A Multidisciplinary Approach to Mine Waste Rehabilitation

A Case Study Integrating Environmental and Social Impacts in the Iberian Pyrite Belt

Double degree combined MSc thesis

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by

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Cover: Image of the inactive San Miguel open pit, obtained during the Q4 AESM fieldwork (2024).

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Abstract

The Iberian Pyrite Belt (IPB), a historically mined Volcanogenic Massive Sulfide (VMS) region in southern Spain and Portugal, suffers from severe environmental degradation due to unregulated mine closures. This thesis develops a scalable rehabilitation strategy for legacy mine waste in the IPB, using data and samples obtained from the inactive San Miguel mine site. The findings are expanded into broader recommendations for an arbitrarily chosen study area, addressing both active and inactive sites, and offering guidance for sustainable mine management in the IPB and similar mining regions worldwide. In doing so, a multidisciplinary methodology is applied, integrating geochemical analysis, ArcGIS-based spatial modelling, literature reviews, cost assessments, and a Social Life Cycle Assessment (S-LCA) to ensure a comprehensive evaluation of rehabilitation potential and impact in the study area.

Heavy metal contamination, primarily arsenic (As), copper (Cu), and lead (Pb), was identified as a major concern, with all sampled materials from San Miguel exceeding regulatory thresholds. The pollution in this area is mainly linked to acid mine drainage (AMD) and mobilization of heavy metals from historic mine waste and slag deposit. Geo-spatial extrapolation using Sentinel-2 imagery enabled mapping of contamination across the study area, justifying area-wide remediation measures.

A multifaceted rehabilitation strategy is proposed for the study area, combining physical and biological treatments to address AMD and heavy metal pollution from the inactive mine sites. The proposed interventions include the installation of geo-membranes in historical mine ponds to prevent leachate migration,while Sulfate Reducing Bacteria (SRB), applied via Diffusion Active Reactive Permeable Barriers (DAPRB) systems, will treat AMD by neutralizing acidity and precipitating insoluble sulfide metal compounds. Phytostabilization, using metal tolerant native plants, will immobilize contaminants in soil, and revegetation will enhance slope stability and support ecosystem recovery. Together, these approaches address historical and present mining related pollution in the study without aiming to eliminate naturally occurring acid rock drainage (ARD), focusing instead on mitigating its mining induced intensification. The total estimated rehabilitation cost for the seven historical mine sites in the study area is approximately €25.2 million, with revegetation and geo-membrane installation being the most expensive components.

A S-LCA was conducted to evaluate the socal and socio-economic impacts of legacy and ongoing mining activities, as well as the projected outcomes of the proposed rehabilitation efforts in the study area. The S-LCA shows that historical and active mining have disproportionately affected local residents, farmers, and municipalities in terms of health and environmental degradation.For instance, the study area is commonly referred to as the triangle of death, whereas it has the largest cancer mortality rate in all of Spain. Conversely, reclamation improves outcomes in those same domains, especially for communities closest to the intervention zone of the study area.

Recommendations are also formulated for Zones 2–4, which include active and inactive mine sites. Inactive mines should adopt the study area plan with minimal adaptation. Active mines must incorporate early-phase AMD mitigation, proactive monitoring, and closure planning to prevent legacy pollution.

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Nomenclature

AMD	Acid Mine Drainage
ARD	Acid Rock Drainage
DAPRB	Diffusion Active Passive Reactive Barrier
EIA	Environmental Impact Assessment
GIS	Geographic Information System
IPB	Iberian Pyrite Belt
KPI	Key Performance Indicator
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NDVI	Normalized Difference Vegetation Index
pH	Potential of Hydrogen (acidity/basicity indicator)
PM	Particulate Matter
S-LCA	Social Life Cycle Assessment
SRB	Sulfate-Reducing Bacteria
VMS	Volcanogenic Massive Sulfide

1 Introduction

1.1. Context and Problem Statement

The Iberian Pyrite Belt (IPB), spanning parts of southern Spain and Portugal, is one of the world's largest metallogenic provinces, and is internationally known for its VMS deposits rich in sulfur, copper, zinc, lead, gold, silver, and other metals. These sought after deposits formed in a submarine back arc basin setting during the Late Devonian to Early Carboniferous periods, so around 350 million years ago. The back arc basin was developed as a result of crustal extension. The resulting submarine volcanic activity and rifting created ideal conditions for hydrothermal circulation, in which seawater percolated through the oceanic crust. Metals present in the hydrothermal fluids, such as copper, zind and lead, were heated by underlying magmas and leached from the surrounding rocks. When these metal rich fluids emerged at the seafloor and mixed with cold seawater, they precipitated sulfide minerals, thereby forming large, stratiform mounds of pyrite, chalcopyrite, sphalerite, and galena. Over time, these deposits were buried by sediments and later deformed during the Variscan orogeny, preserving some of the-largest and most metal-rich VMS systems worldwide. The geological map of the IBP, with the location of the study area pinpointed, is presented in Figure 1.1 [1]. To clarify the lithostratigraphic groups shown in the geological map, a lithostratigraphic column is included (Figure 1.2) [2].

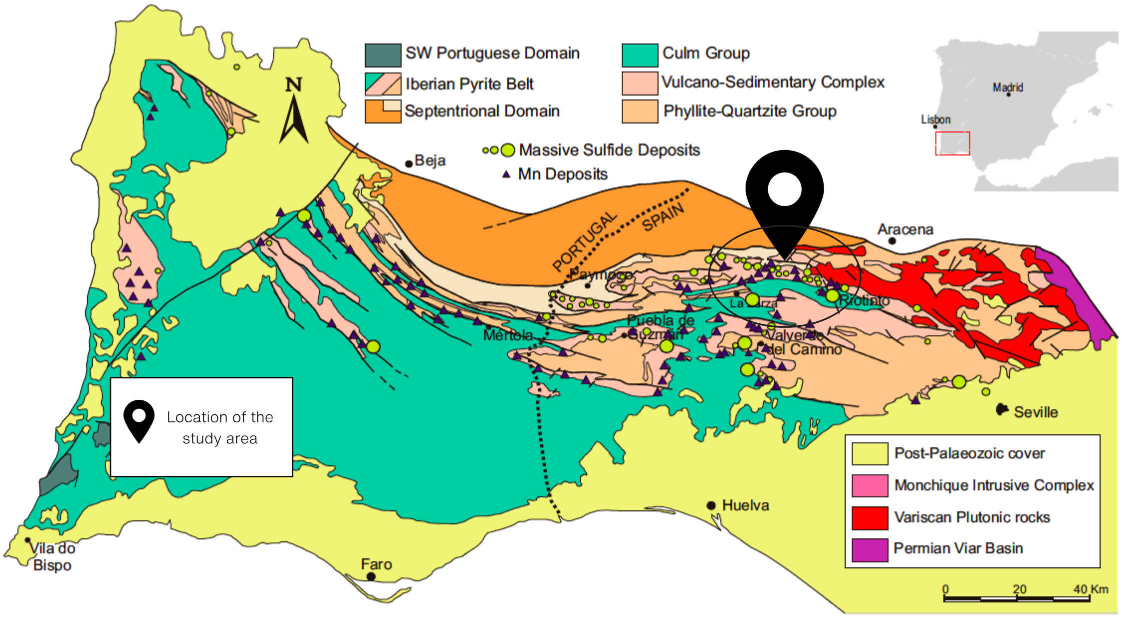


Figure 1.1: Geological map of the Iberian Pyrite Belt with the relevant lithotratigraphic groups present [1]. The location of the study area is marked with a black pin.

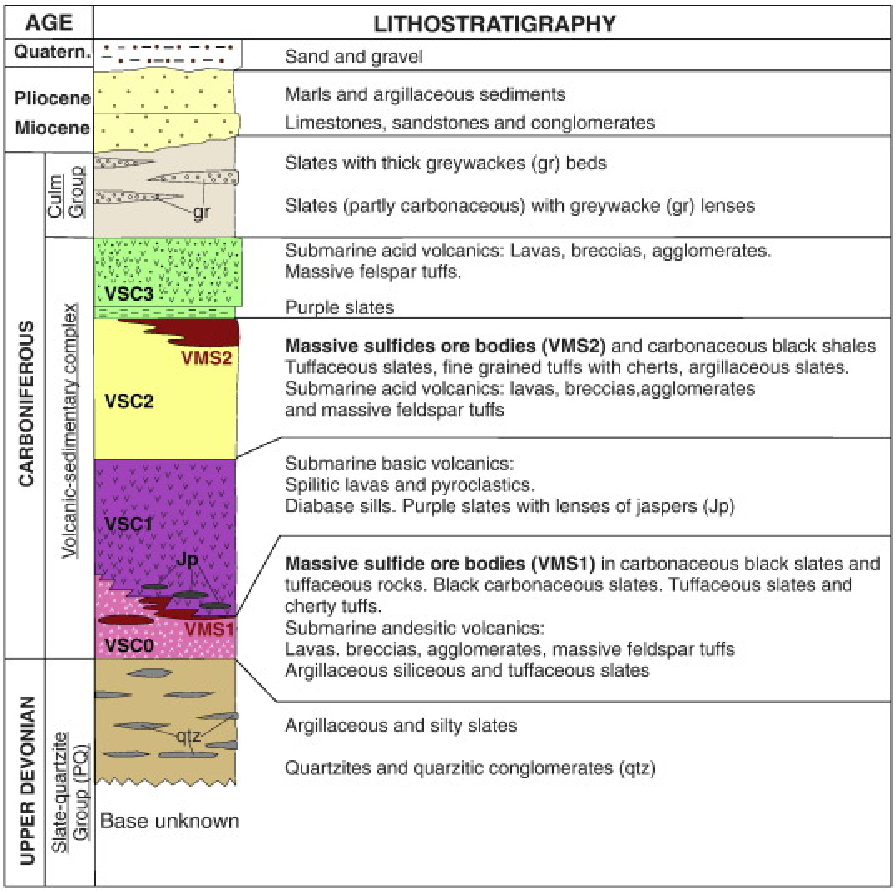


Figure 1.2: Simplified lithostratigraphic sequence of the IPB, highlighting major units such as the Culm Group, VMS deposits, and slate formations [2].

These VMS deposits have been exploited since Roman times, contributing significantly to the region's economy and providing employment for local communities over centuries. However, over centuries of intensive mining, the region has also become one of Europe's most environmentally degraded mining zones. A close up geological overview of the study area of this research is depicted in Figure 1.3.

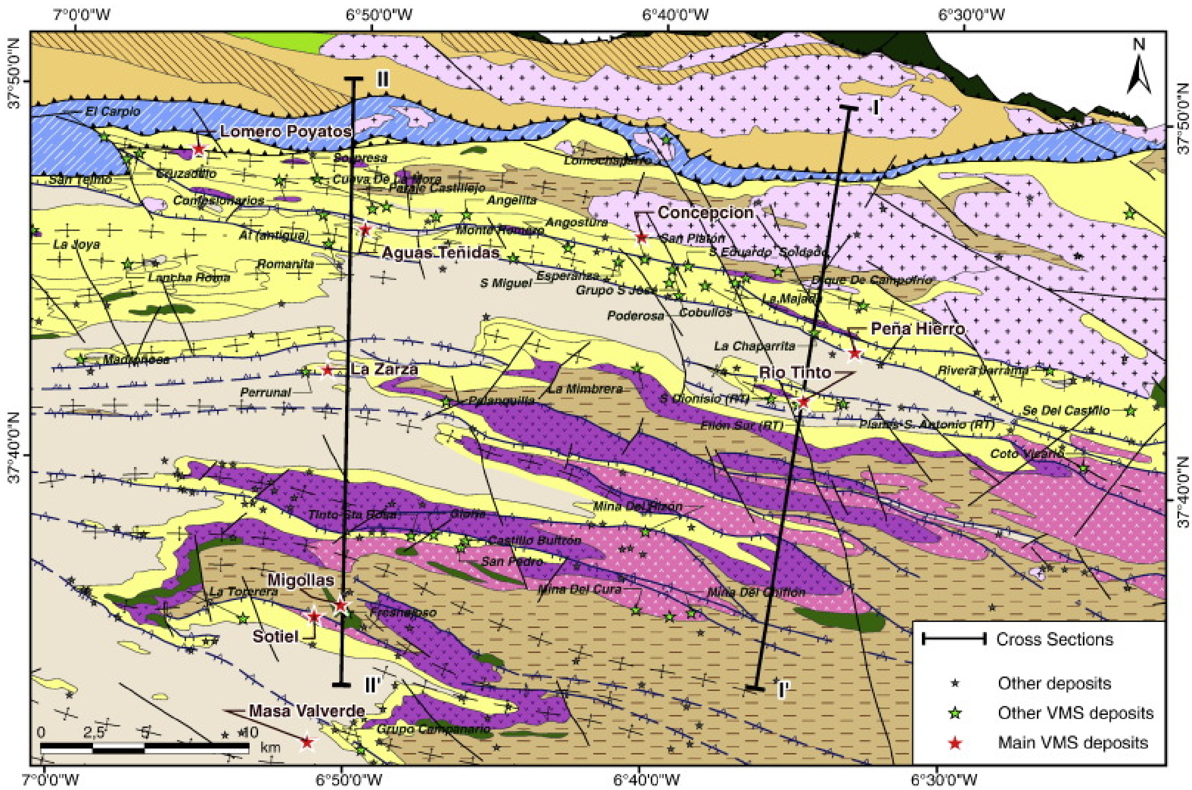


Figure 1.3: Geological map of the study area with lithostratigraphic units corresponding to Figure 1.2 [2].

As mentioned before, the region contains numerous inactive mine sites. Historically, the closure of these mines often occurred without the implementation of environmental regulations or cleanup guidelines, resulting in widespread environmental degradation and contamination in the study area of this research. Many of these inactive sites are characterized by deforested landscapes (Figure 1.7) covered with tailings, waste rock, and overburden material. The exposure of sulfide-rich mine waste to oxygen and water has led to the generation of AMD, a process that produces sulfuric acid. This, in turn, facilitates the mobilization of heavy metals, leading to significant contamination of surrounding soils and water bodies [3].

This thesis aims to develop a scalable rehabilitation strategy and assess the environmental and social impacts of legacy mine waste in the Iberian Pyrite Belt. Field data collected at the inactive San Miguel mine serve as the basis for a site-specific remediation plan, which is extrapolated across the arbitrarily defined Zone 1. Building on these results, broader recommendations are formulated for Zones 1 through 4, encompassing both active and inactive sites, to support sustainable mine management in the IPB and comparable VMS mining regions worldwide.

1.1.1. Study area

The study area is located in the South-West Spanish part of the IBP (Figure 1.1). For the rehabilitation strategy, the study area is divided into arbitrarily chosen different zones, namely 1,2,3 and 4. For zone 1, a reclamation plan will be made available by extrapolating samples obtained at the San Miguel site and Sentinel-2 data, for zone 2,3, and 4 the study will merely aim to give an advice regarding the implementation of a rehabilitation and monitoring plan. An overview of the locations of zone 1,2,3, and 4 is given in figure 2.8. The center of the study area is depicted by the coordinates 37°41'21"N 6°43'10"W.

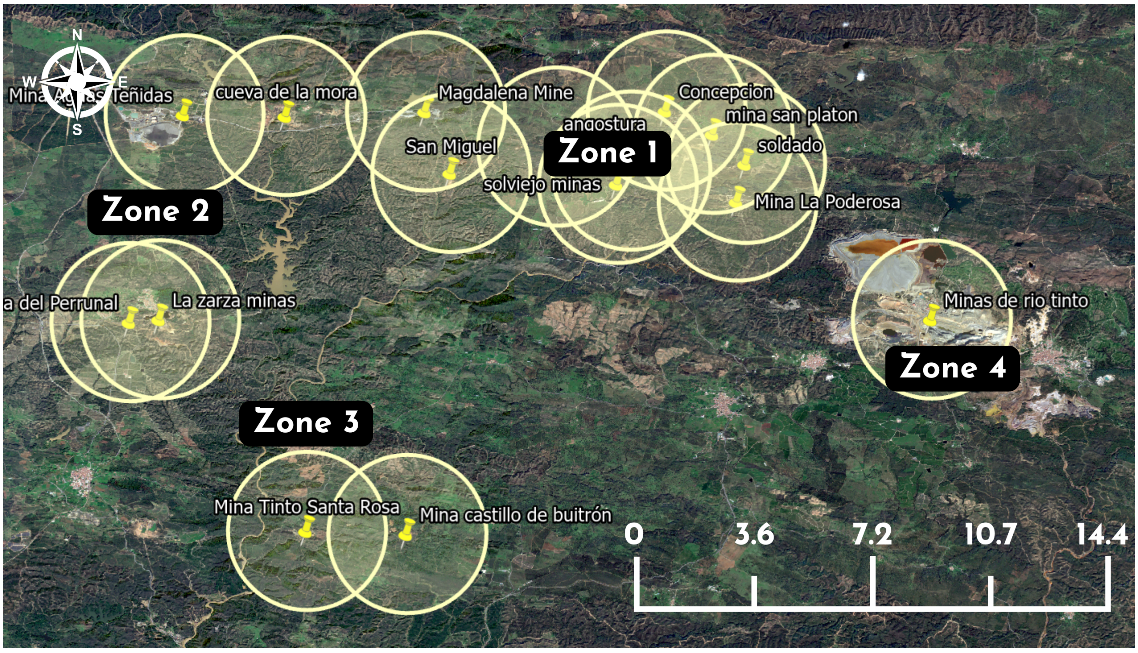


Figure 1.4: Zonation of the study area (Zones 1–4) in ArcGIS. Each mine site is circled by a 3 km buffer. Zone 1 is the primary focus of this study. The scale bar is given in kilometers.

1.1.2. Zone 1

This thesis investigates the environmental impact and rehabilitation strategy for zone 1 of a broader study area within the IPB. Zone 1 comprises several historically inactive mine sites, namely: San Miguel, Poderosa, Concepción, San Platón, Angostura, El Soldado, and Esperanza. These mines, situated in close proximity of one another, are characterized by substantial legacy pollution. Physical samples and geochemical analysis by using portable XRF were conducted exclusively at the San Miguel mine, these findings have been extrapolated to the entirety of zone 1. This extrapolation has been done based on the assumption that the results obtained from the San Miguel site are representative for the remaining inactive mine sites in zone 1, based on the geological and mineralogical similarities among the sites.

San Miguel

Geology

The San Miguel inactive mine site is known for its stockwork and VMS, as well as displaying one of the largest gossan's of the area. Several lenses of VMS were exploited, with the largest lense being the San Miguel lens. The San Miguel lens is about 200 meters long and 10-40 meters thick, extending to a depth of 155 meters. The deposits in this zone are associated with volcanoclastic rocks and intense chloritization of felsic porphyritic rocks. The footwall of the deposit shows strong chloritization, and remobilized sulfides have been observed due to the presence of shear zones in the deposit. Above these sulfide-rich zones, a gossan cap has formed as a result of weathering and oxidation of the ore bodies (Figure 1.6 and 1.5). This gossan, which reaches a depth of up to 12 meters, is predominantly composed of goethite, with secondary minerals present being quartz, hematite, jarosite, barite, and various clay minerals. Due to the absence of natural carbonates in the area, there occurs natural Acid Rock Drainage (ARD), which basically entails that when these sulfide minerals are exposed to oxygen and air, sulphuric acid is generated [4]. A cross section of the San Miguel is included for better visualization (figure 1.5).

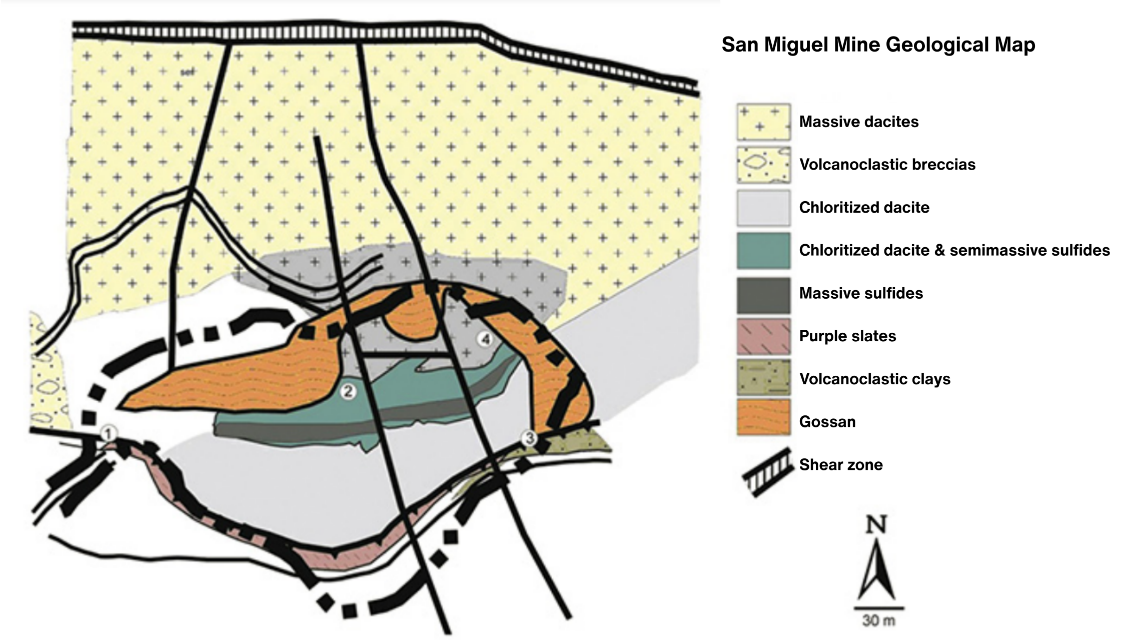
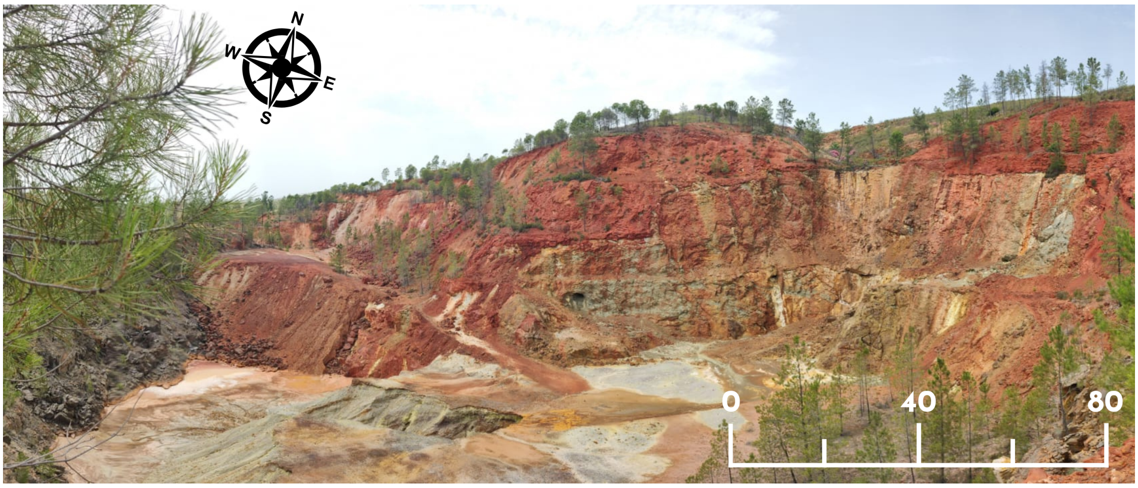
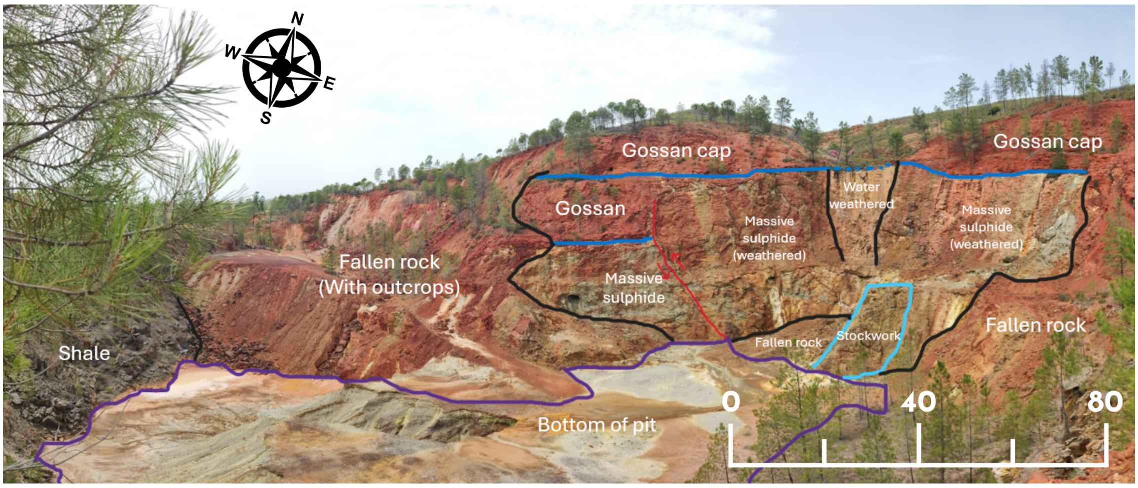


Figure 1.5: Detailed geological map of the San Miguel mine site [4].



(a) Without classification



(b) With classification

Figure 1.6: Photographs of the San Miguel mine face taken in June 2024. The red top layer in both images represents the Gossan cap. The top image shows the unclassified mine face, while the bottom image includes classification for geological interpretation. The scale bar at the bottom right is given in meters.

Mining history

Mining at the San Miguel Mine, one of the predominant inactive mines in zone 1 and the focus of the study area, began in 1851 and continued until 1960, thereby producing around 1.29 million tons of pyritic ore with an average copper grade of 2-3%, and +/-46% sulfur content. The mining method of the San Miguel transitioned from underground to open-pit mining. The richest copper containing parts of the deposit were located just below the gossan, however this gossan layer has completely disappeared since then.

The primary ore mainly consists of pyrite with fine chalcopyrite inclusions and minor sphalerite. Trace amounts of minerals such as galena, tetrahedrite, pyrrhotite, bismuthinite, and bornite are also present and further enhance the mineralization. The gangue minerals at the site are predominantly made up of quartz, chlorite, muscovite, plagioclase, and rutile. In the case of the San Miguel mine, a subdivision can be made between three types of waste produced during active periods, these are: (1) ore related to the 20th century mine exploitation as modern slags & sulfide roasted ashes & brittle pyrite ore & coarse blocks of pyrite & smelting ashes & dumps, (2) gossan & host rocks & local reworked Roman slags & roasted ore related to 19th century open pit/underground exploitation and (3) Roman slags related to supergene and gossan enrichment of the exploitation zone. Roman mining activities are also evident in the cementation and gossan zones, further indicating the site's long history of resource exploitation [5].

Several rehabilitation attempts at the San Miguel mine have failed. Between 1993 and 1996, the Environmental Office of the Junta de Andalucia Government applied restoration techniques to waste piles, but these efforts were unfortunately unsuccessful. Attempts to neutralize acidic soils with limestone in certain areas resulted in the formation of gypsum, indicating that the neutralization was only partially effective and failed to fully address the persistent and ongoing acidity in the area[5].

1.1.3. Impact on environment and local communities

The study area is characterized by a high density of inactive, historical mining sites that were abandoned without regulatory oversight or environmental restoration. As a result, inactive mine sites in the region remain deforested, and surfaces remain blanketed with tailings, waste rock, and overburden rich in sulfide minerals. A visualization of the area is given by Figures 1.7, which present images taken during the 2024 Q4 fieldwork at the San Miguel mine site during the dry period.

(a) deforested surface area in the San Miguel area.

(b) deforested surface area in the San Miguel area.

Figure 1.7: deforested surface areas in the San Miguel area, covered with mine waste. The images show the respective orientation and human's for scale. As well, colour variations between the different types of mine waste can be slightly observed from this picture, varying between yellow, red, brown and white shades (similarly visible in Figure 2.4). Picture taken during the dry season in June, 2024.

Exposure of these sulfide rich materials to oxygen and water triggers AMD, a chemical process in which sulfuric acid is generated. The resulting water has extremely low pH values, creating highly acidic conditions that facilitate the leaching of toxic heavy metals [3]. pH measurements obtained using a calibrated pH probe at multiple locations along the Río Odiel and Río Tinto revealed values as low as 1.3, with typical values generally ranging between 2.0 and 3.5 [6]. During field observations, a clear visual correlation was noted between the coloration of acid mine drainage (AMD) and its acidity. Darker red water consistently indicated lower pH values, while orange tinted streams were typically associated with pH levels ranging from 2.5 to 3.5. An image of AMD drainage encountered during the fieldwork is shown in Figure 1.8.

