8 February 2026, https://www.unepfi.org/wordpress/wp-content/uploads/2024/04/Climate-Risk-Landscape-2024.pdf