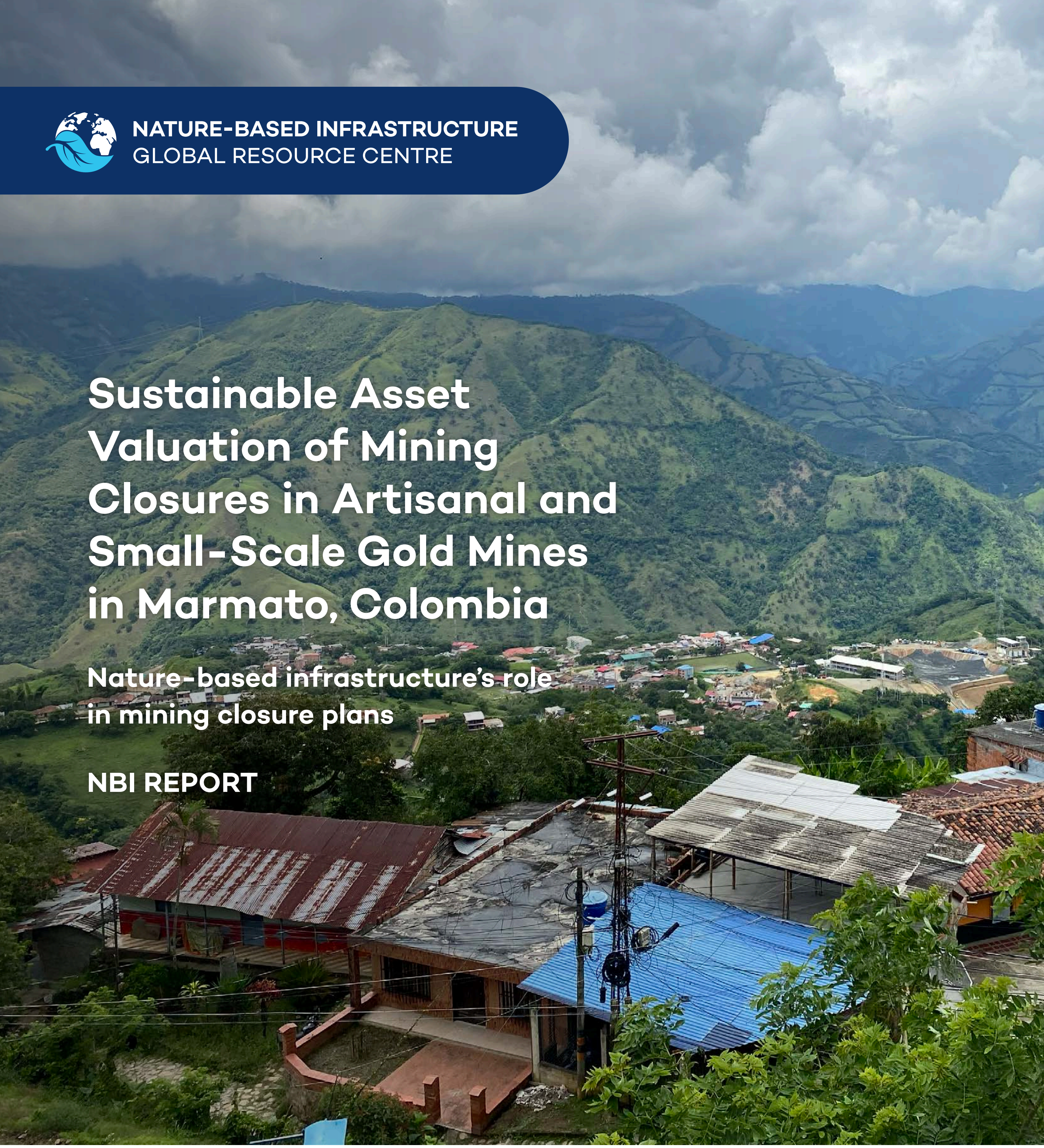

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Sustainable Asset Valuation of Mining Closures in Artisanal and Small-Scale Gold Mines in Marmato, Colombia

Nature-based infrastructure's role in mining closure plans

NBI REPORT

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Sustainable Asset Valuation of Mining Closure in Artisanal and Small-Scale Gold Mines in Marmato, Colombia: Nature-based infrastructure role in mining closure plans

April 2026

Written by Nathalia Niño and Andrea M. Bassi

Photo: Luc Lapointe

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Liesbeth Casier reviewed the analysis and report and provided valuable comments.

Author Contributions

Authors are listed in alphabetical order. Andrea M. Bassi reviewed the model, results, and report, and contributed to writing several sections of the report. Nathalia Niño coordinated communications with Capitals Hub Canada, The Blended Capital Group, the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, and the Colombian National Mining Agency; carried out the literature review; developed an Excel model based on systems thinking and integrated cost-benefit analysis; contributed to defining the scope of the analysis; and led the drafting of the report.

Executive Summary

Marmato, located in the department of Caldas, is one of Colombia's most historically significant gold-mining territories, where artisanal and small-scale gold mining (ASGM) has shaped the local landscape, economy, and cultural identity over centuries. Mining remains a central source of employment and income for the municipality, with hundreds of underground operations distributed across steep and geologically complex hillsides. At the same time, Marmato is currently undergoing an institutional transition, marked by ongoing efforts to recognize ancestral mining practices, advance formalization, and develop scale-appropriate environmental management instruments. In this evolving context, mine-closure planning for ASGM is still emerging, while environmental, geotechnical, and social risks, such as landslides, tunnel instability, water quality pressures, and ecosystem degradation, remain key considerations for the long-term safety, resilience, and sustainability of the territory, particularly in highly concentrated areas such as Cerro El Burro.

To support evidence-based decision making on mine closure in this complex context, the Nature-Based Infrastructure (NBI) Global Resource Centre conducted a Sustainable Asset Valuation (SAVi) assessment to evaluate alternative ASGM closure pathways in Marmato. The assessment focuses on the role of NBI as a core component of mine-closure plans, alongside conventional stabilization measures, and explores how different closure approaches influence long-term environmental, social, and economic outcomes. The analysis is intended to inform national and local authorities, mining stakeholders, and development partners at a time when Colombia's regulatory framework for artisanal and small-scale mine closure is still emerging. The assessment evaluates three closure pathways:

1. a Baseline "no-action" Scenario, in which mines are abandoned without structured closure interventions;
2. a Comprehensive Closure Plan Scenario implemented at the end of mine life in line with anticipated regulatory requirements; and
3. a Progressive Comprehensive Closure Plan Scenario, in which stabilization, rehabilitation, and environmental recovery measures are implemented incrementally during mine operations.

These scenarios are not intended as technically validated closure designs; rather, they are analytically consistent representations of plausible closure pathways that can be assessed using the SAVi framework under current regulatory and data conditions.

The SAVi methodology combines systems thinking with an integrated cost-benefit analysis (CBA). In this assessment, the qualitative analysis plays a central role and constitutes the foundation of the economic valuation exercise. Through participatory systems mapping and the co-creation of a causal loop diagram (CLD), the assessment identifies the key social, environmental, economic, and institutional dynamics shaping ASGM in the territory. The systems map highlights how informal mining, environmental degradation, livelihood vulnerability, and geotechnical risk reinforce one another over time. Landslide susceptibility, tunnel instability, water contamination, biodiversity loss, and declining agricultural productivity interact with limited livelihood alternatives, sustaining dependence on mining despite elevated safety and environmental risks.

Within this system, the qualitative analysis identifies formalization and mine closure as critical leverage points capable of moderating long-term risks. In particular, closure measures that integrate physical and chemical stabilization with ecosystem rehabilitation and hydrological recovery, implemented progressively rather than at the end of mine life, emerge as interventions with the potential to alter reinforcing feedback loops. The systems analysis also underscores that mine closure in Marmato cannot be treated solely as a technical end-of-life obligation but must be understood as a territorial risk-management process embedded in social dependence on mining and evolving institutional arrangements.

Building on these qualitative insights, the quantitative analysis translates a selected subset of indicators into an integrated CBA, implemented as a pilot exercise. Due to data limitations and the absence of empirical post-closure evidence for ASGM in Marmato, the valuation relies on indicative assumptions informed by literature, stakeholder input, and information collected from comparable contexts. The CBA covers the period 2025–2060 and applies a 3.5% social discount rate. Indicators quantified include capital and post-closure costs, selected ecosystem services generated through rehabilitation (erosion control, nutrient recycling, carbon sequestration, and biodiversity recovery), and avoided costs related to risk reduction, particularly avoided mortality risk and avoided infrastructure damage.

The quantitative results are presented as illustrative rather than definitive, serving to demonstrate how qualitative system dynamics can be translated into economic terms within the SAVi framework. The analysis shows that avoided costs dominate total benefits across closure scenarios, with avoided mortality risk linked to reduced exposure to landslides, rockfalls, tunnel collapse, and unstable slopes emerging as the single largest benefit category. Avoided infrastructure damage also contributes meaningfully, reflecting reduced impacts on local roads, access paths, and nearby structures. Monetized ecosystem service benefits from NBI are smaller in magnitude but reinforce the case for integrated rehabilitation, particularly when implemented early.

When aggregated in discounted values, the comprehensive closure plan implemented at the end of mine life yields a benefit-to-cost ratio close to one, indicating near break-even performance and high sensitivity to assumptions. By contrast, the Progressive Comprehensive Closure Plan yields a benefit-to-cost ratio of approximately 1.44, with an internal rate of return above the social discount rate applied. This improved performance is driven primarily by the timing of interventions: earlier implementation allows risk reduction and ecosystem service benefits to accrue sooner, increasing their present value and reducing cumulative exposure to environmental and safety hazards.

Importantly, the assessment does not capture the full range of impacts identified in the qualitative analysis. Several effects, such as avoided non-fatal injuries, long-term health system savings, improvements in water quality and availability, reductions in downstream sedimentation and flooding, land-value recovery, and broader social stability, are not monetized. As such, the quantitative results should be interpreted as conservative and indicative, and primarily as a demonstration of method rather than a final valuation of mine-closure options in Marmato.

Beyond the scenario-specific results, the assessment highlights cross-cutting insights that are critical for understanding mine closure in ASGM contexts such as Marmato. First, mine closure remains a largely underdeveloped component of artisanal and small-scale mining (ASM) formalization processes, despite being a legal requirement under Colombia's environmental licensing framework. This creates a structural gap in which mining activities continue to accumulate environmental and safety liabilities that are unlikely to be addressed at the end of mine life without external support, increasing the likelihood that costs are transferred to communities or the state.

Second, the Marmato case demonstrates the importance of adopting a systems-based perspective, especially when evaluating mine-closure options in data-constrained and institutionally complex settings. The SAVi methodology reveals how qualitative systems mapping can highlight the reinforcing and undesirable feedback loops linking informal mining, environmental degradation, livelihood vulnerability, and exposure to geotechnical and health risks. It can also show how progressive mine closure can function as a leverage point to curb these dynamics. By integrating systems thinking with an indicative economic valuation, the assessment reframes mine closure as a long-term territorial investment in risk reduction and resilience rather than a narrow end-of-life technical obligation.

Overall, this assessment demonstrates the SAVi methodology's applicability and value for analyzing ASGM closure in complex and transitional contexts. By placing systems thinking at the centre of the analysis and using quantitative valuation as a complementary tool, SAVi provides a structured and transparent approach to informing complex policy and investment decisions. The Marmato case illustrates how progressive closure approaches, supported by NBI, can deliver stronger economic performance, earlier risk reduction, and more durable environmental and social outcomes. As such, the methodology offers a replicable pathway to integrate mine closure into ASM formalization strategies in Marmato, across Colombia, and in other ASM territories facing similar challenges.

