

Article

Risk Management Model for Tailings Storage Facilities in Chile: An Approach from Geological and Mining Engineering and the Regulatory Framework

Leslie Vinet, Héctor Valdés-González *  and Mauricio Calderón

Facultad de Ingeniería, Universidad del Desarrollo, Santiago 7610658, Chile; l.vinete@udd.cl (L.V.); mauriciocalderon@udd.cl (M.C.)

* Correspondence: hvaldes@udd.cl

Abstract

Despite technological advancements in mining, Chile lacks comprehensive risk management models for tailings storage facilities (TSFs), which hinders the prevention and mitigation of structural and environmental risks. This study aims to develop an integrated risk management model for TSFs in Chile, combining geological and mining engineering with an updated regulatory framework to enhance safety and reduce environmental impacts. The research adopts a mixed-methods approach. Qualitatively, it draws on 10 semi-structured interviews with engineers, geologists, academics, and professionals from the Chilean mining industry, selected through purposive sampling, to explore how and why the current risk management model should be improved. Quantitatively, it analyzes data from 303 surveys assessing the existing regulatory framework, a proposed new regulatory decree for Chile, and key variables to be considered in TSF risk management. The results present a new model that integrates geochemical and geotechnical characterization, process variables, in situ sensors, remote sensing, and artificial intelligence to generate dynamic risk indicators and early warning systems throughout the life cycle of the facility, including closure and liability valuation. Its multiscale design, adaptable to seismic and hydrogeological conditions and suitable for small- and medium-scale mining, overcomes existing static and fragmented approaches, enabling more effective decision-making with a focus on environmental and community safety. The study concludes that the model provides a robust and coherent tool for TSF risk management by integrating technical expertise, the current regulatory framework, and the management of key variables that enhance the ability to anticipate and mitigate structural and environmental risks.



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Keywords: tailings; geomechanics; mining; risk management; regulation; environmental impact

1. Introduction

The safety and sustainability of tailings storage facilities have become a strategic concern for the Chilean mining sector (Figure 1). This is partly due to the scale of these structures—779 conventional facilities, 176 of which are abandoned according to the National Geology and Mining Service (SERNAGEOMIN) [1]—and partly due to their exposure to earthquakes, steep slopes, and sensitive ecosystems. While the publication of updated standards such as the Global Industry Standard on Tailings Management (GISTM) in 2020 [2] has driven global improvements, significant gaps between policy and practice

persist [3]. Recent literature agrees that addressing these gaps requires management models that integrate geochemical, geotechnical, and mining process data with new monitoring technologies and robust regulatory frameworks [4,5]. The following section synthesizes the theoretical foundations, state-of-the-art technologies, the Chilean regulatory framework, and international lessons.

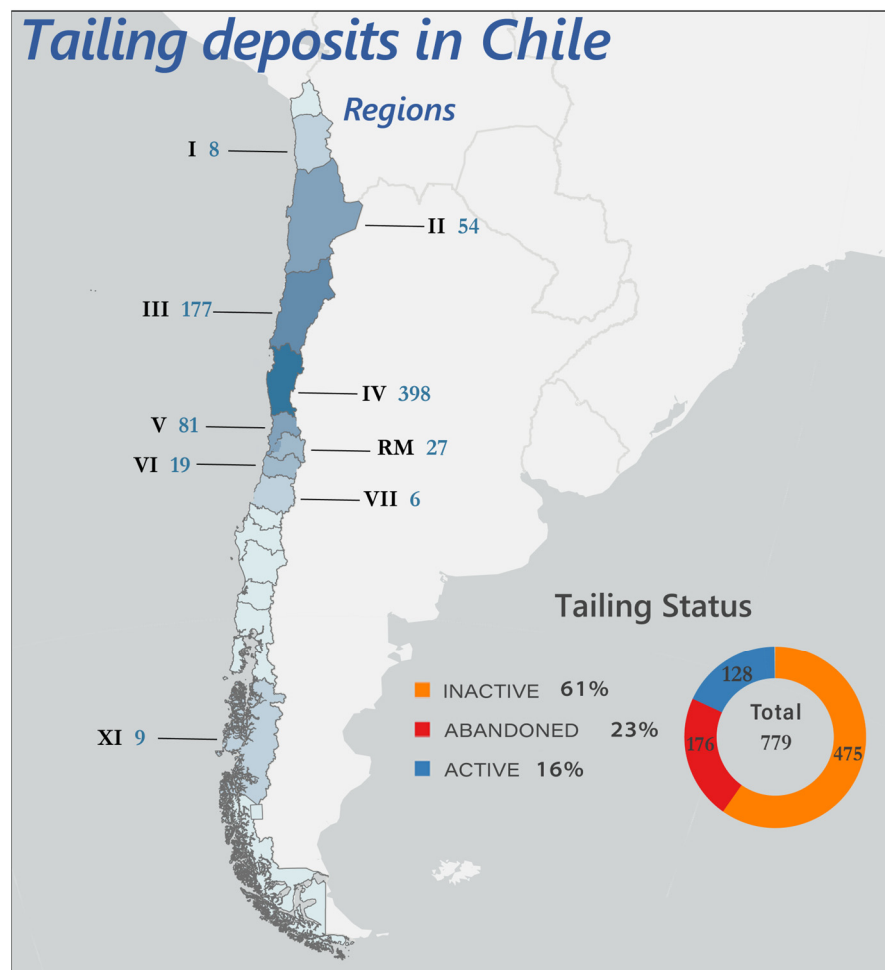


Figure 1. Number and status of tailings facilities in Chile (Source: Authors' elaboration).

1.1. Tailings Storage Facilities

A tailings storage facility (TSF) is a residual secondary mining deposit that contains the fine fractions resulting from the concentration of ores bearing metallic elements such as copper (Cu), iron (Fe), silver (Ag), gold (Au), lead (Pb), molybdenum (Mo), and zinc (Zn), which are all typical of the Chilean mining industry [6]. Within the value chain, the extracted ore is processed to recover the primary product, while the leftover material—thickened tailings or pulp with high water content—is disposed of in dams or impoundments [7].

From a geochemical perspective, these residues contain silicates, metallic sulfides, and iron oxides. Upon oxidation, they generate acid drainage and mobilize heavy metals [8]. Their behavior evolves over decades: submerged tailings tend to precipitate stable secondary phases, whereas those exposed to air undergo progressive oxidation, increasing the risk of contamination [9,10]. An understanding of this long-term dynamic is essential for designing containment and closure strategies that ensure both physical and chemical stability.