Figure 1.8: Acid Mine Drainage observed in the study area during Q4 2024 fieldwork.

Portable XRF analysis of samples collected in the area showed that the most prevalent contaminants include lead (a potent neurotoxin) [7]), arsenic (a known carcinogen,[8]), and copper (which disrupts nutrient cycling, [9]) (Section 2.3). These pollutants accumulate in nearby soils, with agricultural farms being located within a 2 kilometer radius of the inactive mine sites in the zone 1 of the study area. Consequently, livestock grazing in these areas are assumed to exhibit elevated levels of heavy metals, posing serious risks to food safety and public health (Section 6.3.2).

Although a glance at satellite imagery of the area may suggest that the region is sparsely populated, a more detailed assessment reveals that nearly 50,000 people live within a 25-kilometer radius of the contaminated zone (Section 6.3.1). These are predominantly small, local communities that are either currently or historically dependent on mining activities. The prevailing North-East winds transport contaminated dust towards upwind settlements [10], whereas Southward directed groundwater and river flows [11] distribute dissolved metals downstream, compounding the risk of widespread environmental exposure in both North-East and South directions of the study area.

Health statistics for the broader region further underscore the severity of the situation. The provinces of Huelva, Sevilla, and Cádiz, collectively known as the “triangle of death”, report the highest cancer mortality rates in Spain [12]. Alarmingly, even within this high-risk region, the study area demonstrates a cancer mortality rate significantly above the regional average [13], signaling an acute threat to the health and safety of local residents.

1.2. Research objective

The objective of this thesis is twofold: (1) to develop a scalable rehabilitation strategy and (2) to assess the environmental and social impacts of legacy mine waste in the Iberian Pyrite Belt. The San Miguel mine serves as a case study, with XRF data and fieldwork observations and findings extrapolated to the arbitrarily defined Zone 1 of the study area to establish a detailed and scalable rehabilitation plan for the mine sites located there. These results are further extended to encompass Zones 1 through 4, consisting of both active and inactive mine sites, offering general recommendations for rehabilitation and long-term monitoring practices. Furthermore, Zones 1 to 4 are intended to serve as representative examples of other VMS deposit sites within the Iberian Pyrite Belt and comparable mining regions worldwide, making the results a scalable approach to various regions.

This is achieved through (1) the identification and spatial extrapolation of dominant pollutants, (2) the evaluation and selection of sustainable, cost-effective remediation techniques suited to the local geological and climatic conditions, and (3) an analysis of the anticipated effects of rehabilitation on nearby ecosystems, agricultural areas, and communities. Additionally, the thesis provides general recommendations for long-term monitoring and rehabilitation of active and inactive mines in Zones 2–4, aiming to support more informed closure planning and environmental management across the wider region.

1.3. Research questions

This thesis addresses the following research questions:

RQ1. What are the dominant pollutants in the San Miguel mine waste, and how severe is their environmental impact when extrapolated to the broader Zone 1?

RQ2. What are the most suitable, cost-effective, and sustainable rehabilitation strategies for Zone 1, considering the geological characteristics and pollution severity?

RQ3. How would these rehabilitation efforts affect the surrounding ecosystems, agriculture, and communities, particularly those downstream (South) and downwind (North-East)?

RQ4. What general recommendations can be made for active mines (Zones 2–4) and for long-term monitoring beyond Zone 1?

1.4. Research scope

This thesis investigates the environmental impact and rehabilitation potential of legacy mining sites in the Iberian Pyrite Belt (IPB), with a primary focus on the San Miguel mine and the broader Zone 1 cluster of abandoned operations. The scope can be divided in a spatial, thematical and methodological scope:

Spatial Scope

The spatial focus of the thesis is Zone 1 of the Iberian Pyrite Belt, located in southwestern Spain. This zone includes the San Miguel mine and several surrounding sites with similar geological characteristics, primarily consisting of abandoned VMS deposits. Fieldwork, including sample collection and in situ analysis, was conducted exclusively at the San Miguel site during the 2024 dry season in June. Spatial extrapolation of the portable XRF data to other mine sites within Zone 1 was carried out using supervised classification techniques in ArcGIS Pro, applied to Sentinel-2 satellite imagery. This approach enabled the confirmation and spatial mapping of visually distinct mine waste classes, specifically white, yellow, red, brown, and grey mine waste materials across the broader area of zone 1.

Zones 2, 3, and 4, encompassing a mix of active and inactive mining operations, fall outside the primary research focus. However, general guidance and recommendations are offered for these zones based on geological similarity and insights derived from Zone 1. No direct field sampling or site-specific rehabilitation design was conducted for these zones.

Thematic Scope

The research addresses three important aspects of mine site rehabilitation:

1. **Contaminant characterisation:** The thesis identifies and maps the spatial distribution of the most contaminating metals (arsenic, lead, copper) in mine waste at San Miguel.
2. **Rehabilitation and monitoring strategies:** Based on a literature review conducted regarding international best practices for mine site rehabilitation and the specific conditions per mine site, a site specific remediation plan has been proposed. The rehabilitation plan combines geo-engineering (e.g., geomembranes), ecological (e.g., phytostabilisation), and passive biochemical (e.g., SRB systems) solutions. A general advice for long-term monitoring indicators and sampling protocols are also elaborated on in the research.
3. **Socio-economic implications of rehabilitation:** A Social Life Cycle Assessment (S-LCA) is conducted to evaluate the broader social benefits of environmental rehabilitation, with the emphasis being on public health, land usability, and rural development potential.

Methodological Scope

The study employs a combination of methods, including:

- Field-based geochemical analysis using portable X-ray fluorescence (pXRF)
- Remote sensing classification using Sentinel-2 imagery and ArcGIS Pro
- Literature reviews of remediation and monitoring frameworks
- Cost estimation from published sources and benchmarked unit prices
- Social Life Cycle Assessment using spatial population data and qualitative risk categories

Out of Scope

Several topics and approaches, while relevant to mine rehabilitation, were deliberately excluded from the scope of this thesis due to time and data constraints, and the defined research objectives:

- **Hydrogeological and geotechnical modelling:** Although AMD generation and contaminant transport are influenced by subsurface hydrology and slope stability, no predictive modelling of groundwater flow, slope failure, or geotechnical risks was conducted. The focus remained on surface contamination and passive treatment feasibility.
- **Field trials:** The rehabilitation methods proposed in this study were not tested through pilot- or field-scale trials. Their selection is based on their compatibility with already existing site conditions and literature-based reviews of methods.

- **Seasonal and subsurface sampling:** All field samples were collected during a single dry-season campaign and limited to surface materials. As such, seasonal or vertical variations in contaminant behavior were not assessed.
- **Health risk assessment:** While social risks and public health implications are discussed through a S-LCA framework, no quantitative risk modelling (e.g. exposure pathways) was included.
- **Validation of findings:** This research explores a range of interconnected aspects to develop a holistic model for mine site rehabilitation, with a focus on VMS deposits within the IBP and globally. The aim is to provide an integrative framework that may inform rehabilitation strategies for similar mineral systems elsewhere. However, it is beyond the scope of this thesis to empirically validate the proposed model or its outcomes. Practical implementation, site specific calibration, and long-term monitoring of rehabilitation effectiveness fall outside the boundaries of this study and are recommended for future research.
- **Social Life Cycle Impact assessment:** The results of the Social Life Cycle Assessment (S-LCA) are derived from available literature and satellite-based spatial data pertaining to the study area. However, due to limitations in time and resources, no interviews or stakeholder surveys were conducted, which limits the ability to empirically validate the S-LCA findings.
- **Rehabilitation proposal for Active Mines:** No detailed rehabilitation strategies were developed for active mines in Zones 2–4 (e.g., Aguas Teñidas, Riotinto). Only general guidance is provided based on geologic and operational analogies.
- **Economic evaluation:** While a cost estimate was prepared, the thesis does not consider benefit-cost analysis or relevant funding mechanisms (e.g., environmental taxes), or long-term economic sustainability of the proposed rehabilitation methods.

These exclusions reflect the indicative nature of this study, which focuses on developing a site-specific rehabilitation framework for Zone 1. While practicality, environmental relevance, and scalability were key considerations, the recommendations remain preliminary. They are intended as a foundation for future research and refinement before broader implementation can be fully realised.

1.5. Thesis Structure and Methodological Approach

This thesis integrates geochemical, geospatial, engineering, and socio-environmental analyses to propose a comprehensive rehabilitation framework for legacy mining sites in the Iberian Pyrite Belt (IPB), with a focus on the San Miguel mine and surrounding Zone 1. The study is structured around the following analytical steps and corresponding chapters, as presented in Table 1.1 and Figure 1.9.

Table 1.1: Overview of methodological steps applied throughout the research process.

CH	Title	Content
2	Geochemical Characterization and Spatial Pollution Assessment	• **Objective**: This chapter presents the findings from geochemical and spatial analyses conducted on obtained San Miguel sample data, and satellite imagery gathered for the study area. These investigations aim to determine the extent and severity of existing and ongoing pollution in Zone 1 of the studya area, presenting a detailed overview of environmental conditions and potential contamination hotspots. • **Sample acquisition**: During the AESM2024 fieldwork, surface samples were taken from the San Miguel site. The samples consist of tailings, waste rocks and soil samples. The samples were separated based on visible colour differences, distinguishing between white, red, yellow, brown, grey mine waste and soil samples. • **Sample analysis**: analysis of the samples was done by using a portable XRF to determine the concentrations of elements and metals present in the area. • **Data acquisition**: Sentinel-2 data of the area was acquired from Copernicus Data Space Ecosystem [14]. • **Data analysis**: The Sentinel-2 data was used as input in ArcGIS Pro to perform land cover classification using supervised classification methods, differentiation between besides the normal land cover classification types as well between the different visible mine wastes present at the inactive mine sites. The obtained XRF concentrations were modelled and plotted in Python against one another, as well with the allowable concentration limits.

(Continued on next page)

CH	Title	Content
3	Rehabilitation Proposal	• **Objective**: A tailored rehabilitation plan to mitigate the harmful and negative effects of current environmental pollution and degradation on local communities and the environment in Zone 1 of the study area has been composed. • **Data acquisition**: A literature review has been conducted to select and filter out the most suitable methods for the remedial and morhphological recovery of Zone 1 of the study area. The literature review can be found in the Appendix B and C, in the introduction of the chapter, a short overview of the methods considered is given. • **Data analysis & rehabilitation proposal**: Using the literature review and the previously determined pollutat (Chapter 2), a site-specific rehabilitation plan for the inactive mine sites of Zone 1 is proposed. The proposal combines engineered interventions, such as the implementation of SRB with a DAPRB for AMD treatment and geo-membranes, with nature-based solutions, e.g. phytostabilisation and revegetation, using native species. A spatial implementation plan is provided based on the different inactive mine sites present in the area.
4	Monitoring Plan	• **Objective**: In this chapter, environmental monitoring indicators are proposed as analytical tools for the future composition of an in depth monitoring plan of the study area. These indicators serve as measurable variables that reflect key environmental, social, or economic aspects of the study area. The chapter also provides general guidance for selecting, adapting, and applying these indicators to ensure that the monitoring plan is context-sensitive, scalable, and suitable for long-term implementation. • **Data acquisition**: Drawing from existing literature and theoretical frameworks, a curated set of proposed indicators is introduced. • **Data analysis & broad recommendations**: the chapter also lines out broad recommendations concerning key monitoring parameters, sampling frequencies, equipment and institutional responsibilities to support the long-term assessment of rehabilitation performance. long-term assessment of rehabilitation performance. While it does not constitute a fully developed, ready-to-implement monitoring plan for the study area, it emphases which critical environmental and social factors should need to be be considered when designing and conducting monitoring activities associated with rehabilitation efforts for comparable mine site in both the IBP, or worldwide.

(Continued on next page)

CH	Title	Content
5	Cost Assessment	• **Objective**: This section provides an indicative estimation of costs associated with the proposed rehabilitation plan for Zone 1 of the study area, as outlined in Chapter 3. • **Data acquisition**: The methodology draws upon benchmark values found in relevant literature, as well as market-based pricing references, to establish a reliable cost framework. • **Data analysis**: By triangulating between theoretical estimates and practical pricing data, the chapter aims to offer a grounded financial perspective that supports decision-making and budget planning. While precise figures may vary based on local conditions, this approach ensures that the estimation remains transparent, replicable, and sufficiently detailed for preliminary feasibility evaluations.
6	Social Life Cycle Assessment (S-LCA)	• **Objective**: a S-LCA is performed to assess the social implications of rehabilitation, focusing on public health, ecosystem services, and socio-economic conditions in local communities in and near the study area. • **Data acquisition**: Spatial demographic data, including the proximity of inactive mine sites to local communities, population distribution within and around the study area, and agricultural land use, is utilized to identify and map affected local communities in the vicinity of the study area. In parallel, a literature review is conducted to examine the impacts of existing pollutants on public health, the degree of economic reliance on historic mining and rehabilitation activities, and the potential positive or negative implications of land reclamation efforts for nearby communities. • **Data analysis**: A Life Cycle Impact Assessment (LCIA) is conducted to evaluate the effects of historical mining and rehabilitation activities on key stakeholders located within, and up to 25 kilometers around, the study area. Based on this analysis, heat maps are generated to visualize social impact categories, illustrating the degree of influence on various stakeholder groups. These visualizations are derived from collected datasets and reflect the author's interpretation and synthesis of the data.

(Continued on next page)

CH	Title	Content
7	General Recommendations for Zones 2–4 and Long-Term Monitoring	• **Objective**: While this thesis focuses in detail on the rehabilitation of Zone 1, general guidance is provided for the application of similar methods to active and inactive mines in Zones 2–4. A distinction is made between operational restrictions at active mining sites (e.g., Aguas Teñidas, Riotinto) and the challenges of legacy waste management and ongoing environmental pollution at inactive sites (e.g., La Zarza, Tinto Santa Rosa). • **Data acquisition**: the findings from the preceding chapters were combined and analyzed to develop coherent advice, best practices and general recommendations for Zones 2–4 within the study area. • **Data analysis**: these conclusions are exclusively based on the previously conducted analyses and personal interpretation of the author, no new data collection or additional research was undertaken beyond the existing scope.
8	Discussion	• **Objective**: This chapter reflects on the methodology, sample representativeness, and the validity of spatial extrapolation. The opportunities and limitations of the proposed rehabilitation approach are discussed, as well as the scalability of results to other sites. Recommendations for future research are also presented.
9	Conclusion	• **Objective**: The final chapter summarizes the main findings by answering the research questions, and highlights the relevance of this work for sustainable mine site rehabilitation practices in the IPB and comparable mining regions globally.

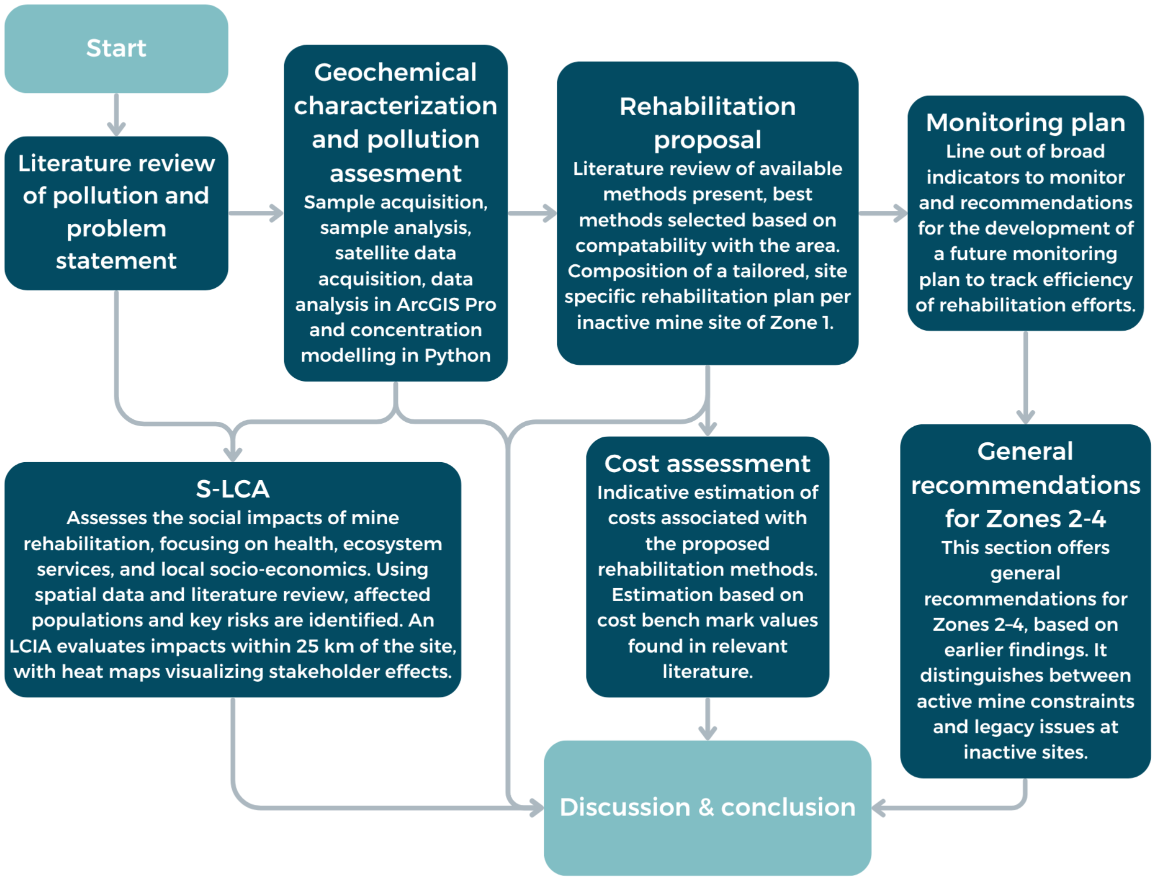


Figure 1.9: Flowchart illustrating the key research processes, illustrating steps from analysis to conclusion

2

Geochemical Characterization and Spatial Pollution Assessment

2.1. Introduction

The Iberian Pyrite Belt (IPB) is a heavily mined metallogenic zone in Europe, and its legacy of environmental degradation is well documented. This chapter focuses on understanding the extent and severity of contamination from historical mining activities in Zone 1 of the study area, using the San Miguel mine as the primary case study. Data from field samples collected from the San Miguel mine site in Q4 2024 were analyzed through X-ray fluorescence (XRF) to quantify concentrations of heavy metals, specifically arsenic (As), lead (Pb), and copper (Cu). These results were extrapolated spatially across Zone 1 using supervised classification in ArcGIS Pro, with Sentinel-2 satellite imagery forming the basis of geo-spatial modelling.

The key objectives of this chapter are:

- To assess metal contamination levels in mine waste samples collected at San Miguel.
- To evaluate contamination severity using risk matrices for major pollutants.
- To model the spatial distribution of contamination across Zone 1.
- To identify priority areas for remediation based on pollution levels and proximity to sensitive receptors (agricultural zones and settlements).

This analysis provides the foundation for the rest of the thesis.

2.2. Pollution

The pollution in the study area can be described as follows:

- **Cyclical pollution:** The heavy metal contamination in the study area is driven by AMD and the cyclical dissolution of metals during rainy periods due to the presence of sulfides, such as pyrite, in the many VMS mine waste types present in the area. During dry periods, pollutants are temporarily retained in the form of evaporitic salts, which later dissolve with the rain, resulting into ongoing cyclic pollution.

- **Leaching and mobilization of metals from residues:** The residues present in the area which pose the highest contamination risk, include modern slag, industrial landfills, country rocks, leaching tank refuses, gossan waste, Roman slag, iron oxides, and finally, melting ashes.

- **Acid Mine Drainage (AMD):** the main source of AMD in the area are the smelting ashes, slags and pyrite rich samples. The high heavy metal content and strong acid potential of the residues at are primarily caused by three factors: (1) their high sulfide content, especially pyrite and secondary sulfate minerals like jarosite, (2) the lack of neutralizing minerals like carbonates and (3) the wide exposure of these residues across the site. The AMD process at the site is still active [15].

Acid Mine Drainage

AMD is generated by the oxidation of sulfide minerals, with pyrite (FeS_2) being the most common sulfide in nature. Sulfides are usually stable and insoluble unless they are exposed to atmospheric conditions, such as oxygen and water. As a result, direct oxidation of pyrite will take place, generating AMD. This can be summarised in the following chemical oxidation reactions [6]:

$$FeS_2 + \frac{7}{2}O_2 + H_2O - \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \tag{2.1}$$

The primary limiting factor in the oxidation process is the transport of oxygen in the subsurface. If oxidation reactions occur below the water table, the availability of oxygen becomes a problem. The quantity of oxygen present depends on the temperature, the salinity, and the altitude of the water. As a result, the rate of oxidation in an environment below the water table is slower than in direct contact with the atmosphere. The ferrous iron of reaction 2.2 converts to ferric iron when oxygen is present [6]:

$$Fe^{2+} + \frac{1}{4}O_2 + H^+ \rightarrow Fe^{3+} + \frac{1}{2}H_2O \tag{2.2}$$

The pH of the solution determines the availability of dissolved ferric iron in water. In neutral and alkaline solutions, the solubility of ferric iron is low, resulting in the direct oxidation of pyrite. For a pH of +/- 3, iron precipitates as ferric hydroxide according to the following reaction [6]:

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \tag{2.3}$$

If the pH values are below 4, the pyrite oxidation reactions by ferric iron are much faster than by oxygen, however, reaction 2.2 is slow, which controls the presence of ferric iron in the water. As a result, the oxidation to ferric iron is the limiting process in the abiotic pyrite oxidation process [6].

The release of contaminants from mining wastes is influenced by factors such as the mineralogical composition, the grain size of the mine waste, and the presence of secondary minerals. As mentioned before, sulfide minerals (particularly pyrite), are the primary contributors to acid production. Smaller grains increases the surface area exposed to oxygen and water and thus increases oxidation, simultaneously releasing metlloids. The formation of secondary minerals, such as iron oxides and sulfates, can temporarily trap metals, but they may be re-dissolved during rain events. This leads to periodic spikes in pollution levels as discussed before. Metals released and mobilized from the mine waste can accumulate in the tissue of animals and humans that live near contaminated sites. For humans, exposure to these metals can occur through inhalation, ingestion, and dermal contact with contaminated dust and water. Arsenic and lead, both imposing risks on human health, can be absorbed through digestive and pulmonary routes, with higher absorption observed via the lungs [16].

2.2.1. River system pollution

Rio Odiel accumulates acid leachates from a large number of mines across the IBP. However, the Rio Tinto only accumulates acid leachates from the several dumps, tailing dams, smelting residues and tunnels of the Rio Tinto mining district, with the source of the Rio Tinto originating in the Peña de Hierro mining complex (Figure 2.1).

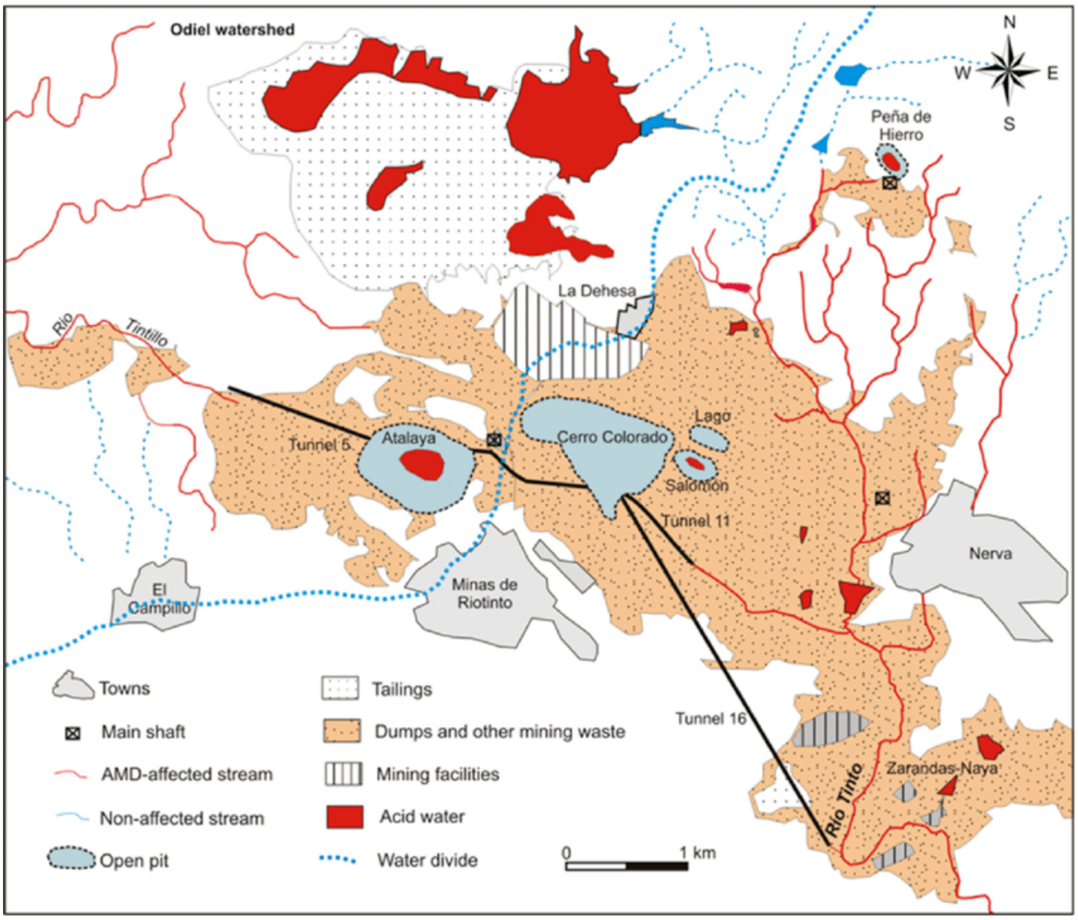


Figure 2.1: AMD-impacted fluvial network of the Río Tinto [17].

Rio Tinto

At the source, a large waste pile containing sulfide blocks is present, from which a continuous flow of AMD is generated, resulting in a pH of around 2, with the average pH of the Rio Tinto being around 2.5. As well, the AMD contains a high concentration of iron (1000-150000 mg/L) and sulfates (8000 mg/L).

As the Rio Tinto progresses the pH deviates because of dilution by the congregation of additional streams. Around 3 km from the source, the pH value increases to 2.1 and contains a more moderate concentration of sulfate and metals (335 mg/L Fe). Around 7 km from the Rio Tinto source, the Zarandas-Naya area is located. At this location, ore from Corta Atalaya and Pozo Al-Fredo was processed by leaching and smelting. Among the various sources of contamination in the fluvial system of the Rio Tinto, Alcojola Creek stands out as the most significant, displaying highly acidic waters with a pH of 1.6 and extremely high concentrations of iron (12 g/L), sulfate (31 g/L), arsenic (42 mg/L), and other elements. Although the creek contributes only 3% to 15% of the total Rio Tinto's flow in the mining area, it is responsible for more than 25% of the iron, arsenic, chromium, and lead input of the river [6].

After passing the Zarandas-Naya area, the Tinto River no longer receives acid leachates, and its flow increases as freshwater tributaries join it. This influx of clean water leads to a significant reduction in pollutant concentrations, mainly due to dilution. The Jarrama and Corumbel rivers, both regulated by reservoirs, play a key role in this process. As a result, the concentrations of aluminum, cobalt, copper, manganese, and sulfate decrease by approximately 90% from the mining area to Niebla, though the total transported load remains constant [6].

Electrical conductivity also declines downstream as dissolved ions decrease, but the pH remains stable between 2.3 and 2.8 due to the buffering effect of ferric iron precipitation. Iron, arsenic, and chromium show a stronger decline in concentration as they precipitate in the form of oxyhydroxysulfates. Arsenic, in particular, is further reduced through adsorption and co-precipitation.

Lead behaves differently, remaining relatively stable or even increasing at certain points, as it precipitates with iron in jarositic phases, and can also form anglesite under specific conditions. Ultimately, while pollutant concentrations drop significantly, the total transported load of most elements remains unchanged along the river's course [6].

Rio Odiel

The AMD conditions of the Rio Odiel vary throughout the river, as can be observed in Figure 2.2: from extreme contamination, to relatively clean areas. The Odiel River can be divided into three sub basins: Odiel, Oraque and Meca. The Odiel sub catchment, at the origin of the river Odiel, contains slightly alkaline water with low concentration of toxic metals. These toxic metals and low pH are drained from metamorphic and plutonic rocks by the natural process of ARD. More downstream (Oraque), several mines start contributing to AMD (Concepción, San Platón & Esperanza). At the Concepción and Esperanza mines, passive treatment plants have been installed. However, pollution still affects the river, especially during dry periods when the water flow is low.