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Abbreviations and Acronyms

ASM	artisanal and small-scale mining
BCR	benefit–cost ratio
CapEx	capital expenditures
CBA	cost-benefit analysis
CLD	causal loop diagram
COP	Colombian peso
ICMM	International Council on Mining and Metals
IGF	Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development
MinEnergía	Ministerio de Minas y Energía
NBI	nature-based infrastructure
NbS	nature-based solution
O&M	operation and maintenance
SAVi	Sustainable Asset Valuation

Glossary

Artisanal and small-scale mining (ASM)	In Colombia, ASM is recognized by law as a low-scale productive activity of a traditional—and in many cases, ancestral—nature, developed through small mining ventures and closely linked to the subsistence and territorial identity of the communities that carry it out, as outlined in the Decree 1153 of 2025 (Ministerio de Minas y Energía, 2025).
Artisanal and small-scale gold mining (ASGM)	A subset of ASM that focuses specifically on the extraction of gold. It often involves underground or alluvial mining methods and may include on-site mineral processing using gravity concentration, amalgamation, or cyanidation.
Discounting	A financial process to determine the present value of a future cash value.
Environmental liabilities	Environmental risks and impacts arising from mining activities that require remediation, management, or long-term monitoring, including those associated with abandoned, inactive, or improperly closed mines. These liabilities may result in financial obligations for operators or, in their absence, for governments (World Bank Group, 2021).
Indicator	Parameters of interest (to one or several stakeholders) that provide information about the development of key variables in the system over time and trends that unfold under specific conditions (United Nations Environment Programme [UNEP], 2014).
Internal rate of return (IRR)	An indicator of the profitability prospects of a potential investment. The IRR is the discount rate that makes the net present value of all cash flows from a particular project equal to zero. Cash flow net of financing gives us the equity IRR.
Methodology	The theoretical approach(es) used for the development of different types of analysis tools and simulation models. This body of knowledge describes the underlying assumptions used, as well as qualitative and quantitative instruments for data collection and parameter estimation (UNEP, 2014)

Mining formalization	The process through which ASM operations transition from informal or illegal status to legal recognition under the national mining, environmental, labour, and fiscal framework. In Colombia, formalization involves obtaining legal mining rights or subcontracts, complying with environmental regulations, implementing occupational health and safety measures, and progressively adopting technical and administrative standards appropriate to the scale of operation (Ministerio de Minas y Energía & Agencia Nacional de Minería, 2023).
Nature-based infrastructure (NBI)	A subset of nature-based solutions with a focus on nature-provided infrastructure services. The NBI Global Resource Centre defines NBI as follows: “natural ecosystems or functional landscapes that can be conserved, rehabilitated, and maintained to enhance capacities and reduce the need for grey infrastructure, as well as hybrid infrastructure that combines engineered and NBS” (Bechauf et al., 2022).
Net benefits	The cumulative number of monetary benefits accrued across all sectors and actors over the lifetime of investments compared to the baseline, reported by the intervention scenario.
Scenarios	Expectations about possible future events used to analyze potential responses to these new and upcoming developments. Consequently, scenario analysis is a speculative exercise in which several future development alternatives are identified, explained, and analyzed for discussion about what may cause them and the consequences these future paths may have on our system (e.g., a country or a business).
Simulation model	Systemic maps that are simplifications of reality to help to reduce complexity and describe, at their core, how the system works. Simulation models are quantitative by nature and can be built using one or several methodologies (UNEP, 2014).

1.0 Introduction

Marmato, located in the department of Caldas, is one of Colombia's most historic gold-mining regions, where artisanal and small-scale mining (ASM) has shaped the local landscape and economy for generations. Mining in Marmato is also ancestral, with historical records documenting continuous gold extraction dating back to the pre-colonial period. Today, mining remains deeply embedded in local livelihoods: the National Mining Agency (Agencia Nacional de Minería [ANM]) has identified 482 mining units, which together generate roughly 3,000 direct jobs (ANM, 2025), most of them associated with traditional artisanal miners. These operations are intertwined with the daily life of the more than 9,000 Marmato residents.

The institutional context of mining in Marmato is currently undergoing a significant transition. In 2025, Colombia enacted Decree 1153, a new regulation that officially recognizes ancestral and artisanal mining in the territory and establishes specific mechanisms, such as registration by mining levels, to support the formalization of artisanal and small-scale miners. While this decree represents an important milestone, the formalization process is still in its early stages, with national plans to accelerate it (Ministerio de Minas y Energía [MinEnergía] & ANM, 2023). Concrete progress has been made by filing subcontracts for dozens of miners and launching a pilot formalization project in one area of Cerro El Burro. However, the majority of production units remain in transition toward formalization.

Because formalization is a prerequisite for developing environmental management instruments, Marmato currently has no officially approved mine-closure plans for ASM. As a result, most mining areas lack structured closure planning, leaving the territory exposed to long-term environmental liabilities, such as erosion, soil instability, and water contamination. These risks are particularly acute due to the predominance of underground mining in steep and geologically unstable hillsides. Assessments show that many mines are located in zones with a high risk of landslides. The situation is particularly critical in Cerro el Burro, where 265 mining units operate in one of the municipality's most geologically sensitive hillsides. The concentration of informal underground workings increases the likelihood of collapse, land subsidence, and mass movements—risks that grow during intense rainfall events. In parallel, pressure on water sources and natural ecosystems, including the Bosque Seco Tropical, is intensified by mining discharges. This is amplified by the fact that multiple water intake points feeding both communities and processing plants originate from this area.

Given this context, the development of effective mine-closure strategies is both urgent and complex. Closure solutions must address environmental degradation and geotechnical instability while also considering that many families depend on artisanal mining. To support the analysis of options that can deliver on both goals, the Sustainable Asset Valuation (SAVi) assessment evaluates three closure scenarios:

- The Baseline Scenario represents a "no-action" situation in which mines are abandoned without any closure intervention, generating ongoing environmental liabilities and leaving the territory exposed to continued degradation.
- The Comprehensive Closure Plan Scenario reflects a closure process carried out in accordance with official regulations, including baseline studies, physical and chemical

stabilization, waste management, ecosystem restoration through nature-based infrastructure (NBI), and post-closure monitoring.

- The Progressive Comprehensive Closure Plan Scenario begins rehabilitation activities years before final closure, allowing early restoration benefits, reducing the intensity and cost of closure at the end of the mine's life, and enabling a smoother and more sustainable transition for the community.

By comparing these scenarios, the assessment helps identify which closure pathway offers the most effective combination of environmental restoration, risk reduction, and socio-economic resilience for Marmato. The assessment provides a structured, forward-looking analysis of mine-closure options at a moment when official data, regulatory guidance, and precedents for artisanal and small-scale gold mining (ASGM) closure in Marmato are largely absent. The results aim to guide local authorities, miners, and stakeholders toward closure strategies that can stabilize the land, protect ecosystems, and support a just transition for artisanal mining communities in one of Colombia's most important historical mining territories.

2.0 SAVi Methodology

The analysis was conducted using the SAVi methodology, a multi-method approach to estimating the social, economic, and environmental impacts of investments, and summarizes the analysis in an integrated cost-benefit analysis (CBA).

The SAVi methodology provides policy-makers and investors with a comprehensive life-cycle analysis of infrastructure projects, capturing impacts that are often overlooked in traditional appraisals. By combining systems thinking with project finance modelling, SAVi identifies and quantifies the full range of environmental, social, economic, and governance risks related to a project. It then calculates the monetary value of externalities, providing an assessment of the overall economic value of an investment, beyond its financial performance alone. This holistic perspective supports decisions that align with regional development priorities, climate adaptation needs, and the UN Sustainable Development Goals, helping ensure sustainable and financially sound outcomes. The SAVi methodology is illustrated in Figure 1.

The SAVi process begins with a qualitative analysis in which the team leverages their methodological expertise to conduct a systems mapping exercise to create a causal loop diagram (CLD) through a co-creation process with project partners and stakeholders. This approach brings together diverse perspectives and fosters a shared understanding of how the social, environmental, and economic dimensions of the problem are interconnected. Through this collaborative process, the team identifies relationships among variables, uncovers feedback loops, reveals root causes, and highlights leverage points to guide more integrated and effective solutions. The resulting systems map reflects stakeholder knowledge and is enriched by relevant literature and contextual insights. This mapping is iterative and may require multiple sessions to refine the diagram until it accurately captures the key interactions within the project scope.

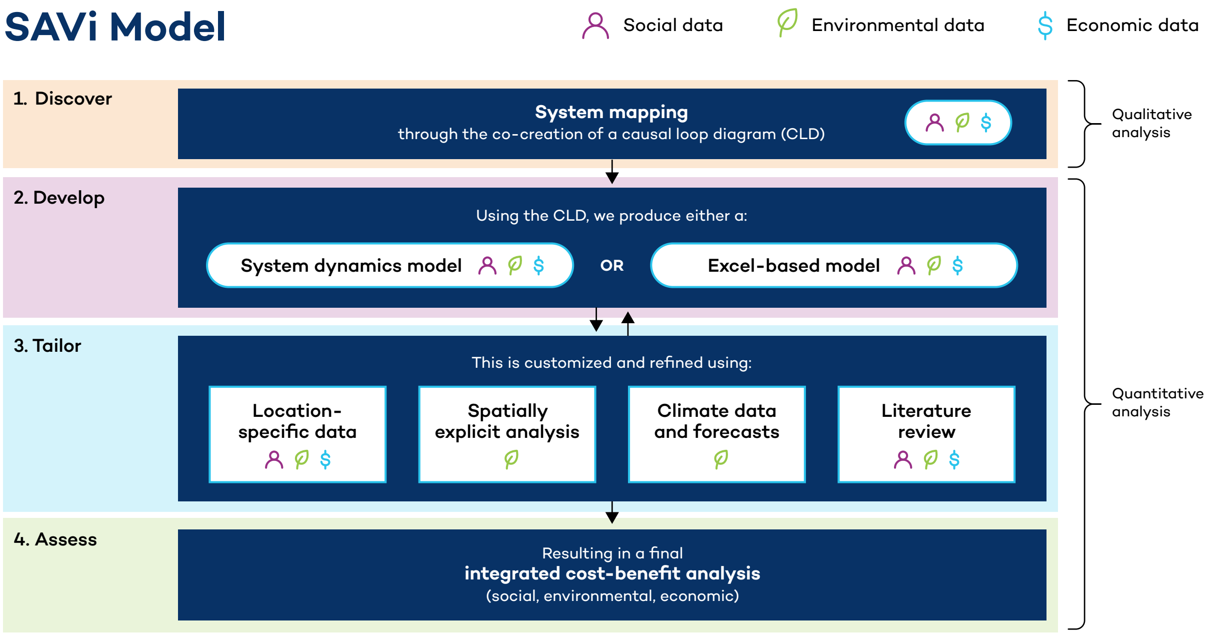
Following the qualitative stage, the quantitative analysis starts and builds on the indicators identified during systems mapping. While not all indicators can be quantified due to data or methodological constraints, their inclusion in the qualitative map ensures they remain visible in the overall assessment and are used to interpret quantitative results. The modelling exercise can use location-specific data, spatially explicit analysis, climate data and forecasts, and additional literature review, as they are relevant to the project and available data.

Using this foundation, the team defines the scenarios to be modelled and develops them through either a system dynamics model or an Excel-based model, as outlined in the SAVi framework. In the case of Marmato, an Excel model was developed. This modelling work resulted in an integrated CBA, in which environmental, social, and economic impacts are expressed in monetary terms. By making these dimensions comparable, SAVi delivers a comprehensive and integrated understanding of project performance across its entire life cycle.

Throughout the SAVi process, the validation of scenarios was conducted through an iterative process of refining assumptions. Scenario design and key assumptions were discussed with stakeholders, including the Capitals Coalition, The Blended Capital Group, and the Colombian National Mining Agency. Preliminary results and report drafts were subsequently reviewed at different stages by project partners to ensure consistency and relevance.

This report applies the SAVi methodology with a dual purpose: first, to represent the use of a systemic framework for an analysis of mine closure and second, to demonstrate its application in the specific context of ASGM closure in Marmato. Given the lack of formal closure plans, limited historical data, and early stage of mining formalization, the assessment recognizes challenges related to data availability, uncertainty, and the quantification of certain indicators. As a result, the analysis presented here should be seen as exploratory, and further customizations to the model and analysis could be implemented in other contexts.

Figure 1. The SAVi methodology



Source: International Institute for Sustainable Development.

2.1 The Importance of Systems Thinking

The SAVi approach uses systems thinking as a core analytical foundation to capture a variety of desirable and undesirable impacts of ASM for different economic actors. In the context of mine closure in Marmato, systems thinking is particularly useful because it complements linear approaches by helping situate specific economic activity within the broader social, environmental, economic, and institutional dynamics of the territory.

Mining in Marmato takes place within a complex territorial setting shaped by ancestral practices, limited livelihood alternatives, informal and emerging institutional arrangements, environmental pressures, and significant geological risk. These elements are closely interconnected and evolve over time, generating feedback effects that influence both mining activity and closure outcomes. A systems perspective allows these interconnections to be considered explicitly, enabling mine closure to be understood not only as a sequence of actions aimed at creating financial value, but also as a process embedded in local development trajectories and social dependence on mining.

Within the SAVi methodology, systems thinking and the development of the CLD constitute the first analytical step (see Figure 1). It provides a structured framework to explore how key indicators and variables interact across social, economic, and environmental dimensions. By mapping relationships, feedback loops, and dynamic interactions, the approach supports the identification of fundamental drivers that shape livelihoods and environmental risk in Marmato, while remaining compatible with more linear analyses used for engineering design, cost estimation, or regulatory compliance.

Applying a systemic lens also helps identify leverage points and policy entry points for targeted interventions to achieve broader, more durable impacts. This enables the design of mine-closure strategies that simultaneously reduce environmental and geological risk, strengthen long-term territorial resilience, and remain sensitive to the social realities of ASM. In this way, systems thinking enhances conventional approaches, contributing to closure processes that are coherent, context specific, and aligned with the broader "big picture" challenges and opportunities facing Marmato.

2.2 Systems Mapping

Systems mapping is a foundational stage of the SAVi methodology that enables practitioners to understand the systemic context within which a nature-based solution (NbS) operates and to make visible the interdependencies, feedback loops, and behaviours that shape system performance over time. As presented in *Integrated Cost-Benefit Analysis for Nature-Based Solutions: A Handbook for Using the Sustainable Asset Valuation Methodology* (Contor, 2025), systems mapping ensures that NbS assessments move beyond isolated project attributes and instead consider the complexity of environmental, social, and economic interactions that determine project outcomes.

