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An Integrated Strategic Model for Managing Coal Mining-Related Environmental Liabilities in Santa Catarina, Brazil

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Abstract

Coal mining in Santa Catarina, Brazil, began in the early 1900s and expanded significantly after 1950, currently representing 13% of national extraction activities. The environmental legacy of this activity includes widespread acid mine drainage (AMD), affecting soil and water quality across the region. Due to the large scale, geological complexity, and diverse stakeholder interests, these areas are classified as complex contaminated sites, where remediation efforts face high uncertainty and long timelines. This study proposes an Integrated Management Strategy based on Adaptive Management principles, emphasizing iterative planning, conceptual modeling, and risk-based prioritization. The strategy is tailored to the Santa Catarina Coal Basin, which spans over 900,000 hectares, and incorporates site-specific data, stakeholder engagement, and performance monitoring. Expected outcomes include the development of a flexible and scalable framework for environmental recovery, capable of guiding decision-making under uncertainty. Practical contributions involve tools for prioritizing interventions, improving coordination among institutions, and enhancing transparency in remediation processes. The findings also offer insights for public policy, supporting the formulation of long-term environmental governance mechanisms and regulatory updates aligned with the complexity of legacy mining liabilities in Brazil.

Keywords

Adaptive Management, Acid Mine Drainage, Complex Areas, Coal Mining

1. Introduction

Coal mining in Brazil dates back to the 1880s, although earlier accounts describe drovers in southern regions using abundant surface "black stones" to fuel campfires. Reports of these combustible rocks reached the imperial court in Rio de Janeiro, prompting land acquisitions in the south and initiating the region's industrial development. Over the decades, coal has remained a strategic energy resource for Brazil, particularly during global shortages in the World Wars and throughout the national industrialization period.

The Santa Catarina Coal Basin spans over 900,000 hectares across 24 municipalities and contains an estimated 4.3 billion tons of coal reserves. Economically viable extraction has historically focused on the Barro Branco, Bonito, and Irapuá seams, associated with Permian-age successions of the Rio Bonito Formation. Following a century of exploitation, the sector declined sharply in the 1990s due to economic liberalization, rendering operations financially unsustainable. Since then, coal production has primarily served the Jorge Lacerda Thermoelectric Complex, which supplies approximately 35% of Santa Catarina's energy demand.

This prolonged mining activity has left significant environmental liabilities, including 6000 hectares of surface disturbance, 16,000 hectares of subsurface degradation, and 820 abandoned mine entrances (**Figure 1**). The most critical impact is acid mine drainage (AMD), where sulfide minerals exposed to oxygen generate acidity and release contaminants into surrounding soils and water bodies. Regional monitoring data indicate that coal mining affects 1241 km^2 of surface waters, with 72% influenced by AMD and 67% classified in poor condition, exhibiting pH levels below 4.5 [1].

Despite two decades of recovery efforts, environmental remediation has yielded limited success. In the most complex cases, interventions have failed to significantly reduce acidification in surface and groundwater systems. These sites align with the definition of "complex contaminated sites" as outlined by the Interstate Technology Regulatory Council [2], where remediation does not meet recovery targets within a reasonable timeframe. Contributing factors include intricate geological and geochemical conditions, as well as non-technical barriers such as social expectations and funding constraints.

This scenario calls for a transition toward Adaptive Management—a framework designed to address uncertainty through the development of robust conceptual models and iterative, long-term strategies that evolve over time [3]. When integrated with environmental and human health risk assessment tools, this approach enables prioritization of actions to mitigate the most critical impacts, such as safeguarding community water supplies and sensitive ecosystems. Given the complexity of these sites, a new management model is needed—one that defines final and intermediate objectives based on site-specific conditions.

Accordingly, this study aims to evaluate the environmental recovery practices implemented in the Santa Catarina Coal Basin over the past two decades and to propose an integrated strategic model capable of delivering consistent and

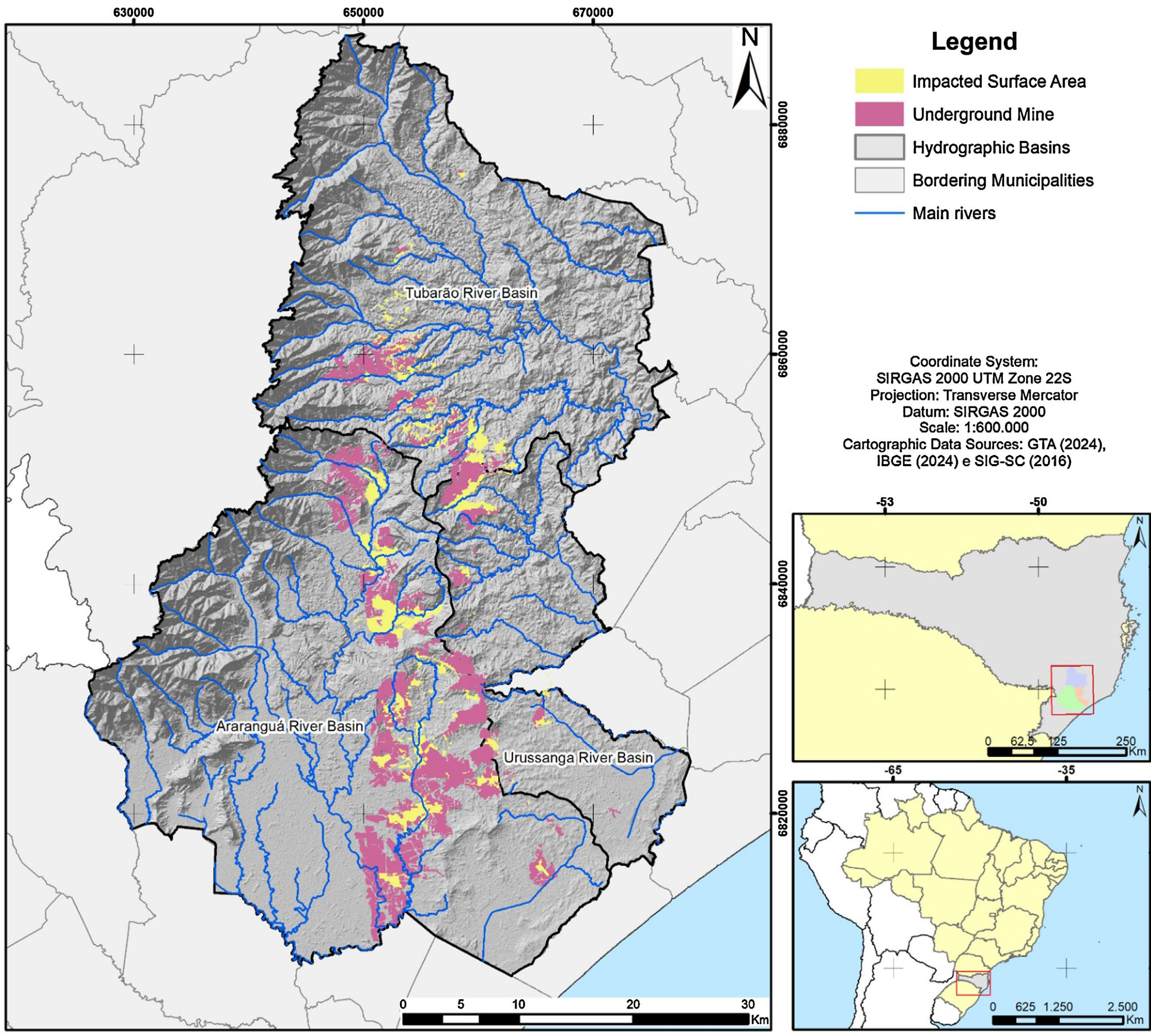

Figure 1. Location of the Santa Catarina Coal Basin and its impacted mining areas in relation to its river basins (Modified from [1]).

realistic improvements in environmental quality over time.