Even more downstream (Meca), the Odiel River receives more heavy pollution from the Agrio River, which carries mining contaminants from the Riotinto mines. This leads to dramatic decreases in pH, with contaminants such as iron and aluminum precipitating in the river. The river's neutralizing capacity is diminished by these inputs, resulting in continued contamination until its mouth at the Huelva Estuary [6].

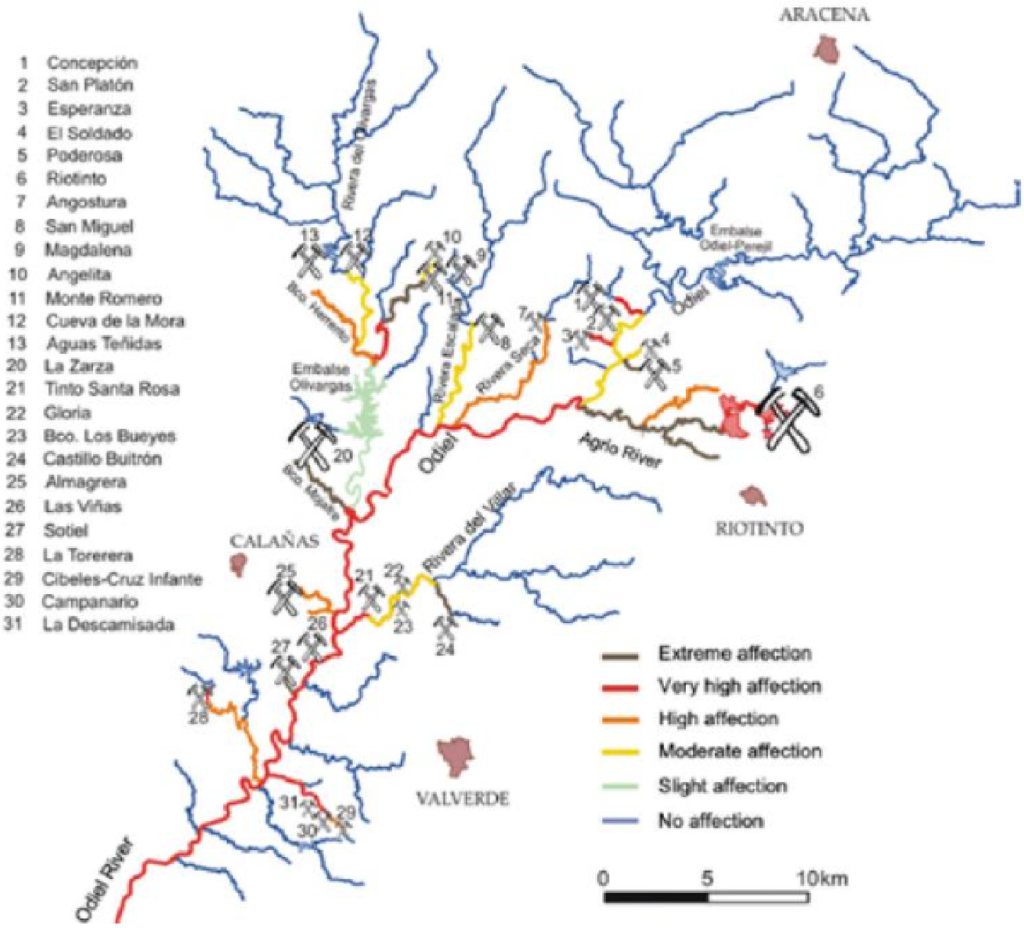


Figure 2.2: AMD-impacted rivers in the Odiel sub-basin, classified by degree of contamination [6].

2.2.2. Wildlife implications

Mining activities in the Iberian Pyrite Belt (IPB) have caused significant environmental contamination, negatively affecting wildlife present in the area. In particular,European rabbits (*Oryctolagus cuniculus*) and red-legged partridges (*Alectoris rufa*) are affected by this pollution. Elevated levels of toxic heavy metals such as lead, cadmium, and arsenic have been detected in these animals near mining sites. Rabbits near mining sites exhibited high lead concentrations in their hair, brain, liver, and kidneys, with liver lead levels reaching as high as 11.6 µg/g. Lead exposure can lead to neurotoxicity, organ damage, and even death. Cadmium was found to be primarily accumulated in the kidneys of these animals, with median concentration levels of 7.36 µg/g, causing nephrotoxicity and renal dysfunction. Arsenic, detected in hair samples, indicates ongoing environmental exposure and is associated with skin lesions, cardiovascular disease, and cancer. Similarly, partridges from the Spanish part of the IBP area showed significantly elevated Pb concentrations, particularly in feathers, liver, and kidneys, with feather levels reaching 11.5 µg/g. Both European rabbits and red-legged partridges play vital roles in the local food web, serving as prey for apex predators such as the Spanish Imperial Eagle and Iberian Lynx. The accumulation of heavy metals in these prey species can lead to biomagnification, where toxin concentrations increase as they move up the food chain. This poses a risk of secondary poisoning to apex predators, potentially causing reproductive issues, immune suppression, and increased mortality rates [18].

2.2.3. End state possibilities

In summary, mining operations in the Iberian Pyrite Belt and similar regions have led to serious environmental damage, mainly through the formation of AMD and the release and mobilization of heavy metals. Efforts to address these impacts are complicated by the vast amounts of exposed mining waste and the intricate chemical interactions between metals, minerals, and surrounding ecosystems.[6, 15, 16, 18, 19, 20, 21, 22].

Given the scale and complexity of the environmental damage, effective rehabilitation strategies are crucial. The following section explores possible end states that may result from successful remediation, which includes both environmental recovery and relevant land use of the area. The following table summarizes the most common end state of mine site possibilities.

Table 2.1: Potential post-mining land use scenarios and corresponding end states.

End State	Type of Area	Land Characteristics	Soil/Water Conditions	Economic Potential	Environmental Concerns
Agricultural Use	Rural	Smooth slope, fertile soil	40 cm min soil depth, rich in humus	High profitability, immediate returns	Soil quality, toxic metals
Forestry Use	Rural	Poor/stony soils, steep terrain	Soil thickness, good drainage	Wood products, resin	Species selection, pest defense
Water Reservoirs	Urban/ Periurban/ Rural	Flooded mines, controlled water inflow	Groundwater / surface water flooding	Water storage, hydroelectric power	Water quality, flood control
Wildlife Habitats	Rural/ Urban	Ecological potential, diverse topography	Edaphic conditions, water scarcity	Supports biodiversity	Biodiversity hosting, toxic contamination
Recreational Use	Urban/ Periurban/ Rural	Dry or flooded, suitable for recreation	Suitable for sports, leisure activities	Geotourism, cultural activities	Environmental impact of activities
Solid Waste Landfills	Urban/ Industrial	Close to urban areas, geological suitability	Controlled waste disposal	Waste management	Environmental impact assessment
Urban and Industrial Use	Urban/ Periurban	Excavations, uneven terrain	Slope stability, drainage	Residential, commercial, industrial use	Contamination remediation

Given the specific rural location, lithostratigraphic composition, dry climatic conditions, and the already existing levels of contamination and pollution at the study area, the proposed final land use for the site has been designated to forestry, with the potential for tourism by implementing historical mining trails. This decision takes into account the site's capacity for ecological recovery, as well as the long-term environmental sustainability goals of the study area with the aim of this research. This particular strategy aims to restore soil stability, enhance biodiversity, and reduce potential environmental contamination through afforestation efforts, making it safe for local inhabitatns and tourists to visit the area and hike. By converting the site to forestry, it not only mitigates the residual impacts of mining activities, but it also promotes carbon sequestration [23].

2.3. Risk assessment metal concentrations

Analyzation of the collected samples of the San Miguel mining area pointed out that a lot of potentially toxic and harmful compounds and elements are present in the collected samples. The largest concentrations of metals in the samples are Arsenic, Copper, Iron, Lead, Titanium, Vanadium and Zirconium (Table D.1). After performing a literature review of the different elements, a risk assessment matrix was constructed (Figure 2.3). From this, it becomes clear that the elements Copper, Arsenic and Lead have the highest severity and likelihood of posing harmful effects on local communities and the environment. Therefore, the main focus of this research will be to limit the concentrations of these elements in the surface, subsurface and fluvial systems of the study area.

	Negligible	Minor	Moderate	Significant	Severe
High				Cu: persists in soil. toxic to microbes, disrupts nutrient cycles. It is essential in small doses but toxic in excess.	As: mobile in soil, toxic, bioaccumulates. Highly toxic, carcinogenic, affects proteins, respiration and metabolism. Pb: persists in soil, binds strongly, toxic to life, neurotoxic, affects aquatic and terrestrial life
Moderate		Fe: naturally abundant, iron itself is non-toxic, but AMD from pyrite is harmful.	V: naturally present, bioavailability depends on oxidation state, only toxic at high exposure.		
Low	Zr: limited environmental mobility, low toxicity (considered non-toxic).	Ti: generally regarded as safe, no guideline limits, nanoparticles may have emerging risks).			

Figure 2.3: Risk assessment matrix of Arsenic, Copper, Iron, Lead, Titanium, Vanadium and Zirconium based on literature sources [7, 8, 9, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41].

Arsenic (As)

Arsenic is a commonly known carcinogenic, and a very toxic metalloid that makes up about 0. 00005% of the Earth's crust. Arsenic is commonly associated with copper, lead and gold ores, such as the VMS deposits in the study area. It can exist in four oxidation states: As(V), As(III), As(0) and As(-III). Pure arsenic is only rarely present in nature, the predominant form of arsenic in aerobic and aqueous environments is arsenate [$H_2AsO_4^-$ & $HAsO_4^{2-}$], in anoxic environments arsenite [H_3AsO_3 & $H_2AsO_3^-$] is more prevalent. Arsenite adsorbs less strongly to minerals compared to Arsenate, which strongly adsorbs to minerals such as alumina and ferrihydrite. As a result, arsenite is the more mobile oxyanion [42].

The toxicity of arsenic depends on its chemical form. Arsenite is toxic as it binds to sulfhydryl groups, thereby limiting protein function and thus affecting respiration by interacting with enzymes, such as pyruvate dehydrogenase. It can also bind to the glucocorticoid receptor. Being uncharged at a pH below 9.2, arsenite enters cells through aqua-glycerolporins. Arsenate on the other hand, resembles phosphate and thereby disrupt oxidative phosphorylation by entering cells via phosphate transporters, impairing the cellular energy production [24].

Cells use multiple methods to detoxify arsenic. In higher eukaryote organisms, glutathione reduces arsenate (As(V)) to arsenite (As(III)), which is then methylated into less toxic compounds like monomethylarsonic acid (MMA) and dimethylarsonic acid (DMA). Other organisms, such as fungi and bacteria, produce additional methylated forms like trimethylarsine. Some microbes also form methylated arsines, while benign forms, such as arsenobetaine and arsenic sugars, are found in marine life and plants [24].

Terrestrial plants can accumulate arsenic (As) through root uptake from the soil or by absorbing airborne As that settles on their leaves. Under natural conditions, plants in uncontaminated soil generally contain low levels of arsenic (<3.6 mg/kg). However, at higher concentrations, arsenic becomes toxic to most plant species. In soils, arsenate is the predominant form of arsenic, and due to its chemical similarity to phosphate, it competes for the same uptake pathways in the roots as phosphate. This competition disrupts natural metabolic processes, leading to arsenic-induced phytotoxicity, which hinders plant growth and development [43].
In the human body, arsenic accumulation takes place in general through the consumption of arsenic contaminated food and the intake of contaminated drinking water. Arsenic poisoning can lead from stomach poisoning from skin lesions to brain, kidney, and liver cancers [44].

Guideline concentration and cut-off grade
In the European Union, the maximum permissible concentration of arsenic in agricultural soils is 20 ppm. However, a risk analysis study investigating the effects of arsenic and lead concentrations in soils found that arsenic levels can reach up to 40 ppm without causing significant toxicological or environmental risks. [42]. Considering groundwater, the World Health Organization (WHO) has established an arsenic threshold level for drinking water of 10 μg/l [44].
Arsenic is usually present in pyrite orebodies, which makes up most of the orebodies in the IPB and thus study area. As such, mining of arsenic is not a primary element to be considered for mining, the aim for extraction is usually copper, lead, gold or iron. In literature, the only top cut supplied for arsenic mining is to distinguish between low and high grade arsenic sub domains, thereby indicating the level of pollution of the area. As such, a cut-off grade of 170 ppm is defined for arsenic mining [25].

Copper (Cu)
Copper is a soft, ductile material with high thermal and electrical conductivity. Due to these properties, copper has been mined and used for centuries, with the earliest findings dating back to 9000 BC. It has 29 isotopes, of which only ^{63}Cu and ^{65}Cu are stable. Naturally occurring copper is composed of approximately 69% ^{63}Cu. Copper forms a variety of compounds and generally exhibits oxidation states of +1 and +2 [27].

Copper is also a micronutrient, and is therefore important for various physiological processes in plants. Examples are processes such as photosynthesis, oxidation, carbohydration, cell wall metabolism and symbiotic N_2 fixation. However, copper levels in cells must be kept low, as excess copper can cause changes in DNA, thereby disrupting cell membrane integrity, damage respiration and photosynthesis, and affect enzyme activity. These effects can inhibit

growth and threaten plant survival.
Copper pollution of the soil is derived from parental rocks and anthropogenic activities, such as pyrite mining in the study area [9].

In soil, copper can bind to organic matter and soil particles (such as sand and clay), where it remains largely immobile. Sensitive soil microbes, including those involved in nitrification, serve as early indicators of ecological changes. Soil contamination can be determined by measuring ammonia-oxidizing microbes (AOA and AOB) and the amoA gene in soil. Increased copper in soil also reduces plant available phosphorus, and decreases essential micronutrients (e.g. Fe, Mn, and Zn), which can lead to copper toxicity. When released into water, copper binds to particles and sediments in rivers, lakes, and estuaries, but some soluble copper can reach groundwater. In humans, prolonged exposure to elevated levels of copper can negatively affect factors such growth, reproductive health, neurological function, enzymatic processes, metabolism, and so on. Nevertheless, humans tend to exhibit greater resilience to copper toxicity compared to plants, whereas plants are generally more sensitive to elevated Cu concentrations.[9].

Guideline concentration and cut-off grade
One of the most referenced guidelines for copper concentrations in soil are those proposed by Finnish and Swedish regulations for soil contamination. According to the Government Decree on the Assessment of Soil Contamination and Remediation Needs, the copper threshold value is set at 100 mg/kg, with a guideline value of 150 mg/kg. The threshold indicates when further assessment is required, while the guideline suggests an ecological or health risk. The copper threshold of 100 mg/kg is also recommended in many studies as an indicator of unpolluted soils. In croplands, an optimal copper range of 5–30 mg/kg is proposed, as lower concentrations can cause plant deficiency, while higher levels may lead to toxicity [27]. The cut-off grade for Copper mining starts at 0.18% [28].

Lead (Pb)

Lead is a heavy metal, which can be found in several mineral forms in the earth's crust. It has been discovered and used for the last 5000 years in several applications due to its preferable material properties, e.g.: softness, low melting point, ductility, and malleability. As well, metallic lead is highly resistant to corrosion, as thin protective films of lead compounds (oxides and carbonates) form on its surface when exposed to air or water. This natural barrier prevents further degradation, which, along with lead's ease of shaping and molding, has made it widely used for centuries [7].

Lead can exist in three main forms: metallic, inorganic, and organic. In the environment, lead rarely occurs in its elemental form, whereas it is typically found in its oxidized state (Pb^{2+}) within various ores. Lead is primarily present in minerals such as galena (PbS), or in a smaller amount as cerussite ($PbCO_3$) or anglesite ($PbSO_4$). Lead minerals are found in association with zinc, copper, and iron sulfides (VMS) as well as gold, silver, bismuth, and antimony minerals [7]. Anthropogenic sources of lead, in case of the San Miguel site, includes mining and smelting of ore. In the atmosphere, lead exists as particulate matter. The solubility of lead compounds in water varies with pH, hardness, salinity, and the presence of humic substances, with solubility peaking in soft, acidic water. Lead primarily accumulates in soil and sediment, where it binds strongly to soil particles and is generally retained in the upper layers, preventing significant leaching into subsoil and groundwater [8].

The fate of lead in soil is influenced by interactions with minerals and the formation of organic-metal complexes. This in turn depends on soil characteristics, such soil pH, type of soil, organic content, and cation exchange capacity. The majority of lead is tightly retained in soil, and only minimal amounts are transported to surface waters. However, when transportation happens, lead's solubility depends on the pH and dissolved salts. For example, at pH 5.4, lead is more soluble in soft water than in hard water. Sulfate ions can decrease lead levels by forming insoluble lead sulfate [7].

Plants and animals near environments with high lead concentrations, such as mining and smelting sites, often accumulate lead. Plants can take up lead through their roots or foliage.
Animals absorb lead through inhalation or ingestion of contaminated food or plants. In aquatic organisms, lead tends to be highest in bottom dwellers (e.g. benthic organisms and algae), and lowest in predators such as carnivorous fish. However, lead poisoning still occurs in carnivorous fish through ingestion of contaminated prey.
For humans, the central and peripheral nervous systems are highly sensitive to lead toxicity, with the central nervous systems in children, and for adults the peripheral nervous system being particularly vulnerable. In the brain, lead can induce damage to important areas, such as the prefrontal cortex, hippocampus, and can therefore cause neurological issues such as cognitive impairment. As well, behavioral disorders, nerve damage, diseases such as Alzheimer's, Parkinson's can be linked to lead intoxication. Short term heavy lead intoxication can lead to encephalopathy, resulting in symptoms such as memory loss, hallucinations, and headaches. At very high exposure levels, severe symptoms such as delirium, and even coma may occur [7].

Guideline concentration and cut-off grade
The allowed concentration of lead in agricultural soils is typically between 50 and 300 ppm. As a result, the maximum allowable concentration is 300 ppm, beyond which harmful or hazardous effects on the environment may occur [8]. The cut off grade for mining of lead varies between 3% to 5% [26].

2.4. Geo-spatial modelling of pollutants

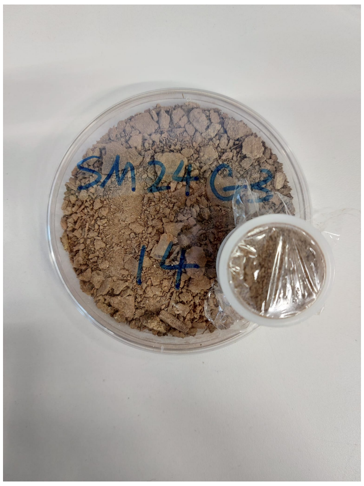
The environmental impact assessment of the San Miguel Mine focuses on the extent of contamination and soil degradation caused by both historical mining activities and natural processes. This chapter delves into the analysis of pollutants in the soil by both portable XRF and ArcGIS.

During the 2024 AESM Geo-Resources fieldwork, samples were collected at the inactive San Miguel mine site. Previous studies have identified arsenic, lead, and copper as the primary metal contaminants in the area. This section examines the pollution levels of these metals, assessing whether their concentrations exceed regulatory thresholds and thereby pose significant risks to human health, contribute to environmental degradation, and harm local ecosystems. To determine this, first the samples are classified into respective, visually distinctive classes. Then, portable XRF is performed on these samples, with the concentrations being plot against one another and against the regulatory thresholds. At last, Sentinel-2 data from Copernicus [14] has been used to perform land cover classification and assess whether the visually distinctive mine waste types identified in the San Miguel area are also present at the remaining inactive mines in Zone 1. This serves to validate the assumption that XRF findings from San Miguel can be extrapolated to the other mines in the area.

2.4.1. Sample classification

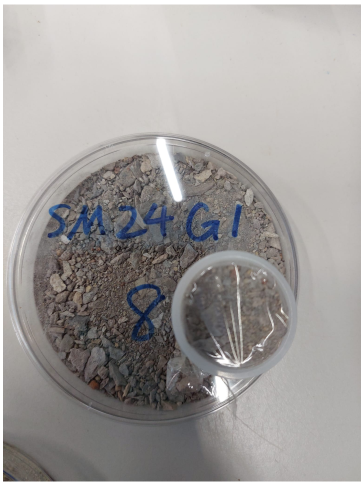
During the AESM 2024 Q4 fieldwork, several samples were collected from the inactive San Miguel mine. Visual inspection revealed distinct color variations from the different samples collected, which corresponded with differences in elemental composition among the sample types. Therefore, a visual classification system was established, categorizing the samples of the San Miguel area by color: yellow 1, yellow 2, brown, grey, white, red, and soil. The two yellow categories reflect subtle, yet significant differences in appearance and chemical content, warranting their separation. An overview of these visually classified sample types is presented in Figure 2.4. Images of the remaining samples can be found in Appendix A.

(a) Yellow 1 sample of the San Miguel Area, sample number: SM24-G2-16.

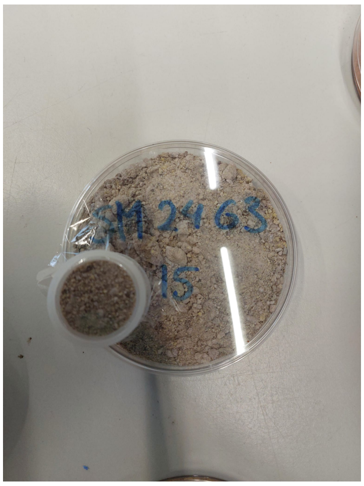


(b) Yellow 2 sample of the San Miguel Area, sample number: SM24-G3-14.

(c) Brown sample of the San Miguel Area, sample number: SM24-G3-02.

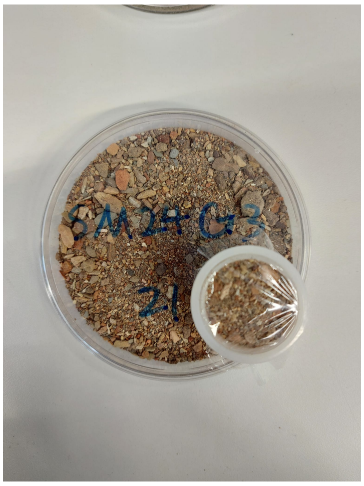


(d) Grey sample of the San Miguel Area, sample number: SM24-G1-08.



(e) White sample of the San Miguel Area, sample number:SM24-G3-15 .

(f) Red sample of the San Miguel Area, sample number: SM24-G3-05.



(g) Soil sample of the San Miguel Area, sample number: SM24-G3-21.

Figure 2.4: Overview of representative samples used for the mine waste classification. The samples were collected from the San Miguel mining area for portable XRF analysis during the AESM 2024 Q4 fieldwork.

2.4.2. XRF analysis

Portable X-ray fluorescence (XRF) is an analytical technique used to determine the elemental composition and concentrations of materials. It operates by directing primary X-rays onto a sample surface, which excites atoms within the material. These atoms then emit secondary (fluorescent) X-rays at energies characteristic of specific elements. By measuring the energies and intensities of these emitted X-rays, the presence and concentration of elements within the sample can be identified [45].

In this study, the Thermo Scientific™ Niton XL5 Plus handheld XRF analyzer was used for elemental analysis of the samples obtained during the fieldwork. The device employs a silver anode X-ray tube, and a high-resolution silicon drift detector (SDD),thereby enabling detection of a broad elemental range [45].

The results of the portable XRF analysis is shown in Tables 2.2 2.3. These tables show the concentrations of the pollutants arsenic, copper and lead in the different types of mine waste obtained from the San Miguel mining site, thereby distinguishing between the different types of mine waste and samples as has been discussed in Section 2.4.1. An overview of all images of the samples analyzed can be found in Appendix A.

Table 2.2: Concentrations (ppm) of yellow type 1 & 2 and brown mine waste samples.

Yellow type 1	As (ppm)	Cu (ppm)	Pb (ppm)
sm24 g216	405.14	325.79	235.46
sm24 g321	121.76	169.84	421.83
sm24 g218	276.91	393.99	787.12
sm24 g222	133.62	245.38	272.22
Average Y1	234.36	219.92	429.16
Yellow type 2			
sm24g103	744.30	270.50	2565.55
sm24g226	265.57	33.18	121 988.40
sm24 g221	795.86	118.05	303.11
sm24 g314	315.08	387.38	1196.02
Average Y2	530.20	202.28	31 513.17
Brown			
sm24g302	397.47	1925.02	2560.14
sm24g113	227.45	425.28	2668.60
sm24g19	106.27	253.51	2113.02
sm24g301	397.89	872.67	5248.42
Average brown	282.27	869.12	3147.55

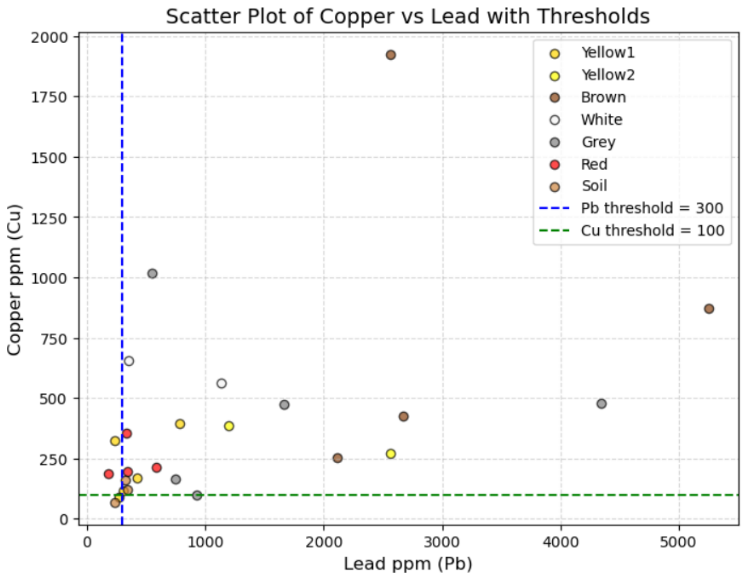
Table 2.3: Concentrations (ppm) of grey, white, and red mine waste and adjacent soil samples.

Grey	As (ppm)	Cu (ppm)	Pb (ppm)
sm24g224	769.49	479.40	4346.69
sm24g108	135.12	474.47	1662.17
sm24g318	243.94	165.93	745.03
sm24g228	641.13	1015.99	552.37
sm24g15	149.22	97.36	923.68
Average grey	387.78	446.63	1645.99
White			
sm24g315	497.83	654.22	354.43
sm24g225	139.82	563.13	1136.47
sm24g119	249.48	34 537.93	3662.83
Average white	295.71	11 918.42	1717.91
Red			
sm24g303	624.70	353.92	336.04
sm24g305	842.78	187.77	180.64
sm24g208	599.67	215.28	586.77
sm24g211	344.28	196.64	339.14
Average red	602.86	238.40	360.65
Soil			
SM24soil1	261.87	68.84	231.62
SM24soil2	690.09	162.06	324.75
SM24soil3	357.18	119.28	340.91
Average soil	436.38	116.73	299.09

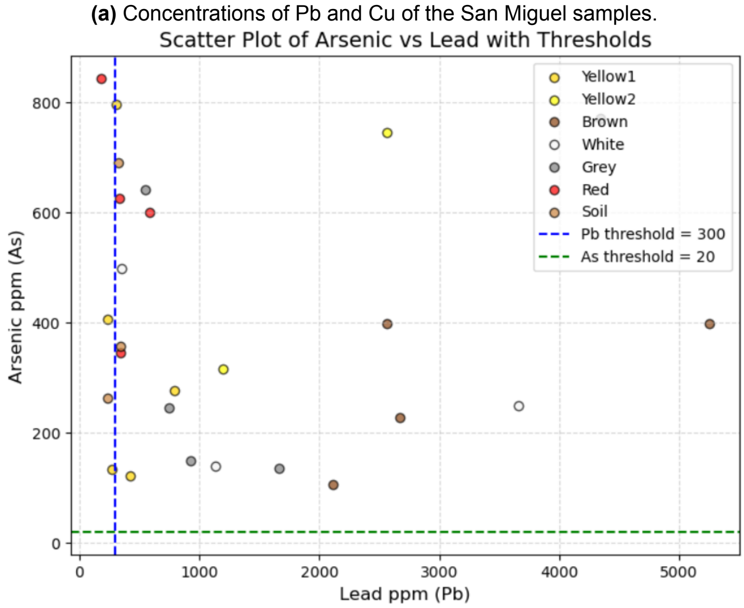
Threshold concentrations of all samples for Arsenic, Copper and Lead

After considering the concentrations presented in table 2.2 and 2.3 for the sample type's Yellow 1, Yellow 2, Brown, Grey, White, Red and Soil, it is still not easily visible which samples exceed the maximum allowable limit as has been established in Chapter 2.3. To clarify, the concentrations of Lead, Copper and Arsenic have been plotted in combination with the corresponding maximum allowed concentration thresholds. The results can be found in Figure 2.5.