1.2. Structural Risk Management

Catastrophic risk management failures have led scholars such as Kossoff et al. (2014) [11] to emphasize the need for proactive monitoring. In Chile, seismic hazards increase the vulnerability of upstream-constructed dams, which are susceptible to liquefaction. Continuous monitoring using piezometers, inclinometers, and radar image interferometry techniques (InSAR) enables the detection of millimetric displacements and anomalous trends weeks before a collapse [12,13]. In parallel, hybrid numerical models, such as the Material Point–Finite Element Method (MPM-FEM), simulate the non-linear response of tailings under seismic loads, providing dynamic safety factors [14]. The integration of these datasets into machine learning algorithms supports early warning systems that predict pore pressure buildup and critical deformations, thus reducing operational risks [15]. Nevertheless, the effectiveness of these systems depends on the implementation of maintenance protocols, independent inspections, and trained personnel capable of interpreting data in real time [16].

1.3. Environmental Risk Management

Acid Rock Drainage (ARD) is the primary environmental threat, as it releases Fe, Cu and Zn into surface watercourses and underground aquifers, impacting high Andean wetlands and downstream communities [17,18]. In Chile, regulations require the characterization and prioritization of mining environmental liabilities based on their potential risk [19]. However, many abandoned facilities lack reliable geochemical data, increasing uncertainty [20,21].

Multispectral remote sensing using satellite optical sensors such as Sentinel-2 and WorldView-3, combined with machine learning algorithms, has proven effective in mapping contaminated zones and accurately estimating the pH of water bodies [22]. Meanwhile, hyperspectral approaches can predict the spatial distribution of metals in soils [23]. Nature-based technologies, such as phytoremediation and soil microbiology, have shown the capacity to reduce metal mobility in arid climates. These technologies offer low-cost solutions with a reduced carbon footprint [24].

1.4. Chilean Regulatory Framework

Chile's legal framework is based on three pillars: the Mining Code, the Mining Safety Regulation (Supreme Decree No. 132), and Supreme Decree No. 248 [25], which is currently under reform (and, to this end, a public consultation was conducted in 2024 to update the decree [26], underscoring its current importance for Chile). These are complemented by Law 20.551 on mine closure [27]. The regulations establish requirements for the design, operation, monitoring, and closure of tailings facilities, all under the supervision of the National Geology and Mining Service (SERNAGEOMIN).

Historically, each major failure has prompted regulatory adjustments. Cacciuttolo & Atencio (2022) [28] have documented the evolution of tailings governance in Chile since 1905; they note substantial progress alongside persistent gaps, such as legacy facilities without clear ownership, uneven enforcement, and limited community involvement. The ongoing regulatory update aims to align the national framework with the Global Industry Standard on Tailings Management (GISTM), by introducing greater transparency, external audits, and emergency response plans. Furthermore, the literature suggests incorporating circular economy principles, including reprocessing and the use of tailings as aggregates, to reduce inventories and associated risks [29].

Although Supreme Decree No. 248 represents a technical milestone, its scope remains limited: it lacks sustainability indicators, traceability mechanisms, and requirements for continuous monitoring. The version of the decree currently under review likewise does

not explicitly incorporate inter-institutional coordination or public participation, revealing regulatory and technical maturity that is still insufficient.

Chile, despite being a regional mining leader, maintains a predominantly reactive rather than preventive approach. However, some other mining countries exhibit an even more incipient regulatory framework for tailings management. Peru, for example, faces similar institutional challenges, but has seen limited progress in traceability and environmental control to date [30].

1.5. Comparative International Practice

Other countries with significant mining activity have adopted comprehensive approaches. Canada mandates regular independent reviews through the Towards Sustainable Mining initiative; Australia combines technical standards with the participation of Aboriginal communities; and Sweden prioritizes minimizing water content in tailings deposits to reduce instabilities [31]. The Global Industry Standard on Tailings Management (GISTM) reinforces these approaches by requiring demonstration of a “zero harm tolerance” and public access to information [2]. Comparative studies show that systems incorporating multifactorial standards, spanning engineering, environmental, and governance dimensions, exhibit lower failure rates and greater social acceptance [3]. Additionally, the integration of sustainability indicators, such as reduced water consumption and co-disposal with coarse waste rock, improves deposit consolidation and lowers emissions [29].

1.6. Toward an Integrated Risk Management Model

The reviewed evidence confirms the feasibility of shifting from reactive to anticipatory management, provided the following elements are combined:

- High-resolution geochemical and geotechnical characterization to assess the temporal evolution of the structure and its contaminants [3].
- Real-time multiparametric monitoring, integrating piezometry, high-precision Global Navigation Satellite System (GNSS), Interferometric Synthetic Aperture Radar (InSAR), and Internet of Things (IoT) sensors within predictive analytics platforms [12].
- Coherent and auditable regulatory protocols, including funded closure plans and binding participation of local communities [28].
- Circular economy approaches and nature-based solutions to reduce the volume of tailings and stabilize contaminants [24,29].

This model requires interdisciplinary capacities, including geological engineering, mining, data science, and environmental sciences, and would enable a shift from static safety factors to continuously updated dynamic risk indices. Its implementation in Chile could strengthen decision-making, improve regulatory oversight resource allocation, and reduce the social costs associated with failures.

1.7. Risk Management Model: Novelty, Proposal, and Contribution

The preceding synthesis reveals both significant advancements and critical gaps in the integration of technologies, regulatory frameworks, and operational practices. Based on this, two research questions emerge:

- What are the key variables in integrated risk management, based on geological engineering and mining processes, that can enhance safety and sustainability in tailings storage facilities in Chile?
- How does the implementation of advanced geotechnical monitoring technologies and mining processes influence the optimization of risk management in Chilean tailings facilities?

Addressing these gaps requires first understanding which geological and mining process variables are decisive for the safety and sustainability of tailings facilities in Chile. Second, it is important to know how advanced geotechnical and process monitoring technologies optimize the management of such risks.

Although Chile possesses a robust regulatory framework and state-of-the-art technological tools, it lacks a holistic model that integrates: (i) high-resolution geochemical and geotechnical characterization; (ii) mining and disposal processes; (iii) real-time monitoring systems; and (iv) regulatory and social requirements. The absence of this integrated approach limits the predictive capacity of both operators and authorities, which increases vulnerability to structural failures or environmental impacts.