Developing a CLD is at the core of this process. It is co-created with stakeholders, integrating scientific evidence, local knowledge, and policy priorities to ensure the map reflects both measurable system relationships and lived realities on the ground. The handbook emphasizes that this is not a linear process, but an iterative learning cycle, where understanding deepens and the map evolves as new insights emerge. Contor's SAVi handbook (2025) outlines a structured eight-step approach for developing the CLD, visually summarized in Figure 2.

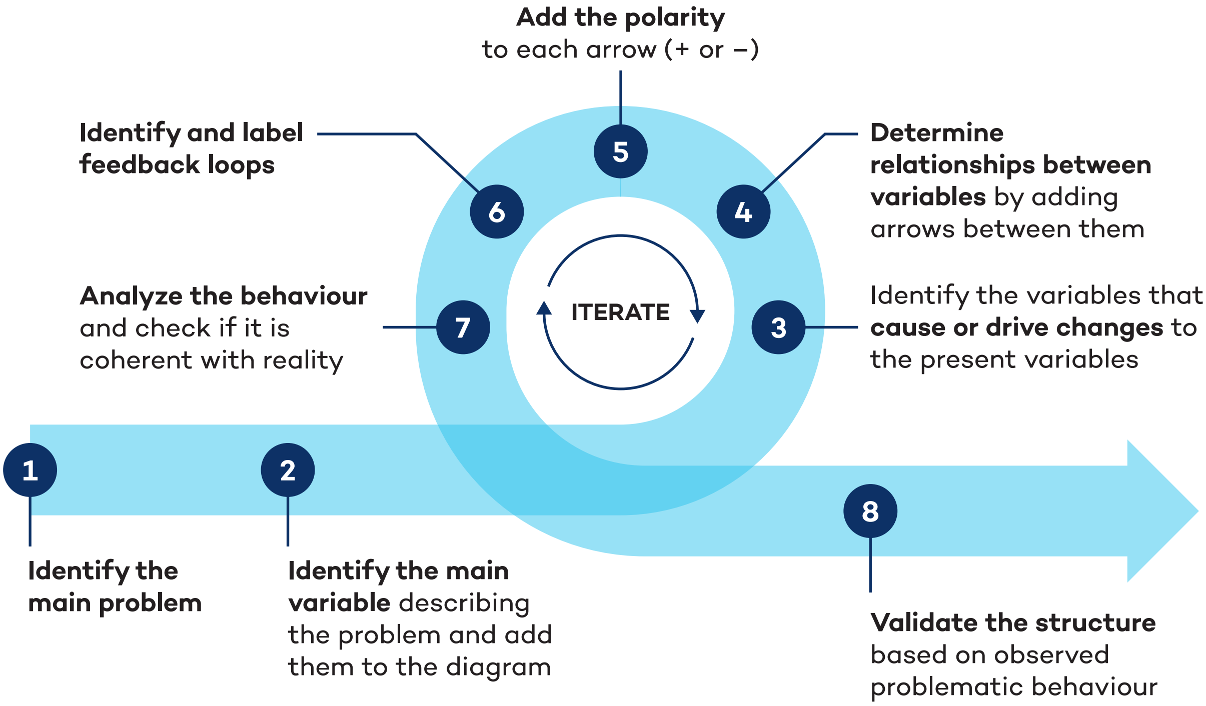
In the Marmato CLD (Figure 3), identifying the core problem and key variables begins with recognizing the territorial impacts generated by mining activities. The central issue is the accumulation of negative environmental and social side effects, such as deforestation, pollution from tailings, geomorphological instability, and safety risks, resulting from both formal and informal mining practices. Within these dynamics, informal mining emerges as a critical variable, as it is strongly associated with lower environmental sustainability, limited risk management, and the absence of closure planning.

The diagram highlights the main drivers of change that make ASM an increasingly attractive livelihood option in Marmato. These motivations include limited economic alternatives, high and volatile gold prices, and external pressures that reinforce residents' decisions to engage in mining despite environmental and safety risks. The feedback structure of the CLD is dominated by reinforcing loops that explain the sustained expansion of mining activity over time, alongside a smaller number of balancing loops that reflect factors capable of slowing or counteracting this growth.

The CLD was validated through participatory discussions with stakeholders during the mapping sessions. Their insights and lived experiences were incorporated to ensure that the diagram accurately reflects the drivers, pressures, and feedback mechanisms shaping mining dynamics in Marmato. The resulting systems map forms the foundation for selecting indicators and defining scenarios in the quantitative phase of the assessment.

The CLD session involved a diverse group of stakeholders to capture multiple perspectives on the dynamics of ASGM in Marmato. Participants included the main partners of the assessment—The Blended Capital Group and Capitals Hub Canada—as well as representatives from the Alliance for Responsible Mining, the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF), CorpoCaldas, and the Municipality of Marmato. Their contributions helped validate the system structure and ensure that the analysis reflected both local realities and institutional perspectives.

Figure 2. Step-by-step process for system mapping



Source: Contor, 2025.

2.3 Identifying Cost and Benefit Indicators

Identifying costs and benefits is a central step in developing the integrated CBA. As described in the SAVi handbook (Contor, 2025), this step builds directly on the systems mapping exercise and ensures that the indicators selected for valuation reflect the full dynamics of the system in which the intervention operates. This step involves the transition of practitioners from the qualitative understanding provided by the CLD to a structured set of indicators representing the costs and the environmental, social, and economic benefits expected over time.

In Marmato, the identification of cost and benefit indicators is particularly significant because this assessment represents one of the first systemic approaches for conceptualizing the costs and benefits of mine closure in a territory where comprehensive closure processes have not yet occurred. As such, this analysis outlines the range of indicators that a closure evaluation should consider in order to evaluate societal impacts, moving beyond a narrow focus on the costs of different closure interventions.

The SAVi methodology allows the identification of costs and benefits based on the systems mapping outcomes, explicitly outlining the indicators that represent how the system performs with and without the intervention. The indicators include financial costs, added benefits, avoided impacts, and harder-to-measure co-benefits such as intangible benefits. Indicators typically cover

- **financial costs,** including capital expenditures (CapEx), operation and maintenance (O&M) costs, and long-term replacement needs;
- **avoided costs,** such as reductions in flood damage, erosion, sediment export, disaster recovery spending, or infrastructure degradation; and
- **added benefits,** including job creation, revenue and value added, increased water availability and quality, carbon sequestration, and increased recreational value.

This step is essential for clarifying the type of data required for future closure assessments and identifying current information gaps. In Marmato, relevant challenges include limited data on post-closure environmental recovery and a lack of empirical evidence to support the monetary valuation of such changes. Similarly, detailed information on the actual costs of implementing closure measures, particularly for artisanal and small-scale operations, is scarce.

Social indicators are especially important in Marmato due to the ancestral nature of mining. Gold extraction is deeply tied to local identity, culture, and intergenerational knowledge. As a result, any closure process must carefully consider its social implications, including the feasibility of alternative livelihoods and the cultural acceptability of reducing or ending mining activities. The strong attachment to mining also explains why miners often continue operating despite known environmental and geotechnical risks, such as landslides and slope instability. Capturing these dynamics is essential for evaluating trade-offs between environmental safety and social continuity.

Another component of this stage is recognizing that different indicators unfold over different time horizons. Some benefits, such as reduced erosion or improved water retention, may appear quickly, while others, like biodiversity recovery or increased soil organic matter, accumulate over years or decades. Ensuring that indicators reflect appropriate time frames prevents long-term resilience benefits from being discounted or omitted.

In the Marmato case, a particularly complex aspect relates to long-term and intangible benefits, such as improved biodiversity, water quality, landscape stability, and reduced disaster risk. Since no permanent closure processes have been implemented in Marmato, envisioning these benefits and later translating them into quantitative estimates requires a forward-looking, scenario-based approach. Nevertheless, these indicators are crucial, as they capture many of the values that underpin long-term sustainability and territorial well-being.

2.4 Defining the Scenarios

The next step, defining scenarios, shapes how the comparative assessment will be carried out. Scenarios provide the structure through which future outcomes are evaluated. Typically, they include

- **a business-as-usual scenario,** showing how the system evolves without new interventions;
- **one or more NbS scenarios,** demonstrating the effects of the proposed measures, whether implemented alone or combined with grey infrastructure;
- **hybrid scenarios,** where NbS and built infrastructure operate together; and
- **climate-risk scenarios,** which may incorporate pathways such as the Shared Socioeconomic Pathways 3 or 5, or the Representative Concentration Pathways 4.5 or 8.5 to assess sensitivity to future climate conditions, as illustrated in the Greece case study in Contor's handbook (2025).

Scenario development is iterative and stakeholder driven, ensuring alignment with plausible futures and decision-maker concerns. It also helps refine indicator definitions and identify system-wide implications of different intervention pathways (Contor, 2025). The indicators and scenarios defined in the qualitative analysis determine the structure of all subsequent SAVi stages. They guide the climate data needs, inform the modelling approach, shape the financial structure assessment, and support the clear communication of results.

For Marmato, the process of identifying scenarios and defining mine types was informed by a combination of literature review and stakeholder consultation. The assessment drew on mine closure experiences in Latin America and other regions, in collaboration with project partners and the Colombian ANM. This collaborative approach was essential given that Colombia's regulatory framework for mine closure, particularly for ASM, is still under development.

2.5 Quantifying Costs and Benefits

Quantifying and monetizing costs and benefits is the analytical core of the SAVi methodology. In this step, the qualitative insights gained from systems mapping and the indicators selected earlier are transformed into a structured economic valuation. As outlined in the SAVi handbook (Contor, 2025), this step brings together climate data, literature, spatial outputs, and stakeholder inputs to calculate how NbS and NBI generate costs, benefits, avoided damages, and long-term co-benefits across different scenarios.

The purpose of this step is to convert selected indicators into quantitative, monetized results that can inform policy and investment decisions. The valuation captures the full life cycle of impacts, including implementation and operation costs, environmental and social benefits, externalities, and long-term risks. When detailed NbS interventions are being assessed, spatial modelling can be used to estimate changes in ecosystem services. As described in the SAVi handbook, spatial analysis can help quantify changes in services, such as carbon sequestration, water retention, sediment reduction, or habitat improvements, and identify where these changes occur, as well as potential trade-offs (Contor, 2025). These outputs can then be incorporated into the Excel-based model to ensure that economic valuation reflects changes in ecosystem functioning.

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Excel-based modelling offers a clear and easy-to-use approach for estimating the costs and benefits associated with NbS projects (Contor, 2025). It offers a transparent and accessible platform to monetize costs and benefits, compare scenarios, and test the robustness of results. Following the approach described in the SAVi handbook, the model organizes and processes all relevant inputs, including project expenditures, ecosystem service values, climate projections, discount rates, and outputs from spatial modelling. To keep the analysis clear and structured, the Excel-based model focuses on

- **data inputs** such as CapEx, O&M costs, time horizons, and monetized ecosystem services (e.g., avoided flood damages, carbon sequestration);
- **cost-benefit calculations,** producing the net present value, benefit–cost ratio (BCR), and internal rate of return (IRR);
- **scenario comparisons,** evaluating business as usual, NbS, and hybrid alternatives; and
- **sensitivity analysis,** testing how results change when adjusting discount rates, cost assumptions, or climate risks.

In this assessment, the qualitative analysis draws on available local information complemented by secondary data identified through a targeted literature review. In Marmato's current context, where formally approved mine-closure plans are still under development, environmental liability studies are emerging, and data availability continues to evolve, the quantitative analysis adopts an exploratory and learning-oriented approach. The quantitative modelling, therefore, makes use of pilot sites and indicative parameters, producing results that are intentionally flexible and open to refinement. As the mining formalization process progresses and more site-specific data become available, the assumptions and estimates applied in this assessment can be updated to further strengthen accuracy and enhance their relevance for policy and decision making.

3.0 Qualitative Analysis

This section presents the outcomes of the qualitative analysis for this SAVi assessment. The qualitative analysis began with two dedicated system-mapping sessions to co-create the CLD for ASGM in Marmato. The first session convened a broad group of stakeholders, including representatives from environmental authorities, government institutions, technical agencies, community organizations, and international partners, to capture the full spectrum of socio-environmental dynamics in the territory. The second session was held with the project partners to refine the structure, strengthen the causal relationships, and ensure that the CLD aligned with the objectives of the mining closure evaluation. Together, these sessions integrated scientific knowledge, local insights, institutional experience, and project expertise, resulting in a robust systems map that underpins indicator selection and scenario definition for the quantitative analysis.