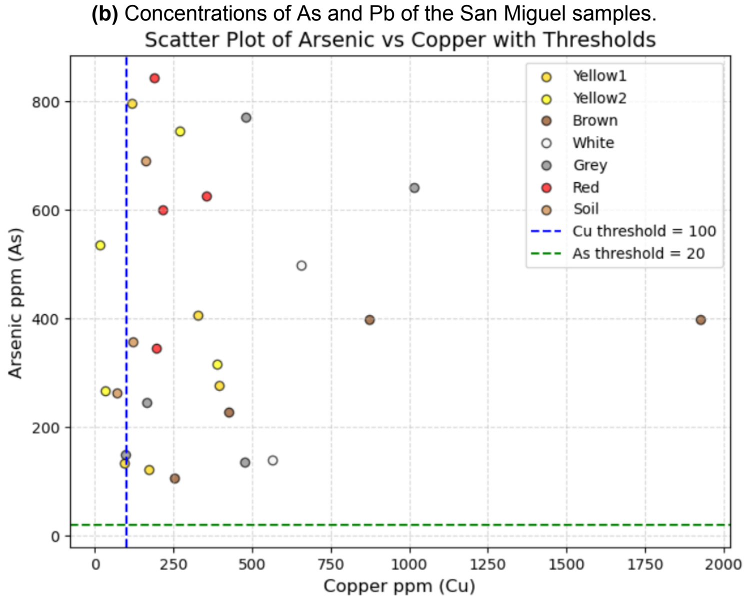
After analyzation of the table, it becomes clear that all samples exceed the maximum allowable Arsenic concentration and the majority of the samples exceed the limits for either Copper or Lead concentrations. As Arsenic is a major carcinogenic, this indicates the severity of the pollution of the area on local communities near the mining site and highlights the need for rehabilitation of the area. Considering the cut-off grades, it is not economically feasible to re-mine the tailings from the area for economic gain.



(a) Concentrations of Pb and Cu of the San Miguel samples.



(b) Concentrations of As and Pb of the San Miguel samples.

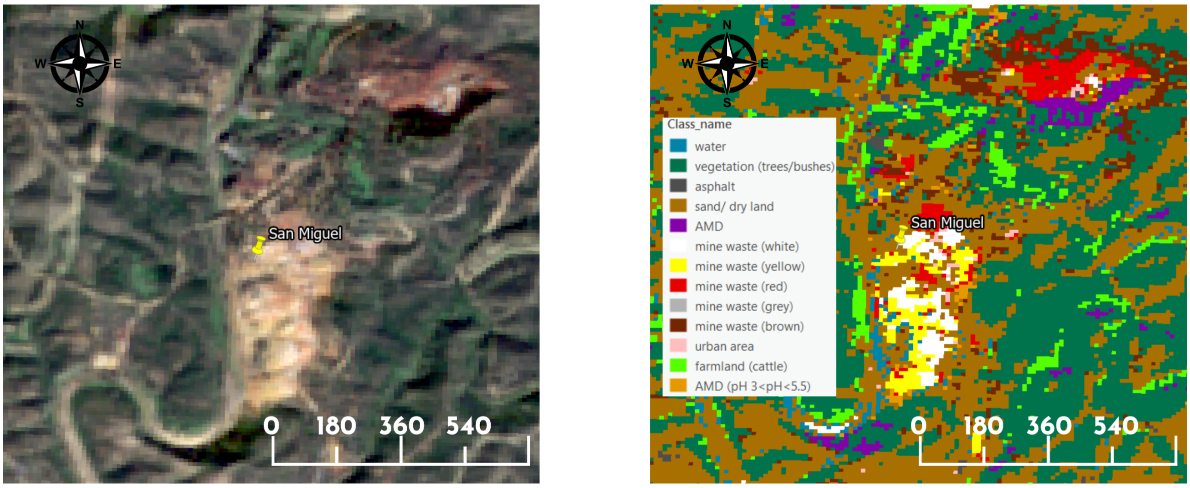


(c) Concentrations of As and Cu of the San Miguel samples.

Figure 2.5: Scatter plot of As, Pb and Cu concentrations from the portable XRF data from San Miguel (Table 2.2 and Table 2.3). Threshold values for As, Cu, and Pb are indicated by dotted lines.

2.4.3. ArcGIS geo-spatial modelling

In order to obtain a more or less accurate classification on a larger scale of the area of the San Miguel mine, Sentinel-2 data was downloaded from Copernicus Browser in ArcGIS in order to perform classification. Unfortunately, the resolution of freely available Sentinel-2 data is lower than that of the paid version. The spatial resolution of the used images is 10m, the Sentinel-2 reference image for classification of the San Miguel area is given in Figure 2.6. The legend gives an overview of the various types of mine waste present at the surface area, being differentiated between the different soil and sample types 'white, yellow, red, grey and brown' and AMD such as discussed in Section D.1. As well, there is differentiated between and vegetation, urban area, asphalt, sand, and water.



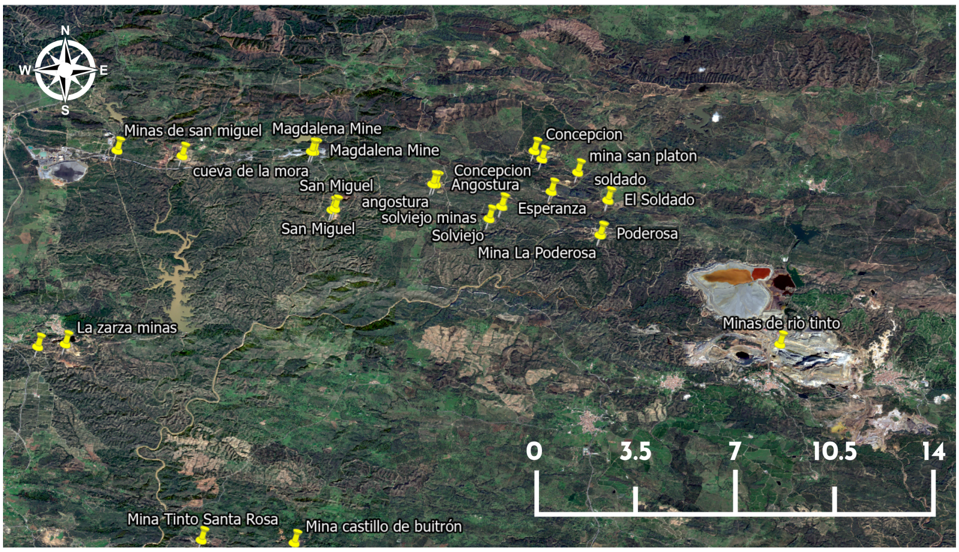
(a) Satellite overview of the San Miguel mine area, the scale bar is given in meters.

(b) ArcGIS Pro classification of the San Miguel mine area, the scale bar is given in meters.

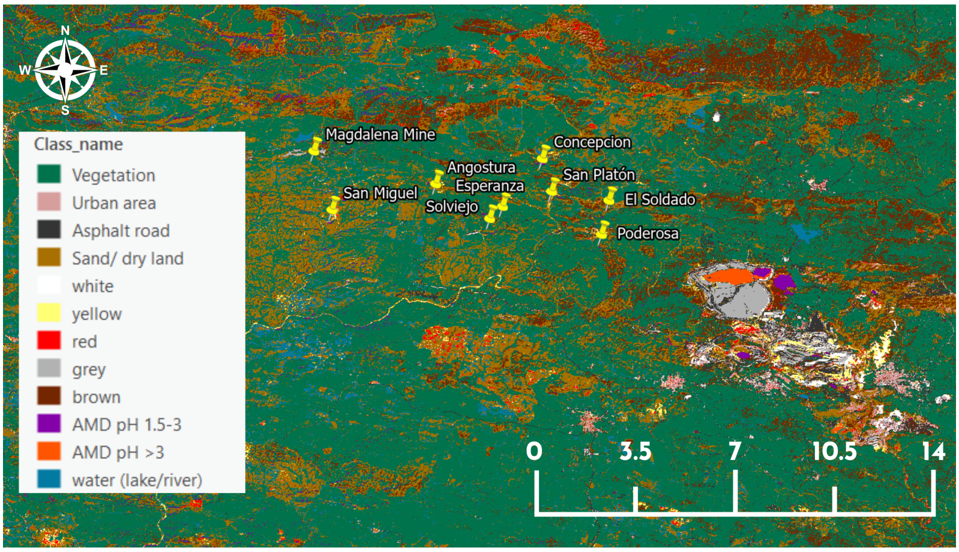
Figure 2.6: Comparison of satellite imagery and ArcGIS Pro classification of the San Miguel area.

2.5. The study area

The San Miguel mine is just one of the many abandoned mine sites in the IBP. The aim of this thesis is to use samples and data regarding the San Miguel mine site and extrapolate these findings to the surrounding study area. An overview of the total area considered in this research can be found in Figure 2.7. Using the large (active) Rio Tinto mine as a reference in this Figure, it can be observed, based on the land cover classification and legend, that its surface is similarly covered with mine waste and overburden rock types comparable to those identified at the San Miguel mine (Figure 2.6). In the Section 3.3, similar observations can be made when zooming into the classification of the inactive mines proposed for rehabilitation in Zone 1, thereby validating the extrapolation of the portable XRF findings to comparable VMS inactive mine sites in the study area.



(a) Satellite overview of the study area, the scale bar is given in kilometers.



(b) ArcGIS Pro classification of the stury area, the scale bar is given in kilometers.

Figure 2.7: Satellite overview vs. ArcGIS classification of the entire study area. Vegetation and grasslands are grouped together for simplification.

2.5.1. Study area zones

For the rehabilitation strategy, the study area is divided into different zones, namely 1,2,3 and 4. For area 1, a reclamation plan will be made available, for zone 2,3, and 4 the study will merely aim to give an advice. An overview of the locations of zone 1,2,3, and 4 is given in Figure 2.8.

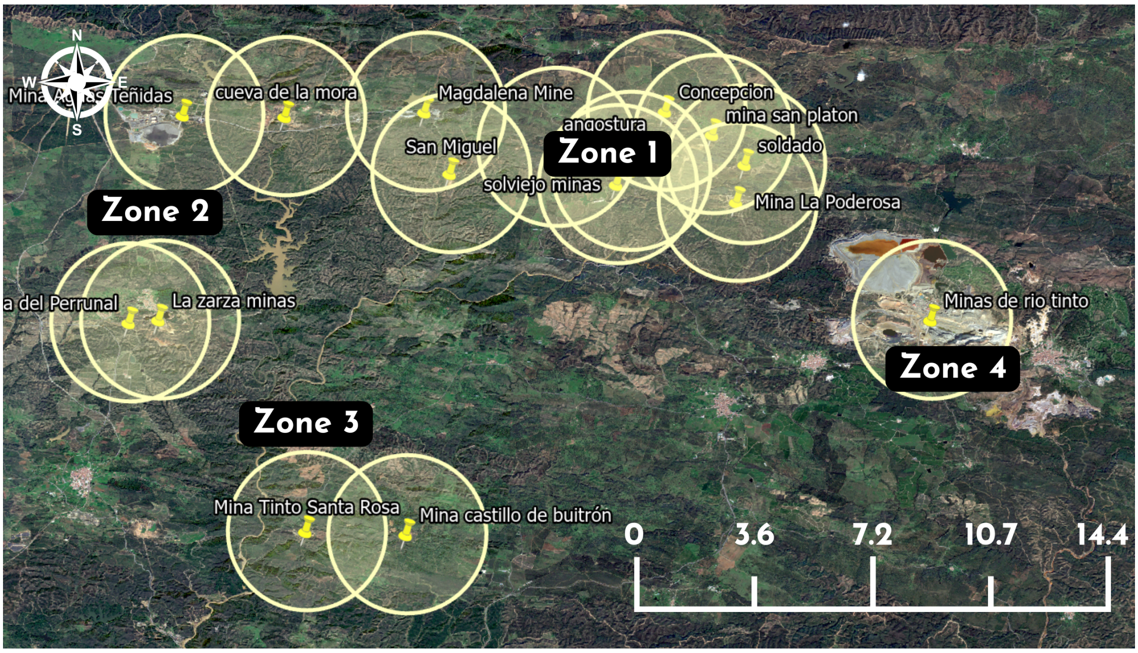


Figure 2.8: Overview of zones 1-4 in ArcGIS. All mine sites in the zones are surrounded by a radius of 3 kilometer. From this, a division has been made between 4 different clusters, with zone 1 being the primary focus of this thesis. The scale bar is given in kilometers.

2.5.2. Characteristics of zone 1

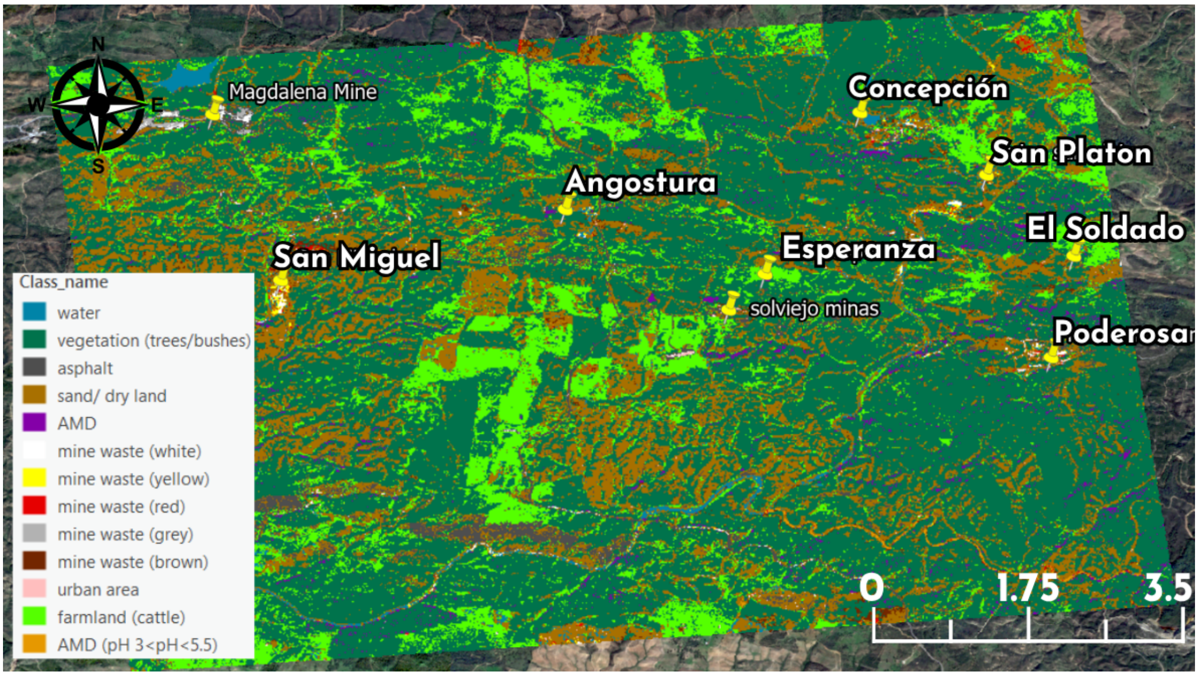


Figure 2.9: Detailed map of Zone 1 with ArcGIS-based classification and legend. The scale bar presents the distance in kilometers.

Characteristics of mines present in Zone 1

An overview of the main characteristics of the mine sites present in zone 1 is given in table 2.4. The majority of the deposits of the mines in the study area are VMS deposits, with similar characteristics such as described in section 1.1.2. However, there is one exception: the Solviejo Mine.

The Soloviejo mine was the largest of many small manganese deposits in its region. Although no longer active, these deposits made Spain the world's top manganese producer by the late 19th century, contributing over 2/3 of global output. The manganese was present in stratabound lenses of oxides and jasper within the upper layers of the purple slate of the Volcano-Sedimentary Complex. These deposits, formed in oxidizing and low-temperature exhalative environments, and are therefore mineralogical composition wise unrelated to the massive sulfide deposits [46].

Table 2.4: Overview of mines in the Zone 1 of the study area with corresponding status, main minerals, and deposit type.

Mine name	Status	Main minerals	Deposit type
San Miguel	Inactive	barite, goethite, pyrite, sphalerite	massive sulfide [47]
Poderosa	Inactive	azurite, pyrite	massive sulfide [48]
Concepcion	Inactive	barite, chalcopyrite, magnetite, galena	massive sulfide[49]
San Platón	Inactive	barite, pyrite	massive sulfide [50]
Angostura	Inactive	pyrite	massive sulfide [51]
Solviejo	Inactive	hematite, cryptomelane, lithiophorite, muscovite, pyrolusite, quartz, rhodonite, todorokite, vernadite, rhodochrosite	manganese [46]
El Soldado	Inactive	pyrite	massive sulfide [52]
Esperanza	Inactive (tourism)	pyrite	massive sulfide [53]
Magdalena	Active	pyrite	Massive sulfide [54]

Table 2.5: Overview of mines in the study area, including deforestation extent, mine pond surface areas, and geographic coordinates.

Mine name	Coordinates	Deforestation (m^2)	Mine ponds	Mine ponds (m^2)
San Miguel	37°45’28”N 6°45’13”W	253863	1	244
Poderosa	37°44’55”N 6°39’17”W	109444	-	-
Concepcion	37°46’46”N 6°40’45”W	220470	3	43770
San Platón	37°45’52”N 6°40’23”W	174411	-	-
Angostura	37°46’01”N 6°43’00”W	76776	1	9725
Solviejo	37°45’16”N 6°41’45”W	23962	2	13676
El Soldado	37°45’40”N 6°39’07”W	14575	-	-
Esperanza	37°45’32”N 6°41’28”W	45180	2	4045
Magdalena	37°46’45”N 6°45’39”W	368057	4	156186

Considering the different deposit types and main minerals present in the Solviejo mines, there appears to be less urgency for rehabilitation compared to the VMS deposit mines whereas there are no sulfides present and there is thus less risk of environmental pollution or contamination due to AMD and heavy metal mobilization. Additionally, the composition of the tailings and the mineralogy differs significantly from the samples taken at the San Miguel mine, indicating that certain assumptions made for San Miguel do not apply to the Solviejo mines. Another important factor to take into consideration, is that the Magdalena mine is still active, with tailings and waste generation still ongoing. As such, the Solviejo and Magdalena mines will be excluded from the current rehabilitation plan for zone 1.

2.6. Assumptions and uncertainties

- Spatial extrapolation: The extrapolation of the portable XRF data from San Miguel to other mines within Zone 1 assumes mineralogical and geological similarity. Although stratigraphic units are comparable, this introduces uncertainty whereas no direct sampling or measurements are taken at the other mine sites in Zone 1.
- Satellite classification resolution: The classification map used Sentinel-2 imagery with a resolution of 10 m. This spatial resolution may not detect small scale contamination patterns or deviations, especially in heterogenous waste deposits. As well, visually similar but mineralogical distinctive characteristics can not be separated or mapped by ArcGIS, giving rise to potential errors.
- Threshold reference values: Pollution thresholds were adopted from European and US EPA guidelines. However, these may not fully align with Spanish or IPB-specific ecological baselines.
- Weathering effects: Time dependent processes such as oxidation, leaching, and seasonal variations regarding e.g. rainfall were not modelled, although they influence metal mobility. As well, the samples at the San Miguel mine site were taken during the dry season, and are therefore not representative for the concentrations and potential pollution during the wet season.
- Exclusion of mine sites: the Magdalena and Solviejo mines were excluded from this research. It is assumed that the manganese deposit does not pose a direct threat to

the environment, however, this is a basic assumption only related from literature and not actual measurements. Similarly, the active massive sulfide deposit of the Magdalena mine is exlcuded whereas mining activities are still happening. However, the impact of the Magdalena mine on zone 1 is not further considered on this research and might result in discrepancies in actual results, having potentially a larger negative impact on human health and local ecosystems compared to the inactive mine sites.

- Groundwater assumptions: Risk was inferred from surface proximity to hydrological features, assuming consistent subsurface flow from topography. No piezometric data has been used or was available.

2.7. Discussion

The results show that all samples exceed allowable limits for As and most of the samples of Cu and/or Pb. These results indicate acute contamination, especially near surface pathways prone to runoff and leaching.

ArcGIS classification provided easy visualisation of the different mine waste types present as identified at the San Miguel mine site for the remaining, inactive mine sites of Zone 1 in the study area, using training datasets from field observations and spectral reflectance characteristics. Even though it provides easier classification of the surface cover of the abandoned mine sites, it does not accurately capture differences due to a resolution of 10 meters. As well, the actual contamination spread of heavy metals to surrounding soils or areas can not be accurately captured by using this classification. However, similar inactive mine site surface classification indicate similarities in geological and mineralogical composition of the mine waste present, indicating that extrapolation of the portable XRF findings of the San Miguel site to the remaining, inactive mine sites in Zone 1 is possible.

While the modelling offers valuable insights, its reliability depends on the accuracy of satellite image interpretation and the assumption of uniformity across mines. The inability to include groundwater flow direction or temporal fluctuations also limits predictive confidence. Nevertheless, the integration of quantitative XRF data with spatial modelling presents a defensible basis for prioritising reclamation interventions.

2.8. Conclusion

This chapter demonstrates that the San Miguel mine and surrounding areas in Zone 1 are severely contaminated with heavy metals, especially arsenic and lead. Using XRF data and ArcGIS-based modelling, contamination patterns were extrapolated, identifying critical hotspots across Zone 1 and the inactive mine sites present. Despite uncertainties linked to extrapolation and remote sensing, this approach offers an overview of a preliminary contamination map. These findings directly support the need for a tailored rehabilitation plan for the inactive mines present in Zone 1.

3 Rehabilitation Proposal

3.1. Introduction

This chapter lines out the selected remediation strategies for Zone 1 of the Iberian Pyrite Belt, based on a literature review of various in situ, ex situ, and rehabilitation and morphological recovery methods (Appendix B and C). The goal is to mitigate AMD and reduce the mobility of the previously identified (Chapter 2) dominant contaminating metals, namely: arsenic (As), copper (Cu), and lead (Pb). The method selection has been based on their environmental and economic compatibility and feasibility.

The reclamation of a mine site can be divided into three main categories, namely: restoration, rehabilitation, and replacement. Restoration entails the process in which the aim is to restore the mine site to the land use before mining. Considering this definition, the aim would be to recreate the original ecosystem function and structure and ground terrain, which is nearly impossible. A comparable solution is rehabilitation, which involves restoring ecosystems, while placing less importance on species composition, structure, and function of the ecosystem. Rehabilitation strives to a partial return of the area to an original state. Conversely, replacement typically does not restore the initial environmental conditions. Replacement entails converting the area to an alternative land use that focuses on aesthetic and economic improvements, aligning with the local development needs. A schematic overview of these three reclamation forms can be observed in Figure3.1. For Zone 1, the only viable solution would be the adaptation of a rehabilitation plan due to the severity of the contamination and presently active mine sites present in the vicinity of the area. The aim is to mitigate the harmful effects of ongoing contamination of inactive mine sites on the ecosystem and local communities inside and near the study area.

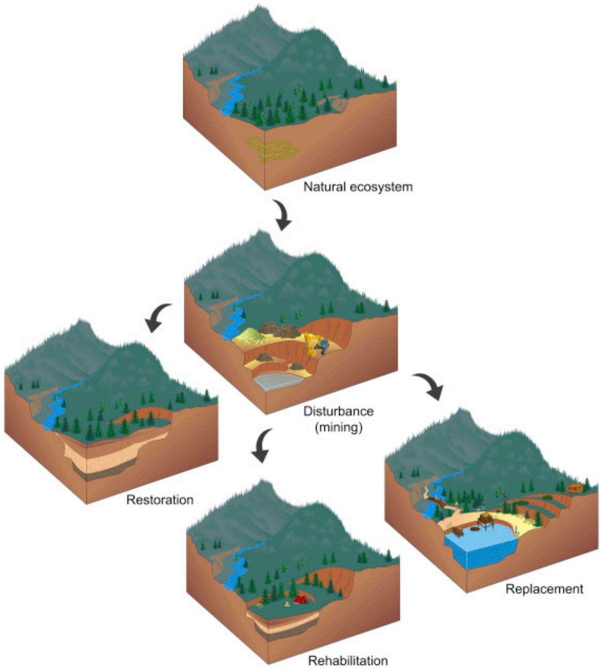


Figure 3.1: Overview of the main reclamation approaches for abandoned mine sites, namely: restoration, rehabilitation and replacement [23].

This chapter presents a rehabilitation plan tailored for Zone 1 of the Iberian Pyrite Belt. For this plan, both remedial and morphological methods are advised. The most suitable methods are selected after an extensive in depth literature review of both Remedial and Morphological work plans, the literature review and all methods considered can be found in Appendix B and C. It also provides a more in-depth theoretical background for the final selected methods for the study area.

The rehabilitation proposal encompasses the inactive mines of San Miguel, Poderosa, Concepción, San Platón, Angostura, El Soldado, and Esperanza. Building upon the contamination patterns and morphological characteristics identified in Chapter 2 and Appendix B and C, this plan integrates biological, physical, and passive chemical treatment strategies to address pollution risks, particularly heavy metal contamination and acid mine drainage (AMD).

The objectives of this remediation proposal are to:

- Stabilize contaminated soils and mine waste to limit the spread of heavy metals.
- Treat AMD at the inactive mine sites using passive, sustainable methods.
- Improve surface stability and prevent erosion through morphological restoration.
- Re-establish ecological function through revegetation and phytostabilization.
- Create a phased, cost-effective, and socially responsible implementation plan.

Considered but Rejected Approaches

Several other methods were reviewed but not selected for full-scale implementation due to various limitations:

- Soil Washing and Stabilization (Ex Situ): Although highly effective in reducing pollutant loads, these techniques are active treatments and therefore require extensive excavation, high water and reagent usage, and large-scale treatment facilities. By excavating the top layers, there is a high risk of ecosystem disruption. As well, while the method is labor and resource intensive, it is also economically not feasible for widespread application in Zone 1 [55], whereas the site is located in a rural area.

- Cemented Paste Backfill (CPB): CPB has strong benefits for structural stability and tailings containment but is impractical in the study area due to high material (cement) import costs, labor intensiveness and potential subsurface damage from re-injecting waste into underground voids [56].
- Technosols and Biochar Amendment: While innovative and beneficial for long-term soil health, these approaches demand precise tailoring of waste inputs and extensive monitoring. Their performance under the specific climatic and geochemical constraints of Zone 1 remains uncertain, therefore this approach is eliminated from this research [57].
- Electrokinetic and Thermal Remediation: These physical treatments are energy intensive, disruptive of soil layers and are more effective for specific soil types and contaminants. They are therefore unsuitable for the heterogeneous and widespread contamination profiles found in the area of zone 1 [58].

A complete and more in depth overview of these considered methods can be found in the appendices B and C.

3.2. Modified rehabilitation plan for the study area

For the study area, a combined approach using geo-membranes, phytostabilization, revegetation, and SRB presents the most effective remediation strategy for ongoing arsenic (As), copper (Cu), lead (Pb), and AMD contamination.

A short overview of the selected methods is presented here:
-**Geo-membranes** The mine ponds present in the study area (totaling 57,784 m^2) will be sealed with Linear Low-Density Polyethylene (LLDPE) geo-membranes to prevent AMD and the leaching of heavy metals into the environment. These synthetic barriers are designed to minimize oxygen and water infiltration of the tailings to the underlying soil, thereby reducing the generation of AMD and improving containment. Geo-membranes offer high chemical resistance and durability, making them particularly suitable for Zone 1's exposed tailings and legacy mining infrastructure [59].

Sulfate-Reducing Bacteria (SRB): Will be applied for the AMD treatment strategy. This method is proposed for the mine sites which are located in the vicinity of/or are located at rivers in zone 1 of the study area. SRB precipitate dissolved metals by converting sulfate into insoluble metal sulfides while simultaneously neutralizing acidity. This passive treatment method is favored, whereas their low operating cost and capacity for long-term, low-maintenance treatment of AMD aligns with the field conditions and socio-economic context of Zone 1 [60].

Phytostabilization: Will be used to manage heavy metal contamination in degraded and deforested inactive site covers and soils. This method employs metal-tolerant vegetation to immobilize contaminants by trapping them in their root system, thereby limiting erosion, runoff, and biological exposure. Phytostabilization is particularly effective in the acidic and heavy metal rich soils of the Iberian Pyrite Belt. Besides the immobilization of heavy metals, it supports ecosystem recovery through revegetation [61].

Revegetation: Will be applied as well to the deforested area to prevent a monoculture by only using phytostabilizing plants. Revegetation focuses solely on soil stabilization through root networks that increase cohesion and prevent erosion, while surface cover reduces water infiltration and enhances the landscape's visual appeal [62].