2. Methods

The methodology of this study was structured into three main phases: 1) integrated data collection, 2) comparative analysis, and 3) critical synthesis to support the development of new management strategies.

The first phase involved a multi-source data collection process. It began with a comprehensive literature review to identify global best practices in managing coal mining-impacted areas, resulting in a curated database of over 50 relevant scientific articles and technical reports. This international perspective was complemented by an in-depth examination of the Brazilian legal framework related to mining and contaminated sites. To contextualize these findings, the study also analyzed site-specific technical documents from the Santa Catarina Coal Basin, including environmental investigation reports, engineering plans, and historical monitoring data.

In the second phase, a comparative analysis was conducted. International remediation strategies and management models were benchmarked against current practices in southern Santa Catarina, aiming to identify key differences, gaps and opportunities for improvement in the local approach.

The final phase consisted of a critical synthesis of the findings. By integrating insights from the literature, regulatory context, and local technical documentation, the study assessed the effectiveness of conventional remediation efforts, especially in cases involving deep and complex contamination. This synthesis provided the foundation for proposing a new strategic model for the long-term management of environmental liabilities associated with coal mining.

The 50-item literature database was assembled through a structured search across Scopus, Web of Science, and Google Scholar, using keywords such as "acid mine drainage", "adaptive management", "complex contaminated sites" and "coal mining remediation." Documents published between 1998 and 2023 were considered, with priority given to peer-reviewed studies and technical reports demonstrating practical applications in mining contexts. Inclusion criteria focused on thematic relevance, methodological robustness, and applicability to the Brazilian regulatory and environmental landscape.

3. Current Regulatory Framework for Environmental Management of Coal-Mined Areas in Santa Catarina

Between the filing of Public Civil Action No. 93.80.00533-4 by the Brazilian Federal Public Ministry in 1993—against coal mining companies, the State of Santa Catarina, and the Brazilian Federation—and the judicial ruling in 2000, both public authorities and the coal sector began seeking solutions to the environmental liabilities resulting from coal mining in the region. One of the main challenges in judicial discussions of this nature is that, despite Brazil's extensive and complex environmental legal framework, there is no specific legislation addressing the remediation of coal-mined areas. This legal gap complicates the consolidation of legal certainty and the effectiveness of judicial decisions, especially within the context of Brazil's civil law system.

During this period, a series of initiatives were undertaken to guide the environmental management of coal-mined areas in Santa Catarina. These initiatives are detailed in the following sections.

3.1. Contributions Obtained through Agreements

Mining in Brazil is governed by a set of legal obligations aimed at ensuring the sustainable exploitation of mineral resources, environmental protection, and operational safety. The National Mining Agency (ANM), established by Law No. 13,575/2017, is responsible for regulating, supervising and promoting the mineral sector. Its duties include issuing mining titles, overseeing operations, controlling production and trade, and managing mineral resources in accordance with current legislation [4]. ANM also engages in international cooperation agreements to strengthen regulatory practices.

- **International Cooperation: JICA Agreement**

Given the complexity of environmental liabilities in the Santa Catarina Coal Basin, the Brazilian Federal Government signed a cooperation agreement with the Japanese government through the Japan International Cooperation Agency (JICA). The initiative aimed to conduct feasibility studies, develop remediation and monitoring plans and transfer relevant technologies. The JICA [5] report highlighted areas with intense acid mine drainage (AMD) and recommended techniques such as wet covers and passive treatment using wetlands. Although wet covers did not yield immediate results, they were expected to improve over time with the establishment of aquatic ecosystems. The report also included cost assessments and institutional strengthening proposals.

- **National Technical Collaboration: CETEM and CANMET**

In the early 2000s, the Santa Catarina State Coal Extraction Industry Union (SIECESC) partnered with the Mineral Technology Center (CETEM/MCT) to develop conceptual recovery projects for the region. Supported by CANMET (Canada Centre for Mineral and Energy Technology), the collaboration produced technical documents that served as the basis for Environmental Impact Assessments (EIAs) and Plans for Recovery of Degraded Areas (PRADs).

CETEM [6] outlined engineering solutions for AMD control and environmental recovery, including: 1) Chemical stabilization of contaminants; 2) Physical stabilization of waste and abandoned mines; 3) Landscape restoration (reprofiling and revegetation); 4) Drainage systems to prevent untreated water discharge; and 5) Evaluation of coal reuse strategies with reduced waste generation. Subsequent reports [7]-[9] detailed the performance of active and passive treatment techniques, including wetlands and dry covers.

- **Consolidated Knowledge and Technological Gaps**

The book Brazilian Coal: Technology and Environment [10] compiled extensive experience from professionals and institutions on mining, environmental impacts, revegetation, phytoremediation and risk analysis. These works identified most of the best available technologies for AMD control in Santa Catarina.

However, they did not incorporate modern tools for prioritizing management actions based on site complexity and uncertainty—such as Geographic Information Systems (GIS) or systematic contaminated site management frameworks. These approaches have only emerged in the last decade and were not part of the earlier agreements.

In the most complex cases, where remediation has failed to significantly reduce water acidification, more advanced environmental investigations are required, similar to those applied in industrial contaminated sites.

3.2. Environmental Monitoring by GTA

In 2007, the Technical Group for Monitoring the Execution of the Sentence (GTA) was established to define technical criteria for environmental recovery efforts, prioritize remediation actions, and minimize judicial conflicts related to coal mining impacts in Santa Catarina. The group is composed of representatives from mining companies, the state environmental agency, federal institutions, and the Federal Public Ministry, which plays a leading role in defining the content of the technical guidelines.

Since its inception, GTA has been responsible for producing annual reports on regional environmental quality in areas affected by coal mining. These reports aim to assess the effectiveness of recovery and control measures implemented by the Federal Government and the companies involved in the judicial sentence resulting from the Public Civil Action.

The monitoring activities include data collection on surface and groundwater quality (using a network of wells and abandoned mine entrances), soil cover conditions and the status of the biotic environment. The monitored region encompasses approximately 195,000 hectares, covering portions of the Araranguá, Urussanga and Tubarão river basins, and includes 17 municipalities (**Figure 1**).