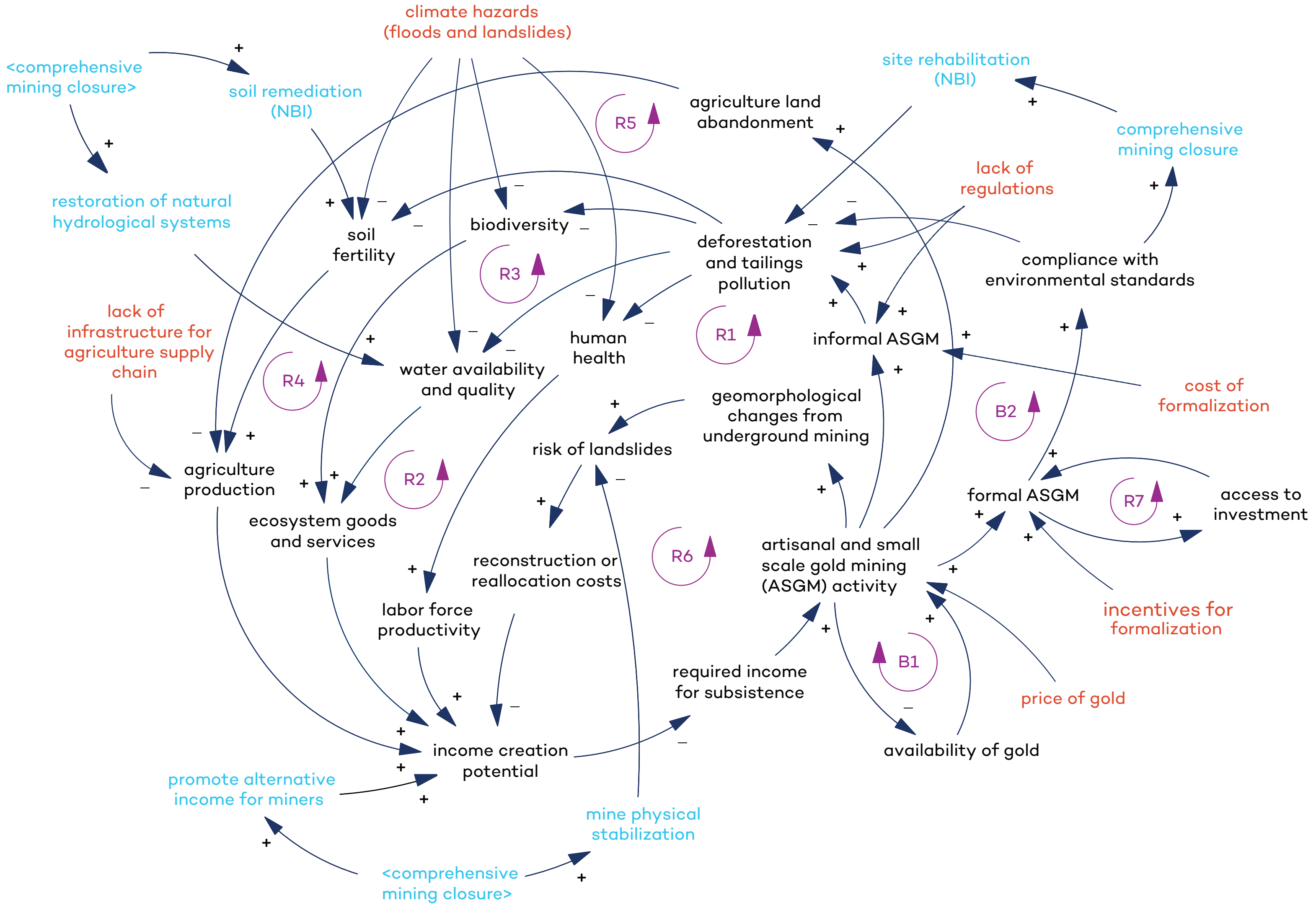
3.1 Causal Loop Diagram

For this SAVi assessment, the CLD (Figure 3) was co-created with representatives from Capitals Hub Canada (CHC), The Blended Capital Group (TBCG), Alliance for Responsible Mining (ARM), the IGF, Institute of Hydrology, Meteorology and Environmental Studies of Colombia (in Spanish, IDEAM Colombia), Corpocaldas, the Ministry of Environment of Colombia, and the World Bank. Its purpose is to map the social, environmental, and economic dynamics influencing ASM in the territory, reveal the underlying drivers of landslide risk and environmental degradation, and support a more integrated understanding of how nature-based interventions could help shift these dynamics toward more sustainable outcomes. The diagram illustrates both the mechanisms that have enabled ASGM to expand over time and the feedback that intensifies or moderates its impacts, particularly elements associated with informal versus formal operations.

The CLD starts by presenting how mining activity in Marmato is deeply rooted in the territory's history and geology. The availability of gold has long shaped local livelihoods, anchoring ASGM as a central economic activity. High levels of gold availability historically encouraged the expansion of ASGM, particularly during periods of elevated international gold prices, which increased the economic attractiveness of extraction. Over time, however, continued mining progressively reduced the remaining gold resource, introducing natural limits to further expansion. As extraction intensifies, declining gold availability constrains future mining activity, reflecting the finite nature of the resource base (loop B1).

From this historical foundation, ASGM in Marmato follows two main pathways: informal ASGM and formal ASGM. In practice, most mining activity has historically taken place through the informal pathway, which is characterized by limited compliance with environmental, technical, and safety standards. External factors (red parameters in the CLD), such as the high cost of formalization (Cárdenas, 2021) and regulatory uncertainty, have further reinforced this pattern, making informal operations the dominant mode of extraction in the territory.

Figure 3. Detailed CLD for ASGM in Marmato



Source: Authors.

Informal ASGM has been closely associated with deforestation and pollution from mining tailings, which trigger a series of interconnected impacts on human well-being and local livelihoods. Exposure to mining-related contaminants used in processing—historically mercury and, more recently, cyanide—directly affects human health, particularly among miners and nearby communities. Climate-related hazards, such as intense rainfall events, exacerbate these impacts by increasing the mobilization of contaminants and the dispersion of pollutants. As health conditions deteriorate, labour productivity declines, reducing the income-generating potential of affected households. Lower income relative to subsistence needs increases reliance on ASGM as a primary livelihood strategy, further intensifying mining activity and associated environmental pressures (loop R1).

Water resources are affected through a similar pathway. Deforestation and tailings-related pollution reduce water quality and availability, particularly during periods of heavy rainfall and flooding, which are becoming more frequent due to climate change. As water conditions deteriorate, the provision of ecosystem goods and services declines, undermining water-dependent livelihoods such as agriculture, small-scale fisheries, and other nature-based activities. Reduced income from these sources increases the need for alternative subsistence income, reinforcing the role of ASGM as a key coping strategy for households (loop R2).

Biodiversity loss follows comparable dynamics. Forest degradation and water pollution reduce biodiversity and the ecosystem services it supports. Climate variability further stresses ecosystems, accelerating species loss and habitat degradation. As biodiversity declines, income opportunities linked to ecosystem services diminish, narrowing livelihood options for local communities. In this context, ASGM becomes a substitute income source, intensifying environmental pressures in the territory (loop R3).

Soil degradation creates another pathway linking environmental change to livelihood dependence. Mining-related land disturbance and deforestation reduce soil fertility, while external factors such as climate change exacerbate soil loss. Declining soil fertility lowers agricultural productivity and income potential from farming. As agriculture becomes less viable, particularly in a context of limited supply-chain infrastructure and market access, households shift labour and time toward mining, further increasing ASGM activity (loop R4).

Changes in labour allocation reinforce this shift. As mining becomes relatively more attractive or necessary than agriculture, families abandon agricultural land in favour of ASGM. This abandonment leads to further declines in agricultural production, reinforcing the reduction in income generation potential from farming, finally increasing the dependence on mining as their primary livelihood strategy (loop R5).

Mining activity also alters the physical stability of the landscape. Excavation on steep slopes destabilizes hillsides and underground structures, increasing the likelihood of landslides and tunnel collapses. These risks are amplified during periods of heavy rainfall, which weaken soils and increase slope instability. When such events occur, households and communities face additional costs related to damage repair, relocation, and risk management. These unplanned expenditures reduce available income and increase dependence on continued mining to meet basic needs (loop R6).

Within this system, formal ASGM plays an important moderating role. Higher levels of formality increase compliance with environmental standards, which generates a reduction in deforestation, better tailings management, and safer working conditions compared to informal mining. While formalization does not eliminate the underlying drivers of ASGM, it reduces the severity of social and environmental impacts and partially offsets the dynamics associated with informal mining (loop B2), counteracting the reinforcing dynamic of cycles R1, R2, R3, and R4. Incentives for formalization are key to accelerate the transition to formality of artisanal and small-scale miners. At the same time, access to investment strengthens income stability and operational efficiency, supporting improved mining practices over time (loop R7).

Greater levels of formalization also enable the preparation and implementation of comprehensive mine-closure plans, which introduce additional opportunities to alter long-term system outcomes. Comprehensive closure for mining plants and their components are the intervention options included in the CLD:

- Physical stabilization of mine sites reduces landslide risks and improves slope stability.
- Reforestation and ecosystem rehabilitation (NBI component) help reduce deforestation, stabilize soils, and mitigate tailings-related pollution.
- Soil remediation (NBI component), through chemical or nature-based approaches, supports the recovery of soil fertility and agricultural productivity.
- The restoration of hydrological systems (NBI component) improves water quality and availability, strengthening ecosystem recovery and community water security.
- In parallel, initiatives that promote alternative income opportunities increase household income generation potential beyond mining, reducing long-term dependence on ASGM.

Overall, the CLD illustrates how a combination of environmental degradation, livelihood constraints, external pressures, and historical mining dependence has shaped ASGM dynamics in Marmato. While these interactions have historically intensified reliance on informal mining, the diagram also highlights how formalization and comprehensive mine-closure interventions can help moderate impacts, reduce environmental liabilities, and support a gradual transition toward more sustainable and resilient territorial outcomes.

3.2 Indicators for ASGM Closure in Marmato

The indicators selected for the integrated CBA are derived directly from the system behaviour represented in the CLD. They reflect the environmental, social, and economic variables most influenced by mine-closure interventions, particularly those related to physical stabilization, ecosystem restoration, water management, and changes in income dynamics. These indicators capture both added benefits of nature-based and hybrid closure measures and the avoided costs resulting from reduced environmental and social impacts.

Table 1. Indicators resulting from the CLD

Indicator	Description
Investment and costs The financial resources required to implement and maintain the project.	
CapEx	Represents the upfront investments required to implement the closure measures under each scenario, including physical stabilization of slopes, reforestation, soil remediation, water treatment systems, and administrative and technical studies.
O&M costs	Covers the recurrent expenditures needed to ensure long-term functionality of closure measures. These costs can be linked to sustained ecosystem performance (e.g., tree survival rates, functioning drainage systems), which affects long-term benefits such as soil stabilization, carbon capture, and water regulation.
Avoided costs Expenses that are reduced or eliminated by the project by preventing or reducing negative outcomes.	
Avoided health costs	Reduced exposure to contaminated water, pollutants, and landslide-related injuries or deaths decreases health expenditures.
Avoided landslide damages and reconstruction costs	Stabilization measures prevent costly infrastructure damage, emergency response needs, relocation expenses, and loss of life.
Avoided water treatment and pollution control costs	By reducing mining-related contamination through slope stabilization, proper drainage, and vegetation recovery, closure interventions decrease the need for future water treatment or emergency clean-ups.
Avoided soil erosion and sediment management costs	Stabilizing exposed soils and restoring vegetation reduces sediment transport into streams, lowering the burden on downstream water users and reducing maintenance costs for infrastructure.
Avoided loss of agricultural productivity	Without intervention, continued degradation reduces soil fertility and agricultural income. Closure actions prevent these losses, generating significant avoided socio-economic damages over time.
Added benefits The positive economic, environmental, and social impacts generated by the project or intervention. The added benefits reflect how the project creates value beyond its direct costs.	
Job creation from the closure plan implementation	Implementation of closure activities—such as reforestation, soil recovery, slope stabilization, and hydrological restoration—creates temporary green jobs.
Job creation (O&M)	Long-term maintenance of restored areas generates recurring employment, helping diversify income sources.

Indicator	Description
Revenues from additional agricultural production	Soil remediation, improved water availability, and reduced erosion—represented as key nodes in the CLD—translate into improved crop productivity. Agricultural recovery as a land-use change could generate new income sources for miners.
Carbon sequestration	Restoration of vegetation and soil carbon pools contributes to climate regulation.
Biodiversity recovery	Reforestation and soil rehabilitation enhance habitat quality, increase ecosystem resilience, and re-establish ecological functions.

Source: Authors.

3.2 Literature Review for Mining Closure Plans

The international and regional literature consistently frames mine closure as a life-of-mine process rather than a discrete end-of-operations event, with rehabilitation and reclamation constituting core operational responsibilities throughout the mining cycle. Across global guidance documents, regional policy analyses, and case-based evidence, mine closure is defined as the integrated pursuit of long-term physical, chemical, ecological, and social stability aimed at preventing the creation of abandoned liabilities and enabling safe, productive, and socially acceptable post-mining land use.