The novelty of the present research lies in proposing and validating an integrated risk management model. This integrated model combines geological and mining process engineering with data analysis from in situ sensors, remote sensing, and artificial intelligence (AI), all within the framework of Chilean regulations. In contrast to previous work, this model offers:

- **A Holistic Approach:** An integrated model is proposed and validated that combines geochemical and geotechnical characterization, mining process variables, in situ sensors, and remote sensing within the national regulatory framework; this approach has not simultaneously been addressed in prior studies.
- **Dynamic Risk Indicators and Early Warning Systems:** The model generates real-time risk indices that feed early warning systems, going beyond the static approach used by most current operations.
- **Life Cycle Coverage and Circular Economy:** It incorporates closure, post-closure, and liability valorization stages, enabling mineral recovery and reducing environmental risks in active, inactive, or abandoned deposits.
- **Multiscale Adaptability:** The model can be adapted to Chile's specific seismic, hydrogeological, and social conditions. It is also applicable to small- and medium-scale mining operations, which have traditionally been beyond the scope of standards like the GISTM.

These innovations provide a replicable tool that enhances decision-making, strengthens governance, and increases community acceptance. It thereby meets the originality standards required by high-impact academic journals. Additionally:

- It merges expert perspectives, collected through interviews with industry professionals, regulators, and academics, with empirical evidence from case studies.
- It adapts international standards to the seismic, hydrogeological, and social particularities of the Chilean context, facilitating replication in other Latin American mining regions.

In sum, it offers a methodological path for integrating multidimensional data and regulatory criteria into a unified decision-making framework. It contributes to the sector by providing a tool capable of reducing social and environmental costs, strengthening governance, increasing community acceptance, and enabling early warning generation throughout the entire life cycle of the tailings facility.

General Objective of the Study: To develop and validate an integrated risk management model for tailings storage facilities in Chile that aligns key variables from geological engineering and mining processes with advanced monitoring technologies and regulatory requirements, in order to ensure structural stability, minimize environmental impact, and safeguard the safety of nearby communities.

2. Methodology

2.1. Qualitative Approach

One part of this study adopts a qualitative paradigm, using an exploratory design based on semi-structured interviews. A schematic summary of the process can be found in Figure 2. This methodology was selected due to its ability to deeply and contextually understand the meanings and behaviors of experts involved in the risk management of tailings storage facilities. This approach allows for a holistic analysis of how professionals address challenges in mitigating structural and environmental risks.

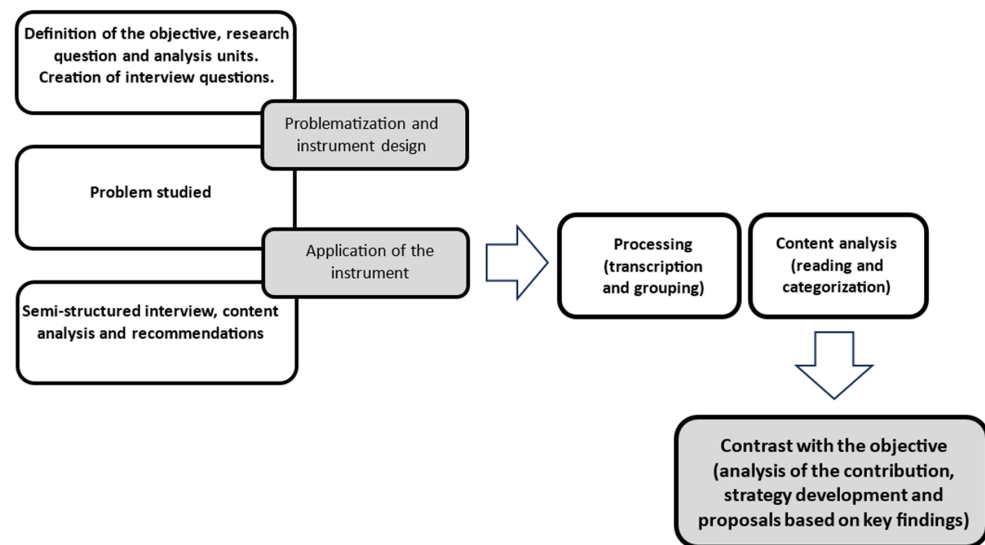


Figure 2. Structure of the proposed study and results selection process (Source: Authors' elaboration).

The study population consisted of 10 expert engineers and geologists, intentionally selected based on their experience in and knowledge of the Chilean mining sector (Table 1). Participants had an average of 20 years of professional experience. They therefore had considerable experience and knowledge of topics such as mine safety and tailings management, encompassing both tailings storage facilities and the current regulatory framework, as well as evolving legislative proposals.

Table 1. Qualitative study sample (Source: Authors' elaboration).

Number	Area of Work	Company/Highest Academic Qualification
1	Professional	NAVA Consulting
2	Professional	BBA Consultants
3	Professional	Rio Tinto Group
4	Professional	Teck Resources Limited
5	Academic	PhD. in Mining, Universidad de Chile, Chile
6	Academic	PhD. Geotechnical Engineering University of California, Berkeley, EE. UU.
7	Academic	MPhil Engineering for Sustainable Development, University of Cambridge, UK
8	Academic	PhD. Mining and Minerals, University of Exeter, UK
9	Academic	PhD. in Science, Mention in Geology, Universidad de Chile, Chile
10	Academic	Masters in Hydrology and Water Resource Management, Universidad de Alcalá de Henares, Spain

To guide the research, a set of eight open-ended questions was developed, organized into two sections to address key variables related to geological engineering, mining processes, and regulatory frameworks.

The first section focused on the characterization and understanding of current tailings-related risks. It contained two questions to explore the perception of current risks, one question addressing geomechanical and mining engineering techniques, and one question focusing on environmental considerations.

The second section centered on proposals for improving tailings risk management and conceptualizing model stages. It comprised two questions on the challenges and opportunities associated with the issue, and two additional questions to understand the needs for an integrated risk management model from the perspective of experts.

For data analysis, key categories were established based on the interview content, which were examined through an inductive approach. This involved identifying comments on patterns, critical factors, and shortcomings in current risk management models (Table 2). A comparison with the existing regulatory framework was conducted to assess the alignment of the proposed practices with current legislation.

Table 2. Study categories (Source: Authors' elaboration).

Items	Categories	Representation
Item 1: From your perspective, what are the main risks and challenges currently facing tailings storage facilities in Chile?	Tailings dam failure	(2/10)
	Environmental liabilities	(4/10)
	Lack of management	(4/10)
Item 2: Do you believe that current risk management methods are sufficient to adequately mitigate these risks? Why?	Lack of management	(2/10)
	Tailing's stability	(4/10)
	Operational challenges	(4/10)
Item 3: What practices, processes, or procedures are currently used for risk management in tailings storage facilities?	Regulations and standards	(2/10)
	Risk analysis	(2/10)
	Forecasting and monitoring	(3/10)
	Operational management	(3/10)
Item 4: How are environmental impacts currently addressed in tailings storage facilities? Do you believe the measures are sufficient?	Policies and regulations	(4/10)
	Expert collaboration	(3/10)
	Monitoring and prevention	(3/10)
Item 5: What are the main challenges you perceive in implementing an integrated risk management model in the Chilean mining industry?	Knowledge and reuse	(3/10)
	Standardization	(1/10)
	Lack of integration	(6/10)
Item 6: How do you perceive the future progress of risk management in tailings storage facilities in Chile?	Social perception	(2/10)
	Regulations and standards	(3/10)
	Technical improvements	(2/10)
	Outstanding challenges	(3/10)

In terms of ethical considerations, participants were fully informed of the study's objectives and methodology, the voluntary nature of their participation and the confidentiality of their responses: All gave their written consent to participate. All data were handled impartially, with their integrity maintained throughout the analysis to ensure the validity and confidentiality of the findings.