3.3. Technical Criteria Established between the Federal Public Ministry and Mining Companies

In 2008, the Federal Public Ministry consolidated the first version of the document Criteria for the Recovery or Rehabilitation of Areas Degraded by Coal Mining, following consensus discussions within the Technical Group for Monitoring (GTA). This document was developed during the execution phase of Public Civil Action No. 93.80.00533-4, with the objective of ensuring the effectiveness of the judicial decision issued by the Brazilian courts.

The technical criteria outlined in the document guide the monitoring and remediation of environmental liabilities and address the following aspects: 1) Control of acid mine drainage (AMD); 2) Monitoring of surface and groundwater quality; 3) Rehabilitation of contaminated soils; 4) Removal and proper disposal of waste materials; 5) Development of recovery plans for degraded areas; 6) Assessment of risks to public health; and 7) Promotion of community participation and transparency.

The first chapter of the document defines key concepts such as degraded area, recovery, restoration, rehabilitation and future use. It establishes that areas degraded by coal mining must undergo recovery and rehabilitation processes aimed at achieving an environmental condition that, while not identical to the original, enables appropriate future use. This approach differs from restoration, which seeks to return the ecosystem to its original state as closely as possible.

However, the document does not specify the conditions or criteria for concluding these activities, nor does it define the requirements for obtaining a formal certificate of recovery. This omission is notable given the strict interpretation of civil environmental liability by the Brazilian Superior Court of Justice, which tends to impose rigorous obligations on environmental degraders.

In terms of water resource management, the absence of detailed mapping of regional aquifers limits the ability to assess long-term impacts comprehensively. Although the GTA's technical criteria provide a structured framework for guiding recovery efforts, persistent information gaps and implementation challenges (particularly those related to contamination complexity and technological constraints), suggest that effective solutions may only be achievable over extended timeframes, potentially spanning decades.

3.4. Conditions for Concluding Obligations

To strengthen the effectiveness and accountability of environmental recovery efforts in coal-mined areas, the Technical Group for Monitoring the Execution of the Sentence (GTA) established two key technical criteria. These include: 1) the soil and water quality parameters required to demonstrate the success of remediation activities, and 2) the standards for evaluating surface water resources to verify the effectiveness of isolation measures in areas affected by tailings and waste deposits. These guidelines were formalized during GTA's 30th meeting, in September, 2017.

According to the established protocol, responsible parties must monitor water quality for a minimum of four years following the completion of recovery works. At the end of this period, surface water quality should be equal to or better than that of upstream reference points. If this condition is not met, corrective actions must be implemented, or monitoring should be extended for up to eight years if there is evidence of declining contaminant concentrations. The parameters to be monitored include iron, sulfate, manganese, acidity, dissolved oxygen, aluminum, pH, and redox potential (Eh).

The record also acknowledges that, in cases where contaminant levels do not evolve as expected, alternative criteria may be necessary. These could be based on environmental risk assessment and contaminated site management principles, allowing for more flexible and context-sensitive decision-making.

Given the complexity of contamination scenarios and the limitations of current criteria, it becomes increasingly relevant to consider complementary approaches. These include the classification of complex sites and the adoption of adaptive management strategies, which rely on robust conceptual models (geological, hydrogeological, and contamination-related), as well as ecological and human health risk assessments. Such frameworks help define clear remediation and rehabilitation goals for each chemical parameter and support the prioritization of actions across impacted sites.

Although these concepts are not yet fully incorporated into the existing criteria, they are supported by key regulatory instruments such as CONAMA Resolution No. 420/2009 (federal) [11] and Normative Instruction No. 74/2023 [12] issued by the Santa Catarina Environmental Institute (IMA-SC). Their integration into the environmental management of coal-mined areas will be further explored in the next chapter, which presents a strategic model designed to address the long-term challenges of recovery in the Santa Catarina Coal Basin.

3.5. Evaluation of Improvements Resulting from Environmental Recovery Works

The 13th report issued by the Technical Group for Monitoring the Execution of the Sentence (GTA), published in 2020, consolidates water quality monitoring data collected since 2002 [1]. Several key findings emerge from this report.

Regarding surface water bodies, the historical data series indicates a 90% reduction in acid load, which likely reflects the gradual recovery of impacted areas through interventions such as land reshaping and revegetation. However, the report highlights that contaminant concentrations in rivers vary depending on the origin of tributary waters. Rivers receiving inflows from non-mining areas tend to show dilution effects, while those fed by tributaries impacted by coal mining continue to exhibit elevated acid loads.

In relation to groundwater, the monitoring network reveals persistent contamination patterns in wells influenced by mining activities, with no significant signs of improvement. These patterns are consistent with those observed in waters from abandoned mine entrances, which continue to exhibit high levels of conductivity, acidity, aluminum, iron, manganese and sulfate.

With respect to soil cover, the report notes that some areas previously subjected to recovery interventions have deteriorated due to lack of maintenance, resulting in setbacks in environmental quality. Conversely, other areas have benefited from ongoing recovery efforts.

As for the biotic environment, the monitoring scope has expanded to include additional sites. Nonetheless, certain areas have experienced negative impacts on the recovery process due to third-party activities, such as agricultural practices and vegetation removal.

3.6. Information Gaps in Regional Groundwater Monitoring

The GTA report [1] acknowledges that groundwater-related issues are being addressed, but highlights important technical limitations in the current monitoring framework. It is assessed that the existing aquifer monitoring network fails to produce representative data on regional groundwater conditions. Most wells reflect highly localized conditions with limited statistical significance, rendering them inadequate for synthesizing information or conducting assessments at a basin-wide scale.

Moreover, the reports do not present a regional geological or hydrogeological conceptual model, nor do they include construction profiles of the monitoring wells. The most relevant groundwater quality data appear within the "integrated analysis of environmental indicators in the sub-basins of notable points," where historical information is presented at a local scale, without broader interpretative context.

Given that the primary objective of regional monitoring is to evaluate the effectiveness of environmental recovery and control measures, the ability to demonstrate improvements in monitored media, particularly groundwater, is essential for concluding remediation cases. Therefore, a critical evaluation of the criteria and methodological procedures used in regional groundwater studies emerges as a necessary and foundational step toward achieving these objectives.

These gaps reinforce the need for more advanced conceptual modeling and integrated assessment frameworks, which will be further explored in the next chapter through the proposal of a strategic model for managing environmental liabilities in coal-mined areas.

3.7. Concepts of Rehabilitation and Remediation: CONAMA 420/2009

The National Environmental Council (CONAMA) is a Brazilian collegial body that plays a central role in formulating and implementing environmental policy. Created under Law No. 6,938 of August 31, 1981, which established the National Environmental Policy (PNMA), CONAMA is composed of representatives from federal, state, and municipal agencies, as well as civil society, ensuring broad democratic participation in environmental decision-making.

Among its responsibilities is the issuance of resolutions—normative instruments that regulate environmental matters nationwide. One such instrument is CONAMA Resolution No. 420/2009, which "provides criteria and guiding values for soil quality regarding the presence of chemical substances and establishes guidelines for the environmental management of contaminated areas by these substances as a result of human activities".