3.2.1 Mining Closure Objectives

A central convergence across the literature is the articulation of closure objectives that extend beyond environmental remediation alone. Closure plans are expected to ensure public safety, protect water and soil resources, restore land capability, and support a just social and economic transition for workers and surrounding communities (International Council on Mining and Metals [ICMM], 2025; IGF, 2021). At the policy level, closure is increasingly embedded within broader sustainable development, ESG, and green mining frameworks, particularly in Latin America, where mine closure is recognized as a key determinant of territorial resilience and long-term development outcomes (Alonso et al., 2020; Rojas-Hayes et al., 2023).

3.2.2 Mining Closure Plan

From a technical perspective, rehabilitation and reclamation are anchored in three interdependent foundations: physical stability, chemical stability, and ecological recovery. All reviewed documents identify landform stability as the prerequisite for successful rehabilitation, requiring the reshaping and stabilization of waste rock dumps, tailings facilities, pits, and underground workings to withstand erosion and geotechnical failure over extended time horizons, often well beyond regulatory monitoring periods (Autoridad Nacional de Licencias Ambientales [ANLA], 2022; ICMM, 2025; World Bank Group, 2021). Climate variability and long-term geomorphological processes are explicitly recognized as critical design considerations, reinforcing the need for defensible, conservative rehabilitation designs.

Evidence from abandoned mine interventions in Colombia confirms the primacy of physical stability. A report by Universidad Nacional de Colombia (2018) documents that sealing mine adits, recontouring slopes, stabilizing tailings, and controlling mass-movement processes account for a significant share of total intervention costs, reflecting the technical complexity and long-term risks associated with unstable mine features.

Chemical stability constitutes a second core pillar of closure planning, with strong emphasis on preventing acid rock drainage, metal leaching, and the long-term contamination of surface and groundwater systems. The literature converges on the requirement that closure measures must eliminate or effectively control contamination pathways, using waste segregation, encapsulation, engineered covers, and long-term water management systems where necessary (Asia-Pacific Economic Cooperation [APEC], 2018; ICMM, 2025; World Bank, 2018). Case-based evidence, such as the Golden Pride Mine in Tanzania, demonstrates that achieving regulatory approval and site relinquishment is contingent on demonstrable long-term chemical stability supported by monitoring data (IGF, 2021).

The results report of abandoned mining activities diagnostics similarly highlight uncontrolled mine drainage and sediment transport as persistent sources of environmental risk in abandoned sites, often requiring the installation of drainage systems, sediment control structures, and long-term water management measures during post-abandonment interventions (Universidad Nacional de Colombia, 2018).

Ecological rehabilitation is addressed through soil reconstruction, revegetation, and, where feasible, ecosystem restoration. The literature distinguishes clearly between rehabilitation, which aims to create stable and self-sustaining ecosystems that may differ from baseline conditions, and ecological restoration, which seeks closer alignment with pre-disturbance ecosystem structure and function (ANLA, 2022). Closure plans are expected to justify the chosen approach based on ecological feasibility, risk, and intended post-closure land use. Revegetation using locally appropriate species is consistently identified as both a functional and socially visible indicator of closure performance (ICMM, 2025; World Bank Group, 2021).

In practice, a study on abandoned mining activities shows that revegetation is often limited or delayed in abandoned mines due to poor soil conditions, steep slopes, and unresolved land-use planning, reinforcing the importance of early soil management and progressive rehabilitation during operations to avoid costly and uncertain post-abandonment restoration (Universidad Nacional de Colombia, 2018).

An important extension of ecological considerations in the Latin American literature is the role of biodiversity compensation. Biodiversity offsets are presented as a last-resort mechanism, applicable only after avoidance, minimization, and on-site rehabilitation measures have been exhausted (Alonso et al., 2020). The literature emphasizes that compensation cannot substitute for inadequate rehabilitation and must deliver measurable, additional, and long-term conservation outcomes. Importantly, biodiversity compensation obligations may extend well beyond physical mine closure, reinforcing the need for durable post-closure governance and monitoring arrangements.

3.2.3 Progressive Mining Closure

A strong and recurring conclusion across all documents is the superiority of progressive closure and rehabilitation over end-of-life remediation. Progressive rehabilitation, implemented during operations, reduces cumulative environmental risk, lowers final closure costs, improves regulator confidence, and allows early testing and refinement of rehabilitation techniques (APEC, 2018; ANLA, 2022; ICMM, 2025; IGF, 2019). Progressive closure is therefore framed not as an optional good practice, but as a normative expectation of modern mine management, with direct implications for financial assurance requirements.

This conclusion is directly supported by Colombian evidence: a study by the Universidad Nacional de Colombia (2018) demonstrates that delayed interventions at abandoned sites result in significantly higher remediation costs compared to preventive or progressive measures, particularly for geotechnical stabilization and social risk management.

3.2.4 Post-Mining Closure

Post-closure land use emerges as a unifying theme linking technical rehabilitation, social outcomes, and territorial planning. The literature consistently stresses that rehabilitation success cannot be evaluated independently of an agreed and realistic post-mining land use, whether agricultural, ecological, infrastructural, or mixed (Alonso et al., 2020; IGF, 2021; World Bank Group, 2021). Closure designs are expected to demonstrate compatibility between landform geometry, soil reconstruction, vegetation, and intended land use, while recognizing that post-closure land use may evolve through stakeholder engagement over time.

Monitoring and adaptive management are presented as integral extensions of rehabilitation rather than as discrete post-closure phases. Closure frameworks require measurable success criteria, long-term monitoring proportional to residual risk, and adaptive responses if performance targets are not met (APEC, 2018; ICMM, 2025). Financial assurance mechanisms are consistently linked to the achievement of these criteria, with release of bonds or guarantees conditioned on demonstrated closure performance rather than administrative timelines (IGF, 2019; World Bank Group, 2021).

Social dimensions are embedded throughout the closure literature, with strong emphasis on stakeholder engagement, transparency, and socio-economic transition. Effective closure planning is shown to require early and sustained community participation in defining post-closure land use, managing expectations, and addressing residual risks (IGF, 2021; Rojas-Hayes et al., 2023). Workforce retrenchment, retraining, and livelihood diversification are treated as closure domains equivalent in importance to environmental rehabilitation, with evidence indicating that failure to manage social transition can undermine otherwise successful technical closure outcomes (APEC, 2018; ICMM, 2025). The abandoned mining activities study reinforces this conclusion, identifying inadequate social engagement and unresolved community risks as key drivers of post-abandonment conflict and public opposition (Universidad Nacional de Colombia, 2018).

Finally, robust governance and financial assurance are essential enabling conditions for credible closure and rehabilitation. Legally binding closure plans, cost estimates based on third-party execution, regular plan updates, and institutional capacity for enforcement are identified as prerequisites for protecting the public interest and avoiding legacy liabilities (ANLA, 2022; Rojas-Hayes et al., 2023; World Bank Group, 2021). Progressive rehabilitation creates positive incentives by reducing closure liabilities and associated financial assurance over time (IGF, 2019), a finding that is consistent with the high public costs observed in the remediation of abandoned mines in Colombia (Universidad Nacional de Colombia, 2018).

3.3 Scenarios Modelled

For this SAVi assessment, scenarios were developed to represent plausible mine-closure pathways for ASGM operations in Marmato under current and anticipated regulatory conditions. Given the absence of formally approved closure plans, limited site-specific closure data, and ongoing formalization processes, the scenarios use a simplified approach for the quantitative modelling while remaining grounded in local mining practices and conditions.

Given the challenges in defining a single mining closure pilot site for this SAVi assessment, scenario creation involved first defining representative mine types that reflect the physical and operational characteristics of ASGM in Marmato and then assigning an appropriate closure approach to each mine type. This process was informed by a combined targeted literature review and stakeholder consultation, drawing on experiences with mine closure in Latin America and other comparable contexts. Close collaboration with project partners, including the ANM, was particularly important in light of Colombia's evolving regulatory framework for mine closure, especially as it relates to ASM.

The resulting closure scenarios should be understood as illustrative pathways rather than technically validated, site-specific closure designs. They aim to raise awareness of the importance of considering the range of possibilities related mine closure and their potential impacts. The scenarios are based on typical components of mine-closure plans and current knowledge of Marmato's terrain, geomorphological processes, and mining context. Key technical details, such as material quantities, engineering specifications, and implementation methods, would need to be defined in a subsequent step through dedicated closure plan studies and adjusted to evolving regulations and the specific conditions of individual mines. In this sense, the scenarios provide a coherent analytical basis for integrated CBA under data-constrained conditions, rather than prescriptive closure solutions.

3.3.1 Type of Mines

Two representative ASGM mine types were identified for the assessment. The first corresponds to operations that remain predominantly artisanal, relying largely on manual labour and limited mechanization. The second represents small-scale but more mechanized operations, with deeper galleries and higher potential for cumulative environmental and stability impacts. These mine types form the basis for applying the different closure scenarios and estimating their respective costs and benefits.

Table 2. Type of ASGM mines and characteristics

Mine type	Description	Main characteristics
Type A Predominantly artisanal ASGM	Manual or semi-manual underground mining operations	Pithead dimensions of approximately 1.7 m × 1.8 m (minimum 3 m^2); gallery length of ~100 m; limited mechanization
Type B Mechanized ASGM	Small-scale underground mines with mechanical transport systems	Pithead dimensions of approximately 1.8 m × 2.0 m (minimum 3 m^2); galleries up to 500 m deep; use of rail cars or similar systems

Source: Authors.

Average employment per mine: 4–8 workers (maximum four simultaneously underground).

These mine types serve as the basis for applying closure plans and estimating costs, benefits, and avoided impacts under each scenario.

3.3.2 Mine Closure Scenarios

Three scenarios were modelled in the SAVi assessment. Each scenario represents a distinct closure pathway with different implications for environmental liabilities, risk reduction, and long-term territorial outcomes.

Scenario 1: Baseline

The Baseline Scenario represents a hypothetical "no-action" closure pathway in which no closure plan is designed or implemented. This scenario reflects the likely outcome for informal ASGM operations where closure obligations are undefined, unenforced, or unfunded. Under this scenario, environmental liabilities accumulate over time, including unstable underground workings, unmanaged waste piles, contamination of soil and water resources, and progressive ecosystem degradation. The Baseline Scenario serves as the reference case against which the costs and benefits of formal closure strategies are evaluated.

Scenario 2: Comprehensive Closure Plan

The Comprehensive Closure Plan Scenario represents a formal mine closure executed once mining operations reach their definitive end. Closure activities are implemented in accordance with anticipated regulatory requirements and technical standards for formal mining operations. This scenario includes diagnostic studies, physical and chemical stabilization, waste management, ecosystem restoration through NBI, and post-closure monitoring. The plan is applied separately to each mine type, reflecting differences in scale and technical complexity.

Table 3. Components of the comprehensive closure plan per ASGM type

Closure component	**Type A mine:** Predominantly artisanal ASGM	**Type B mine:** Mechanized ASGM
1. Diagnosis/ baseline	• Simple mapping of adits, tunnels, waste piles, and processing areas. • Basic rock–sediment–water sampling (pH, metals, sulphates, cyanide). • Identification of unstable slopes and drainage paths.	• Detailed mapping of underground tunnels, adits, collapsed zones, and waste piles on steep slopes. • Sampling of water, sediments, and rocks for cyanide and metals. • Assessment of slope stability and landslide-prone areas.
2. Physical stability	• Seal adits using rock fill, thin masonry wall, and external grille. • Reshape waste piles into small terraces; install manual gabions and rainfall diversion. • Basic erosion control using channels, brush barriers, and light compaction.	• Seal adits with reinforced plugs while maintaining controlled drainage. • Regrade and terrace waste rock disposed downslope. • Install gabions, berms, and surface water diversion channels. • Apply erosion control measures (fibre rolls, geotextiles, gully repair).
3. Chemical stability and water protection	• Neutralize remaining cyanide using simple chemical methods (e.g., bleach). • Clean processing tanks. • Apply lime or soil cover to reactive waste to reduce acid drainage.	• Remove and neutralize cyanide residues. • Clean or dismantle cyanidation tanks and secure contaminated soils. • Characterize and cover tailings; encapsulate reactive waste rock. • Construct sediment ponds and small passive water treatment systems.
4. Waste management	• Separate hazardous waste (oils, reagents) and deliver to municipal collection systems. • Recycle scrap metal. • Dispose of non-hazardous solids in shallow, covered trenches.	• Full inventory of wastes (sterile rock, tailings, cyanide residues, oils, scrap). • Stabilize or relocate waste to controlled disposal areas. • Remove hazardous materials and recycle metals.
5. Environmental rehabilitation/ revegetation	• Apply a simple soil layer mixed with organic matter on stabilized slopes. • Plant low-maintenance native species (grasses, shrubs, vetiver). • Use mulch and stones for rapid erosion protection.	• Reconstruct soils and improve organic content. • Plant native, fast-rooting species for long-term slope stabilization. • Integrate rehabilitated areas into the surrounding hillside landscape.

Closure component	**Type A mine:** Predominantly artisanal ASGM	**Type B mine:** Mechanized ASGM
6. Post-closure monitoring	• Water quality monitoring twice per year (upstream, downstream, and adit). • Seasonal inspections of slopes for erosion or cracks. • Annual replacement of failed vegetation.	• Regular monitoring of water quality (pH, metals, cyanide) upstream and downstream. • Routine inspection of slopes and waste rock terraces. • Monitoring of vegetation survival and erosion trends.
7. Documentation and community engagement	• Not systematically required; limited documentation due to scale and informality.	• Maintain closure documentation (maps, inventories, monitoring records). • Share closure progress and outcomes with local hillside communities.