By integrating a combination of these approaches, this thesis aims to mitigate and decrease the harmful effects of ongoing heavy metal and AMD contamination in, and near, the study area in the IBP. As well, the methods are selected with the objective to minimize environmental risks and maintenance costs. The following subsections will delve into more detail about the discussed rehabilitation methods.

3.2.1. Geo-membranes

In the study area, seven mine sites have been identified with varying levels of deforestation and the presence of mine ponds. A total of 7 mine ponds have been recorded across San Miguel, Concepción, Angostura, and Esperanza, covering a combined total surface area of 57,784 m². These identified mine ponds will be excavated, and geo-membranes will be installed to cover the bottom of these ponds, after which the tailings will be backfilled into the pond. An illustration of a similar geo-membrane application for the proposed mine ponds in the area is given by figure 3.2.

Figure 3.2: Illustration of a geo-membrane representative, proposed for mine pond rehabilitation [63]

Geo-membranes are thin polymeric barriers designed to prevent water and oxygen infiltration into mine tailings, thereby mitigating acid mine drainage (AMD) and reducing the risk of heavy metal leaching into surrounding soils and water bodies (Section C.3.1, [59]). In the study area, the implementation of geo-membranes is particularly crucial given the fact that earlier rehabilitation of a mine pond in Mina Concepción failed due to inadequate sealing of the pond (Section C.3).

Summary of Mine Ponds in the Study Area:

- San Miguel: 1 pond (244 m²)
- Concepción: 3 ponds (43,770 m²)
- Angostura: 1 pond (9,725 m²)
- Esperanza: 2 ponds (4,045 m²)
- Total: 7 ponds (57,784 m²)

The depth per mine pond in the study area is uncertain, however, during the 2024 fieldwork it was noted that the San Miguel mine pond is very shallow, with an estimated depth of about 60 cm. An assumption is taken that the absolute maximum depth of a mine pond in this area will be about 30 m depth. This range is implemented to provide an estimate of the volumes of the mine ponds present in Zone 1 of the study area. An overview of the estimated volumes of the mine ponds is presented in Table 3.1.

Table 3.1: Overview of mines with associated pond surface areas and estimated volumes.

Mine name	Mine ponds (m^2)	Mine ponds (m^3)	Mine ponds average volume (m^3)
San Miguel	244	146-7.320	3.733
Concepcion	43.770	26.262- 1.313.100	669.681
Angostura	9.725	5.835-291.750	148.792
Esperanza	4.045	2.427-121.350	61.888
Total	57.784	17.335-1.733.520	828.394

In order to install geo-membranes in the area, first the mine ponds will need to be excavated, covered with geo-membranes and then backfilled with the tailings. Therefore, excavational equipment such as bulldozers will be needed as well. To ensure optimal performance and adaptability to site conditions, Linear Low-Density Polyethylene (LLDPE) geomembranes are recommended for use across all mine pond covers in the study area. Compared to High-Density Polyethylene (HDPE), LLDPE offers higher flexibility and more resistance to stress cracking, and ease of installation [59] on uneven terrain. This is important for the sites in the study area, given the variable topography and the potential for differential settlement between these sites. On average, LLDPE's have a lifetime of +/- 36 years [64].

Geo-membrane surface calculation

To determine the required surface area of geomembranes for the mine ponds in the study area, a simplified cylindrical geometry is assumed. Each pond is modelled as a vertical cylinder, where the geo-membrane must line both the top surface and the inner sidewalls.

Methodology

The total surface area to be covered by geomembranes for each mine pond is calculated as follows:

$$A_{\text{total}} = A_{\text{top}} + A_{\text{side}} = \pi r^2 + 2\pi r h \tag{3.1}$$

Where:

- A_{top} is the horizontal surface area of the pond (provided by the surface area of the mine ponds as determined in Table 3.1),
- r is the radius of the pond, computed from the area via $r = \sqrt{A/\pi}$,
- h is the assumed depth of the pond (in three scenarios: 0.6 m, 15.3 m, and 30 m).

The surface areas of each mine site are based on the total top surface area and the number of ponds located at each site. For simplification, individual ponds are assumed to be circular and equally sized at each location.

3.2.2. Assumptions

- All ponds are approximated as perfect cylinders with circular tops.
- Each site's total surface area is distributed evenly among its ponds.
- The geomembrane must cover both the top surface and the full inner sidewall.
- Three depth scenarios are considered:
  1. **Low**: 0.6 meters
  2. **Average**: 15.3 meters
  3. **High**: 30 meters

Estimated Geomembrane Surface Areas

Table 3.2: Estimated geo-membrane surface areas required for coverage at inactive sites in Zone 1.

Mine name	60 cm depth (m^2)	15.3 m depth (m^2)	30 m depth (m^2)
San Miguel (1 pond)	318	7.039	13.770
Concepción (3 ponds)	56.899	1.255.343	2.452.958
Angostura (1 pond)	12.638	278.465	543.110
Esperanza (2 ponds)	5.180	114.085	222.493
Total (7 ponds)	75.035 m^2	1.654.932 m^2	3.232.331 m^2

Best practices

Best practices to be implemented regarding the installation of geo-membranes in the study area:

- Use of reinforced LLDPE geomembranes at inactive mine sites in Zone 1 where mine ponds are present.
- Installation of lateral drainage layers to reduce water pressure and enhance slope stability.
- Application of continuous monitoring methods (e.g., electrical leak detection surveys) to detect and mitigate any post-installation defects [59].

3.2.3. Phytostabilization

As shortly has been explained before, phytostabilization entails the removal or immobilization of contaminants in contaminated mine sites by using selected plant species. The metal-tolrant plant species in this process promote the reduction of toxic metal mobilization, by trapping and retaining these metals in their root system. Therefore, the plant roots are critical as they influence and change the biological, physical and chemical properties in the soil, as well as enriching the soil with organic substances such as (amino) acids, sugards, lipis proteins and enzymes [61].

The mechanism of phytostabilization starts in the rhizosphere, which is the area surrounding the roots. It is a zone of intense chemical and biological activity. During phytostabilization, the mobility of themetalloids within the rhizosphere and soil is reduced by interactions between the plant roots and the tailings. One of these processess is called 'root induced alkalilization'. Root induced alkalization alters, for instance, the dynamic speciation of copper in very acidic soils by decreasing the concentration of copper ions and their mobility. The dissolved concentration of organic matter induced by the roots also results in decreased activity of copper ions. As well, the secreted substance enhances the heterotrophic microbial community [65].

Besides alkalilization, the following processes in the rhizosphere contribute to metal immobilization:

- **Adsorption and ion exchange**: Metalloid mobility is mainly controlled by adsorption and desorption processes, for instance, ion exchange. On the surfaces of soil particles (such as clay minerals and organic matter), metals are adsorbed onto the surface, where they become immobilized. These adsorption processes depend on various soil characteristics, such as the pH of the soil,the presence of organic acids, and the availability of binding sites on soil particles. Competitive ion exchange processes influence the nutrient dynamics in the root zone of the plants. Low-demand cations, e.g. magnesium, can displace essential nutrients from soil particles, thereby affecting the plants uptake of these nutrient. Complexation also helps to immobilize metals, as Fe-Al-Si minerals in mine tailings can form secondary minerals with large surface areas. These larger surface areas improve metal retention in the root system [61].
- **Precipitation and dissolution:** depending on the pH and geochemical conditions of the tailings, metals such as iron, zinc and copper can precipitate as sulfates, hydroxides or carbonates. These precipitated forms are less mobile and less bio-available to plants. Carbonate minerals, or lime, can be added as amendments to neutralize the acidic soils and tailings, while simultaneously precipitating the metals as carbonates. The total nutrient availability in the soil is improved by enhanced cation exchange between the roots and soil, as a result of the precipitation and dissolution of minerals around the roots [61].
- **Microbial activity:** soil microorganisms can transform metals into less soluble forms or promote conditions (such as increased pH or redox potential) that favor metal stabilization. As well, microbes play a key role in the decomposition of organic matter, which helps to create stable soil aggregates that are able to trap metals [62] .

There are several advantages of phytostabilization, for starters, there is a reduced environmental risk. Unlike approaches such as phytoextracction, which involves the uptake of metals into plant tissues, phytostabilization focuses on keeping metals immobilized in the soil, with the method being able to reduce the mobility of metals between 60-80% [66]. Therefore phytostabilization minimizes the risk of metals entering the food chain by leaching into groundwater or through plant consumption.

As well, phytostabilization provides long term sustainability once a stable vegetative cover is established. This follows basically the same principle as revegetation (Section 3.2.4). At last, phytostabilization is a relatively low-cost approach and can be implemented over large areas [62].

The first step of the phytostabilization process is the revegetation of contamined mine waste soils. This step requires the addition of adequate amendments and suitable plant species [65].

Erica Australis & Nerium Oleander

It is essential to consider autochthonous plants for the phytostabilization program, especially in the IPB where the climatic conditions (dry and hot) can be harsh for non-native flora. Therefore, it is necessary to consider plant species which are already present in the area.

In the area of the Rio Tinto mines (near the study area), several plant species colonised the bank sediments of the Rio Tinto (river) and metal-enriched substrata of the mine tailings. Currently, there are around 50 different plant species established, growing in extremely acidic conditions of the Rio Tinto waters, with the plant species *Erica Australis L.* and *Nerium Oleander L.* being the most common in terms of cover and occurrence [61]. The Latin specific epithet australis means 'southern', referring to its native habitat of southern Europe and not Australia.

Table 3.3: Concentrations of lead and copper present in *E. Australis* and *N. Oleander* in the Rio Tinto area [61]

Concentration	*Erica Australis* L.	*Nerium Oleander* L.
Pb (mg/kg)	383	764
Cu (mg/kg)	158	264
pH	4.22	4.9

Erica Australis and *Nerium Oleander* are both metallophytes, which means that they both tolerate metal-rich soils and use mechanisms to regulate the uptake and transport of metals. Studies found that *Erica Australis* and *Nerium Oleander*from the Riotinto mining area accumulate metals like Cu and Pb in root tissues, preventing them from reaching metabolically active parts.

However, these two plant species exhibit different exclusion mechanisms and are therefore able to compertmentalize slightly different metals. *Erica Australis* compartmentalizes aluminum and iron more strongly than *Nerium Oleander*. Moreover, *Nerium Oleander* excludes manganese whereas *Erica Australis* adsorbs and distributes manganese and thus serves as an accumulator. In the soils of the Rio Tinto mining area, minerals such as lead, copper, arsenic and iron is present in very large concentrations. Both plant species accumulate these metals in their leaves. However, the concentrations of copper, iron and zinc remain in *Erica Australis* within normal plant levels whereas for *Nerium Oleander*a less controlled uptake has been noticed [61].

PCA analysis of soil samples linked species distribution to the geochemical properties of the Iberian Pyrite Belt. The elemental composition of the leaves varied less in *Erica Australis* than in *Nerium Oleander*, suggesting that *Nerium Oleander* has a weaker homeostatic control and may therefore accumulate more toxic elements in aerial parts. Due to this, *Nerium Oleander* could facilitate metal transfer through the food chain. However, its high biomass and ability to trap airborne metal particles may help mitigate erosion in mining areas, indicating that it is still one of the relevant species to use for phytostabilization efforts in the study area [61].

lavandula pedunculata: phytoextraction

Another plant species to be considered for the study area is *Lavandula Pedunculata*, which is an aromatic and medicinal autochtonous plant suitable for phytoextraction. Lavandula Pedunculate is natively present in the soils and surfaces of the IBP.

Phytoextraction is a type of phytoremediation technique that uses plants to absorb contaminants, mainly heavy metals and metalloids, from polluted soils or water into their eaves, stems, and shoots which can then be harvested and removed from the site [67].

The species thrives in Mediterranean climates and adapts well to nutrient poor and metal rich soils. In the IBP, this species prevails naturally on surfaces derived from mine wastes and altered host rocks. Its tolerance to elevated concentrations of potentially hazardous elements

(PHEs) including the dominant metal pollutants as established in this research, makes it a good candidate for stabilizing contaminated landscapes. Compared to plants in a nearby uncontaminated reference area with similar climatic conditions, *Lavandula Pedunculata* growing in the IBP accumulates higher levels of PHEs in aerial tissues, particularly As, Cu, Pb, and antimony [68].

Lavandula Pedunculata could be used as a valuable natural resource, whereas the plant takes up heavy metals and turns this into economically interesting compounds (such as fenchone, eucalyptol, verbenone, bornyl acetate, borneol, and linalool oxide) for the medicinal, fragrance and cosmetic industry [68]. Therefore, it might be interesting to plant *Lavandula Pedunculata* in the area due to its potential economic gain after harvesting, while simultaneously treating polluted surface covers and areas.

Arundo Donax & Phragmites Australis

There is another type of plant species to be considered for phytostabilization, especially for locations at and nearby the water bodies in the area: reeds.

Certain reed species, especially reeds such as *Arundo Donax* (giant reed) and *Phragmites Australis* (common reed). These reeds have demonstrated an ability to tolerate high concentrations of heavy metals in soils, making them suitable candidates for phytoremediation strategies at fluvial systems and surrounding mine ponds [69].

For starters, research has shown that reeds can effectively accumulate heavy metals in their phytoliths, while limiting their uptake in plant shoots. Phytoliths extracted from these reeds showed elevated levels of As, Cu, Mn, Pb, and Zn, suggesting that these phytoliths act as preferential sequestration structures for the metalloids present in the soil and water. This compartmentalization indicates that these reed species are tolerant to heavy metal stress and that phytoliths may play a key role in mitigating toxicity by immobilizing harmful elements, thereby supporting plant growth on heavily contaminated soils [69].

As well, the decomposition of reed biomass can improve soil quality over time by providing organic matter, thus aiding in nutrient cycling. This is important for the initiating of revegetation in the study area, where diverse native species can take root and further enhance ecosystem recovery.

Lastly, using reeds for phytoremediation offers a sustainable and cost effective approach compared to traditional physical and chemical remediation techniques. Given their ability to adapt and thrive in metal enriched environments, reeds can be integrated into long-term management practices for contaminated sites [69]. An overview of the plants available for phytoremediation is given in table 3.4.

Table 3.4: Additional benefits of selected plant species for phytoremediation, beyond metal immobilization and uptake. *(Note: The Latin epithet australis refers to Southern Europe, not Australia.)*.

Species	Location	Advantages
Erica Australis	soil	compartmentalizes metals more strongly than *Nerium Oleander*
Nerium Oleander	soil	ability to trap airborne metal particles
lavandula pedunculata	soil	economic gain for fragrance industry
Arundo Donax	wetland environment	erosion control
Phragmites Australis	wetland environment	erosion control

3.2.4. Revegetation

Revegetation mainly focuses on establishing a protective vegetation surface cover. Soil stabilization occurs because the roots form a subsurface network that increases soil cohesion, thus preventing erosion. Morevoer, surface cover by e.g. grasses or bushes reduce the impact of water infiltration, as well as creating a more aesthetically pleasing landscape [62].

There are several options for the revegetation of the affected land in the study area. For starters, the previously identified *Erica Australis* and *Nerium Oleander* [61] in the phytostabilization section are useful species to consider for revegetation efforts.

Nonetheless, in order not to create a mono-culture of plants, more indigenous (non-phytostabilizing) species will need to be considered. A study carried out in the mining area of Tharsis (IPB, in near proximity of the study area) provides us with an overview of more suitable, woody plant species to be considered for revegetation efforts in the study area. A total of 15 woody plant species were recorded in the study area, from which the most suitable and tolerant ones are summarised in table 3.5 and 3.6 [70].

Table 3.5: Basic characteristics of woody plant species identified in the IPB [70].

Plant Species	Common Name	Growth Habit	Nutritional Role
Cistus Ladanifer	Gum rockrose	Shrub	Soil stabilization
Retama sphaerocarpa	Spanish broom	Shrub	Nitrogen fixation
Pinus pinea	Stone pine	Tree	Timber
Olea europaea	Olive tree	Tree	Soil stabilization
Acacia saligna	Australian wattle	Tree/Shrub	Erosion control

Table 3.6: Remediation relevance of selected plant species for the study area of the IPB [70].

Plant Species	Tolerance to Heavy Metals	Notes
Cistus Ladanifer	High	Dominant in remediated plots, naturally abundant
Retama sphaerocarpa	Moderate	Spontaneous colonizer, adapted to dry conditions
Pinus pinea	Low	Planted species, slow-growing
Olea europaea	Low	Planted species, limited coverage
Acacia saligna	Moderate	Not planted; invasive characteristics noted

For the study area, it is important to introduce plant species which are native to the area and do not have invasive characteristics. It is therefore necessary to eleminate the Acacia Saligna from the final revegetation list. Considering table 3.6, the most beneficial plants to use are the *Cistus Ladanifer* and *Retama Spaherocarpa*, whereas they are both abundant, grow fast and have a moderate to high tolerance to heavy metals. However, in order to prevent a monoculture, *Pinus pinea* and *Olea europaea* will also be planted. *Pinus pinea* could also be used for timber purposes, contributing to potential economic gain in the area.

Table 3.7: Final selection of vegetation species recommended for reforestation in the study area [70].

Plant Species	Common Name	Growth Habit	Nutritional Role
Cistus Ladanifer	Gum rockrose	Shrub	Soil stabilization
Retama sphaerocarpa	Spanish broom	Shrub	Nitrogen fixation
Pinus pinea	Stone pine	Tree	Timber
Olea europaea	Olive tree	Tree	Soil stabilization

Revegetation & phytoremediation overview

The deforested areas will be revegetated with a mix of the previously discussed phytostabilization species and revegegation species. The overview of the phytostabilization species is presented in Table 3.4. This mix will include *Erica Australis*, *Nerium Oleander*, and *lavandula pedunculata*. Phytostabilization will also be implemented along the riverside adjacent to the mine sites within the study area, where reed species such as *Arundo Donax* and *Phragmites Australis* will be planted.

The revegetation plant species are listed in Table 3.7. This mix will primarily consist of the shrub species *Cistus Ladanifer* and *Retama sphaerocarpa* , which exhibit higher tolerance to heavy metals compared to the tree species *Pinus pinea* and *Olea europaea*. The latter two species will only be planted on deforested soils where no tailings or mine waste are present. An overview illustration of the plants used for both phytostabilization and revegetation is given by Table 3.8 and Figure 3.3.

Table 3.8: Final selection of vegetation and phytoremediation species for phytostabilization and revegetation [70]. *(Note: Australis refers to Southern Europe, not Australia.)*.

Plant Species	Growth Habit	Nutritional Role
Cistus Ladanifer	Shrub	Soil stabilization
Retama sphaerocarpa	Shrub	Nitrogen fixation
Pinus pinea	Tree	Timber
Olea europaea	Tree	Soil stabilization
Erica Australis	shrub	phytostabilization
Nerium Oleander	shrub	phytostabilization
lavandula pedunculata	shrub	phytostabilization & economic gain for fragrance industry
Arundo Donax	reed	phytostabilization
Phragmites Australis	reed	phytostabilization

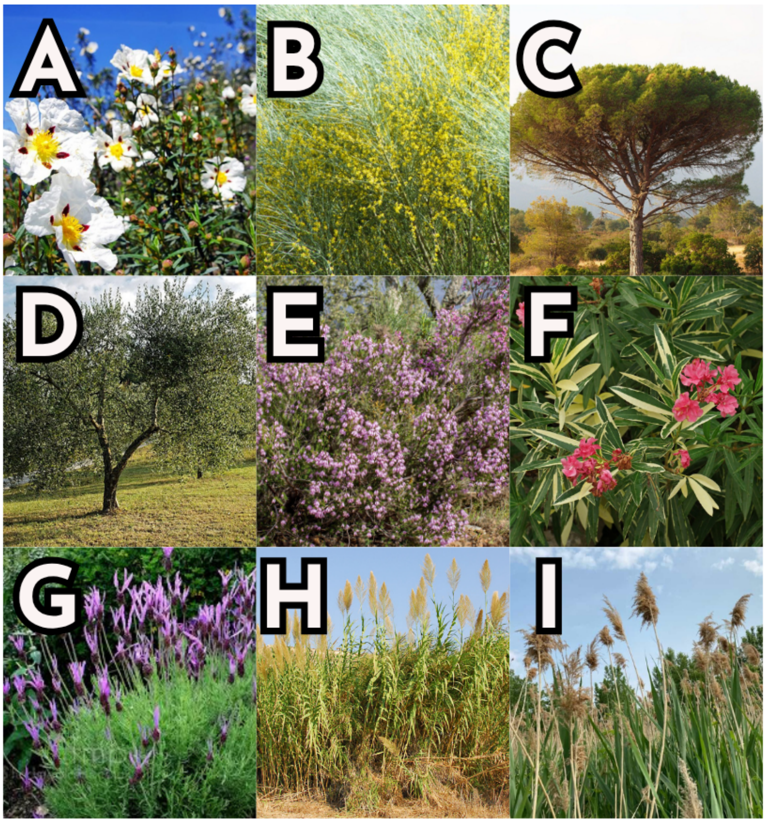


Figure 3.3: Illustration of the plant species selected for revegetation and phytostabilization purposes. A: *Cistus Ladanifer* [71], B: *Retama Sphaerocarpa*, C: *Pinus Pinea* [72], D: *Olea Europaea* [73], E: *Erica Australis* [74], F: *Nerium Oleander* [75], G: *Lavandula Pedunculata* [76], H: *Arundo Donax* [77], I: *Phragmites Australis* [78].

3.2.5. Passive treatment Sulfate Reducing Bacteria (SRB)

One promising approach is the use of SRB. SRB are anaerobic microorganisms, which can reduce sulfate to sulfide by sulfate reduction.

Once sulfate reducing conditions are established, sulfide precipitation turns into a process for metal removal from AMD, whereas the generate sulfide reacts and binds to the heavy metals present. This results into the precipitation insoluble metal sulfides . This mechanism is effective because metal sulfides are highly insoluble and less bio-available compared to other metal species [79].

For this process, an additional organic carbon source (e.g. lime) is needed, as AMD in general contains low concentrations of dissolved organic carbon. This organic carbon source functions as an electron donor under anoxic conditions. As a result, bicarbonate (HCO_3^-) and hydrogen sulfide (H_2S) are produced. The overall reaction can be described as follows:

$$2CH_2O + SO_4^{2-} \rightarrow 2HCO_3^- + H_2S \tag{3.2}$$

This process directly benefits AMD treatment, as the production of bicarbonate acts as a natural buffering agent, increasing the pH of the system and neutralizing acidity in AMD water. Following up, the hydrogen sulfide reacts with dissolved metal ions, forming insoluble metal sulfides:

$$M^{2+} + H_2S \rightarrow MS + 2H^+ \tag{3.3}$$

Copper and lead ions are depicted by M^2+, resulting in the formation of the following two sulfides:

$$Cu^{2+} + H_2S \rightarrow CuS(s) + 2H^+$$

$$Pb^{2+} + H_2S \rightarrow PbS(s) + 2H^+$$

Copper and lead in particular form highly insoluble sulfides, making SRB-based treatment an effective approach for their remediation. Arsenic is more complex, as it is generally present as arsenate ($As(V)$) under aerobic conditions. Under the reduced conditions established by SRB, arsenate may be converted to arsenite ($As(III)$) and react with sulfide to form precipitates such as orpiment (As_2S_3). The efficiency of these reactions is therefore dependent on the local pH, the redox potential, and the presence of competing ions in the groundwater [80].

SRB can not directly break down complex organic carbon compounds, such as lipids and proteins. The activity of SRB relies on an interaction with acidogenic and methanogenic bacteria, which decompose these compounds into short-chain organic molecules usable by SRB [81].

There are several organic carbon sources which can be used for sulfate reduction. These can be divided into simple and complex organic carbon sources:

- **Simple organic carbon sources:** A simple organic carbon source consists of easily degradable organic matter, such as lactate, glucose, or ethanol. Among these, lactate is highly effective as an electron donor, whereas it facilitates both energy production and acidity neutralization. However, only certain SRB species, such as Desulfotomaculum, can fully oxidize lactate and ethanol to carbondioxide, whereas others partially convert them to acetate.
- **Complex organic carbon sources:** this type is usually used to reduce costs, as these entail waste materials from food processing and agricultural industries. The complex organic carbon source acts then as an alternative organic substrate, which can be further subdivided into: cellulosic wastes (such as hay, wood chips, alfalfa, sawdust) and organic waste (manure, peat, compost, sewage sludge and so on).

Studies found that a single organic substrate often fails to significantly improve the activity of the sulphate reducing bacteria; therefore, a mixture of biodegradable (manure/sludge) and recalcitrant (wood chips/sawdust) is advised to maximise the efficiency of the SRB. Therefore, the passive treatment system generally consists of an engineered reactive zone, where the contaminated soil is amended with organic substrates to serve as carbon sources for SRB in an anaerobic environment [81].

There are several designs for the implementation of SRB for AMD remediation, such as:

- **Reactive Barriers:** Permeable reactive barriers constructed in-situ allow contaminated water and soil to contact the amended zone by diffusion, controllably supporting the conversion of sulfate to sulfide minerals.
- **Flow Control:** Low permeability designs or controlled water flow is used to limit oxygen intrusion, ensuring persistent anaerobic conditions.
- **Integration with Constructed Wetlands:** In certain designs, the passive barrier is coupled with wetlands to harness additional natural remediation mechanisms. However, as the study area is considered relatively dry and hot, wetlands might not be the best solution [81].

For the IBP, the most suitable approach seems to be several Diffusion Active Permeable Reactive Barriers at inactive mine sites in Zone 1 in the near vicinity of fluvial systems. With this approach, groundwater moves through a layered treatment zone during which sulfate of the AMD is conversed to sulfide, which in its turn react with the heavy metals in the water en precipitate insoluble metal sulfides.

A Diffusion Active Permeable Reactive Barrier (DAPRB, Figure3.4) removes contaminants by incorporating alternating layers of low and high conductivity materials. The low-conductivity (low-K) layers contain reactive materials and increase microbial activity, while the high-conductivity (high-K) layers enhances groundwater flow. This layered structure uses diffusion driven transport in the reactive zones, creating chemical gradients that ensure that microbial communities are protected from toxic metals [60].

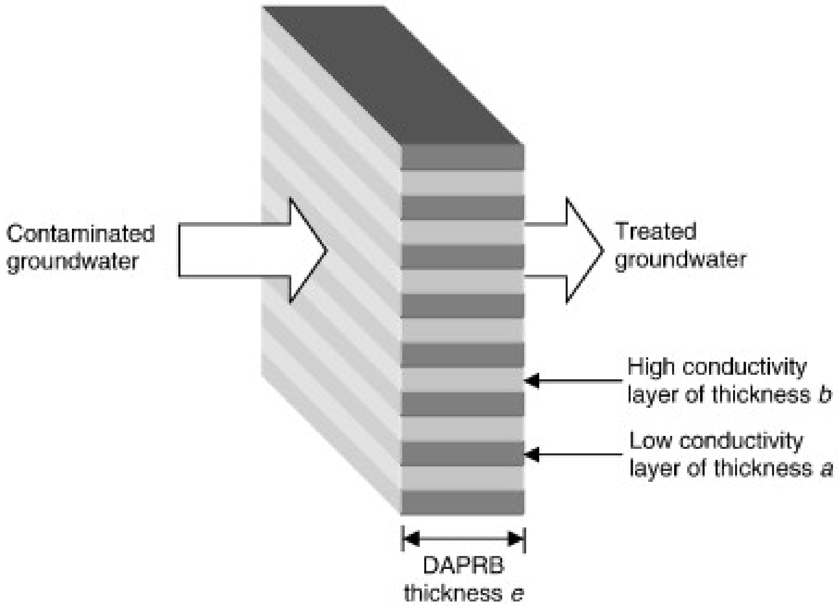


Figure 3.4: Schematic overview of a diffusion active permeable reactive barrier [60]

The primary advantage of this design is that most groundwater, carrying contaminants, flows through the high-K layers, while microbial activity occurs in the low-K layers. Diffusion allows for chemical exchange between the low- and high K-layers. Due to this diffusion, sulfide produced in the low-K layers diffuses into the high-K layers, where it encounters metal-laden groundwater. Precipitation of metal sulfides happens within the high-K layers, forming a so called biosink zone. These reactive zones provide a controlled environment where detoxifying sulfide compounds can be introduced gradually. This setup resembles a plug-flow reactor, where sulfide generated in the low-K layers continuously diffuses into the high-K layers to neutralize contaminants (Figure3.5) [60].