2.2. Quantitative Approach

The qualitative analysis was used to develop a quantitative survey in order to provide a more robust and generalizable understanding of risk management in tailings storage facilities (Figure 3). Data collected via the survey facilitated the evaluation of consensus and divergences in opinion on specific aspects of risk management models, such as the effectiveness of monitoring technologies, the implementation of regulatory frameworks, and practices related to mitigating structural and environmental risks. The survey asked about trends, perceptions, and practices perceived by a broad sample of professionals in the mining sector. In total, the survey was completed by 303 professionals who had

been intentionally and non-randomly selected through academic networks that connect professionals with relevant performance in mining and tailings during the year 2024). The survey was designed to enable data triangulation and therefore enhance the validity and reliability of the proposed model.

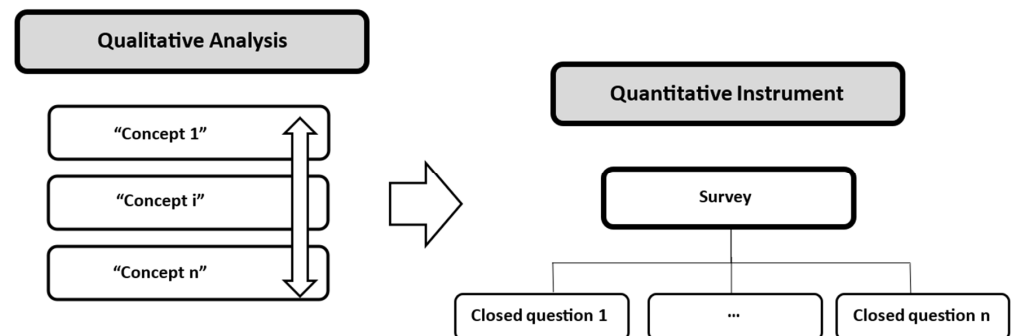


Figure 3. Model for generating quantitative study (survey) from the qualitative study (Source: Authors' elaboration).

The semi-structured interview was validated through an iterative process, beginning with a pilot test conducted among a small group of five expert engineers and geologists who met the study's selection criteria. This pilot phase made it possible to identify issues related to interpretation, ambiguity, and potential biases in the wording of the questions. After each pilot participant, the questions were refined to improve clarity and ensure alignment with the research objectives.

A preliminary qualitative analysis of the responses to the pilot version was conducted to evaluate whether they effectively facilitated the exploration of technical perceptions regarding key factors such as structural stability, mining processes, and the regulatory framework. Following each revision, the instrument was re-tested until a final, consistent version was achieved, one that elicited detailed and relevant responses to the research question.

The survey focused on current perceptions and practices related to risk management in tailings storage facilities. It was organized into five key sections: professional background (3 questions addressing type of work, years of experience, and area of specialization in mining) and four thematic sections, each containing 3 questions on a 5-point Likert scale, covering perception of risks, evaluation of the regulatory framework, use of monitoring technologies, and implementation of mitigation measures. Each section explored variables identified during the qualitative phase.

2.3. Response Scale and Analysis

For the analysis of the survey data, frequencies, means, and correlation analyses were conducted to identify patterns between risk perceptions and the perceived effectiveness of the regulatory framework or monitoring technologies. These mixed methods approach not only provided additional empirical validation for the proposed model but also helped identify areas for direct improvement, offering a more comprehensive overview of tailings risk management in Chile.

3. Results

The following section presents the findings obtained from each research instrument. The categories associated with each of the questions are summarized in Table 2.

3.1. Key Findings from the Qualitative Analysis

The analysis of categorized responses yielded the following key findings for the qualitative stages:

- Two main approaches to risk management in tailings storage facilities in Chile were identified:
 1. Operational and regulatory challenges
 2. Environmental awareness
- The lack of an integrated management approach was identified as a key challenge, particularly for small- and medium-scale mining operations.
- There is a need to standardize practices across all stages of the tailings' life cycle. Of particular importance is the implementation of unified models based on risk categorization and management, which address risk management from the design phase through closure and post-closure. These stages include:
 - Classification
 - Governance and management
 - Emergency management
- The lack of integration and fragmentation of tasks poses a significant challenge to process coordination.
- Participants expressed concern over the impacts of climate change and the vulnerability of older tailings facilities that were constructed without accounting for current risks such as seismic activity and increased waste volumes.
- The findings highlight the need to address not only technical challenges (e.g., AI and smart monitoring) but also the importance of managing public image and social perceptions related to tailings facilities.

3.2. Key Findings from the Quantitative Analysis

The analysis of quantitative results revealed the following main findings across the five established sections:

- There is a strong perception of structural and environmental risk associated with tailings facilities.
- Respondents emphasized the need to address risks through an integrated approach that combines technical, environmental, and organizational dimensions.
- The proportion of specialists and technicians dedicated to tailings management is low, with a predominance of professionals with limited experience in the field.
- There is a critical view of the current regulatory framework, which many consider inadequate or insufficient.
- Respondents identified a lack of regulatory updates and poor enforcement.
- Budgetary constraints and gaps in technical training were noted as significant limitations.
- A disconnect was observed between declared commitments to sustainability and the actual implementation of concrete actions.
- The results point to weaknesses in the sustainable management of tailings facilities.

3.3. Discussion of Qualitative Results

The interview data confirm two critical axes in tailings management in Chile: (i) the gap between regulatory requirements and operational practices, and (ii) the limited social legitimacy of the industry. Both findings reinforce international evidence linking catastrophic failures to deficiencies in design and monitoring [11], as well as to low levels of community involvement [32]. As a result, the social license to operate remains fragile.