Source: Authors.

Scenario 3: Progressive Comprehensive Closure Plan

The Progressive Comprehensive Closure Plan represents a phased version of Scenario 2, in which closure and rehabilitation activities begin during the operational life of the mine rather than being concentrated at the end. The same core components are applied, but implementation is distributed over time. By implementing most closure actions during the operational phase, this scenario reduces final closure costs, limits cumulative environmental liabilities, and delivers earlier environmental and social benefits.

Table 4. Components and timing of the progressive comprehensive closure plan for both ASGM types

Project phase/ timing	**Key objective**	**Main activities implemented**	**Expected outcomes**
Current operation (mid-life start point)	Establish control over existing environmental and safety risks	• Update mapping of all active, inactive, and abandoned adits, tunnels, and waste areas. • Initiate periodic water, sediment, and rock sampling (pH, metals, cyanide). • Conduct systematic inspections of slopes, waste piles, and drainage, especially during rainy seasons. • Establish or regularize a simple operational record (bitácora) for impacts and corrective actions.	• Baseline understanding of existing liabilities. • Early identification of critical risk areas requiring priority action.

Project phase/ timing	Key objective	Main activities implemented	Expected outcomes
Mid-life of mine (progressive implementation)	Reduce physical and chemical risks while mining continues.	• Seal inactive or abandoned adits shortly after identification. • Regrade and terrace waste rock progressively; maintain and improve drainage channels. • Repair erosion features following rainfall events. • Neutralize cyanide residues routinely and manage contaminated materials in lined areas. • Apply preventive measures for acid rock drainage as reactive materials are identified.	• Stabilization of slopes and underground openings during operations. • Reduced risk of accidents, collapses, and water contamination.
Mid- to late-life of mine	Initiate and expand environmental recovery.	• Manage tailings in small, controlled containment areas and cover progressively. • Apply soil layers incrementally on stabilized slopes and terraces. • Implement revegetation each rainy season using fast-growing native species. • Rehabilitate inactive areas as soon as they are no longer needed for operations.	• Most closure actions completed before cessation of mining. • Lower technical and financial effort required at final closure.
Late operation/ pre-closure	Minimize remaining closure burden.	• Complete stabilization of remaining waste areas and slopes. • Expand revegetation to all inactive and marginal areas. • Continue routine monitoring of water quality, slope stability, and vegetation performance.	• Most closure actions completed before cessation of mining. • Lower technical and financial effort required at final closure.

Project phase/ timing	Key objective	Main activities implemented	Expected outcomes
Final closure	Complete residual actions and verify stability.	• Seal final active adits and access points. • Complete vegetation in any remaining bare zones. • Final inspection of drainage systems, terraces, and erosion control measures. • Final water and sediment quality assessments.	• Minimal residual environmental liabilities. • Stable post-mining landscape.
Post-closure (short term)	Confirm effectiveness of closure measures.	• Periodic water quality monitoring upstream and downstream. • Inspection of rehabilitated slopes and terraces. • Replacement of failed vegetation where necessary.	• Verification that closure objectives are met. • Reduced likelihood of long-term corrective interventions.

Source: Authors.

4.0 Quantitative Analysis

Building on the qualitative systems analysis and the CLD developed in the previous section, the quantitative analysis translates a selected set of priority indicators into economic terms through an integrated CBA. The objective is not to produce a definitive valuation of mine-closure impacts, but to demonstrate how systemic interactions, risks, and benefits identified qualitatively can be expressed in monetary terms under data-constrained conditions. Given the absence of formally approved closure plans, limited empirical post-closure evidence, and the pilot nature of the assessment, the analysis relies on literature-based assumptions, proxy values, and scenario-based modelling. The results should therefore be interpreted as indicative and exploratory, serving to compare alternative closure pathways and illustrate the added value of applying SAVi to progressive closure and NBI options.

4.1 Indicators Quantified

The quantitative component of this SAVi assessment translates a selected subset of indicators into monetary values in order to develop an integrated CBA of alternative mine-closure scenarios. The indicators monetized correspond to those presented in Table 5 and were selected based on three criteria: (i) their relevance within the CLD and systems mapping exercise, (ii) the availability of defensible data or proxy values in the literature, and (iii) their suitability for economic valuation under current data constraints in Marmato.

The indicators quantified in economic terms include CapEx associated with implementing closure measures (e.g., tunnel sealing, physical stabilization, waste management, and rehabilitation works), as well as post-closure O&M costs, reflecting long-term monitoring and upkeep requirements. These cost indicators represent the direct financial resources required to implement each closure scenario.

On the benefit side, the analysis quantifies avoided costs and added benefits. Avoided costs include (i) avoided mortality risk, capturing reductions in fatal accidents linked to landslides, tunnel collapse, rockfalls, and unstable slopes, and (ii) avoided infrastructure damage, reflecting reduced impacts on roads, access paths, and nearby structures due to improved slope stability and erosion control. These indicators represent risk-reduction outcomes that would otherwise impose social and economic losses under a no-closure baseline.

Added benefits are represented through a limited set of ecosystem services generated by rehabilitation and NBI. These include erosion control, which reduces soil loss and sediment transport; nutrient recycling, reflecting improvements in soil functioning that support vegetation and potential post-mining land uses; carbon sequestration, associated with revegetation and biomass accumulation; and biodiversity recovery, capturing habitat provision and ecosystem support functions. These services are monetized using conservative unit values derived from the literature and comparable contexts.

It is important to emphasize that these indicators represent only a subset of the full spectrum of impacts identified in the qualitative analysis. Several relevant dimensions, including avoided non-fatal injuries, long-term health system costs, water quality improvements, flood-risk reduction, land-value recovery, and broader social outcomes, are not monetized due to data and methodological limitations. As such, the economic results should be interpreted as partial and indicative, and the inclusion of additional indicators would result in a more complete and robust valuation of mine-closure benefits.

4.2 Literature Review

The literature reviewed for this assessment highlights that mine-closure valuation, particularly in ASGM contexts, relies heavily on qualitative and semi-quantitative methods to structure impacts before they are translated into economic terms. Across the reviewed sources, a common methodological sequence emerges: qualitative risk characterization, identification of impact pathways, selection of appropriate valuation methods, and application of unit costs or value-transfer approaches where site-specific data are unavailable.

The study from the Universidad Nacional de Colombia (2018) on establishing a baseline of areas affected by Abandoned Mining Activities constitutes the primary methodological reference for this assessment. The framework applies structured field inspections and expert judgment to classify abandoned mining sites according to physical, environmental, and social risk levels. While qualitative in nature, this classification directly informs quantification by linking risk categories (low, medium, high) to intervention typologies and standardized unit costs, such as costs per square metre for soil cover, drainage works, slope stabilization, or adit sealing. This approach is particularly relevant for Marmato, where heterogeneous mine conditions and limited site-specific data make fully engineering-based cost estimation impractical. The study by Universidad Nacional de Colombia (2018) therefore provides a defensible bridge between qualitative diagnosis and numerical cost estimation and is the main guidance used in the definition of closure costs and physical intervention assumptions in this report.

Complementing this approach, Gasparinnetti et al. (2024) demonstrate the importance of qualitative impact pathway analysis as a prerequisite for economic valuation in ASM contexts. Their framework distinguishes between reversible impacts (e.g., erosion, deforestation, soil degradation) and irreversible impacts (e.g., human health effects), which determines whether restoration cost methods, avoided cost approaches, or welfare-based valuation techniques should be applied. This conceptual structuring supports the use of value transfer and proxy indicators, reinforcing the methodological logic used in the Marmato assessment to quantify avoided mortality risk and ecosystem service benefits.

At the national policy level, the *Guide to the Application of Environmental Economic Valuation* (Ministerio de Ambiente y Desarrollo Sostenible, 2018) provides a qualitative screening framework for matching environmental impacts with appropriate valuation methods, such as restoration costs, avoided costs, or benefit transfer. This guidance underpins the methodological coherence of the CBA, particularly in ensuring alignment with Colombian regulatory and policy expectations for environmental valuation.

Finally, broader strategic planning literature (e.g., Oliveros-Sepúlveda et al., 2025) reinforces that early and progressive consideration of closure costs and liabilities consistently reduces long-term economic risk. While largely qualitative, this literature links closure planning directly to quantitative indicators such as net present value, BCR, and IRR, supporting the analytical structure adopted in the SAVi framework.

Taken together, the reviewed literature confirms that robust mine-closure valuation in data-constrained ASGM contexts is inherently grounded in qualitative and semi-quantitative methods, with the study by Universidad Nacional de Colombia (2018) serving as the most operational and contextually relevant reference for translating risk characterization into economic terms in the Marmato assessment.

4.3 Results: Pilot ASGM

The CBA results (see Table 5) for this SAVi assessment present cumulative discounted values for the period 2025–2060, applying a 3.5% social discount rate used in Colombia. Two mine-closure scenarios were assessed: a Comprehensive Closure Plan, in which closure activities are concentrated at the end of mine life, and a Progressive Comprehensive Closure Plan, in which closure and rehabilitation measures are implemented gradually over time. The results are presented relative to the Baseline Scenario, showing the net benefits of the interventions.

Table 5. Integrated CBA results in million COP,[1] cumulative and discounted, between 2025 and 2060

CBA, cumulative discounted values from 2010 to 2060	**Comprehensive Mining Closure Plan Scenario** COP million	**Progressive Comprehensive Mining Closure Plan Scenario** COP million
Total costs	**100.7**	**76.9**
Mining closure CapEx	94.8	71.0
Post-closure costs	5.9	5.9
Total added benefits	**4.1**	**5.4**
Nutrient recycling	0.4	0.5
Erosion control	3.4	4.5
Carbon sequestration	0.1	0.1
Biodiversity	0.3	0.3
Total avoided costs	**95.7**	**105.7**
Avoided mortality risk	71.9	81.9
Avoided infrastructure damage	23.8	23.8

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[1] COP = Colombian peso

CBA, cumulative discounted values from 2010 to 2060	**Comprehensive Mining Closure Plan Scenario** COP million	**Progressive Comprehensive Mining Closure Plan Scenario** COP million
Net benefits	**(0.8)**	**34.1**
BCR	0.99	1.44
IRR	3.40%	7.12%

Source: Authors.

In discounted terms, total costs reach COP 100.7 million under the comprehensive closure scenario, compared to COP 76.9 million under the progressive closure scenario. In both cases, CapEx represents the largest share of total costs, reflecting the importance of physical stabilization, tunnel closure, waste management, and rehabilitation actions in the Marmato context. The lower total cost of the progressive closure scenario is largely explained by differences in the timing and execution of capital-intensive activities. In particular, this scenario assumes that tunnel refilling is carried out progressively using material generated during mining operations, which reduces the need to purchase and transport additional fill material at the end of mine life. Post-closure monitoring costs are identical across scenarios, indicating that long-term oversight requirements are largely independent of the timing of closure implementation.

Across both scenarios, the results show that avoided costs constitute the largest share of total benefits, substantially exceeding the monetized ecosystem service benefits. Total avoided costs amount to COP 95.7 million in the comprehensive closure scenario and COP 105.7 million in the progressive closure scenario. These avoided costs are primarily driven by avoided mortality risk, valued at COP 71.9 million and COP 81.9 million, respectively, reflecting the reduction in fatal accidents associated with mine closure. This includes avoided deaths resulting from landslides and rockfalls on steep slopes, structural failure or collapse of underground tunnels, accidents affecting miners during informal or abandoned operations, and risks to non-mining populations exposed to unstable slopes or abandoned mine openings. Given Marmato's geomorphological conditions, steep terrain, dense concentration of underground workings, and the historical presence of informal and abandoned mines, mortality risk emerges as a particularly relevant impact category. In addition, the analysis includes avoided infrastructure damage, valued at COP 23.8 million in both scenarios, capturing reductions in damage to local infrastructure such as roads, access paths, and nearby structures resulting from improved slope stability and reduced mass-movement processes.

The analysis also includes the valuation of four ecosystem services generated through mine closure and rehabilitation: erosion control, nutrient recycling, carbon sequestration, and biodiversity (habitat and ecosystem support). Together, these ecosystem services generate total added benefits of COP 4.1 million in the Comprehensive Mining Closure Plan Scenario and COP 5.4 million in the Progressive Comprehensive Mining Closure Plan Scenario. Among these services, erosion control represents the largest contribution, reflecting the role of slope stabilization, revegetation, and reduced sediment transport in Marmato's steep terrain. Nutrient recycling and biodiversity benefits contribute more modestly, while carbon sequestration yields relatively low monetized values, reflecting conservative assumptions and the limited availability of site-specific data for ASGM reclamation contexts.

The higher ecosystem service benefits observed under the Progressive Comprehensive Mining Closure Plan Scenario are explained by the earlier initiation of rehabilitation activities, which allows ecological functions to begin recovering sooner and generate benefits over a longer discounted time horizon.