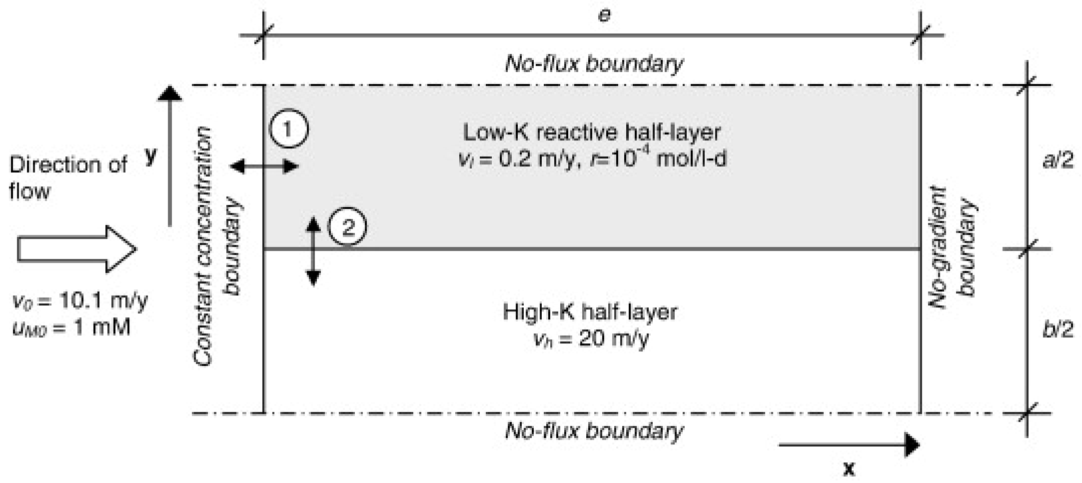


Figure 3.5: Example DAPRB layout with boundary conditions and transport parameters. [60].

For optimal performance, high-K layers can be composed of gravel or coarse sand, whereas low-K layers can contain sand mixed with particulate organic matter (POM). The hydraulic conductivity of these materials is selected to ensure effective contaminant treatment while maintaining hydraulic control. To sustain sulfate-reducing conditions, electron donors (POM) and sulfate as an electron acceptor must be available. If sulfate relies solely on groundwater transport, reactions may be limited by diffusion. However, the inclusion of solid sulfate minerals such as gypsum within the reactive material provides an enduring source of sulfate,therefore continuously supporting ongoing biological activity without being limited by transport processes.[60].

Efficiency

Acidic waste waters, such as present in the IPB, require adicophilic sulfate reducing bacteria. For instance, at a pH of 3.25, SRB can only achieve a removal of 38.3%, resulting into a pH increase to 5.82. However, higher removal efficiencies can be achieved (up til 97%) if the pH is in the range of 5-8. As mentioned before, higher sulfate reduction rates can be obtained by combining several carbon sources. Research has indicated that for comparable, acidic conditions such as present in the study area, a mixture of 40 sawdust, 29% limestone, 10% alfalfa, 10% wood chips, 10% cow manure and 1% cement dust provides the best sulfate reduction efficiency long term [81].

Restoration and rehabilitation method summary

The remediation strategy for the Iberian Pyrite Belt (IPB) study area integrates **phytostabilization, revegetation, geo-membranes** and **SRB** based passive treatment to mitigate contamination from heavy metals and acid mine drainage (AMD). This approach ensures both immediate and long term remediation whereas the system is passive. Another benefit of passive systems is the low associated environmental risks and maintenance costs.

Phytostabilization involves using metal tolerant plant species, such as *Erica Australis* and *Nerium Oleander*, to immobilize heavy metals in the soil and prevent their spread through leaching or erosion. By enhancing soil stability and improving organic matter content, revegetation and phytostabilization create a self-sustaining vegetative cover that reduces environmental risks associated with toxic metal mobility and erosion. The selection of autochthonous plant species (Table 3.8) makes sure that the proposed plan is adaptable and specific to the local conditions in the study area.

For AMD treatment, a **DAPRB** is proposed, utilizing SRB to promote sulfate reduction and metal sulfide precipitation. This passive treatment system creates anaerobic conditions where SRB can thrive, converting dissolved metal ions into insoluble sulfides such as CuS and PbS, thereby reducing their bioavailability. The barrier consists of alternating layers of high- and low-permeability materials, optimizing microbial activity in the low-K layers while ensuring effective water flow and contaminant removal by the diffusion of sulfides into high K-layers and thereby precipitating insoluble metal sulfides. To sustain SRB activity, a mixture of simple and complex organic carbon sources (e.g., manure, wood chips, and sludge) will be introduced as an energy source for microbial processes [81].

Geo-membranes offer an additional barrier layer to prevent the infiltration of water and oxygen, both of which are critical drivers of AMD generation. Geo-membranes are thin, polymeric sheets primarily composed of chemically resistant polyolefins. They act as impermeable barriers that significantly limit contaminant migration and leaching out of AMD and heavy metals, thereby limiting the ongoing pollution at inactive mine sites in Zone 1 of the study area [63].

3.3. Rehabilitation strategy

The rehabilitation methods summarised in Section 3.2.5 will be applied to inactive mine sites present in Zone 1 of the study area. In this section, per inactive mine site, an overview of the applied methods will be given. These findings will support the cost analysis in Chapter 5.

3.3.1. Overview of zone 1

Groundwater flow and wind direction

The regional groundwater flow in the IPB follows a North-South direction, extending over approximately 50 kilometers from the Cortegana area (altitude 800 m) toward the Atlantic Ocean.

The mean annual rainfall in the region is approximately 700 mm, with effective rainfall estimated between 150 and 225 mm. The wettest months occur outside the dry season, which spans from April to October, making November to March the most critical period for groundwater recharge [11].

The wind direction is North-East [10]. This suggests that dust and air pollution will likely be more concentrated northeast of each inactive mine site, whereas (ground)water pollution will predominantly affect areas Southward and downstream of the mine waste dump sites. An overview of the study area with the respective wind and (ground) water flow directions is given in Figure3.6.

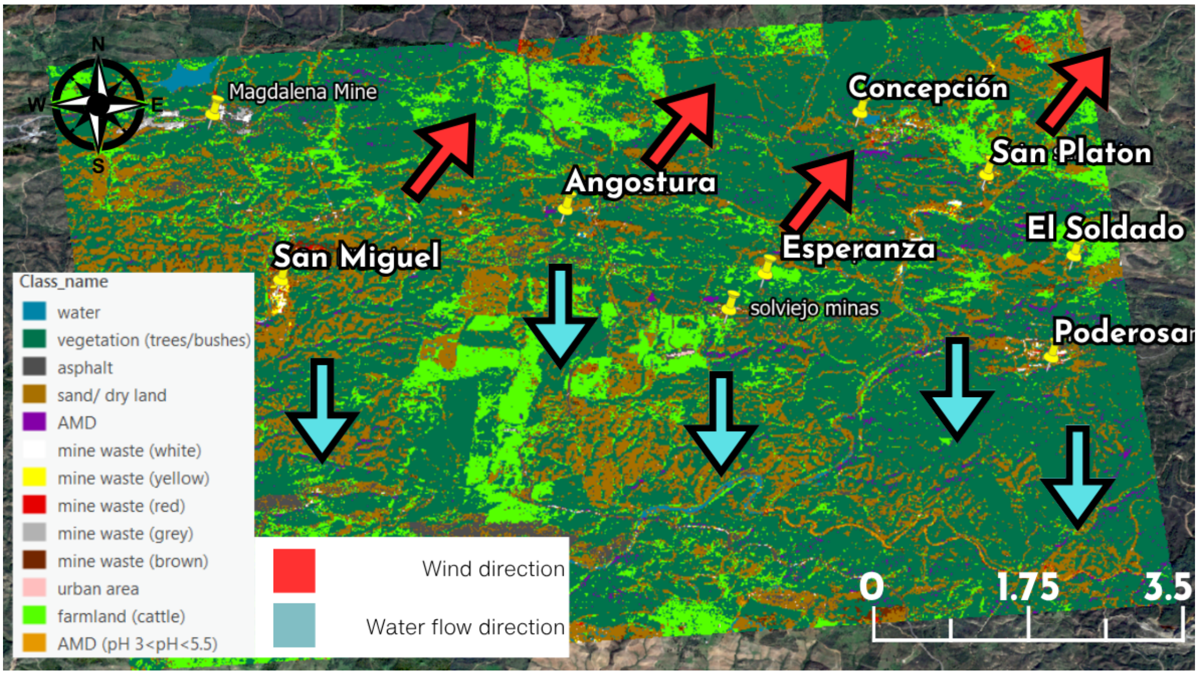


Figure 3.6: Overview of the mines considered for reclamation with wind and groundwater flow directions, scale bar in kilometers.

Characteristics of the mines present in zone

Table 3.9 gives an overview of the coordinates, the total deforested surface area, the presence and quantity of mine ponds present and the surface area of the identified mine ponds. Data has been obtained from using the measuring tool in ArcGIS Pro. The surface area of the mine ponds in the last column is the total sum of all mine ponds present in the area of the mine. A short analysis of the to be applied remediation methods will be given per selected mine site.

Table 3.9: Rehabilitation related overview of mine sites in Zone 1 of the study area, including deforestation extent, pond areas, and coordinates.

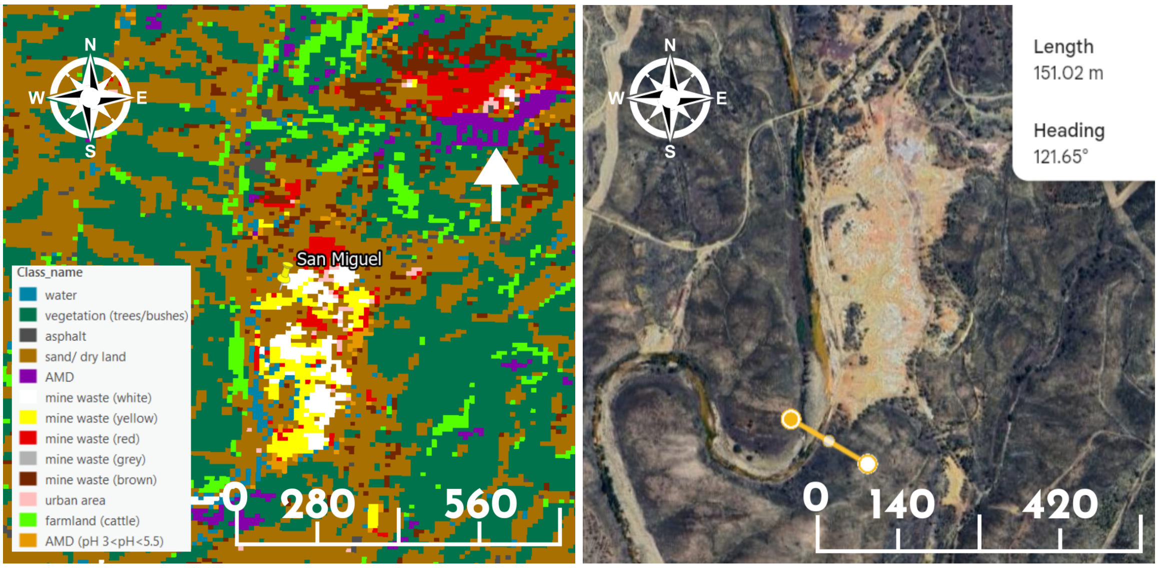
Mine name	Coordinates	Deforestation (m^2)	Mine ponds	Mine ponds (m^3)
San Miguel	37°45’28”N 6°45’13”W	253863	1	3.733
Poderosa	37°44’55”N 6°39’17”W	109444	-	-
Concepcion	37°46’46”N 6°40’45”W	220470	3	669.681
San Platón	37°45’52”N 6°40’23”W	174411	-	-
Angostura	37°46’01”N 6°43’00”W	76776	1	148.792
El Soldado	37°45’40”N 6°39’07”W	14575	-	-
Esperanza	37°45’32”N 6°41’28”W	45180	2	61.888

3.3.2. Timespan of the rehabilitation proposal

A 25-year timespan has been chosen and implemented for the current rehabilitation proposal, especially in the costs Chapter5. This timespan is appropriate for evaluating the rehabilitation of the legacy mine sites in Zone 1 due to the long-term nature of geochemical and ecological recovery processes. The mitigation of contaminant leaching and immobilization by implementing methods such as SRB and phytostabilization, often unfolds over decades. This period also allows for phased implementation, monitoring, and adaptive management. Moreover, a 25-year timeframe allows for the integration of Social Life Cycle Assessment (S-LCA) indicators that capture impacts and long-term effects on local communities.

San Miguel

The San Miguel area (37°45'28"N 6°45'13"W, Figure 3.7) is located in the West part of Zone 1 of the study area. It is the most important area for this research, whereas the samples analysed in chapter 2 were obtained from this site. As Table 3.9 already showed, there is 1 tailings pond present at the mine site with a surface of 244 m^2 and deforestation takes up around 25.4$\cdot 10^4 m^2$. The site is located at the Rio Odiel, strategic placement of the DAPRB would therefore need to be determined carefully.



(a) ArcGIS surface cover characterisation of the San Miguel mine site with legend, the white arrow depicts the mine pond, scale bar is depicted in meters.

(b) Satellite overview of the San Miguel site , the yellow bar indicates the location of the DAPRB. Scale bar is depicted in meters.

Figure 3.7: Spatial overview and classification of the inactive San Miguel mine site. The figure combines geographic information system (GIS) analysis and satellite imagery to illustrate surface cover types and structural features of the San Miguel area. Key locations for the rehabilitation proposal, such as the mine pond and the location of the DAPRB, are indicated with annotated markers. Subigure 3.7a illustrates the classified mine waste surface cover, highlighting barren areas designated for rehabilitation through phytostabilization and revegetation.

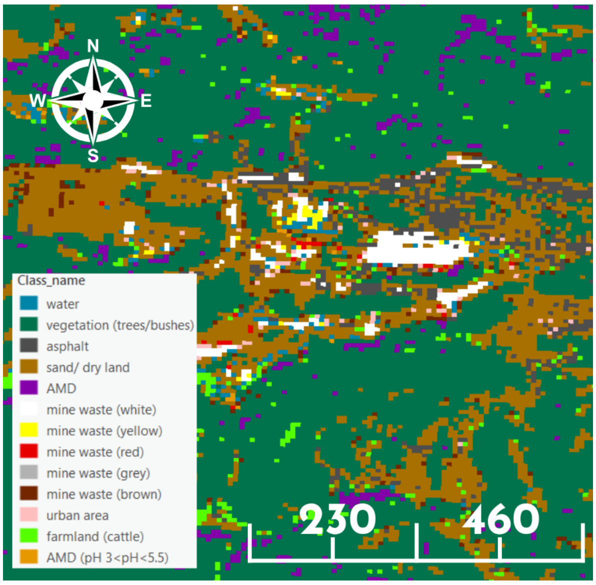
Approach

- **Phytoremediation & revegetation**: Revegetation of the 25.4$\cdot 10^4 m^2$ deforested area will be carried out using the phytostabilizing and native plant species as described in section 3.8. The Río Escalada flows along the western side of the mine site; therefore, *Arundo Donax* and *Phragmites Australis* will also be planted along the riverside.
- **SRB treatment with a DAPRB**: whereas the river Escalada passes the inactive site, SRB with a DAPRB will be implemented in the area. The DAPRB must be installed downstream from the groundwater runoff of the mine site. Regionally, the general groundwater flow direction is North-South. However, locally at the San Miguel location, the Rio Odiel draws shallow groundwater and runoff toward the river, as the river is at lower elevation than the mine site, assuming that the the river acts a hydraulic sink for local drainage. The groundwater flow at the San Miguel site becomes thus West or South/West. Thus, the DAPRB will be installed downstream South-West of the mine site as indicated in Figure3.7b.
- **Geo-membranes**: there is one mine pond present at the site, with a top surface of 244 m^2. Excavation of the mine pond (around 3.733 m^3) will first take place. After

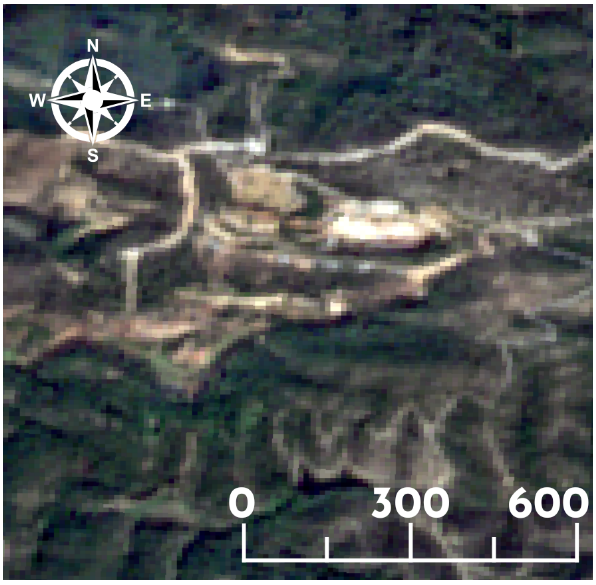
excavation, a geo-membrane will be installed to cover this surface, to prevent further leaching of the pond in the future, after which the tailings will be backfilled into the mine pond. Surrounding the edges of the mine pond, *Arundo Donax* and *Phragmites Australis* will be planted for phytostabilization purposes. For the surface to be covered by the geo-membrane, an estimate of pond thickness betwee 0,6 meter and 30 meters will be used, such as described in Table 3.2, therefore varying between 318 m^2 and 13.770 m^2.

Poderosa

The Poderosa mine site (37°44’55”N 6°39’17”W, Figure 3.8) is located in the East part of the study area and has a deforested area of around 10.9$\cdot 10^4 m^2$. The site is not located closeby a large water body or river and also does not contain a (visible) tailing pond on satellite imaging.



(a) ArcGIS surface cover characterisation of the Poderosa mine site with legend, scale bar is depicted in meters.



(b) Satellite overview of the Poderosa mine site. Scale bar is depicted in meters.

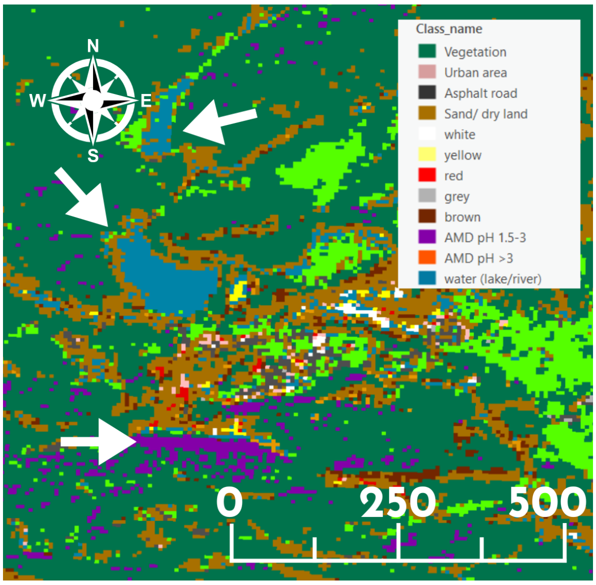
Figure 3.8: Spatial overview and classification of the inactive Poderosa mine site. This figure combines ArcGIS surface cover analysis and satellite imagery to illustrate land cover and geographic context of the Poderosa mine site. The surface characterisation highlights barren areas proposed for environmental rehabilitation through phytostabilization and revegetation.

Approach

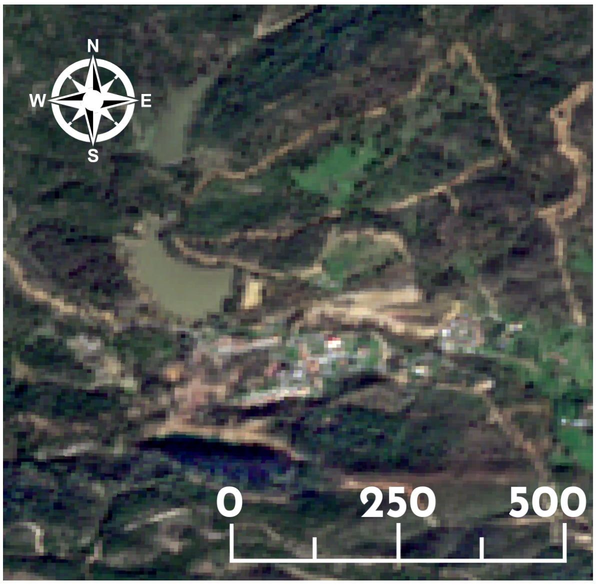
- **Phytoremediation & revegetation**: Revegetation of the 10.9$\cdot 10^4 m^2$ deforested area will be carried out using the phytostabilizing and native plant species as described in section 3.8.
- **SRB treatment with a DAPRB**: the closest distance to a water body/ river is measured at 1.4 km from the Esperanza mine site. A DAPRB is only effective when there is a clear, continuous groundwater flow from the contaminated zone to the recepter, the river. There is no data or clear indication of a groundwater plume migrating through a saturated subsurface zone, so more data would be needed to make this assumption. For now, the DAPRB is therefore excluded for the rehabilitation of the Esperanza site.
- **Geo-membranes**: there is no tailings pond visible on the satellite data in proximity to the site.

Concepción

The Concepcion mine site (37°46’46”N 6°40’45”W, Figure 3.9) is located in the East part of the study area and has a deforested surface area of around 22.0$\cdot 10^4 m^2$. The site is not located closeby a river, however, it does contain 3 tailing ponds with a total added up surface of 43770 m^2. When considering the classification (Figure 3.9a), it becomes clear that due to error margins in the classification process, two of the three mine ponds have been incorrectly identified as normal water bodies instead of AMD containing mine ponds.



(a) ArcGIS surface cover characterisation of the Concepción mine site with legend, the white arrows depict the mine ponds, scale bar is depicted in meters.



(b) Satellite overview of the Concepción mine site with three visible mine ponds present in the area. Scale bar is depicted in meters.

Figure 3.9: Spatial overview and classification of the inactive Concepción mine site. This figure combines ArcGIS-based surface cover analysis and satellite imagery to depict land cover features and spatial context of the Concepción mine site. Multiple mine ponds are visible across the area and identified with annotated markers. The classified mine waste surface highlights barren zones designated for environmental rehabilitation through phytostabilization and revegetation.

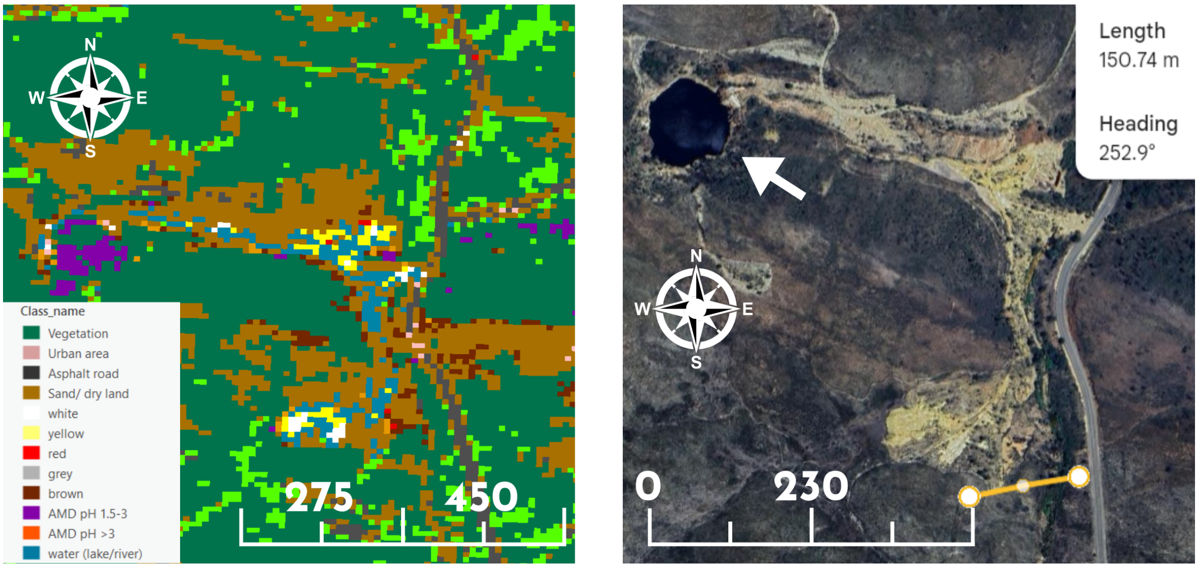
Approach

- **Phytoremediation & revegetation**: Revegetation of the 22.0$\cdot 10^4 m^2$ deforested area will be carried out using the phytostabilizing and native plant species as described in section 3.8.
- **SRB treatment with a DAPRB**: the closest distance to Rio Odiel is measured at 1.6 km from the Concepcion mine site. A DAPRB is only effective when there is a clear, continuous groundwater flow from the contaminated zone to a river. There is no data or clear indication of a groundwater plume migrating through a saturated subsurface zone, so more data would be needed to make this assumption. For now, the DAPRB is therefore excluded for the rehabilitation of the Esperanza site.
- **Geo-membranes**: there are in total 3 mine ponds present at the site, with a total added up top surface of 43770 m^2 and volume of about 669.681 m^3. First, the mine ponds will be excavated, after which 3 separate geo-membranes will be installed to cover the mind pond surfaces, to prevent further leaching of the pond in the future. After the installation of the geo-membrane, the tailings will be backfilled again. Surrounding the edges of the mine ponds, *Arundo Donax* and *Phragmites Australis* will be planted for phytostabi-

lization purposes. For the surfaces to be actually covered by the geo-membranes, an estimate of pond depth between 0,6 meter and 30 meters will be used, such as described in Table 3.2, therefore varying between 56.899 m^2 and 2.452.958 m^2.

Angostura

The Angostura mine site is located central-North (37°46'01"N 6°43'00"W, Figure 3.10) in the study area and has a deforested surface of around 7.7$\cdot 10^4 m^2$ and a large tailing pond with a surface of 9725 m^2. At the mine site, a very small river, River Seca, is located, which later on flows out into the Rio Odiel. River Seca translates to 'dry river', indicating that in summer times the river is probably dry. In Figure 3.10, it is visible that there are several errors with the ArcGIS based classification, mainly indicating the presence of water in the deforested surface area.



(a) ArcGIS surface cover characterisation of the inactive Angostura mine site with legend. The scale bar is depicted in meters.

(b) Satellite overview of the Angostura mine,the mine pond and location of the DAPRB is depicted by a white arrow and yellow bar. Scale bar is depicted in meters.

Figure 3.10: Spatial overview and classification of the inactive Angostura mine site. This figure combines ArcGIS-based surface cover analysis and satellite imagery to depict land cover features and spatial context of the Angostura mine site. Annotated markers indicate key locations such as the mine pond and the location for the installation of the DAPRB. The classified mine waste surface highlights barren zones designated for environmental rehabilitation through phytostabilization and revegetation.

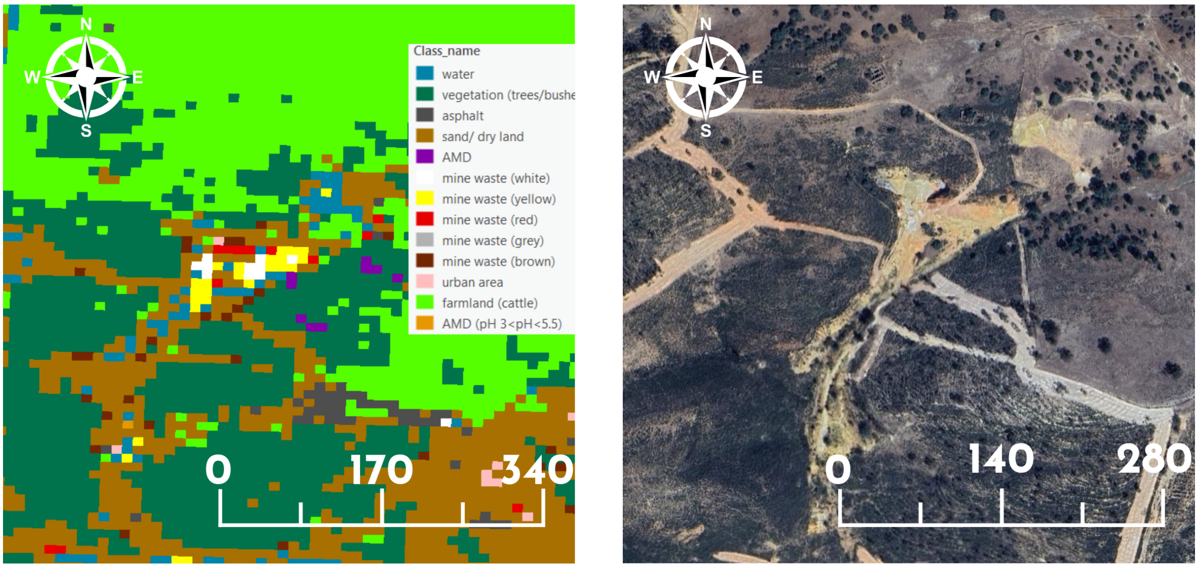
Approach

- **Phytoremediation & revegetation**: Revegetation of the 7.7$\cdot 10^4 m^2$ deforested area will be carried out using the phytostabilizing and native plant species as described in section 3.8. The Río Seca flows along the eastern side of the mine site; therefore, *Arundo Donax* and *Phragmites Australis* will also be planted along the riverside. Surrounding the edges of the mine pond, *Arundo Donax* and *Phragmites Australis* will be planted for phytostabilization purposes.
- **SRB treatment with a DAPRB**: the DAPRB must be installed downstream from the groundwater runoff of the mine site. Regionally, the groundwater flow direction is North-South. However, locally at the Angostura location, the Rio Seca draws shallow groundwater and runoff toward the river, as the river is at lower elevation than the mine site, making the river act as a hydraulic sink for local drainage. The groundwater flow at the Angostura site becomes thus East or South/East. Thus, the DAPRB will be installed South-East of the mine site as indicated in Figure3.10b.
- **Geo-membranes**: there is one large mine pond present at the site, with a surface of

9725 m^2 and a volume of about 148.792 m^3. First, the mine pond will be excavated. A geo-membrane will be installed to cover the excavated surface, to prevent further leaching of the pond in the future. For the surface to be actually covered by the geo-membrane, an estimate of pond depth between 0,6 meter and 30 meters will be used, such as described in Table 3.2, therefore varying between 12.638 m^2 and 543.110 m^2. After the installation of the geo-membrane, the tailings will be backfilled into the mine pond.