Lack of an Integrated Approach: Interviewees highlighted the absence of holistic models, a problem particularly acute in small- and medium-scale mining. Previous studies have pointed out that fragmentation between design, operation, and closure phases hinders risk prevention [33] and compromises sustainability [31]. Similarly, Adamo et al. (2021) [34]

and Zare et al. (2024) [35] show that monitoring systems based on remote sensing are only effective when embedded in standardized surveillance and response protocols. To address this gap, the following is proposed:

- Standardize management plans in small and medium mining, allocating specific funds for monitoring technologies and training, as suggested by Zhi et al. (2023) [36].
- Implement unified classification and emergency frameworks aligned with the Global Tailings Review (2020) [31] and reinforced through more rigorous state audits.
- Create collaborative information platforms that integrate geochemical and geotechnical data in real time, following the recommendations of Das et al. (2024) [12] and Raspini et al. (2024) [13].

Need for Standardization and Coordinated Governance: The literature demonstrates that the absence of common protocols exacerbates failure risks [37]. The findings of this research align with this view: interviewees called for guidelines that span from design through post-closure. To address this need, the following measures are recommended:

- Adopt a multilevel governance system in which public and private entities coordinate inspections and share responsibilities, thereby reducing duplication of efforts.
- Strengthen state oversight through procedures segmented into verifiable milestones, increasing both preventive and response capacity.

Climate Vulnerability of Legacy Tailings Facilities: There is a marked concern about the resilience of tailings deposits built under outdated regulations. The literature confirms that older tailings facilities are more susceptible to extreme weather events and recent seismic activity [38–40]. In line with this, the Global Tailings Review (2020) [31] calls for the incorporation of climate adaptation measures throughout the entire life cycle. Accordingly, three lines of action are proposed:

- Update technical standards to integrate climate and seismic variables applicable to both active and legacy facilities.
- Conduct regular geotechnical audits that include climate change scenarios, using remote sensors and real-time monitoring.
- Design rehabilitation and closure plans based on nature-based solutions that reduce environmental footprints and improve stability.

Circular Economy and Tailings Valorization: Villachica et al. (2021) [41] and Kinnunen et al. (2022) [29] emphasize that the adoption of circular economy strategies requires regulatory incentives and support for innovation. While interviewees recognize the potential of such strategies, they also warn of technical and regulatory barriers. To catalyze this transition, the following is suggested:

- Introduce tax incentives for reprocessing projects and co-disposal with waste rock.
- Establish public–private consortia to finance applied research and technology transfer.

Social Legitimacy and Communication: The deficit in public trust emerges as a cross-cutting challenge. The literature underscores that social license depends on transparent communication and meaningful community participation [42–44]. In line with these findings, the following is proposed:

- Implement public monitoring programs that provide communities with access to real-time data.
- Strengthen permanent dialog mechanisms by integrating local working groups throughout the entire life cycle of the tailings facility.
- Develop awareness campaigns about the risks and benefits of circular economy practices, reinforcing shared responsibility.

The results confirm that despite progress in monitoring technologies and regulatory frameworks, a fragmented management approach persists. This fragmentation increases the technical, environmental, and social vulnerability of tailings storage facilities. Bridging these gaps requires an integrated framework that combines standardization, funding for technologies, climate adaptation, circular economy strategies, and community participation. Only through such a comprehensive approach can Chilean mining effectively meet the demands of safety, sustainability, and legitimacy inherent to a high-impact industry.

To address the applicability of the proposed model in light of operational scale and the prevailing regulatory framework, three options should be considered, according to operation size:

- Small-scale mining: These operations generate minimal or no tailings, so the usefulness of management tools designed for larger-scale activities is limited.
- Medium-scale mining: The model supports the gradual integration of geotechnical technologies and the strengthening of environmental governance. Governmental oversight associated with the model should begin at this level.
- Large-scale mining: A full implementation is envisaged, including real-time monitoring, digital traceability, and external audits, with flexibility and adaptability to diverse operational contexts and regulatory requirements.

3.4. Discussion of Quantitative Results

Given the exploratory and descriptive nature of the study, the data collected are not intended to achieve statistical representativeness; rather, they serve to identify salient variables and contextual factors that underpin the construction of a coherent conceptual model. In this regard, the non-random selection of expert participants is consistent with the study's purpose. Although this approach imposes statistical limitations on the findings, the proposal is oriented towards integrating lived experiences, operational contexts, and regulatory frameworks within a theoretically informed methodological approach aligned with the stated objective.

The survey administered to 303 professionals from the Chilean mining sector reveals a widely shared perception that tailings storage facilities pose a critical risk in both structural and environmental terms: 79% of respondents rated both aspects as “highly critical.” This finding supports Edraki et al.'s (2014) [33] assertion that tailings management must encompass the entire life cycle, i.e., design, operation, and post-closure, to ensure safety and sustainability. It also reinforces the view of Franks et al. (2011) [45], who identify tailings as one of the most significant liabilities in modern mining. Their social acceptability hinges on the application of sustainable development principles and transparent communication [32].

Need for a Systems-Based Approach: Factor analysis confirms that respondents view risk management as an integrated process that brings together technical, environmental, and organizational variables. This consensus aligns with the arguments of Juutinen et al. (2023) [46] and Adiansyah et al. (2015) [31], who stress the influence of geochemical and mineralogical evolution on structural stability. To bridge the gap between this understanding and current practice, the implementation of an integrated risk management model is proposed. It combines advanced technical monitoring, periodic environmental audits, and robust institutional structures to better anticipate potential failures.

Human Capacity Deficit: Only 22% of respondents reported having specific training in tailings management, indicating a critical shortage of specialists. This issue, also noted by Meggyes et al. (2008) [47], Kemp et al. (2024) [48], and Spencer et al. (2022) [49], hinders the adoption of best practices and emerging technologies. It is recommended that national competency standards be established and supported by continuous certification programs. Such programs should be developed through partnerships between universities,

regulatory bodies, and the mining industry to ensure that personnel meet the skills required by international standards.

Regulatory and Oversight Limitations: Some 64% of professionals consider the current regulatory framework “inadequate” for addressing today’s challenges. These results echo the critiques of Owen et al. (2020) [37] regarding the insufficiency of regulatory frameworks in Latin America and the oversight gaps documented by Zare et al. (2024) [35]. Moreover, Ehrnström-Fuentes & Kröger (2017) [50] point out that regulatory legitimacy depends on its capacity to respond to emerging societal demands. This underscores the urgency of regulatory updates that incorporate requirements for continuous monitoring, independent technical audits, and mechanisms for citizen participation.

Barriers to Technological Adoption: While 68% of respondents recognize the value of real-time monitoring systems, only 31% report their effective use. This disconnect is attributed to the absence of regulatory mandates [51], a lack of trained inspectors (Rana et al., 2024) [52], and budget priorities that favor productivity over safety [53,54]. Clarkson et al. (2020) [55] further note that regulators often lack the competencies to evaluate emerging technologies. Financial incentives for smart monitoring investment, the expansion of digital oversight, and the training of inspectors in geotechnical data analysis are therefore proposed.