When considering total costs and benefits together, the Comprehensive Mining Closure Plan Scenario results in slightly negative net benefits of –COP 0.8 million, with a BCR of 0.99. Although this discounted BCR does not indicate economic viability in a strict sense, its proximity to one suggests that the outcome is highly sensitive to the parameters used in the valuation. Given the indicative nature of several assumptions, particularly those related to risk levels, impact areas, and the magnitude of avoided damages, relatively small changes in real-world conditions could shift the balance toward positive net benefits. For example, higher observed damage levels, greater exposure of infrastructure to landslide risk, or an expansion of the affected area would increase avoided costs, while larger or more productive rehabilitation areas would raise the value of ecosystem services. Such changes would improve the economic performance of the closure scenarios, regardless of whether closure is implemented progressively or at the end of the mine life.

By contrast, the Progressive Comprehensive Mining Closure Plan Scenario yields positive net benefits of COP 34.1 million and a BCR of 1.44, alongside a higher IRR of 7.12%, compared to 3.40% under the Comprehensive Mining Closure Plan Scenario. The main distinction between the two scenarios lies not only in the magnitude of benefits but in their timing. Because the Progressive Comprehensive Mining Closure Plan Scenario begins implementation earlier, it allows avoided risks, both to human life and infrastructure, and ecosystem service benefits to materialize sooner, increasing their present value once discounted and reducing cumulative exposure to environmental and safety risks over time.

Overall, the Progressive Comprehensive Mining Closure Plan Scenario performs better than the Comprehensive Mining Closure Plan Scenario due to differences in the timing of investments and benefits. Under the modelling assumptions, the definitive closure year is set in 2035, approximately 10 years from the base year of analysis. While the Comprehensive Mining Closure Plan Scenario concentrates most investments in 2034–2035, the Progressive Comprehensive Mining Closure Plan Scenario begins implementation earlier, starting in 2026, with a gradual rollout of the same technical measures. From an economic perspective, this earlier implementation leads to earlier risk reduction and benefit generation, which strengthens the overall economic performance of the closure intervention under conditions of uncertainty.

These results indicate that, when considering only the limited set of monetized indicators included in this assessment, mine closure derives its economic justification primarily from risk reduction and damage avoidance rather than from direct revenue generation. The valuation should therefore be interpreted as an underestimate of the full economic value of mine closure, as it focuses on a subset of indicators that could be quantified with available data. Several systemic effects and longer-term impacts identified in the qualitative analysis are not yet reflected in monetary terms. Within this constrained framework, the Progressive Comprehensive Mining Closure Plan Scenario performs better than the Comprehensive Mining Closure Plan Scenario by combining lower total costs with higher avoided risks and greater ecosystem service benefits, particularly due to earlier implementation. As additional indicators are incorporated and more empirical data become available, such as broader avoided damages, enhanced ecosystem services, and social and economic effects, the economic performance of both closure scenarios is expected to improve, reinforcing the case for early and progressive mine-closure interventions.

4.4 Interpreting Results and Outlining Limitations

The results of the integrated CBA should be interpreted in light of the fact that they represent a partial and indicative valuation of the benefits associated with mine closure in Marmato. The assessment was conducted with limited empirical evidence and evolving regulatory practice, which influences both the scope of the analysis and the interpretation of the quantified results.

First, the analysis includes a restricted set of monetized indicators. While avoided mortality risk, avoided infrastructure damage, and selected ecosystem services capture key dimensions of closure-related benefits, other relevant impacts could not be quantified due to data limitations. These impacts include avoided non-fatal injuries, changes in long-term health system expenditures, avoided damage to housing and local infrastructure, improvements in water quality and availability, reductions in downstream sedimentation and flood-related impacts, land-value recovery, and broader social outcomes associated with improved safety and environmental conditions. The exclusion of these elements means that the results do not reflect the full range of potential closure impacts.

Second, data availability constitutes an important constraint. Marmato currently lacks formally approved closure plans, systematic long-term monitoring data, and empirical evidence on post-closure environmental recovery for ASM. Additionally, many stakeholders involved in ASGM operate within transitional or partially formalized arrangements and are aware that current practices do not fully comply with environmental, technical, or regulatory requirements, all of which disincentivize sharing information. As a result, a number of parameters rely on secondary sources, proxy values, or averages derived from comparable contexts. While these inputs are informed by the literature and stakeholder input, they may not fully reflect site-specific conditions or the diversity of operational practices across individual mines.

Third, several valuation results are theoretical in nature. In the absence of real-world closure cases in Marmato, the assessment relies on modelled relationships between closure measures and expected environmental and safety outcomes. Assumptions were therefore required regarding the scale of mine impacts, the spatial extent of affected areas, and the magnitude of risk reduction achieved through closure interventions. These assumptions are intended to be plausible and transparent rather than predictive, and the resulting values should be interpreted as indicative estimates rather than empirically verified outcomes.

Fourth, the ecosystem service assessment does not capture potential interactions among services or longer-term ecological dynamics that may emerge beyond the modelled time horizon. Similarly, some benefits may materialize non-linearly over time or depend on implementation quality, maintenance effectiveness, and broader land-use changes, which are difficult to represent within the current modelling framework.

Fifth, the quantitative analysis focuses on one representative ASGM mine type (purely artisanal mine) due to time and data constraints. More mechanized ASGM operations, which typically involve larger underground networks and higher material volumes, are likely to generate different cost and benefit profiles. Extending the analysis to additional mine types in future work could refine aggregate results and improve representativeness at the territorial scale.

Finally, a range of social and institutional dimensions of mine closure, such as community perceptions of risk, cultural and historical ties to mining, institutional capacity, and enforcement conditions, are addressed in the qualitative analysis but are not monetized. These factors influence both the feasibility and effectiveness of closure implementation and are important for interpreting the results within a policy and governance context.

Taken together, these considerations suggest that the BCRs reported in this assessment should not be interpreted as definitive measures of the overall societal value of mine closure. Rather, they reflect the outcome of a structured, exploratory valuation exercise carried out under data and knowledge constraints. Within this context, the analysis is an example of the use of a systemic approach to mine-closure evaluation, and the results indicate that progressive closure approaches tend to perform better economically, while also offering a more structured pathway for reducing environmental and safety risks in Marmato.

5.0 Conclusions and Recommendations

Overall, the assessment demonstrates that mine closure in Marmato should be viewed as a necessary investment to reduce accumulated environmental and social liabilities, enhance territorial safety, and enable a gradual transition toward more resilient post-mining land uses. From both a systems and economic perspective, progressive closure represents the most robust and defensible pathway under conditions of uncertainty, informality, and evolving regulation. By addressing risks earlier, spreading costs over time, and strengthening environmental and social outcomes, this approach improves the overall performance and feasibility of mine-closure strategies in Marmato.

The analysis assessment applies the SAVi methodology to explore mine-closure pathways for ASGM in Marmato, a territory characterized by steep geomorphology, long-standing mining dependence, high levels of informality, and emerging regulatory frameworks. By combining systems thinking with an integrated CBA, the study provides one of the first structured attempts to evaluate mine closure not only as a technical obligation, but as a territorial risk-management and development challenge.

Insights from the qualitative analysis, grounded in participatory systems mapping, highlight that current ASGM dynamics in Marmato are shaped by reinforcing feedback loops linking informal mining, environmental degradation, livelihood vulnerability, and exposure to geotechnical and health risks. Landslide susceptibility, tunnel instability, water contamination, infrastructure damage, and declining ecosystem services interact with limited economic alternatives to sustain reliance on mining, even under hazardous conditions. Within this system, formalization and mine closure emerge as critical leverage points capable of moderating long-term risks, particularly when closure is conceived as a progressive, life-of-mine process rather than a single end-of-life intervention.

The quantitative analysis confirms that mine closure in Marmato is fundamentally a risk-reduction and damage-avoidance investment rather than a revenue-generating activity. Under both modelled closure scenarios, CapEx dominates total expenditures, reflecting the technical complexity of physical stabilization, tunnel closure, waste management, and rehabilitation in steep and densely mined terrain. Avoided costs constitute the largest share of monetized benefits, driven primarily by reductions in mortality risk associated with landslides, rockfalls, and tunnel collapse, and complemented by avoided infrastructure damage resulting from improved slope stability and reduced mass-movement processes. Monetized ecosystem service benefits, particularly erosion control, play a secondary but reinforcing role under current data constraints.

The integrated CBA results reveal a clear differentiation between closure pathways. The Comprehensive Mining Closure Plan Scenario yields a BCR close to 1, indicating near break-even performance under discounted terms. This outcome is highly sensitive to the parameters used in the valuation, particularly those related to risk levels, impact areas, and the magnitude of avoided damages. Given the indicative nature of several assumptions, relatively small changes in real-world conditions, such as higher observed damage levels, greater exposure of infrastructure, or larger areas affected, could shift this scenario toward positive net benefits.

By contrast, the Progressive Comprehensive Mining Closure Plan Scenario consistently outperforms the end-of-life closure scenario, generating positive net benefits, a BCR above 1, and a higher IRR. This improved performance is driven not only by lower discounted costs but also by the earlier realization of avoided risks and ecosystem service benefits.

Importantly, the numerical results should not be interpreted as a definitive or exhaustive measure of the economic value of mine closure. The valuation captures only a limited subset of indicators that could be quantified with available data and that were prioritized through the systems mapping exercise and CLD. As such, the results should be interpreted as conservative and likely to underestimate the full societal value of closure. Several systemic effects identified in the qualitative analysis, such as avoided non-fatal injuries, reduced long-term health system costs, improvements in water quality and availability, reductions in downstream flooding and sedimentation, avoided damage to housing, land-value recovery, and broader social stability, are not monetized. The inclusion of additional indicators and improved empirical data would be expected to strengthen the economic performance of both closure scenarios.

From a policy and implementation perspective, four priority recommendations emerge from the assessment. First, progressive mine closure should be promoted as the reference approach for ASGM in Marmato, as earlier and incremental stabilization and rehabilitation actions reduce cumulative environmental liabilities, improve economic performance, and deliver earlier risk-reduction benefits. Second, mine-closure planning should be integrated into the formalization process through simplified, scale-appropriate closure requirements that reflect artisanal operating conditions, improving feasibility and compliance while reducing long-term public liabilities. For this, financing mechanisms for ASGM formalization and mine-closure planning should be prioritized and enhanced. Third, NBI should be treated as a core component of mine-closure plans, playing a central role in site stabilization, water and soil recovery, and ecological rehabilitation, and contributing to the long-term functionality and durability of closure outcomes. Fourth, pilot closure projects and strengthened environmental and safety monitoring are needed to generate site-specific data on costs, recovery trajectories, and social outcomes, thereby reducing uncertainty and improving the robustness of future valuations and policy design.

Finally, the assessment shows the value of adopting systemic and integrated approaches to mine-closure analysis. Methods grounded in systems thinking, such as the SAVi framework, are particularly well suited to contexts like Marmato, where environmental risks, social dependence on mining, and institutional dynamics are deeply interconnected. By combining qualitative systems mapping with quantitative valuation, such approaches support more transparent, forward-looking, and adaptive decision making under uncertain conditions.

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Appendix A. Data Inputs and Assumptions

This appendix describes the data sources, assumptions, and calculation methods used to quantify the indicators included in the integrated cost-benefit analysis (CBA). It explains how biophysical and social impacts, such as restored areas, ecosystem service provision, and mortality risk reduction, are translated into monetary values to enable a consistent comparison of costs and benefits across scenarios. For each indicator, the appendix documents the underlying assumptions, unit values, spatial and temporal parameters, and reference sources, ensuring the transparency and replicability of the valuation exercise.

Investment and Costs

Indicator: Mining closure capital and post-mining costs

The capital expenditures (CapEx) and post-closure costs included in the SAVi assessment are derived from the components of the Comprehensive Mining Closure Plan Scenario defined for artisanal and small-scale mining in Marmato. Most closure-related interventions are classified as CapEx, as they represent one-time investments required to achieve physical stabilization, environmental control, and site rehabilitation. These include, among others, tunnel and gallery backfilling, pithead sealing, waste-pile terracing, drainage works, stabilization structures, waste management, and ecosystem rehabilitation measures.

Post-closure costs are limited to monitoring and site visitation activities. These costs are not assumed to be permanent or indefinite; instead, they are incurred over a short, defined period, typically 2–3 years, following the completion of closure works. They cover activities such as site inspections, water quality sampling, and verification of slope stability and vegetation establishment.

All cost estimates are calculated by multiplying the quantity of each intervention (e.g., number of analyses, cubic metres, square metres, or linear metres) by an applicable unit cost derived from Colombian reference studies or official price lists. The resulting total costs are summarized in Table A1, which also reports the source used for each unit cost.

The difference between the Comprehensive Mining Closure Plan Scenario and the Progressive Comprehensive Mining Closure Plan Scenario relates exclusively to the timing and sequencing of investments. Under the Comprehensive Mining Closure Plan Scenario, all closure activities are implemented within a narrow window between 2034 and 2035, with 2035 defined as the year of definitive mine closure. Monitoring and site visitation costs are incurred during the subsequent 2 years (2036–2037).