Although the concepts of rehabilitation and remediation are commonly associated with mining activities, they are also central to the management of contaminated sites, as defined in Resolution 420/2009. In this context, rehabilitation refers to intervention actions aimed at achieving a tolerable level of risk for the declared or future use of a contaminated area—a definition that aligns with the interpretation found in the GTA report [1]. Remediation, in turn, is defined as one of the possible actions within the rehabilitation process, involving techniques that remove, contain or reduce contaminant concentrations to levels that no longer pose risks.

This distinction is particularly relevant to the present study, as remediation can serve as a milestone within broader rehabilitation strategies.

The Ministry of the Environment [13] defines a contaminated area as "any site or region that contains concentrations of chemicals or waste, introduced anthropogenically, accidentally or even naturally occurring, that cause or can cause harm to human health, the environment, or other assets to be protected". This interpretation allows for the classification of impacted coal mining areas as contaminated sites, subject to the management procedures outlined in Resolution 420/2009.

The resolution further defines contamination as the "presence of chemicals in air, water or soil, resulting from anthropogenic activities, in concentrations that restrict the use of this environmental resource for current or intended uses, defined based on risk assessment to human health and assets to be protected, in standardized or specific exposure scenarios". In this framework, risk assessment becomes the central criterion for determining the scope and duration of remediation efforts, offering a more objective basis for defining the limits of rehabilitation.

These concepts and approaches are not explicitly addressed in the Technical Criteria document (see item 3.3). Therefore, it is recommended that the criteria be revised to incorporate the possibility of managing environmental liabilities in coal-mined areas as contaminated sites. This revision should be grounded in risk assessment methodologies and aligned with the provisions of CONAMA Resolution 420/2009 and the state-level Normative Instruction IN74/2023 issued by the Santa Catarina Environmental Institute (IMA-SC), which regulates the recovery of contaminated areas.

3.8. Management of Contaminated Sites in the State of Santa Catarina

The procedures for managing contaminated sites in Santa Catarina are outlined in Normative Instruction IN74/2023, issued by the Santa Catarina Environmental Institute (IMA-SC). This state-level regulation was developed to align with the federal framework established by CONAMA Resolution No. 420/2009 and provides detailed criteria and guidelines for the submission of plans and programs aimed at recovering contaminated areas within the state.

The initial version of the regulation was published in 2018, primarily addressing contamination cases related to hydrocarbon spills and industrial activities. In 2023, the regulation was updated to explicitly include coal mining areas among those subject to its provisions.

IN74/2023 introduces specific methodologies for developing conceptual models of contamination exposure, based on progressively detailed environmental investigations and risk assessments to human health and the environment. These models serve as the foundation for defining intervention plans that prioritize actions and optimize resource allocation. This approach is particularly relevant to coal mining areas, given the complexity of contamination patterns and the diversity of exposure pathways, which demand site-specific risk assessment strategies.

The regulation also defines Compliance Points as "monitoring points located near receptors potentially exposed to contaminants, whose concentrations must comply with established targets". This concept allows for the implementation of risk-based monitoring networks that reflect actual exposure scenarios, rather than relying solely on generic environmental standards. It reinforces the practical application of the principles set forth in CONAMA Resolution 420/2009.

Another key provision of IN74/2023 concerns the development of Intervention Plans, which must include long-term remediation or containment measures. These plans are subject to periodic review (at least every five years) to assess the feasibility of achieving the objectives initially established. Considering that coal mining areas often qualify as complex contaminated sites, the regulation's emphasis on adaptive and iterative management is consistent with the need to address environmental liabilities over extended timeframes.

The alignment between IN74/2023 and federal standards, combined with its applicability to coal mining contexts, provides a robust regulatory foundation for the strategic environmental management model proposed in the next chapter.

4. Proposal for a New Approach for the Environmental Management

The content explored in the previous chapter revealed several critical gaps in the current environmental management model applied to coal mining areas in Santa Catarina. These include the absence of regional hydrogeological conceptual models, insufficient groundwater monitoring networks, lack of standardized criteria for closure of environmental obligations, and the absence of systematic tools for risk-based prioritization. These limitations hinder the effectiveness of remediation efforts and underscore the need for a strategic, adaptive framework capable of addressing complexity and uncertainty across the basin, whose content is explored in the next items.

4.1. Adaptive Management: An Effective Framework for Structuring Environmental Decision-Making

The Adaptive Management approach was originally developed for natural resource management initiatives [14]-[17]. It was later adapted by the National Research Council (NRC) for application to contaminated sites and formally conceptualized in 2003, with specific recommendations for contexts marked by high uncertainty and inconclusive remediation outcomes [3]. The NRC emphasized that Adaptive Management should incorporate comprehensive monitoring to reduce uncertainty and enable iterative refinement of strategies, thereby advancing scientific understanding while improving operational effectiveness.

The Interstate Technology & Regulatory Council [2] recommends Adaptive Management for complex contaminated sites, as it helps integrate and structure decision-making processes. This approach enhances the selection and implementation of protective actions, while optimizing costs and timelines.

According to ITRC [2], a complex contaminated site is one where conventional remedial approach are unlikely to achieve closure or transition to sustainable long-term management within a reasonable timeframe. This is often due to persistent technical and non-technical challenges, conditions that characterize many coal mining areas in Santa Catarina.

Technical complexities include geological, hydrogeological, and geochemical variability, as well as the nature and distribution of contaminants and the scale of impacted areas. Non-technical challenges may involve the definition of final and interim environmental objectives, overlapping institutional responsibilities, evolving land use, and financial constraints. These factors collectively hinder the ability to reliably predict the success of environmental management efforts.

The Adaptive Management framework proposed by ITRC [2] includes a structured decision-making flowchart for developing and managing a Conceptual Site Model (CSM) in contaminated areas. The process unfolds in sequential steps: evaluating the need for adaptive management, revising environmental objectives, planning remedial and long-term strategies, and continuously monitoring intervention effectiveness. Feedback loops are embedded throughout, allowing for iterative adjustments whenever outcomes deviate from expectations, making Adaptive Management a powerful tool for navigating technical and institutional uncertainties.

Applications of Adaptive Management in mining contexts have been documented in the United States [2], Canada [18] and Australia [19]. Elements of this methodology are also present in the Global Acid Rock Drainage (GARD) Guide developed by INAP [20].