Internal Governance and Fragmentation: A significant majority (77%) of respondents perceive organizational governance as fragmented across engineering, environmental, and safety departments. This finding is consistent with the conclusions of Ehrnström-Fuentes & Kröger (2017) [50]. This fragmentation impedes information traceability and coordinated responses. Shared data platforms and interdisciplinary risk management committees are recommended as solutions.

Gap Between Sustainability Discourse and Practice: Respondents identified a disconnect between the sustainability policies declared by mining companies and their implementation in the field. They claimed it is evident in the slow uptake of clean technologies, limited transparency in monitoring practices, and overall skepticism toward industry commitments to sustainability. In fact, 49% of participants rated the industry’s commitment as only moderately strong, and 32% considered it weak. Similar observations are documented by Araya et al. (2021) [56], Araujo et al. (2022) [57], and Mancini et al. (2024) [58]. To reverse this trend, independent social and environmental audits and the publication of verifiable public reports are proposed to reinforce accountability.

Shortcomings in Integrating Sustainability Principles: Eighty-five percent of professionals rated current environmental mitigation measures as insufficient or only moderately sufficient. This perception aligns with findings by Suppes & Heuss Aßbichler (2021) [59], Beylot et al. (2022) [60], Cacciuttolo & Marinovic (2022) [30], and Adewuyi et al. (2024) [61]. It is recommended that regulatory frameworks be updated to include binding environmental and social performance standards, complemented by public monitoring and community participation.

The quantitative results reveal that while risk perception is high, risk management capacity remains constrained by technical, regulatory, and governance deficits. To move toward safe and sustainable tailings management, seven lines of action are proposed, consistent with the academic literature: (1) implement an integrated risk management model; (2) certify professional competencies; (3) modernize regulatory frameworks; (4) finance technological adoption; (5) integrate data and disciplinary perspectives; (6) audit sustainability performance, and (7) establish binding environmental standards. Together, these measures would align national practices with the best international standards and strengthen the social license to operate.

4. Proposed Model

Based on the responses to the research instruments described in Section 2 of this document, Supreme Decree DS No. 248 [25], and the specialized references already cited, the following proposal is made for an “Integrated Risk Management Model for Tailings Storage Facilities (TSFs)”. It incorporates three essential components: risk classification and evaluation; governance and technical management; and emergency management and preparedness (Figure 4).

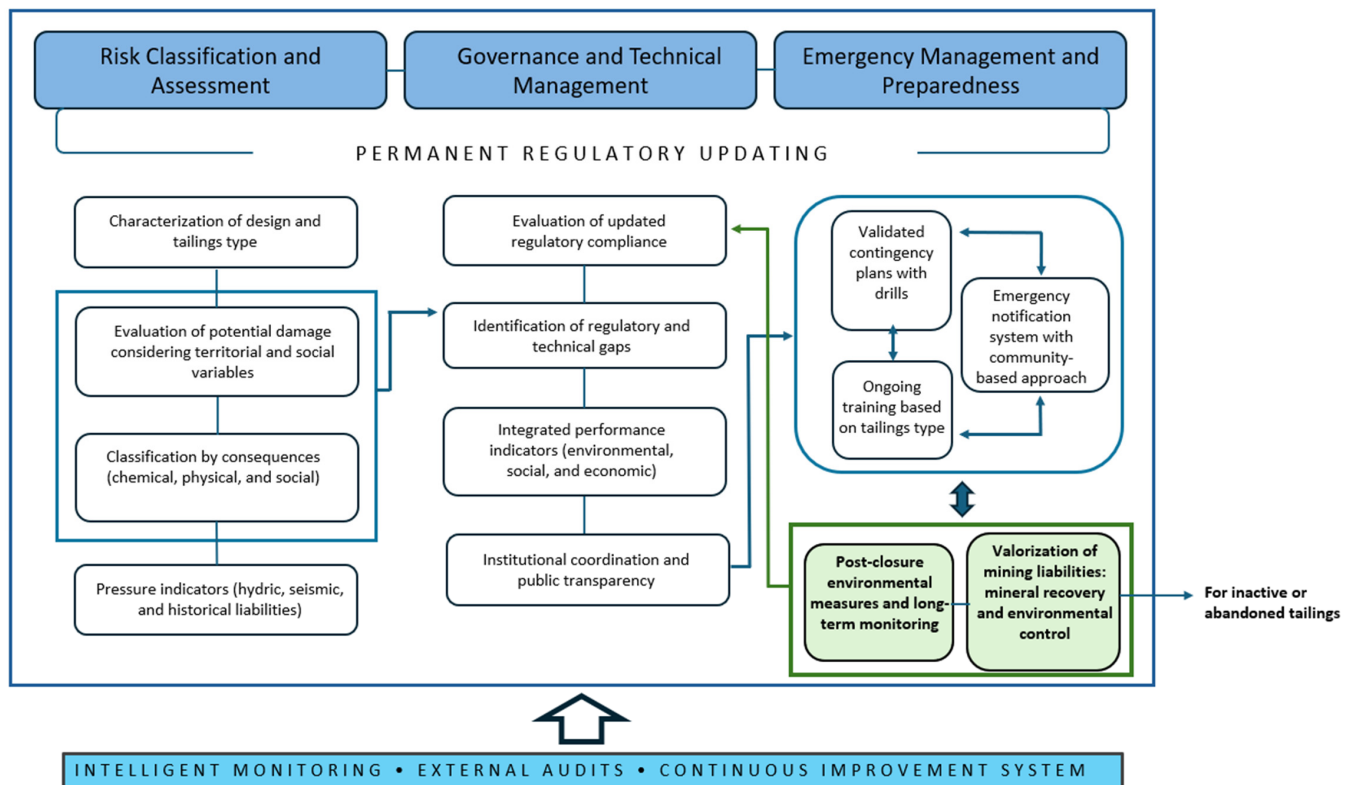


Figure 4. Integrated Risk Management Model (source: Author’s own elaboration).

- This model includes continuous regulatory updates as its backbone, guiding all components to operate in line with current and flexible standards that can be adapted to diverse technical, social, and environmental contexts. It is also supported by cross-cutting mechanisms such as smart monitoring, external technical audits, and continuous improvement systems, all of which systematically feed into the decision-making process.
- Each component integrates the main pillars that should govern risk management in TSFs, under a framework of continuous improvement, territorial sustainability, and regulatory adaptation. The model follows a sequential and feedback-based logic, where each functional block is dynamically connected to the others, ensuring traceability and consistency across the system.

To enhance methodological transparency and traceability, Table 3 links the specific survey items and the categories derived from the interviews to the final components of the integrated model. This demonstrates how the qualitative and quantitative findings converge in the structuring of the proposed model.