El Soldado

The El Soldado mine (37°45’40”N 6°39’07”W, Figure 3.11) is a smaller site compared to the surrounding mine sites present in Zone 1, with no tailings pond visible on satellite imaging. Deforestation takes up around 1.5$\cdot 10^4 m^2$.



(a) ArcGIS surface cover characterisation of the El Soldado mine site with legend, scale bar is depicted in meters.

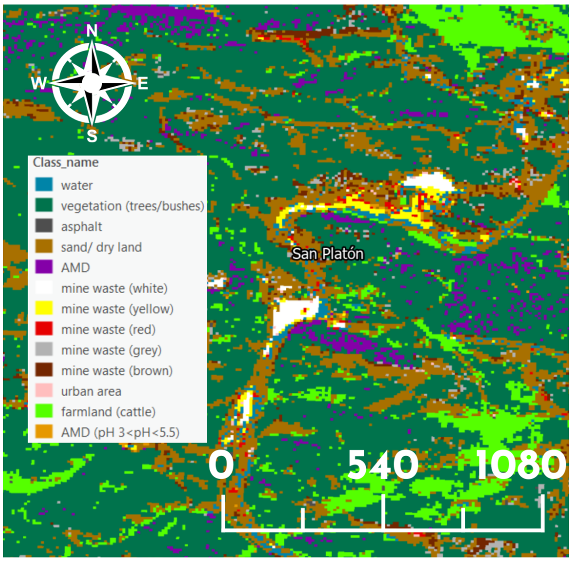
(b) ArcGIS satellite overview of the El Soldado mine site, scale in meters

Figure 3.11: Spatial overview and classification of the inactive El Soldado mine site. This figure combines ArcGIS-based surface cover analysis and satellite imagery to depict land cover features and spatial context of the El Soldado mine site. The classified mine waste surface highlights barren zones designated for environmental rehabilitation through phytostabilization and revegetation. Both panels include legends and scale bars shown in meters.

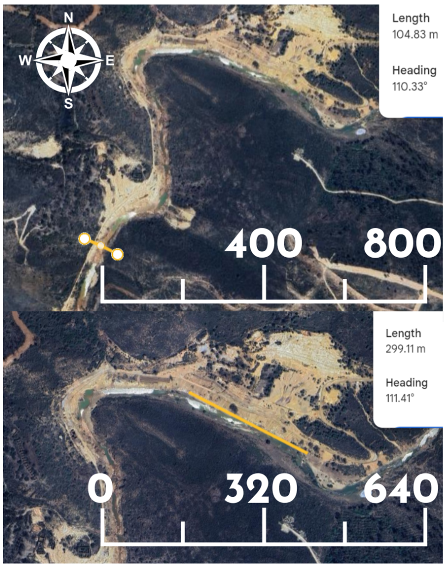
- **Phytoremediation & revegetation**: Revegetation of the 1.5$\cdot 10^4 m^2$ deforested area will be carried out using the phytostabilizing and native plant species as described in section 3.8.
- **SRB treatment with a DAPRB**: the closest distance to a downstream water body/ river is measured at 1.8 km from the El Soldado mine site. A DAPRB is only effective when there is a clear, continuous groundwater flow from the contaminated zone to the recepter, the river. There is no data or clear indication of a groundwater plume migrating through a saturated subsurface zone, so more data would be needed to make this assumption. For now, the DAPRB is therefore excluded for the rehabilitation of the Esperanza site.
- **Geo-membranes**: there is no tailings pond visible on the satellite data in proximity to the site.

San Platon

The San Platon mine site is located in the East of Zone 1 of the study area (37°45’52”N 6°40’23”W, Figure 3.12) and has a deforested surface of around 17.4·$10^4 m^2$. The Rio Odiel flows past the site, thereby facilitating downstream transport of contaminants along the river surface. The inactive mine site is oriented horizontally from west to east, resulting in extensive exposed surfaces that contribute to Southward surface runoff. To mitigate the associated soil and water contamination, two DAPRB installations are proposed: one positioned at the horizontal, Northernmost part of the site, where South-ward runoff originates, and a second located downstream along the Rio Odiel.



(a) ArcGIS characterisation with legend of the inactive San Platon mine site, N-E-S-W orientation, the scale bar is depicted in meters.



(b) ArcGIS satellite overview of the San Platon mine site, the yellow bars indicate the locations of the two DAPRB’s, scale in meters.

Figure 3.12: Spatial overview and classification of the inactive San Platon mine site. This figure combines ArcGIS-based surface cover analysis and satellite imagery to depict land cover features and spatial context of the San Platon mine site. The majority of the site oriented along a North–West horizontal axis. Annotated yellow bars indicate the proposed locations of two DAPRB installations. The classified mine waste surface highlights barren zones designated for environmental rehabilitation through phytostabilization and revegetation.

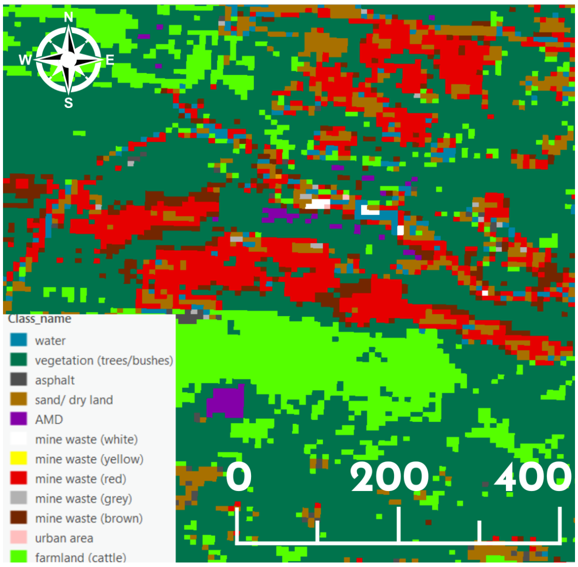
Approach

- **Phytoremediation & revegetation**: Revegetation of the 17.4·$10^4 m^2$ deforested area will be carried out using the phytostabilizing and native plant species as described in section 3.8. The Río Odiel flows along the Eastern side of the mine site; therefore, *Arundo Donax* and *Phragmites Australis* will also be planted along the riverside.
- **SRB with a DAPRB**: the DAPRB must be installed downstream from the groundwater runoff of the mine site. Regionally, the groundwater flow direction is North-South. However, locally at the San Platon location, the Rio Odiel draws shallow groundwater and runoff toward the river, as the river is at lower elevation than the mine site, making the river a hydraulic sink for local drainage. The groundwater flow at the San Platon site becomes thus East or South/East. Thus, the DAPRB will be installed South-East of the mine site as indicated in Figure3.12b. For San Platon, 2 DAPRB locations are indicated whereas the groundwater flow at the location of the proposed top DAPRB will still contaminate the surface south of the mine and not only downstream, such as is the case with the San Miguel and Angostura mine sites.

- **Geo-membranes**: there is no tailings pond visible on the satellite data in proximity to the site.

Esperanza

The Esperanza site is located approximately Center-East of Zone of the study area (37°45'32"N 6°41'28"W, Figure 3.13). The site is located in close proximity to the inactive Solviejo mine site. However, with the Solviejo site being of a manganese deposit style, rehabilitation of the site is excluded for this research as the deposit does not contain harmful minerals and sulfides. As table 3.9 already showed, there are 2 tailing ponds present at the mine site with a combined total surface of 4045 m^2 and deforestation takes up around 4.5$\cdot 10^4 m^2$.



(a) ArcGIS characterisation with legend of the Esperanza mine site with N-E-S-W orientation, the scale bar is depicted in meters.

(b) ArcGIS satellite overview of the Esperanza mine site, white arrows pinpoint the locations of the mine ponds present, scale bar in meters.

Figure 3.13: Spatial overview and classification of the inactive Esperanza mine site. This figure combines ArcGIS-based surface cover analysis and satellite imagery to depict land cover features and spatial context of the Esperanza mine site. The site is oriented along a north–east–south–west axis. Annotated white arrows indicate the locations of mine ponds present within the area. The classified mine waste surface highlights barren zones designated for environmental rehabilitation through phytostabilization and revegetation.

- **Phytoremediation & revegetation**: Revegetation of the 4.5$\cdot 10^4 m^2$ deforested area will be carried out using the phytostabilizing and native plant species as described in section 3.8. Surrounding the edges of the mine ponds present, *Arundo Donax* and *Phragmites Australis* will be planted for phytostabilization purposes.
- **SRB treatment with a DAPRB**: the closest distance to a water body/ river is measured at 2 km from the Esperanza mine site. A DAPRB is only effective when there is a clear, continuous groundwater flow from the contaminated zone to the river. There is no data or clear indication of a groundwater plume migrating through a saturated subsurface zone, so more data would be needed to make this assumption. For now, the DAPRB is therefore excluded for the rehabilitation of the Esperanza site.
- **Geo-membranes**: there are two mine ponds present at the site, with a surface of 4045 m^2 and a total volume of 61.888 m^3. First, the mine ponds will need to be excavated. After excavation, geo-membranes will be installed to cover this surface, to prevent further leaching of the pond in the future. For the surface to be actually covered by the geo-membrane, an estimate of pond depth between 0,6 meter and 30 meters will be used, such as described in Table 3.2, therefore varying between 75.035 m^2 and 222.493 m^2. After the installation of the geo-membranes, the excavated tailings will be backfilled into

the mine ponds.

3.4. Overview rehabilitation methods

For simplification, an overview of all proposed methods for rehabilitation of Zone is given in both Table 3.10 and Figure 3.14.

Table 3.10: Overview of the proposed rehabilitation strategies (revegetation, phytoremediation, and/or geo-membranes, and SRB with DAPRB) per mine site.

Mine name	Revegetation (m^2)	Geo-membranes (m^2)	SRB with DAPRB (m)
San Miguel	25 $\cdot 10^4$	244	150
Poderosa	11 $\cdot 10^4$	-	-
Concepcion	22$\cdot 10^4$	43770	-
San Platón	17$\cdot 10^4$	-	400
Angostura	77$\cdot 10^4$	9725	150
El Soldado	1.5 $\cdot 10^4$	-	-
Esperanza	4.5$\cdot 10^4$	4045	-

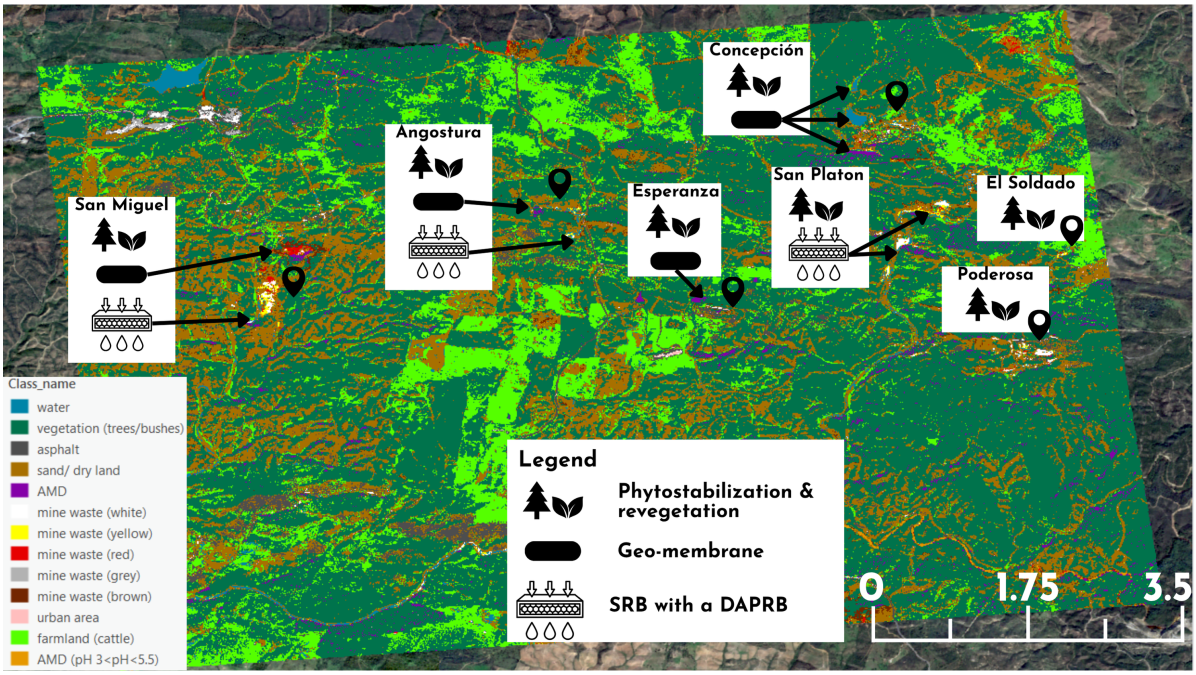


Figure 3.14: Schematic summary of proposed rehabilitation strategies for all sites in Zone 1. The scale bar is given in kilometers

3.5. Assumptions and uncertainties

- Pollution extrapolation: The treatment plan for all the inactive mine sites present in Zone 1 assumes similar contamination levels and waste composition as found at San Miguel. In reality, there will probably be some differences in composition per mine site, therefore more sampling at the remaining inactive mine sites will need to be done in the future to tailor the rehabilitation plan to their specific characteristics.

- Biological response: Assumes plant species selected for phytostabilization can establish successfully in remediated soils, despite variability in pH, salinity, or trace metal toxicity.
- Site accessibility: Terrain constraints, weather events, or land ownership boundaries could limit machinery access or implementation timelines.
- Hydrological dynamics: Subsurface water flow and its interaction with remediation structures (e.g., SRB cells or barriers) is not directly measured and introduces uncertainty, especially whereas no implementation of SRB at mine sites is proposed where there is no clear river system nearby.
- Maintenance needs: Assumes passive systems like SRBs and vegetation will require minimal long-term maintenance, although climatic variability or vandalism could interfere.
- Community acceptance: The plan assumes no major resistance from local stakeholders, though land use transitions and visual changes may provoke concern.

3.6. Discussion

The proposed remediation strategy is spatially divided into functional zones. Areas where an active groundwater flow could be determined (e.g. in proximity of a river), the installation of a DAPRB is proposed for the application of SRB to reduce and mitigate AMD. This only holds for the mine sites San Miguel, Angostura, and San Platon. This does not mean that there is no potential groundwater pollution and flow from the other mine sites, however, whereas the exact groundwater flow is not known they are due to viability reasons excluded from the research.

The installation of geo-membranes is proposed to limit the mobilization and leaching out of AMD and heavy metals into surrounding soil and groundwater from the historical mine ponds.Satellite imagery reveals that mine ponds are visually identifiable at four of the six historical mine sites in Zone 1. However, it is likely that the remaining two sites also contained mine ponds in the past, even though no clear visual traces remain today. This introduces a degree of uncertainty into the rehabilitation plan, as undetected or undocumented tailings ponds may not be adequately addressed, potentially resulting in gaps in the currently proposed remediation plan for the study area.

All selected mine sites for rehabilitation will be revegetated to prevent erosion and direct infiltration of water and mobilization of elements. As well, phytostabilization is proposed to explicitly limit the mobilization of heavy metals by trapping them in their root system.

3.7. Conclusion

A combination of several rehabilitation approaches is proposed for Zone 1, combining physical and biological methods. Geo-membranes will be installed to prevent leachate migration and reduce AMD into surrounding soils and groundwater. For AMD treatment, SRB will be used to neutralize acidity and immobilize dissolved metals. SRB will be applied through a DAPRB, which are proposed to be installed immediately downstream of inactive mine sites in Zone 1. Their placement aims to intercept and treat contaminated runoff of inactive mine sites and contaminated water flows, thereby preventing further downstream pollution. Heavy metal contamination in soils will be addressed through phytostabilization, by using metal-tolerant vegetation. Additionally, revegetation efforts will enhance soil stability, prevent erosion, and support ecosystem restoration. Plant species considered for the area are all considered to be non-invasive, native species to improve ecological conditions. These methods are selected for their long-term effectiveness, low environmental, cost-efficiency, and compatibility with Zone

1's environmental conditions.

The proposed remediation plan integrates revegetation, phytostabilization, passive AMD treatment with SRB, and geo-membrane based sealing into a holistic strategy for the selected mine sites of Zone 1, namely: San Miguel, Poderosa, Concepción, Angostura, El Soldado, San Platon, and Esperanza. The aim of the rehabilitation plan is not to completely clean the affected area, whereas this is also not possible due to the natural process of ARD. However, it does aim to minimize the negative and harmful effects for the affected environment, ecosystems and communities, both North-East windward as South/downstream ward of Zone 1.

4

Monitoring plan

The study area, located in the Iberian Pyrite Belt, is characterised by extensive mining activities, particularly for massive sulfide deposits enriched in Cu, Pb, Fe, and other metals. These operations have led to the creation of numerous mine waste deposits and mine ponds containing heavy minerals, which can generate AMD and contaminate surrounding soils and ground- and surface water. Effective monitoring of reclaimed mine ponds is critical for assessing the long-term environmental impacts after rehabilitation efforts are done. This is needed to ensure the stability and effectiveness of the applied reclamation measures, as well as to ensure that ongoing contamination of surrounding ecosystems is prevented.

Due to time considerations and the scope of this thesis, this chapter does not propose a complete monitoring plan for the study area. However, it will go over a few potential monitoring approaches, which can be used to monitor changes of water, soil quality, air quality and biodiversity of the study area. Section 4.1 highlights the key parameters, which will need to be taken into consideration in the actual monitoring plan for the rehabilitation of this area.

The primary goals of the monitoring plan are to:

- Track changes in contaminant concentrations in soil and water.
- Assess the long-term performance of remediation interventions, focusing in this proposal on methods such as phytostabilization, SRB-based AMD treatment, and the implementation of geomembranes.
- Detect erosion, vegetation cover, and geo-membrane integrity through remote sensing methods.
- Provide transparent data to stakeholders, including affected communities, regulatory bodies, and future land managers.

4.0.1. Surface water and groundwater

AMD originates from the oxidative weathering of sulfide minerals, most notably pyrite (FeS_2), present in mine waste deposits. In the study area, where extensive volcano-sedimentary massive sulfide deposits are exposed, the geological setting is particularly sensitive to pyrite oxidation and subsequent acid generation. When exposed to oxygen and water, pyrite decomposes to produce sulfuric acid and thus mobilizes toxic metals, which pose a serious threat to surrounding aquatic systems [3].

AMD has profound, and long lasting effects on both surface water and groundwater quality in mining regions. To evaluate these impacts and assess the success of remediation efforts, systematic and long-term monitoring is essential, especially after the failed mine pond rehabilitation efforts of Mina Concepción (Section C.3). The case of Mina Concepción illustrates how insufficient waterproofing and lack of sustained monitoring can lead to the recurrence of AMD, even after initial reclamation efforts were thought to be successful. Critical water quality parameters to be regularly monitored and assessed to detect AMD include pH, electrical conductivity, redox potential, sulfate concentration, and the presence of dissolved metals such as iron, copper, zinc, and lead. These indicators provide direct evidence of ongoing acid generation and metal mobilization, as well as the potential for toxicity in adjacent water bodies. Geophysical surveys could be implemented to detect potential seepage pathways and potential ruptures or leakage of the geo-membranes [82].

Rivers and streams affected by AMD exhibit pronounced seasonal variations in salinity and acidity. During dry periods, soluble sulfates (salts) accumulate in the sediments of riverbeds and mine surfaces. These salts are subsequently flushed into waterways during rainfall events, leading to fluctuation of contamination and episodic degradation of water quality.

Advanced remote sensing techniques further complement ground-based monitoring methods. Hyperspectral imaging has proven effective in identifying mineralogical changes associated with AMD, such as the formation of secondary iron-bearing minerals (e.g. jarosite, goethite, and hematite on mine surfaces [83]). These minerals serve as indicators for oxidative processes and can therefore be used to map areas of active AMD generation. As well, the mapping of these minerals ensures that the spatial effectiveness of the rehabilitation plan can be evaluated.

Groundwater monitoring is equally critical, as contaminants from mine waste can infiltrate aquifers and re-emerge in surface water bodies downstream. The installation of piezometers around rehabilitated sites enables the measurement of groundwater levels and gradients, while periodic sampling of groundwater chemistry provides insight into pollutant migration. Coupling hydrochemical data with tracer tests or isotopic analyses can reveal groundwater-surface water interactions and define the spatial extent of AMD influence [83].

4.0.2. Soil quality

Monitoring soil quality in reclaimed mine areas is important in order to understand contaminant mobilization and ecosystem health. The oxidation of pyrite leads to the formation of sulfate salts and secondary minerals that accumulate in soil crusts. Hyperspectral imaging techniques have proven succesful in identifying and mapping these mineral crusts, revealing spatial patterns of oxidation and weathering [83].

Changes in soil mineralogy, specifically the stages of sulfide mineral oxidation (e.g., pyrite transforming into jarosite, goethite, and other iron oxides), reflect environmental moisture availability and evaporation rates. For example, the precipitation of soluble sulphate salts is correlated seasonally with climate. Therefore, temporal monitoring with hyperspectral data can provide information on both short-term climatic variations and the ongoing geochemical evolution of soils [84].

Soil texture, especially particle size, also influences mineral reactivity and weathering rates. Fine-grained mud tailings tend to react faster and their mineralogy is more sensitive to short weather events. Conversely, coarser mine waste piles provide more stable records of seasonal or longer-term environmental changes [83]. Therefore, soil quality assessment should integrate mineralogical mapping with soil physical properties characterization to better interpret contamination dynamics and reclamation status.

4.0.3. Air quality

Air quality monitoring is important throughout the mine rehabilitation process and remains important in the post rehabilitation phase as well. During rehabilitation, disturbed surfaces such as tailings impoundments and exposed surface areas pose significant risks for dust emissions, particularly in dry or windy conditions or seasons. In case of the study area, especially ecosystems and communities located North-East windward of Zone 1 are at risk for dust contamination [10]. Surface wetting techniques can be applied to prevent this, however, they often provide only temporary control and are therefore not sustainable as long-term solutions. Therefore it is important to monitor the concentration of particulate matter in and near the study area during rehabilitation interventions.

A comprehensive monitoring plan should focus on particulate matter of inhalable sizes, especially PM10 and PM2.5, taking into account not only the quantity but also the chemical and mineralogical composition of the dust, which can influence its environmental and health impacts. Regular assessments during rehabilitation allow for timely adjustments to dust suppression methods in dry and windy conditions, and therefore ensure that air quality targets are met before closure [85].

After rehabilitation efforts are done, air quality monitoring must continue to ensure that residual dust emissions from the rehabilitated surface areas are effectively controlled. Post-rehabilitation monitoring should be designed based on a current and accurate source inventory reflecting all remaining emission sources, as uncertainties in these inventories can limit effective management. Strategically placed ambient monitoring stations around the site can provide continuous data on dust levels, serving both as an early warning system and as a long-term indicator of rehabilitation effectiveness. [85].

Stakeholder engagement remains an important component during both rehabilitation and post closure monitoring phases, even though it has not been thoroughly discussed during this research due to time constraints. Involving local communities and regulators helps maintain transparency and ensures that management measures protect public health and environmental quality [85].

4.0.4. Biodiversity

Vegetation cover plays an important role in stabilizing mine wastes. The application of a vegetative surface cover reduces erosion, as well as mediating biogeochemical cycles in reclaimed areas. However, the harsh chemical environment of acid-generating mine wastes poses challenges to natural revegetation processes, therefore making it essential that the phytostabilization and revegetation efforts in the area are regularly monitored [86].

Traditional ground-based methods, such as vegetation plots, provide valuable information but are often time consuming and are limited in accurately determining spatial coverage. Therefore, integrating remote sensing techniques has become important to complement field surveys. Optical satellite imagery, like Sentinel-2, provides over large areas observations which can be done frequently and cost-effectively [87].

By analyzing vegetation cover from satellite images collected across multiple moments in time, it is possible to monitor plant growth and land cover. Advanced approaches, such as harmonic decomposition of vegetation index time series, can capture seasonal and annual variations in vegetation, which may relate to species diversity and ecosystem health. Additionally, methods including Dynamic Time Warping (DTW) help compare temporal vegetation signals across different rehabilitated patches to evaluate their similarity and development stage [87].

However, challenges remain due to the heterogeneity of rehabilitated landscapes with variable topography, soil conditions, and mining histories [87].

4.1. Monitoring Plan Parameters

A comprehensive monitoring plan for mine site rehabilitation should include the following key parameters:

- **Water quality (surface and ground water)**: Key parameters for monitoring of AMD include: pH, redox potential (Eh), and concentrations of heavy metals (e.g., Cu, Pb, Zn, As) and sulfate. These indicators reflect current acidity levels, fluctuations in metal mobilization, and shows the oxidative state of water bodies. Water samples should be taken from both surface water (e.g., rivers, mine ponds) and groundwater sources (e.g. aquifers), and monitored seasonally to capture temporal variability and fluctuations[82].
- **Soil quality**: Soil quality and potential contamination can be assessed by regularly monitoring of the pH, thetotal and bioavailable metal concentrations, and the soluble sulfate salt content in the surface cover. These parameters provide insight into contaminant mobility in the soil, potential plant growth limitations, and the influence of climatic conditions (e.g., evaporation-driven salt precipitation). Soil texture should also be characterized, as finer materials react more rapidly and are more sensitive to short-term environmental changes [83].
- **Air quality**: Monitoring particulate matter (PM10 and PM2.5) is important during and after mine rehabilitation to assess dust emissions from exposed mine wastes and tailings. This includes not only the quantity of airborne particles, but also their chemical and mineralogical composition. The chemical composition is important, whereas it can influence both environmental dispersion and human health impacts [85].
- **Biodiversity and vegetation**: Vegetation metrics such as vegetation cover, diversity of fauna species presents and the corresponding biomass provide valuable information on ecosystem recovery and health. Optical satellite imagery (e.g., Sentinel-2) enables regular and efficient spatial monitoring of vegetation cover through indices, such as the Normalized Difference Vegetation Index (NDVI). Advanced methods, such as Dynamic Time Warping (DTW), allow for analysis of seasonal trends and the comparison of revegetation success across different rehabilitated zones [87].
- **Mineralogical composition**: Monitoring changes in mineralogy, particularly the transformation of primary sulfide minerals (e.g., pyrite) into secondary oxidation products (e.g., jarosite, goethite, hematite), provides insights into the intensity and progression of weathering processes. These transformations evaluate potential ongoing AMD generation. Hyperspectral remote sensing is particularly useful for detecting these mineral changes due to their distinct spectral signatures of iron oxides and sulfates [82, 83].
- **Spatial extent of contamination**: Mapping the geographic distribution of contaminated areas is critical to understand the environmental footprint of mining activities. Spectral classification tools such as the Spectral Angle Mapper (SAM) can be applied to hyperspectral or multispectral data to identify contaminated areas and monitor the spread or containment of pollutants over time.[84].
- **Temporal variation**: Seasonal and long-term monitoring is essential to detect trends and fluctuations in contaminant mobilization, mineralogical compsosition of surface waters and soils, and vegetation development. Performing periodic surveys, especially at the end of dry and wet seasons, can help capture variations driven by climate and

hydrological cycles [83, 84].