Figure 2 illustrates the Adaptive Management strategy proposed for addressing environmental liabilities in coal mining areas of Santa Catarina. The framework begins with a Preliminary Assessment and, if necessary, emergency actions. It then advances to the development of an initial CSM, followed by successive investigation

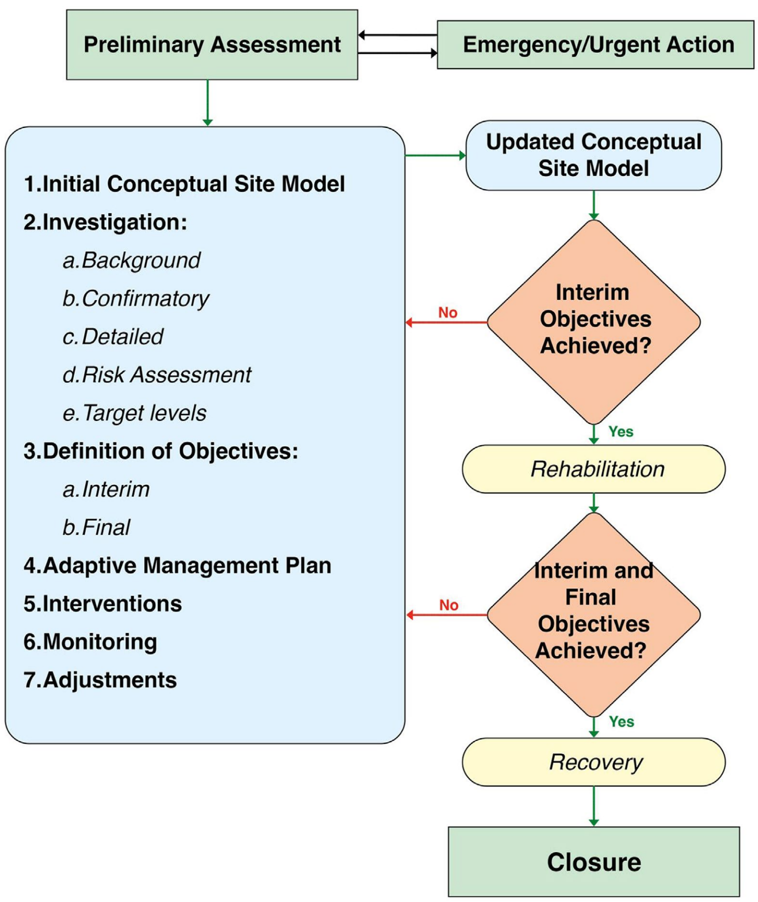

Figure 2. Adaptive management strategy proposed for addressing environmental liabilities associated with coal mining sites in Santa Catarina.

phases—background, confirmatory, detailed and risk assessment. These stages lead to the establishment of target levels and the definition of interim and final environmental objectives. An Adaptive Management Plan is then formulated to guide interventions, monitoring and necessary adjustments. Decision points are incorporated to evaluate progress, enabling feedback loops that refine the CSM and update strategies. Once objectives are met, the site transitions through rehabilitation, remediation, and ultimately closure.

This approach aligns with the guidelines set forth in Normative Instruction IN74/2023, which allows for periodic reassessment and adjustment of environmental measures throughout the implementation of Intervention Plans. The regulation also mandates five-year reviews for long-term actions, directly supporting the iterative and flexible nature of Adaptive Management recommended by ITRC for complex contaminated sites.

4.2. Definition of Objectives for Areas of Environmental Interest

The proposed strategy for the rehabilitation and environmental recovery of sites impacted by coal mining in Santa Catarina is outlined in **Table 1**. This structured framework presents a phased approach, defining both interim and final objectives that range from eliminating acute risks to public safety and human health to achieving full environmental recovery and preparing the site for future use. Timeframes vary from months to decades, depending on the technical and non-technical complexities of each site. Actions are grounded in human-health and ecological risk assessments and involve remediation, engineering, institutional and monitoring measures. The strategy emphasizes immediate risk mitigation while laying the foundation for long-term sustainability and ecological restoration.

The primary goal in contaminated coal mining areas is to achieve environmental rehabilitation tailored to the site's declared future use. This rehabilitated condition may differ from the original pre-mining state but must ensure safety and

Table 1. Proposed interim and final objectives for the rehabilitation and environmental recovery of the contaminated sites related to coal mined areas in Santa Catarina.

Interim Objective	Final Objective	Deadline	Base of Actions	Activities
1. Elimination of risk to the safety of the population	Rehabilitation for the declared future use of the soil	Months	Assessment of sources of risks	Application of engineering and institutional measures
2. Elimination or mitigation of risks to human health		Months to Years	Human health risk assessment	Investigation activities to improve the conceptual model; remediation, containment, engineering, institutional and monitoring measures
3. Elimination or mitigation of ecological risks			Ecological risk assessment	
4. Elimination or mitigation of risks considering legal standards and natural background concentrations	Environmental Recovery	Years to Decades	Legal Standards and background concentrations	

suitability for future use. These standards are consistent with the guidelines established in the Technical Criteria document [21] and CONAMA Resolution 420/2009.

In this context, rehabilitation refers to intervention actions aimed at achieving tolerable risk levels for the declared or intended use of the area [11]. Remediation is one such intervention, involving techniques to remove contain or reduce contaminant concentrations to acceptable levels. These actions are prioritized based on risk assessments that quantify threats to human health, species, communities or ecosystems. Risk assessment thus serves as the principal tool for determining the scope and timing of remediation, helping to define the limits of rehabilitation. In cases where remediation alone is insufficient to meet environmental goals, institutional measures are applied to distance receptors from impacted media.

Environmental liabilities in the region vary in complexity. Less complex areas are expected to reach rehabilitation goals more quickly, while complex sites require an adaptive management approach. The greater the complexity, the more time and resources are needed to refine the Conceptual Site Model (CSM), which underpins all intervention planning. These models must define both final and intermediate objectives. After implementing intervention measures, various environmental media are monitored. If goals are not met within reasonable timeframes, the CSM is updated to support new actions.

Given the prevalence of complex contamination scenarios, it is essential to establish a prioritization of intermediate objectives to progressively enhance safety. The proposed hierarchy is as follows: 1) Elimination of acute hazards to life or health; 2) Elimination or mitigation of risks to human health; 3) Elimination or mitigation of ecological risks; and 4) Elimination or mitigation of risks based on legal standards and natural geochemical background concentrations (for surface and groundwater).

Each site will be evaluated using these criteria to define progressive objectives for the relevant media (soil, water, air, sediments and food). The highest priority involves short-term actions to eliminate acute hazards, while achieving compliance with legal standards is a long-term goal.

To illustrate the proposed prioritization logic, consider two hypothetical sites: Site A is located near a rural community reliant on groundwater for domestic use, while Site B lies within a decommissioned industrial zone with no immediate human receptors. Applying the risk-based scoring criteria, Site A would receive a higher priority due to direct exposure pathways and potential health risks, triggering immediate containment and stakeholder engagement measures. Site B, with lower immediate risk, would be scheduled for further investigation and long-term planning. This approach enables targeted resource allocation and enhances protection of vulnerable populations.

This strategy is aligned with Normative Instruction IN74/2023, which requires acute hazard assessments for each area of environmental interest during CSM refinement. If such hazards are identified, emergency interventions must be implemented to remove receptors from acute exposure scenarios, such as flammable materials or inadvertent recreational use of acidic waters.