Table 3. Links between interview categories, survey items, and integrated model components (Source: Authors' elaboration).

Interview Category (Qualitative)	Survey Item (Quantitative)	Component of the Integrated Model	How Each Component Responds to the Data Collected
Management gaps/Environmental liabilities	Perception of environmental risk	Environmental component	Strengthens preventive measures against impacts and acid drainage.
Operational challenges/Lack of integration	Critical factors for stability	Structural and operational component	Improves standardization across the design, operation, and closure stages.
Insufficient policies and regulations	Adequacy of the regulatory framework	Regulatory component	Updates the DS 248 framework and recommends more effective enforcement.
Expert collaboration/Monitoring and prevention	Use and effectiveness of monitoring technologies	Technological component	Reinforces the role of innovation and predictive monitoring in preventing failures.
Knowledge and reuse/Standardization	Mitigation and sustainability practices	Sustainability component	Promotes reuse and valorization of tailings to support sustainability.
Social perception and outstanding challenges	Commitment to sustainability is needed	Socio-community component	Reduces gaps between declared commitment and concrete actions in tailings management.

4.1. Risk Classification and Evaluation

This initial component organizes the essential processes to identify, assess, and anticipate the risks associated with tailings facilities. Through progressive deployment, the infrastructure and its territorial context are characterized:

- **Design and Tailings Type Characterization:** Identifies the construction design, dam type (upstream, downstream, centerline), tailings material, and technology employed. This characterization provides the technical basis for assessing structural stability and performance under adverse conditions.
- **Potential Damage Assessment Based on Territorial and Social Variables:** Incorporates contextual elements such as proximity to populations, the presence of critical infrastructure, or sensitive ecosystems, with the goal of estimating the magnitude of potential damage in the event of failure.
- **Consequence-Based Classification (Chemical, Physical, and Social):** Prioritizes TSFs based on their potential impacts on the environment and local communities. It considers factors such as toxicity, dispersion potential, human vulnerability, and exposure level.
- **Pressure Indicators (Water Load, Seismic Activity, Historical Liabilities):** Assesses geographic, climatological, and structural conditions that may elevate risk, including hydrological load, seismic activity, and past incident history.
- **Site-specific implications for stability and contamination control:** Geotechnical stability is the primary risk driver. Given the local geological setting, the seismic environment and the geometry of the embankments, the most critical scenarios are associated with loss of shear strength in the tailings mass and foundation materials, as well as excess pore-water pressures during extreme hydrometeorological or seismic events. Therefore, the model prioritizes engineering measures such as regular slope-stability back-analyses under updated loading and saturation conditions, optimization of drainage and seepage control systems (internal drains, toe drains, and improvement of surface water management), and, where required, buttressing or re-profiling slopes. These measures are coupled with an enhanced monitoring strategy that includes pore-pressure, displacement and deformation monitoring, integrated into an early-warning

system consistent with the site's emergency response plan. Contamination, in turn, emerges as a combined issue resulting from the interaction of seepage, potential acid mine drainage, metal mobilization, and surface dispersion of fine particles. In the case study, the model identifies critical exposure pathways linking the tailings body with downstream watercourses, groundwater and the surrounding environment. To address these combined effects, the risk management framework recommends a set of engineering interventions, including improvement of base and peripheral liners where feasible, installation or upgrading of seepage collection and return systems, reinforcement of cover systems to reduce oxygen ingress and infiltration, and implementation of water-treatment or polishing units for contact water before discharge. Additionally, measures for dust control and erosion protection are incorporated to minimize airborne dispersion of contaminants, in line with the regulatory thresholds and environmental quality standards applicable to the site. Together, these site-specific measures illustrate how the proposed model can guide practical decision-making while maintaining consistency with the Chilean regulatory framework and international best practice.

This block directly informs technical governance, providing both technical and contextual information necessary for a regulatory evaluation that aligns with the operational reality of each facility. Risk characterization is not treated as an isolated diagnostic, but rather as an active input for regulatory improvement. Normative and technical gaps are not defined abstractly but derived from concrete risks identified in the territory. A functional feedback loop is created between technical analysis and governance.

4.2. Governance and Technical Management

This component integrates the regulatory, institutional, and technical dimensions of the model, ensuring consistency between diagnosis, planning, and execution:

- **Evaluation of Regulatory Compliance:** Assesses whether the facility meets current legal requirements and international standards. This is supported by audits and technical documentation to ensure regulatory alignment.
- **Identification of Regulatory and Technical Gaps:** Detects legal and technical shortcomings, particularly in the context of small- and medium-scale mining, where there are often asymmetries in resources, capabilities, and regulatory oversight.
- **Integrated Performance Indicators (Environmental, Social, and Economic):** Provide a multidimensional view of the facility's behavior, enabling real-time monitoring and facilitating evidence-based decision-making.
- **Institutional Coordination and Public Transparency:** Promotes interoperability among agencies, companies, regulators, and communities. Ensures information traceability, public access, and shared oversight.

This component draws from the previous risk characterization stage and, in turn, feeds back into the system by incorporating data from post-closure monitoring. It thereby strengthens regulatory standards through practical learning and iteration.

4.3. Emergency Management and Preparedness

This axis operationalizes the capacity to anticipate, respond to, and contain critical events:

- **Contingency Plans Validated through Drills:** Operational technical documents that must be validated through practical exercises to ensure functionality and correct weaknesses.
- **Ongoing Training Based on Tailings Type:** A training program tailored to the specific characteristics of the deposit. It strengthens the technical capacities of both personnel and local communities, ensuring effective responses to critical events.

- **Community-Based Emergency Notification System:** An early warning system centered on the local community. It promotes rapid response times, institutional trust, and participatory oversight.

The closed loop of arrows within the emergency block represents the continuous interaction between contingency plans, differentiated training, and the community-based notification system. It connects distinct components and illustrates how the knowledge generated in the risk evaluation block informs governance. In turn, it enables the operationalization of emergency preparedness. Thus, the model ensures that technical decisions are not isolated, but rather interdependent and dynamic.

This block also extends the preventive approach to the closure or abandonment stages, addressing both environmental aspects and mineral recovery. These two components are:

- **Post-Closure Environmental Measures and Long-Term Monitoring:** Includes physical and chemical stabilization, drainage control, structural monitoring, and progressive ecological restoration. These actions aim to prevent degradation, avoid disasters, and restore the environment in alignment with the current legal framework.
- **Mine Waste Valorization: Mineral Recovery and Environmental Control:** Proposes the reprocessing of legacy tailings with economic potential, integrating them into a remediation circuit under safe conditions. This strategy allows the model to also apply to inactive or abandoned tailings deposits.