Under the Progressive Comprehensive Mining Closure Plan Scenario, closure activities are initiated earlier and distributed over a longer period while mining operations are still ongoing. Site diagnosis, mapping, and baseline assessments begin as early as 2026. Tunnel and gallery backfilling starts in 2029 and continues through 2035, alongside progressive waste-pile terracing, drainage works, gabion installation, bio-barriers, and slope stabilization measures.

Waste management actions and nature-based infrastructure interventions also begin earlier, reflecting a phased approach to risk reduction and rehabilitation.

A key cost difference between the two scenarios concerns tunnel and gallery backfilling. In the progressive scenario, excavated material generated during ongoing mining operations is assumed to be temporarily stored and reused for backfilling purposes. This substantially reduces the need for externally sourced material and associated transport and handling costs. As a result, the unit and total costs of gallery refill are lower than in the comprehensive end-of-life closure scenario, where backfilling relies more heavily on purchased material. This efficiency is the primary driver of the lower total CapEx observed under the Progressive Comprehensive Mining Closure Plan Scenario. Consequently, the total CapEx of the Progressive Comprehensive Mining Closure Plan Scenario is lower than that of the Comprehensive Mining Closure Plan Scenario.

Table A1. Parameters, values, and sources used for the cost calculation of mine-closure plans

Parameter/indicator	Value	Units	Source
Site diagnosis & mapping			
Site diagnosis and mapping (3 analyses)	3	analysis	Assumption
Site diagnosis and mapping cost	874,918	Colombian pesos (COP)/ analysis	Universidad Nacional de Colombia (2018)
Total cost	2,624,755	COP	Calculated
Tunnel/gallery refill scenario 1			
Gallery volume for refill	306.0	m^3	Assumption
River gravel fill	174,749	COP/m^3	Alcaldía Mayor de Bogotá (2020)
Total cost	9,782,682	COP	Calculated
Tunnel/gallery refill scenario 2			
Gallery volume for refill	306.0	m^3	Assumption
Fill selected material from excavation compacted	31,970	COP/m^3	Findeter (2020)
Total cost	9,782,682	COP	Calculated
Pithead sealing			
Bocamina (pithead) area	3.1	m^2	Assumption
Bocamina sealing cost	192,482.0	COP/m^2	Universidad Nacional de Colombia (2018)

Parameter/indicator	**Value**	**Units**	**Source**
Total cost	588,994.9	COP	Calculated
Waste-pile terracing			
Waste pile terracing volume	150	m^3	Assumption
Waste-pile terracing cost	44,621	COP/m^3	Universidad Nacional de Colombia (2018)
Total cost	6,693,124	COP	Calculated
Drainage trenches			
Drainage trenches size	50	m	Assumption
Drainage trenches cost	19,248	COP/m	Universidad Nacional de Colombia (2018)
Total cost	962,410	COP	Calculated
Gabion barriers			
Gabion barriers	3	barriers	Assumption
Gabion barriers cost	288,723	COP/unit	Universidad Nacional de Colombia (2018)
Total cost	866,169	COP	Calculated
Biotrinchos/bio-barriers			
Treatment of disturbed slope	100	m^2	Assumption
Biotrinchos/bio-barriers cost	82,242	COP/m^2	Universidad Nacional de Colombia (2018)
Total cost	8,224,231	COP	Calculated
Chemical neutralization (cyanide)			
Contaminated solution with cyanide residues	4	m^3	Assumption
Chemical neutralization cost	1,294,879	COP/m^3	Universidad Nacional de Colombia (2018)
Total cost	5,179,516	COP	Calculated

Parameter/indicator	**Value**	**Units**	**Source**
Chemical neutralization (encapsulation of contaminated soils)			
Contaminated material burial	5	m^3	Assumption
River gravel fill	174,749	COP/m^3	Alcaldía Mayor de Bogotá (2020)
Total cost	873,747	COP	Calculated
Lime/soil cover on reactive waste			
Lime/soil cover on reactive waste	20	m^3	Assumption
Waste-pile terracing cost	44,621	COP/m^3	Universidad Nacional de Colombia (2018)
Total cost	892,417	COP	Calculated
Waste management			
Hazardous waste removal	2	m^3	Assumption
Non-hazardous waste burial	5	m^3	Assumption
Waste removal cost	174,749	COP/m^3	Alcaldía Mayor de Bogotá (2020)
Total cost	1,223,246	COP	Calculated
Terrain reconformation (NBI)			
Terrain reconformation area (environmental rehabilitation)	40	m	Assumption
Terrain reconformation cost	192,482	COP/m^2	Universidad Nacional de Colombia (2018)
Total cost	7,699,280	COP	Calculated
Vegetation establishment (NBI)			
Native vegetation area	300	m^2	Assumption
Vegetation establishment cost	138,237	COP/m^2	Universidad Nacional de Colombia (2018)
Total cost	41,471,124	COP	Calculated
Vetiver planting (NBI)			
Vetiver strips size (steep slope stabi-lization)	40	m	Assumption

Parameter/indicator	Value	Units	Source
Vetiver planting cost	13,727	COP/m	Universidad Nacional de Colombia (2018)
Total cost	549,099	COP	Calculated
Monitoring/site follow-up			
Number of visits post-closure monitoring (2 years)	2	visits	Assumption
Monitoring and site visits cost	4,374,591	COP/unit	Universidad Nacional de Colombia (2018)
Total cost	8,749,182	COP	Calculated

Source: Authors' compilation.

Added Benefits

Indicators: Nutrient recycling, erosion control, carbon sequestration, and biodiversity

The four additional benefits associated with ecosystem services are estimated by multiplying the defined impact area by the corresponding per-hectare value of each ecosystem service. The added benefits associated with ecosystem services are estimated using a benefit-transfer approach, in which per-hectare annual values are applied to the areas affected by mine closure and rehabilitation interventions. The per-hectare values for carbon sequestration, nutrient recycling, erosion control, and biodiversity are drawn primarily from a study from the Universidad Nacional de Colombia (2018), which in turn adapts values from earlier international studies (i.e., U.S. values from 1996). All values were originally expressed in 2017 Colombian pesos and were updated to 2025 prices using an inflation correction factor based on Colombia's consumer price index.

Table A2. Parameters, values, and sources used for the calculation of ecosystem services

Paremeter	Value	Unit	Source
Value of the carbon sequestration ecosystem service per ha	129,834	2017 COP/ha/year	Universidad Nacional de Colombia (2018)
Value of the nutrient recycling ecosystem service per ha	68,374	2017 COP/ha/year	
Value of the erosion control ecosystem service per ha	669,712	2017 COP/ha/year	
Value of the biodiversity ecosystem service per ha	50,091	2017 COP/ha/year	
Inflation correction factor 2017/2025	1.56	Dimensionless	Departamento Administrativo Nacional de Estadística (2025)
Value of the carbon sequestration ecosystem service per ha	202,577	2025 COP/ha/year	Updated values
Value of the nutrient recycling ecosystem service per ha	106,682	2025 COP/ha/year	
Value of the erosion control ecosystem service per ha	1,044,932	2025 COP/ha/year	
Value of the biodiversity ecosystem service per ha	78,155	2025 COP/ha/year	

Source: Authors' compilation.

Ecosystem service values are calculated by multiplying the relevant per-hectare value by the area of influence of the closure interventions. For services directly linked to revegetation, such as carbon sequestration, the calculation is based on the restored native vegetation area. In this assessment, the revegetated area is assumed to be 300 m^2, equivalent to 0.03 ha.

For nutrient recycling, erosion control, and biodiversity, the benefits are assumed to extend beyond the immediate footprint of the rehabilitated area. A buffer radius of 30 m around the closure site is applied, corresponding to an indirect impact area of approximately 2,827 m^2, or 0.28 ha. This same area is used consistently across these three ecosystem services to maintain internal coherence in the valuation.

With respect to the timing and accounting of benefits, under the Comprehensive Mining Closure Plan Scenario, ecosystem service benefits are assumed to materialize only after the completion of closure works in 2035. Under the Progressive Comprehensive Mining Closure Plan Scenario, benefits begin to accrue earlier, in line with the phased implementation of rehabilitation activities. During the implementation period, only a proportion of the full benefit is attributed, reflecting the interventions' partial functionality. Full ecosystem service benefits are realized only once the relevant components of the closure plan are fully implemented.

Avoided Costs

Indicator: Avoided mortality risk

The avoided mortality risk is estimated by multiplying the value of a statistical life for Colombia by the expected reduction in the number of deaths associated with mining activities in Marmato.

To determine the reduction in mortality risk, a review of press reports and secondary sources was conducted to identify fatal events related to mining activities in the recent period. Based on this review, the following records were identified: no deaths were reported in 2020; three fatalities occurred in 2021; two in 2022; none in 2023; two in 2024; and five in 2025. On the basis of this information, an average of two mining-related deaths per year was estimated for the municipality.

Subsequently, the probability of a fatal event occurring in the specific mine analyzed was estimated. Considering an approximate total of 265 mines in operation (ANM, 2025), a baseline probability of 1 out of 265, equivalent to 0.38%, was assumed for a fatality to occur at a given mine. This probability was further adjusted by applying a factor reflecting the share of mining-related deaths attributable to rockfall or landslide events, assumed at 50%. The combination of these probabilities provides an approximation of the annual mortality risk associated with the mine under analysis, which is then used to quantify the economic benefit associated with avoided fatalities resulting from the implementation of the closure plan.

The combined probability yields the compound probability of a fatal event occurring in a single mine in Marmato, estimated at 0.189%. This probability is then applied to the average of two mining-related deaths per year in the municipality to estimate the expected number of fatalities attributable to one representative mine, which is the unit of analysis in this assessment. This expected number of fatalities is subsequently adjusted to reflect the assumed effectiveness of mine-closure interventions. Both the Comprehensive Mining Closure Plan Scenario and the Progressive Comprehensive Mining Closure Plan Scenario are assumed to reduce mortality risk by 70%. Applying this reduction factor to the expected number of fatalities yields the estimated number of deaths avoided as a result of mine closure.

The resulting avoided mortality figure, constant across the assessment period and equal to 0.00264 avoided deaths per year, is then multiplied by the value of a statistical life for Colombia (Mardones & Riquelme, 2018), originally in 2013 USD prices and then converted to 2025 prices and estimated at approximately COP 2,262 million, to obtain the monetized benefit associated with reduced mortality risk.

Indicator: Avoided infrastructure damage

Avoided infrastructure damage is estimated for two asset categories: roads and housing. The analysis assumes the occurrence of a single landslide event attributable to mining activity over the assessment horizon, from the present year to the end of the evaluation period in 2060. Under the closure scenarios, this event is assumed to be avoided.

To estimate avoided road damage, the length of road affected by the hypothetical landslide is assumed to be 40 m. The reference construction cost for secondary roads in Colombia is taken as approximately COP 1,532 million per kilometre, based on data for comparable regions, including Armenia, Pereira, and Manizales (Morera-Molina, 2019). For repair scenarios, it is assumed that only 40% of the full construction cost is required, reflecting partial damage rather than complete road reconstruction. This results in an estimated repair cost of approximately COP 612 million per kilometre.

The avoided road repair cost is then calculated by multiplying the affected road length (40 m, equivalent to 0.04 km) by the estimated repair cost per kilometre. This yields an avoided road damage cost of approximately COP 24.5 million.

For housing damage, the analysis assumes that four residential units would be affected by the hypothetical landslide event. For each dwelling, wall repairs are assumed to involve a surface area of 2.5 m in height and 3.5 m in length. This results in a total repair area of 32 m^2 across the four houses. The total repair area is then multiplied by the estimated unit cost for wall repairs, set at approximately COP 131,000 per m^2 (CYPE Ingenieros S.A., 2025). This yields an avoided housing repair cost of approximately COP 11.6 million.

Appendix B. Undiscounted Results

The undiscounted results of the integrated cost-benefit analysis for the nature-based infrastructure scenarios are presented in Table B1.

Table B1. Integrated cost-benefit analysis results in million COP,[2] cumulative and undiscounted, between 2025 and 2060

Cost-benefit analysis, cumulative discounted values from 2025 to 2060	Units	Comprehensive Mining Closure Plan Scenario	Progressive Comprehensive Mining Closure Plan Scenario
Total costs	**COP million**	**140.1**	**96.1**
Mining closure capital expenditure	COP million	131.3	87.3
Post-closure costs	COP million	8.7	8.7
Total added benefits	**COP million**	**8.8**	**10.4**
Nutrient recycling	COP million	0.8	0.9
Erosion control	COP million	7.4	8.7
Carbon sequestration	COP million	0.2	0.2
Biodiversity	COP million	0.6	0.7
Total avoided costs	**COP million**	**188.7**	**201.9**
Avoided mortality risk	COP million	152.6	165.8
Avoided infrastructure damage	COP million	36.1	36.1
Net benefits	**COP million**	**57.5**	**116.3**
Benefit-to-cost ratio		1.41	2.21
Internal rate of return		3.40%	7.12%

Source: Authors.

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[2] COP = Colombian peso

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