These assessments and corrective actions should be executed promptly upon hazard identification. Possible measures include emergency remediation (removal, containment or reduction of contaminants), engineering solutions and institutional actions to isolate receptors and communicate risks.

4.3. Risk Assessments

Human health risk assessments must be conducted for all areas of environmental interest in southern Santa Catarina, in accordance with item 6.4.2 of Normative Instruction IN74/2023 (IMA-SC) and the provisions of CONAMA Resolution No. 420/2009. These assessments serve as the foundation for defining risk-based remediation goals for all identified receptors and affected environmental media, including soil, water, air, sediments, and food, at designated compliance points. The selection of environmental chemicals of interest should be based on the results of investigations carried out during the refinement of the Conceptual Site Model (CSM).

To ensure the accuracy and relevance of these assessments, each area must undergo detailed and updated mapping of receptors, including the registration of tubular wells and cisterns. This information is essential for characterizing exposure pathways and determining the intensity of human health risks.

Intervention actions (whether remediation, engineering, or institutional measures) must be described in the Intervention Plan, prioritized according to the severity of identified risks and implemented accordingly. Where applicable, remediation goals should also be defined based on ecological risk assessments, particularly in areas located near Conservation Units of significant environmental relevance, such as the Morro Albino and Estevão Environmental Protection Areas (APA) in the municipality of Criciúma.

These procedures ensure that both human health and ecological integrity are considered in the decision-making process, reinforcing the adaptive and risk-based approach proposed for managing environmental liabilities in coal mining regions.

4.4. Compliance with Legal Standards and Background Concentrations in Water Resources

Brazil currently lacks federal legislation specifically addressing the rehabilitation and remediation of contaminated areas. Among all states, only São Paulo has developed a comprehensive legal framework and accumulated significant experience in managing such sites. In contrast, most other states operate with limited regulatory instruments and institutional capacity. Although Bill No. 2732/2011 seeks to establish national guidelines, it remains under review in the federal legislative chambers.

As a result, regulation in this field is primarily administrative, relying on resolutions and normative instructions issued by environmental agencies, such as those previously discussed in this study.

Within this context, item 6.4.2.1 of Normative Instruction IN74/2023 (IMA-SC) establishes that potential risks in contaminated areas can be identified when substances of interest exceed applicable legal standards for surface and groundwater. These exceedances characterize the respective media as receptors of potential contamination.

For surface waters, CONAMA Resolution No. 357/2005 [22] defines quality standards based on watercourse classification, aiming to protect natural ecosystems, particularly those within Permanent Preservation Areas. For groundwater, potability standards are defined by Ordinance No. 888/2021 [23] and CONAMA Resolution No. 396 [24], which set maximum permissible concentrations for chemical parameters at compliance points. IN74/2023 further clarifies that groundwater ingestion risks exist when substances of interest exceed potability limits in wells, springs or monitoring points.

However, in mining areas, natural geochemical conditions may result in background concentrations of certain substances that exceed these legal thresholds. In such cases, site-specific standards, based on statistical geochemical background studies, may be adopted in place of the default federal criteria. This flexibility is essential for ensuring that remediation goals are technically feasible and environmentally meaningful.

In general, legal standards for water quality are highly conservative, often requiring very low contaminant concentrations. Achieving these targets can demand long timeframes and substantial technical and financial resources, even in areas with relatively low contamination complexity. For this reason, it is not recommended to prioritize legal compliance goals in the initial stages of remediation. Instead, a phased approach should be adopted, focusing first on acute risk mitigation and progressively refining conceptual models to guide long-term interventions. The effectiveness of these measures should be evaluated through extended monitoring programs.

This perspective contrasts with the Technical Criterion established by the GTA in its 30th meeting (September, 2017), which mandates a four-year post-recovery monitoring period for surface waters. If water quality does not meet upstream reference levels, corrective actions must be taken, or monitoring extended to eight years if declining trends are observed. At that time, no consensus was reached regarding groundwater criteria.

The contaminated area management approach, particularly when guided by adaptive management principles, advocates for greater flexibility in setting timelines and remediation targets. These determinations should be based on site-specific conceptual models, incorporating background concentration assessments and complexities such as commingled plumes. This methodology is supported by technical and legal references, including research from centers of excellence (e.g., ITRC), CONAMA Resolution No. 420/2009, and IN74/2023 (IMA-SC).

4.5. Definition of Compliance Points

According to Normative Instruction IN74/2023 (IMA-SC), Compliance Points are monitoring locations situated near receptors potentially exposed to contaminants, where concentrations in various environmental media, such as soil, water, air, sediments, and food, must meet established environmental goals. These points serve as benchmarks for evaluating whether remediation and management efforts are effectively protecting human health and ecological integrity.

Intermediate monitoring locations between the source of contamination and the receptors are referred to as Sentinel Points. These are instrumental in identifying concentration trends and assessing the effectiveness of intervention measures over time.

The definition and spatial distribution of both Compliance and Sentinel Points must be guided by detailed environmental investigations and risk assessments. Monitoring points should be strategically placed along the pathway from contamination sources to receptors, enabling a comprehensive understanding of exposure dynamics.

From a technical standpoint, it is acceptable to observe less restrictive contaminant concentrations near source areas, while applying more stringent environmental targets at Compliance Points. This gradient reflects the prioritization criteria discussed earlier, where risk mitigation is progressively reinforced as proximity to receptors increases.

Importantly, the proposed environmental management strategy supports the gradual reduction of contaminant concentrations over time at both Compliance and Sentinel Points. This progression should be pursued regardless of fixed deadlines for achieving final remediation goals, emphasizing the adaptive nature of the approach and its alignment with long-term sustainability objectives.

4.6. Impacted Area Recovery Strategies

The recovery strategy for areas impacted by coal mining should be structured along two complementary fronts. The first involves evaluating the environmental effectiveness of previously implemented interventions. The second focuses on planning and executing new remediation and engineering measures, to be detailed within a formal Intervention Plan.

In all cases, whether interventions have been completed or are ongoing, a multidisciplinary evaluation is essential. Teams should assess the specific conditions of each site to determine whether environmental objectives have been met, whether the current strategy remains appropriate, and whether adjustments are needed. These assessments must be grounded in accumulated technical experience and site-specific data.

To ensure a comprehensive evaluation, the following professional contributions should be considered: 1) Geotechnical engineers, to assess the structural stability of waste deposits and identify the need for maintenance or reinforcement measures; 2) Geologists, to evaluate subsidence risks and geological integrity; 3)

Geochemists, to analyze the effectiveness of interventions in reducing acid mine drainage generation; and 4) Biologists, to monitor vegetation development and its role in stabilizing soils and mitigating acid generation.

This integrated approach reinforces the principles of adaptive management, allowing for iterative refinement of strategies based on observed outcomes. It also ensures that recovery efforts are technically sound, environmentally effective and aligned with long-term sustainability goals.

4.7. Intervention and Remediation Plans

According to Normative Instruction IN74/2023 (IMA-SC), the Intervention Plan must encompass all techniques (remediation) and measures (engineering and institutional controls) necessary to enable the future use of environmentally impacted areas. These plans must be aligned with the environmental objectives and goals defined for each area of interest.