The feedback from post-closure management into regulatory evaluation suggests a virtuous cycle of continuous improvement: lessons learned from tailings monitoring reinforce standards applicable to active facilities. The bidirectional relationship between post-closure management and tailings valorization and the emergency systems implies shared learnings, protocols, and community oversight needs. It is also linked to the emergency block through community monitoring and post-closure surveillance. It extends its application beyond operational sites to inactive or abandoned mining liabilities. This broadens the strategic scope of the model and enables the design of integrated recovery interventions across mining, environmental, and social domains, even in contexts where no current operation exists.

4.4. Cross-Cutting Support: Monitoring, Audits, and Improvements

- **Smart Monitoring:** Use of sensors, AI, remote systems, and predictive analytics to detect deviations in tailings facility behavior in real time.
- **External Audits:** Impartial technical reviews by specialized third parties, ensuring that evaluations and operations comply with technical and regulatory criteria.
- **Continuous Improvement System:** A framework that turns data into decisions. It converts evidence from monitoring and audits into regulatory, operational, or structural adjustments that strengthen the system.

These three elements are not confined to a specific block, but rather interact with all components of the model. This interaction enhances its adaptability, oversight capacity, and timely response to emerging risks.

This proposed model constitutes a comprehensive, robust, and flexible tool capable of addressing the environmental, technical, and social challenges posed by tailings deposits in Chile. Its scalable design allows for application both in active operations and in legacy mine sites, thereby strengthening sustainable and preventive risk management.

Building on the above, the proper implementation of the proposed model depends on corporate cooperation and effective governmental oversight. These areas require further empirical substantiation but the 2024 public consultation [26] provides strong preliminary evidence, helping to avoid an initiative that is “dead on arrival.” Voluntary participation

and accountability will vary with legal and economic context; consequently, clear incentives and monitoring mechanisms, still to be designed and operationalized, are needed. Public acceptance and the backing of key stakeholders, including communities and non-profit organizations, are essential to render the associated improvement costs viable. Moreover, because tailings composition and hazard levels are heterogeneous, management strategies must be tailored to each facility, with due consideration of geochemical analyses and site-specific risks. In sum, this is a problem of the many that must be addressed by all—particularly in a context where the generation of revenues from mining has been so necessary that tailings management has, to some extent, been neglected.

4.5. Model Validation

The validation of the conceptual model was carried out through a focus group with experts, serving as a bridge between theory and practice and strengthening the model's credibility and applicability in real-world settings [62,63]. In this case, the validation process considered functional validation, i.e., the model's practical utility and applicability within its operational environment. This included discussion of complex cases raised by the experts. It also considered participatory validation: the focus group comprised key stakeholders (academics, technicians, managers).

4.6. Conducting the Focus Group

Six experts and key figures in the mining sector were invited, representing a range of perspectives within the relevant domain. The group included both academic researchers (3) and industry professionals (3). A brief 10–15 min presentation was given to the group, summarizing the conceptual model, its components, and the process by which it was developed, along with the definitions that underpin its operation. An open-ended question guide was used, following a moderated protocol with questions such as:

- Does this model accurately reflect the reality of the process?
- Are there variables that are missing or overrepresented?
- Do you find the relationships between the different stages and components of the model clear and coherent? Where could articulation be improved?
- What adjustments would you make to improve its applicability?
- Do you find the model useful for supporting decision-making in real mining contexts?

The session was recorded and transcribed. Thematic coding was applied to synthesize observations and feedback, which guided adjustments made to the original proposed model, represented in Figure 4.

5. Conclusions

This study confirms that integrated risk management for tailings storage facilities in Chile must systematically articulate technical, environmental, regulatory, and social variables. The technical axis is grounded in the physical and chemical stability of the deposit and in geotechnical design that incorporates the country's high seismicity, drainage control, and the assessment of potential failure mechanisms. This must be complemented by proactive risk analysis, the adoption of up-to-date international standards, and ongoing training of specialized personnel. Following a life cycle logic, the proposed model links the phases of design, operation, closure, and post-closure. It integrates tailings recovery within a circular economic approach as a vector for sustainability. Likewise, it highlights the need for a strengthened and coherent regulatory framework, along with the explicit consideration of social perception in order to legitimize and enable projects in a context of high density of active, inactive, and abandoned tailings deposits.

Empirical evidence demonstrates that the early detection of instabilities can be enhanced by the implementation of advanced monitoring technologies, such as real-time sensors, early warning systems, next-generation numerical modeling, drones, and predictive analytics platforms based on artificial intelligence. Early detection strengthens the response capacity to critical events and reduces uncertainty in decision-making. However, deployment of these technologies remains limited outside of large-scale mining due to investment, training, and regulatory update gaps. The model addresses these limitations through a continuous improvement structure that demands effective oversight, incentives for technological adoption, and clear professional competency guidelines. It also proposes interdisciplinary teams that bring together geotechnics, environmental management, territorial participation, and regulation. This approach ensures alignment between current regulations, real operational conditions, and socio-environmental impacts. It aims to reduce the fragmentation observed among the various actors and advance toward robust and transparent risk governance.

When applied at the site scale, the proposed risk management model shows that geotechnical stability remains the key issue for mine landfills and tailings storage facilities, whereas contamination must be understood as a combined hydrogeological and geochemical problem. For the reference facility, the highest priority is to ensure long-term stability under seismic and hydrological loading, which translates into concrete engineering actions such as optimized slope design, improved drainage and seepage control, systematic stability back-analysis, and strengthened monitoring and early-warning systems. In parallel, the model highlights the need to manage contamination through an integrated set of measures that includes seepage collection and treatment, enhancement of cover systems, control of dust and erosion, and continuous surveillance of groundwater and surface-water quality.

These site-specific insights confirm that the usefulness of the model lies not only in structuring risk assessment but also in guiding the selection and prioritization of engineering interventions adapted to the local geological, hydrological and regulatory context. Consequently, the framework can support regulators, operators and communities in negotiating and implementing risk-reduction strategies that are technically sound, transparent and aligned with both Chilean regulations and international standards.

A key innovation of the model is the explicit inclusion of the post-closure stage and the valorization of mine waste, which extends its applicability to inactive or abandoned deposits. By promoting environmental remediation and the recovery of remaining minerals under rigorous standards, the model creates synergies between risk mitigation, the remediation of accumulated impacts, and tangible benefits for nearby communities. The proposal is particularly relevant to small and medium-scale mining sectors that host most of the country's tailings deposits and require adapted, clear, and operational tools. In summary, the integrated risk management model helps close structural gaps, supports informed decision-making, and promotes safer, more responsible, and environmentally sustainable mining across Chile.

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