The regulation establishes specific requirements for coal mining areas, stipulating that remediation measures (aimed at controlling or eliminating primary contamination sources) must be selected based on bench-scale and pilot tests. The chosen techniques must be described in detail, including their sizing, implementation procedures and performance evaluation criteria [12] (item 6.4.5.1). Intervention measures are categorized by duration: short-, medium- and long-term (exceeding five years). For long-term measures, periodic reviews every five years are required to assess the feasibility of meeting the objectives outlined in the Intervention Plan. This cyclical review process is consistent with the adaptive management framework proposed in this study.

All selected measures must be technically justified and thoroughly documented in the Intervention Plan. Remediation techniques should prioritize two overarching goals: 1) reducing or isolating primary contamination sources, and 2) minimizing or eliminating acid drainage generation in both surface water bodies and aquifers. Several best practices for controlling acid mine drainage have already been identified and are available for application in coal mining areas of Santa Catarina, as documented in international technical guides such as the Mining Waste Treatment Technology Selection [25] and the Global Acid Rock Drainage Guide [20].

Significant contributions to this knowledge base were made through international cooperation agreements, notably those involving JICA and CETEM-CANMET during the 1990s and 2000s. These initiatives provided technical foundations for a range of engineering solutions applicable to environmental recovery and acid drainage control.

Conventional engineering solutions that should be considered in Intervention Plans include: 1) Alternatives for economic coal utilization with reduced solid waste generation; 2) Physical stabilization of waste disposal areas and abandoned mines; 3) Chemical stabilization of contaminants; 4) Construction of drainage systems to prevent water contamination or untreated discharge, including techniques such as wet and dry covers, passive treatment systems, waste isolation, mine sealing, and chemical or biological treatment of acidic waters; and (5) Landscape recovery through regrading and revegetation.

Despite the availability of established techniques, there remains ample opportunity for scientific research aimed at developing innovative and cost-effective remediation solutions tailored to the local geographic context. For example, pilot tests could explore the use of regional resources (such as rice straw and livestock residues) as organic matter sources to create anoxic subsurface environments that inhibit acid drainage formation. Steelmaking by-products (e.g., steel slag) could be evaluated as alkaline materials in passive treatment systems, and native plant species could be tested for phytoremediation potential.

Such research initiatives, integrated into pilot-scale remediation efforts, would contribute to expanding the technical toolkit for managing environmental liabilities in coal mining areas and reinforce the adaptive, site-specific nature of the proposed management strategy.

Despite the structured nature of the proposed intervention plans, certain limitations must be acknowledged. The current groundwater monitoring network lacks sufficient spatial coverage to support basin-wide assessments. Additionally, scaling the model to the full 900,000 ha area introduces uncertainties related to geological variability, data availability and institutional capacity. These constraints highlight the need for iterative planning and ongoing refinement of remediation strategies.

4.8. Communication with Stakeholders

According to the procedures outlined in Normative Instruction IN74/2023 (IMA-SC), public authorities must establish risk communication mechanisms that are appropriate to the diverse profiles of stakeholders, ensuring clarity and accessibility, particularly for socially and environmentally vulnerable groups. This requirement includes the formal registration of contaminated areas and the implementation of inclusive communication strategies.

In the context of coal mining, a specific communication plan should incorporate public hearings integrated into the activities of the Technical Monitoring Group (GTA), as well as the dissemination of information through public Geographic Information Systems (GIS). These platforms should detail environmental impacts such as river acidification and restrictions on the use of wells, enabling transparent and accessible dialogue with affected communities.

An effective communication strategy plays a critical role in facilitating public understanding, advancing environmental recovery plans and minimizing risks and conflicts arising from misinformation or lack of engagement. International experience reinforces this need: in the United States, the Interstate Technology & Regulatory Council [2] found that institutional control measures failed in 41% of cases due to ineffective stakeholder communication. While 90% of former property owners had access to relevant information, only 43% of new owners and 20%

of tenants or adjacent neighbors were adequately informed.

Risk communication must be tailored to the specific context of each area, considering the diversity of stakeholders, their relationships, and levels of understanding. Ideally, these factors should be evaluated in advance to optimize the focus of communication efforts and reduce the likelihood of misunderstandings.

To ensure consistency and effectiveness, communication strategies should be formalized within a dedicated Communication Plan. This plan should include: 1) Contextual analysis of the area and stakeholders; 2) Clear objectives and expected outcomes; 3) Identification of responsible parties; 4) Selection of tools and communication channels; 5) Implementation schedule; and 6) Methods for evaluating effectiveness (quantitative and qualitative).

The success or failure of communication efforts can be measured through both technical indicators and social feedback. As emphasized by ITRC [26], "the heart of good risk communication is building trust among all, so that it is readily understood, for the public to make informed choices".

The proposed GIS-based communication tools should be anchored to tangible data layers, including groundwater monitoring points, land-use zoning maps, and environmentally restricted areas. This integration enhances transparency by allowing stakeholders to visualize contamination risks, remediation progress and decision-making criteria in a spatially explicit format, thereby fostering trust and accountability.

4.9. Institutional Control Measures and Long-Term Monitoring

The procedures for managing contaminated areas, as defined in Normative Instruction IN74/2023 (IMA-SC), establish that environmental monitoring must be conducted across distinct stages. These include: 1) Evaluation of the efficiency and effectiveness of remediation measures; 2) Assessment of the performance of institutional and engineering control measures; and 3) Monitoring of post-remediation conditions to support rehabilitation.

Following these monitoring activities, the responsible party may request the issuance of the Rehabilitation Term for Declared Use/Closure from the environmental authority (IMA). This request must be substantiated by the results of monitoring and by demonstrated compliance with all stages of the contaminated area management process. The Rehabilitation Term must also include a description of the engineering and institutional control measures to be maintained, along with the corresponding long-term monitoring plan. This instrument provides legal certainty for the closure of environmental obligations while ensuring continued oversight where necessary.

In cases where institutional control measures must remain in place, the request must be accompanied by a new proposal detailing their location, duration of application, and the associated monitoring procedures. The Rehabilitation Term must explicitly include this information to ensure transparency and enforceability.

This framework is particularly relevant for coal mining areas, where complete remediation may not be technically feasible or economically viable. In such contexts, long-term management and monitoring become essential to safeguard human health and environmental integrity. The approach outlined in IN74/2023 enables the productive reuse of impacted areas while maintaining appropriate environmental controls, aligning with the principles of adaptive management and risk-based decision-making.

5. Conclusions

The analysis of the state of the art in environmental management of mined areas reveals a growing convergence between international best practices and the methodologies used for managing contaminated sites. Central to this convergence is the emphasis on developing robust Conceptual Site Models (CSMs) and conducting ecological and human health risk assessments as prerequisites for designing effective intervention plans. These elements are essential for guiding the recovery of both physical and biotic components of degraded environments.

In the case of coal mining areas in Santa Catarina, the environmental liabilities are extensive, complex, and distributed across multiple sites and responsible parties. These areas involve numerous potential receptors and require long-term management strategies. Given the limitations of current technical criteria and the diversity of contamination scenarios, the adoption of new approaches that incorporate sustainability principles and adaptive management is both necessary and urgent.

The proposed framework, centered on Adaptive Management, is particularly suited to mining sites classified as Complex Areas, where technical and institutional uncertainties hinder the achievement of conventional remediation goals. This methodology allows for iterative refinement of strategies, integration of multidisciplinary knowledge and prioritization of actions based on risk and feasibility.

From a social perspective, the adoption of this approach has the potential to influence public authorities in the development of new environmental policies tailored to complex contaminated areas. This represents an unprecedented advancement in the management of mined lands in Brazil and could serve as a model for other mining regions across the country.

From an economic standpoint, Adaptive Management offers a more sustainable pathway for addressing long-term environmental liabilities. It enables more realistic financial planning, legal accountability and resource allocation, especially in contexts where full remediation is not immediately feasible.

In terms of practical contributions, the implementation of this strategy, supported by IN74/2023 and CONAMA Resolution 420/2009, can generate technical references applicable to similar cases. The development of geochemical background studies, for instance, may result in site-specific standards that inform future remediation efforts in other Brazilian mining areas.

Looking ahead, the proposed model opens avenues for scientific research, technological innovation and institutional strengthening. Pilot projects involving alternative remediation techniques, stakeholder engagement plans, and long-term monitoring frameworks can serve as laboratories for refining the approach. Moreover, the integration of public Geographic Information Systems (GIS) and transparent communication mechanisms will be essential for building trust and ensuring accountability.

In summary, the proposed strategy not only addresses the immediate challenges of coal mining liabilities in Santa Catarina but also lays the groundwork for a broader transformation in environmental governance, with implications for policy, practice, and public engagement across Brazil.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] GTA: Grupo Técnico de Assessoramento à Execução da Sentença (2020) 13th Monitoring Report of Environmental Indicators. v. 1. Compliance Process of Sentence, 345.

[2] ITRC: Interstate Technology and Regulatory Council (2017) Remediation Management of Complex Sites. https://rmcs-1.itrcweb.org

[3] NRC: National Research Council (2003) Environmental Cleanup at Navy Facilities: Adaptive Site Management. National Academies Press.

[4] Brasil, Agência Nacional de Mineração (2022) Resolução ANM nº 143, de 21 de novembro de 2023. Altera a Resolução ANM nº 122, de 28 de novembro de 2022, que aprova o novo Regimento Interno da Agência Nacional de Mineração—ANM. Diário Oficial da União: Seção 1, 95.

[5] JICA: Japan International Cooperation Agency (1998) Feasibility Study on Recuperation of Mined-Out Areas in the Southern Region of Santa Catarina State, Federative Republic of Brazil. https://openjicareport.jica.go.jp/667/667/667_703_11416336.html

[6] CETEM: Centro de Tecnologia Mineral (2001) Conceptual Project for Environmental Recovery of the Southern Coal Basin of Santa Catarina. Technical Reports for SIESESC. CETEM/MCT.

[7] CETEM: Centro de Tecnologia Mineral (2002) Sub-Project: Treatment of Acid Drainage Effluents through Active Processes. Technical Report for SIESESC. CETEM/MCT.

[8] CETEM: Centro de Tecnologia Mineral (2002) Sub-Project: Treatment of Acid Drainage Effluents Using Passive Processes and Wetlands. Technical Report for SIESESC. CETEM/MCT.

[9] CETEM: Centro de Tecnologia Mineral (2002) Project III: Mitigation Processes for Acid Drainage Formation Using Dry Covers. Technical report for SIESESC 2002-038-00. CETEM/MCT. https://clu-in.org/issues/

[10] Soares, P.S.M., Santos, M.D.C. and Possa, M.V. (2008) Brazilian Coal: Technology and Environment. CETEM, 300.

[11] CONAMA: Conselho Nacional do Meio Ambiente (2009) Resolution no. 420, of December 28, 2009. Diário Oficial da União, 81-84.

[12] IMA: Instituto do Meio Ambiente de Santa Catarina (2023) Normative Instruction no. 74: Management of Contaminated Areas. IMA, 31.

[13] Brasil, Ministério do Meio Ambiente (2020) Programa Nacional de Recuperação de Áreas Contaminadas: Agenda Nacional de Qualidade Ambiental Urbana. MMA.

[14] Holling, C.S. (1980) Adaptive Environmental Assessment and Management. *Forest Science*, **26**, 435-436.

[15] Walters, C.J. and Holling, C.S. (1990) Large-Scale Management Experiments and Learning by Doing. *Ecology*, **71**, 2060-2068. https://doi.org/10.2307/1938620

[16] Lee, K.N. (1993) Compass and Gyroscope: Integrating Science and Politics for the Environment. Island Press, 225-235.

[17] Lee, K.N. (1999) Appraising Adaptive Management. *Conservation Ecology*, **3**, Article 3. https://doi.org/10.5751/es-00131-030203

[18] Lima, A.T., Mitchell, K., O'Connell, D.W., Verhoeven, J. and Van Cappellen, P. (2016) The Legacy of Surface Mining: Remediation, Restoration, Reclamation and Rehabilitation. *Environmental Science & Policy*, **66**, 227-233. https://doi.org/10.1016/j.envsci.2016.07.011

[19] Swayne, N. (2012) Regulating Coal Seam Gas in Queensland: Lessons in an Adaptive Environmental Management Approach. *Environmental and Planning Law Journal*, **29**, 163-185.

[20] INAP: International Network for Acid Prevention (2009) Global Acid Rock Drainage Guide. http://www.gardguide.com

[21] GTA: Grupo Técnico de Assessoramento à Execução da Sentença (2008) 2nd Monitoring Report of Environmental Indicators. v. 1. Compliance Process of Sentence, 240.

[22] CONAMA: Conselho Nacional do Meio Ambiente (2005) Resolution no. 357, of March 17, 2005. Diário Oficial da União, 58-63.

[23] Brasil, Ministério da Saúde (2021) Portaria GM/MS nº 888, de 4 de maio de 2021. Altera o Anexo XX da Portaria de Consolidação GM/MS nº 5, de 28 de setembro de 2017, para dispor sobre os procedimentos de controle e de vigilância da qualidade da água para consumo humano e seu padrão de potabilidade. Diário Oficial da União, 126.

[24] CONAMA: Conselho Nacional do Meio Ambiente (2008) Resolution no. 396, of April 3, 2008. Diário Oficial da União, 64-68.

[25] ITRC: Interstate Technology and Regulatory Council (2010) Mining Waste Treatment Technology Selection. https://projects.itrcweb.org/miningwaste-guidance/

[26] ITRC: Interstate Technology and Regulatory Council (2020) Risk Communication Toolkit. https://rct-1.itrcweb.org