4.2. Assumptions and uncertainties

- Baseline conditions: Due to limited pre-remediation data from most Zone 1 sites, it is assumed that current field values from San Miguel represent the baseline for all other mine sites present in Zone 1.
- Hydrogeological inference: Groundwater monitoring is proposed based on flow patterns inferred from topography, but the lack of borehole or piezometer data adds spatial uncertainty to the assessment.
- Sensor reliability: It is assumed that automated sensors (e.g., pH, EC, turbidity) will perform reliably in field conditions, without accounting for potential drift or malfunction over time.e.
- Vegetation indicators: Assumes that changes in vegetation cover and spectral signatures from Sentinel-2 imagery correlate reliably with vegetation establishment and soil stability.
- Stakeholder cooperation: Assumes consistent access to monitoring sites and no disruptions from land use changes or restricted access due to land owners.
- Slope stability: In the monitoring plan, geo-technical slope stability is not taken into consideration due to its complexity and time considerations. Future research should integrate slope stability into the monitoring and rehabiliation plan.
- Long-term funding: The monitoring plan assumes stable funding for the duration of the rehabilitation proposal, which may not be guaranteed. Think of monitoring costs such as periodic sampling, analysis, and equipment maintenance.

4.3. Discussion

A well designed monitoring plan should strike a balance between technical accuracy, cost-effectiveness, and practical feasibility. For soil and water quality, quarterly sampling during the first two years is recommended, gradually shifting to semi-annual sampling as and if conditions stabilize over the years. Key parameters to monitor include both total and bioavailable concentrations of arsenic, lead, and copper, along with pH, EC, and sulfate levels in both groundwater, surface waters and soils.

For passive AMD treatment systems such as SRB, regular monitoring at both the inlet and outlet is essential to track the effectiveness and potential of AMD mintigation. Key parameters to monitor encompass the redox potential, dissolved oxygen- and metal concentrations. Geomembrane seals, should be visually inspected twice a year to detect potential failures.

Remote sensing, especially using Sentinel-2 imagery, offers a cost-effective way to monitor vegetation cover, landform stability, and signs of erosion at a broader scale. NDVI thresholds can help flag areas where revegetation and/ or phytostabilization efforts are failing, and may therefore need re-seeding. Using drone imagery also helps with monitoring by providing detailed views of slope stability and spotting early signs of gully formation.

Since developing a detailed monitoring plan is beyond the scope of this thesis, it is recommended that future research focuses on designing and evaluating such a plan specifically for the IBP study area.

4.4. Conclusion

The proposed monitoring framework outlines key parameters essential for implementing an effective plan to support the rehabilitation of Zone 1 of the study area. A future to be implemented monitoring plan should combine traditional sampling methods with automated sensors and satellite imagery to provide comprehensive and effective spatial coverage. Regularly monitoring ensures that timely adjustments can be made and implemented in case of failure, and therefore help ensure that rehabilitation goals are achieved. While uncertainties remain, particularly around groundwater flow patterns and long-term funding, the parameters to be monitored are assumed to be reliable and scalable to comparable VMS deposits and mine sites worldwide.

Since developing a detailed, site-specific monitoring plan is beyond the scope of this thesis, it is recommended that future research focus on designing and evaluating such a plan for the IBP study area. With effective monitoring in place, environmental outcomes can be safeguarded, and decision-making can remain well-informed long after active rehabilitation has ended.

5

Costs

Cost considerations play a central role in the feasibility and implementation of any environmental rehabilitation project. This chapter presents an indicative cost analysis for the remediation and monitoring plan proposed for Zone 1, as found in Chapter 3. The objectives of this chapter are to estimate the total cost of the remediation plans and to provide cost benchmarks for the chosen remediation techniques.

The current plan entails the (1) revegetation and phytostabilization of the deforestated mine sites in Zone 1, (2) the implementation of SRB by using a DAPRB in selected mine sites (near a river sysem), and (3) using Geomembranes in historical mine ponds in Zone 1 of the study area. Due to time constraints, the cost analysis will exclude both phytoremediation using reeds at the water bodies in the study area and the installation of a drainage system beneath the geo-membranes.

5.1. Revegetation and phytoremediation

Revegetation and phytoremediation of the inactive mine sites in Zone 1 is a key element of post mining land reclamation. Revegations aims to restore ecological functions and mitigate environmental risks, such as soil erosion. The costs associated with revegetation and phytostabilization depend on various factors, including terrain modification, soil amendments, runoff control, planting activities, and ongoing maintenance [62].

5.1.1. Key Cost Factors

- **Slope Reshaping:** Stabilizing and contouring slopes prevent erosion and improve soil conditions for plant establishment. This is one of the main cost drivers, whereas mechanical reshaping uses equipment such as bulldozers and excavators.
- **Soil Amendments:** Before revegetation can start, application of soil amendments, such as lime, are needed. Lime is used to neutralize the soil acidity present in the study area, thereby reducing metal mobility. The cost of amendments varies depending on the type and amount used.
- **Addition of Topsoil:** The addition of a topsoil is needed, whereas this supplies organic matter, nutrients, and beneficial microorganisms before reseeding can happen. In general, the topsoil improves the soil conditions, thus enhancing revegetation success. The cost depends on soil acquisition, transportation, and application.
- **Erosion and Drainage Control:** Installation of barriers and channels to mitigate runoff

erosion, especially on steep slopes.

- **Vegetation:** The revegetation process itself is also a key cost factor. The costs for this process entails the planting or seeding of native plant species. This includes the costs for seedlings and maintenance, such as watering and protection.

From an economic standpoint, various rehabilitation efforts in the Iberian Pyrite Belt illustrate the typical costs involved with revegetation of Zone 1 of the study area. Restoring vegetation on acidic soils polluted by metal mining operations generally costs between 10 and 20 euros per square meter [70]. This expense usually covers slope reshaping, soil amendment application, runoff control measures, and vegetation planting or seeding. Moreover, when integrated with additional remediation methods, revegetation can cut acid mine drainage by as much as 50% [70]. The study dates from 2021, the prices used for calculation in this section will therefore give an indication of the cost, but will not mirror the inflation correction.

5.1.2. Cost calculation

Considering the total surface areas of the six mine sites, the aggregated area is:

Table 5.1: Surface area of deforestation at selected mine sites in Zone 1 of the San Miguel region.

Mine Site	Area (m^2)
San Miguel	253,863
Poderosa	109,444
Concepcion	220,470
San Platon	174,411
Angostura	76,776
El Soldado	14,575
Esperanza	45,180
Total	**817,943**

Calculating the estimation of the total revegetation costs [70]:

- **Lower estimate (10 €/m²):**

$$€ = 817{,}943\,\text{m}^2 \times 10\,€/\text{m}^2 = \mathbf{€}8{,}179{,}430$$

- **Upper estimate (20 €/m²):**

$$€ = 817{,}943\,\text{m}^2 \times 20\,€/\text{m}^2 = \mathbf{€}16{,}358{,}860$$

- **Average estimate (15 €/m²):**

$$€ = 817{,}943\,\text{m}^2 \times 15\,€/\text{m}^2 = \mathbf{€}12{,}269{,}145$$

5.1.3. Conclusion

Revegetation and phytoremediation are essential components of mine site rehabilitation, particularly for erosion control and restoring ecological stability in the study area. The costs of revegetation and phytostabilization are largely driven by terrain reshaping, soil treatment, and vegetation establishment, with mechanical soil reshaping being the most significant expense.

For the six evaluated mine sites in the San Miguel region, total revegetation and phytostabilization costs are estimated to range between approximately €8.2 million and €16.4 million, with the average being €12.3 million. These costs are determined when applying revegetation and phytoremediation to cover all barren surfaces in the mining areas, the application of reeds surrounding water bodies and rivers for phytostabilization purposes is not considered due to time constraints.

5.2. Sulfate reducing bacteria DAPRB

To mitigate AMD at the San Miguel, Angostura, and San Platon mine sites, the proposed rehabilitation strategy includes the installation of permeable reactive barriers, which are enriched with SRB. These barriers are designed to limit the migration of contaminants into groundwater and surface water systems. Four PRBs are planned, with respective lengths of 150 m (San Miguel), 150 m (Angostura), and 105 m and 300 m (San Platon).

To estimate the implementation costs for these barriers, data from comparable remediation projects using a DAPRB was analyzed. The estimates provided are derived from a detailed cost analysis report, which includes installation data from the NWIRP Dallas and NWIRP McGregor sites [88]. The NWIRP McGregor site considers a biowall permeable reactive barrier approach, which would be the best approach for using SRB. Therefore, the discussed costs in the article for the bio-wall will be considered for this case study.

5.2.1. Key cost factors

Based on the referenced report, the following key cost factors influence biowall DAPRB implementation:

- **Installation and material procurement:** This step includes trench excavation, backfilling, and the placement of organic substrates. Bio-walls at NWIRP McGregor were constructed using a mixture of mulch, compost, soybean oil, and gravel, and were installed with a rock trencher.
- **Operation and monitoring:** Routine groundwater monitoring is necessary to evaluate barrier performance. This is necessary, whereas in the case study in the 7 years that followed installation, 13 of the 34 biowalls required replenishment of carbon five years after initial installation. Reported maintenance costs ranged between $0 (no replenishment) and $3,800 (replenishment after 5 years) per wall. For these four barriers, the best case scenario would therefore be that there is no replenishment needed in the 25 year timespan of the project, thereby indicating that there is no maintenance costs. The worst case would be that every 5 years replenishment and maintenance would need to be conducted, with a cost of $15,200 for 7 years according to the paper [88].

5.2.2. Cost calculation

At NWIRP McGregor, the total biowall installation cost was reported as $1,800,000 for approximately 34 biowalls, accounting for a total 3,096 meters. This results in an average cost of $581 per meter, including design and implementation [88]. This unit cost was used to estimate the installation costs of the four proposed DAPRB at the San Miguel, San Platon, and Angostura mine sites. The report dates from 2021, the calculations performed in this section do not take inflation correction into account.

- A **best case scenario**: no replenishment is needed over 25 years.
- A **worst case scenario**: all four barriers require carbon replenishment every 5 years, resulting in five replenishment cycles. This totals $15,200 per cycle or $76,000 over 25 years.

5.2.3. Conclusion

This preliminary cost estimate suggests that the implementation of four bio-wall PRBs for AMD mitigation using SRB at the San Miguel, Angostura, and San Platon sites will require an investment of approximately $447,305, inclusive of installation, design, and five years of monitoring

Table 5.2: Installation cost estimates based on reference data from the NWIRP McGregor site ($581/m) [88].

Mine site	Barrier Length (m)	Installation Cost ($)
San Miguel	150	87,150
San Platon	105	60,705
San Platon	300	174,300
Angostura	150	87,150
Total installation	**705**	**409,305**

Table 5.3: Operation and maintenance cost scenarios for a permeable reactive barrier over 25 years [88].

Cost Scenario	Replenishment Cycles	25 year cost ($)	Total Cost ($)
Best case	0 × every 5 years	0	409,305
Worst case	5 × every 5 years	76,000	485,305
Average	—	38,000	**447,305**

and maintenance.

Because all barrier installations are located relatively close to one another, certain fixed costs (e.g., mobilization) could potentially be reduced, however this is just an assumption. Trenching is assumed based on the reference projects, though final costs may vary if alternative techniques (e.g., injection or hydraulic fracturing) are selected. As well, the type and quantity of reactive media used can affect material costs. For example, the Dallas project attributed 12% of its total installation cost to soil excavation and disposal, which may be higher or lower depending on local geology and contamination levels [89]. At last, ongoing operational expenditures are not included but should be considered in a full life cycle cost assessment.

5.3. Geo-membranes

The implementation of geo-membrane liners in existing mine ponds will be done to mitigate leaching out of heavy metals and AMD to (ground) water and soil. This section provides an indicative cost analysis for the deployment of geo-membranes, specifically HDPE and LLDPE types, across four mine ponds in the San Miguel. As determined in section 3.3, the inactive mine sites with ponds to be interved area: the mine ponds at San Miguel, Concepción, Angostura and Esperanza. The findings are based on a recent comparative study regarding geo-membranes [90], dating from 2023. The calculations performed in this section do not take inflation correction into account. As well, the installation and costs do not take into account the installation and maintenance of a drainage system, as is proposed in Section 3.2.1 due to a lack of data regarding costs and time constraints.

5.3.1. Key Cost Factors

The primary cost factors influencing the use and installation of geo-membranes in existing mine ponds include:

- **Excavation & backfilling:** One of the costs to be considered for geo-membranes is the excavation and backfilling of tailings in mine ponds prior and after the installation of the geo-membrane.

- **Material Cost:** Determined by the type of geomembrane selected (HDPE or LLDPE) and its thickness.
- **Production Cost:** Costs associated with manufacturing the geo-membrane sheets.
- **Transportation Cost:** Delivery expenses that vary with site accessibility and the distance from its suppliers.
- **Installation Cost:** Labor and machinery required for surface preparation, lining, welding, and anchoring [90].
- **Maintenance Cost:** Inspection, repair, and performance assurance, geo-membranes namely have a typical 36 year life cycle [64].

5.3.2. Cost calculation

Excavation and backfilling

Before geo-membranes can be installed in the mine ponds of the San Miguel, Concepcion, Angostura and Esperanza mine sites, first excavation of these ponds needs to happen. In Table 3.1, an estimation of the volumes of the mine ponds present can be found by using the assumption that the depth of these ponds vary between 60 cm and 30 m, with an average estimate of depth of 15.3 m.

In order to calculate the costs associated with excavation, various factors need to be taken into consideration. First, the type of equipment needs to be chosen. For this project, a Caterpillar 320 was chosen, which has an average productivity of 90 $m^3/hour$ [91]. Whereas the mine ponds must first be excavated and then backfilled, the calculated volumes (Table 3.1) are multiplied by a factor of 2 to account for both processes. It is assumed that the transportation time between the different mine zones is negligible, whereas the mine sites are located in close proximity to one another (Figure 3.6).

Cost scenario: excavation works of max. 1 year

From a project planning perspective, it would be undesirable for excavation works to extend up to 15 years. Therefore, an arbitrarily chosen scenario is implemented, setting a baseline in which excavation across all areas is completed within a maximum of 1 year. Based on general data from the Cost Estimation Handbook of the Australasian Institute of Mining and Metallurgy [92], the following assumptions and baseline parameters are used (Table 5.4).

Table 5.4: Parameters for realistic excavation cost estimations [92]

Parameter	**Value**
Efficiency	74% work efficiency
Working hours	12-hour shifts, 11 effective working hours per shift, 2 shifts/day
Operating days per annum	352 days, accounting for 13 average weather delay days
Total effective hours worked per year	5,730.56
Total volume excavated per annum	515,750.40 m^3 (at 90 m^3/hour per excavator)

According to these estimations, the total volume excavated per year is approximately 515,750 m^3 per excavator. The salary of an excavator operator is €14.42 per hour [93], which results in an annual labor cost of €82,520.06 per excavator.

The Caterpillar 320 has a purchase price of $250,000 and a weekly rental rate of $3,460, equivalent to €2,949.97 per week [89]. This implies that a one-year rental would cost €153,398.44 per excavator, which is lower than the acquisition cost. Under the assumption that all mine ponds are to be excavated and backfilled within one year, the total baseline cost per excavator—including rental and labor—amounts to €235,918.50. This baseline cost is then multiplied by the number of excavators per year, as listed in column 3 of Table 5.5, to calculate the total excavation cost for each depth scenario (column 4), including both excavator rental and operator salary costs. Considering the previously volumes of the mine ponds per depth scenario:

Table 5.5: Estimated costs for the excavation of depth scenarios 0.6 m, 15.3 m, and 30 m, based on baseline excavation data from Table 5.4 [92], assuming a one year project duration

Depth Scenario	Excavation & backfill (m^3)	Excavators/year	Costs (EUR)
Mine ponds at 0.6 m depth	34,670	0.066	15,570.62
Mine ponds at 15.3 m depth	1,656,788	3.2	754,939.20
Mine ponds at 30 m depth	3,467,040	6.7	1,580,653.95

Geo-membrane costs

Given the potential for differential settlement, irregular terrain, and the need for flexibility during installation, LLDPE is generally more suitable for covering the mine ponds in the study area whereas LLDPE geomembranes are better able to conform to irregular terrains. As well, it has a lower stress cracking risk, which is necessary whereas previous rehabilitation efforts of one of the mine ponds of Mina Concepción already failed due to terrain issues (Section C.3). Based on a reference case involving a 10,000 m² landfill installation with 1.0 mm thick liners [90], the following cost estimations apply:

Table 5.6: Estimated unit costs of geomembrane installation (1.0 mm thickness) [90].

Cost Component	HDPE (USD/m²)	LLDPE (USD/m²)
Material	3.00	3.50
Production	1.00	1.20
Transportation	0.20	0.15
Installation	2.50	2.00
Maintenance	1.00	1.50
Total	**$7.70**	**$8.35**

5.3.3. Conclusion

Converting $8.35 to euros results in an average LLDPE price of €7.14 per m^2. The total installation costs of geo-membranes for the three mine pond depth scenarios at inactive mine sites in Zone 1 are shown in Table 5.7. Although geo-membranes have a lifespan of 36 to 50 years, no replacement would be required within the 25-year duration of the reclamation project [64].

Table 5.7: Estimated total costs for geo-membrane installation in the study area following pond excavation. An assumed categorization is used for shallow (0,6 m), average (15,3 m), and deep (30 m) mine ponds (Table 3.2). The last column depicts the total costs including the excavation and back filling costs (Table 5.5) [90, 92]

Depth scenario	Geo-membranes (m^2)	Geo-membranes (€)	Total (€)
Mine ponds at 0,6 m depth	75,035	535,749.90	551,320.52
Mine ponds at 15,3 m depth	1,654,932	11,816,214.48	12,571,153.68
Mine ponds at 30 m depth	3,232,331	23,078,843.34	24,659,496.95

5.4. Summary

This chapter has presented an indicative cost analysis of the main components proposed for the rehabilitation of the selected mine sites in Zone 1 of the study area. These components include (1) revegetation & phytostabilization of deforested and degraded surface areas, (2) the installation of DAPRB with SRB, and (3) the implementation of geo-membranes in historical mine ponds in the study area. As this analysis is based on pre-feasibility level cost estimates derived from data between 2021 and 2023, a contingency range of ±25% is applied to account for market volatility and design uncertainties [94]. Therefore, the total estimated rehabilitation cost of €25.2 million may in reality range between approximately €18.9 million and €31.5 million. A summary of these cost components is provided below, with the average determined costs in the previous sections to be taken as the estimated costs value.

5.4.1. Cost Summary Table

Table 5.8: Summary of total estimated costs for all proposed rehabilitation measures [70, 88, 90, 92].

Rehabilitation Measure	Estimate (€)	Estimate range +/-25% (€)
Revegetation (6 sites)	12,269,145	9,201,858.75-15,336,431.25
DAPRBs (4 barriers, 25 years)	382,365.26	286,773.95-477,956.58
Geo-membranes (4 ponds)	12,571,153.68	9,428,365.26-15,713,942.10
Total	25,222,663.94	18,916,997.96-31,528,329.93

5.5. Assumptions and uncertainties

- Preliminary design phase: Cost estimates are based on conceptual designs and carry a ±25% accuracy range typical of pre-feasibility studies [94].
- Uniform costs: Unit costs per hectare or treatment unit are assumed constant across sites, despite possible variations in the different terrains of the study area, variations in contamination depth, or access logistics challegnes.
- Inflation and material pricing: the cost analysis is based on values sourced from reports published in 2021 and 2023, adjusted to 2025 price levels. However, the estimates do not account for inflation over the projected 3–5 year implementation period or the 25-year operational lifespan considered for certain measures.
- Unquantified ecosystem services: Ecosystem services such as enhanced biodiversity and improved water quality are often excluded from economic valuations. However, these unquantified benefits have the potential to offset perceived environmental or financial costs.
- Labour availability: Assumes skilled and unskilled labour availability at regionally averaged rates, which may fluctuate with demand or policy changes.
- Monitoring duration: A 25-year monitoring window is assumed, with diminishing intensity over time. Longer durations or regulatory changes may increase total costs.
- Simplification of reality: The costs included in this sector merely gives an indication of the actual costs, as not all costs include aspects such as labour costs or long-term maintenance costs. Moreover, the cost estimation for the SRB with DAPRB system is based on data from an American study, and therefore may not accurately represent the cost conditions specific to the Iberian Pyrite Belt scenario. As well, the costs of the geo-

membranes installation does not include the costs of installation and maintenance of a drainage system, which would be necessary whereas the rehabilitation efforts of one of the mine ponds in the area already failed in the past (mine pond of Mina Concepción) due to a tearing and lack of a drainage system (Section C.3).

- Depth of Mine Ponds: The assumed depth of the mine ponds ranges from 60 cm to 30 m, a substantial variation. As a result, the cost determined estimates should be interpreted as indicative of the potential order of magnitude of the associated costs, rather than as precise reflections of the costs. Additionally, the scenarios are modeled assuming uniform depths across all ponds (0.6 m, 15.3 m, or 30 m), with no calculations accounting for ponds of varying depths within Zone 1.

5.6. Discussion

The rehabilitation cost estimation for the seven selected mine sites in the San Miguel region provides a valuable preliminary financial overview of the measures required to mitigate the proposed environmental risks. However, several assumptions and uncertainties underlying the indicative cost estimates warrant careful consideration when interpreting the results.

The total estimated cost of approximately €25.2 million reflects the scale and complexity of the rehabilitation efforts. The costliest component is for both the installation of geo-membranes and revegetation, accounting for an average of both about €12.3 million. While essential, these interventions may vary significantly in cost depending on site-specific topography, access, and degradation severity—factors not fully captured in the current uniform cost coefficients.

The installation of DAPRB (Direct Application of Passive Reactive Barriers) systems, although relatively modest at $0.45 million, represents a focused intervention aimed at improving water quality by stimulating sulfate-reducing bacterial activity. These barriers are particularly relevant for reducing acid mine drainage (AMD) migration at groundwater–surface water interfaces.However, the cost estimate is based on favorable installation conditions and may not account for logistical challenges that could arise in more remote or geotechnically complex locations. Additionally, the implementation of DAPRB systems is considered only for mine sites located near surface water bodies, overlooking the influence of subsurface water flow and aquifers at other sites. As a result, the broader issue of acid mine drainage and heavy metal mobilization across the area remains unaddressed.

Geo-membrane liners are identified as an effective solution to limit the leaching of AMD and heavy metals from historical mine ponds to surrounding soils, surface and groundwater. The estimated total costs of this approach is around €12.6 million across the mine ponds in Zone 1, including excavation and backfilling. However, the estimate does not include the costs for associated drainage systems, which are critical components to prevent hydrostatic pressure buildup and membrane failure. Notably, previous rehabilitation at Mina Concepción failed due to the absence of such a system, emphasizing the importance of integrating full containment infrastructure in future cost models.

Several assumptions and limitations affect the accuracy of the current cost analysis. The estimates are derived from conceptual designs typical for pre-feasibility studies, with an expected accuracy range of ±25% to correct for e.g. inflation and different socio-economic conditions. This uncertainty is further increased by the use of uniform unit costs across diverse sites, which oversimplifies variations in terrain, contamination levels, and site accessibility. Labor availability and costs are assumed to reflect regional averages, but these may shift depending on market conditions or policy changes over the course of implementation.

It is important to note the exclusion of costs for reed-based phytoremediation in and near water bodies. Although not quantified in this cost analysis due to time constraints, such solutions could provide environmentally sustainable support to the rehabilitation of Zone 1 and should be considered in future planning and budgeting.

Finally, the monitoring strategy is based on a 25-year post-implementation period with decreasing intensity over time. However, if regulatory standards become more strict or site conditions change, extended or more intensive monitoring may be required, potentially increasing long-term costs.

5.7. Conclusion

The total estimated costs for the rehabilitation of seven selected mine sites in the San Miguel region indicate a significant financial investment, reflecting the scale and complexity of the required interventions.

- **Revegetation** is together with the installation of geo-membranes the most expensive component, ranging from approximately €9.2 million to €15.3 million, with an average of €12.3 million. This includes slope reshaping, soil amendments, erosion control, and planting. Mechanical reshaping is identified as the primary cost driver.
- **DAPRB systems** to introduce sulfate reducing bacteria represent a focused AMD intervention at approximately $0.45 million, primarily driven by installation logistics and material procurement. These barriers are expected to effectively reduce acid mine drainage migration, especially in groundwater-surface water interfaces.
- **Geomembrane liners** is similarly to revegation a more expensive method in the study area, however, it offers effective prevention for mine pond AMD and metal leaching into surrounding soil. The costs include both the material costs, as the excavation and back filling of the mine ponds. LLDPE geomembranes are recommended due to durability and economic benefits, costing approximately €12.36million USD in total across four ponds (San Miguel, Concepción, Angostura, and Esperanza).

Overall, the total costs for the rehabilitation plan is estimated to be around €25.2 million for the selected mine sites in the study area. This cost estimation excludes the implementation of phytoremediation with reeds at the water bodies present in the study area, however, for future research purposes it is advised to consider this practice in the cost estimation as well.

6

Social Life Cycle Assessment

6.1. Introduction

Environmental rehabilitation directly impacts local communities, regional economies, and broader social systems. This chapter presents a Social Life Cycle Assessment (S-LCA) of the proposed remediation plan for Zone 1 in the Iberian Pyrite Belt.

A Social Life Cycle Assessment (S-LCA) is a framework which can be used to assess the socio-economic and social impacts of products throughout their life cycle. In contrast to a traditional Life Cycle Assessment (LCA), the S-LCA evaluates how a products life cycle affect local people and communities, instead of focusing on the environmental impacts of the product. It provides insights into the social sustainablity of products.
A S-LCA will be performed to determine the social and socio-economic impacts of the mines present in Zone 1 on the focus area of the study [95].

Steps

1. Goal and scope definition
2. Life Cycle Inventory (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation

6.2. Goal and scope definition

The primary goal of this SLCA is to evaluate the potential social impacts associated with the rehabilitation and legacy of the San Miguel, Poderosa, Concepción, San Platon, Angostura, El Soldado and Esperanza mine sites located in Zone 1 of the study area. By integrating social dimensions, the assessment offers a more holistic view of mine site legacies and contributes to sustainable decision-making for future remediation efforts. This assessment aims to provide a systematic understanding of the mine's historical and ongoing influence on local communities, with a particular focus on stakeholder well-being, employment, land use, and access to resources.

The study area encompasses the immediate surroundings of Zone 1 of the study area, and includes nearby towns and villages within a 25 km radius. The communities in the study area have historically been intertwined with mining activities in the IPB and are directly or indirectly affected by mining operations, closure of mines, and subsequent rehabilitation efforts.

For this assessment, the functional unit is the set of mine sites in Zone 1 that are proposed to be rehabilitated, evaluated over their post-operational life span. The focus is on the social impacts that emerge in both the short and long term. The system boundaries encompass historical factors, such as the legacy of mining-related employment, current on-site activities (including the proposed rehabilitation efforts) and environmental monitoring as well as subsequent outcomes such as land reuse, public health impacts, and broader socio-economic changes.

The SLCA looks at the impacts on the key identiefied stakeholder groups in the study area, such as residents, mining employees, authorities, NGO's, farmers and so on. To gather insights, a mix of methods is used: literature reviews and determination of indicators, demographic data, satellite data and local historical data. The results of the S-LCA are based on the author's interpretation of the available data.

Indices to monitor

The subject of the S-LCA will be focused on human health. Indices to evaluate can therefore be summarised as:

- Proximity of mine waste dump sites to villages
- Amount of inhabitants of the area and nearby communities/ villages.
- Proximity of mine waste dumps to agricultural activities
- Human health risks
- Economic dependency on (historical) mining and rehabilitation activities
- Positive or negative effects of reclaiming on local communities

A matrix will need to be developed with a ranking of 0 to 5 to define the impact on the respective stakeholder per impact category.

6.3. Life Cycle Inventory

6.3.1. Local communities and residents

The Life Cycle Inventory (LCI) phase forms the data-driven foundation of this research. In this stage, all relevant inputs and outputs for the S-LCA associated with the rehabilitation of the Zone 1 mine sites are systematically identified and quantified [95].

The social context of the study area is essential to understand the potential local impacts of historical, current and future mining activities on the study area. The selected study area lies within the IPB and encompasses several small towns and villages. The central point of Zone 1 the study area is marked with a green pinpoint on the map (Figure 6.1) and corresponds to the approximate center of past and ongoing mining related activities of this area.

The surrounding settlements are represented by red pinpoints, with symbol sizes corresponding to population ranges:

Small: fewer than 100 inhabitants

Medium: 100–999 inhabitants

Large: 1,000–4,999 inhabitants

Extra-large: 5,000 inhabitants or more

The proximity of these communities to the study area is an important factor in assessing social risks and impacts. Table 6.1 provides a detailed overview of all identified villages and towns within a 25 km radius, listing their distances from both the pinpointed center and the closest edge of the study area as well as their total population size. As well, their orientation relative to the study area is given whereas downstream (Southward) communities are affected by ground and surface water pollution[11] and North-East windward [10] the communities are affected by dust pollution.

As shown in Table 6.1, only a limited number of villages are situated exclusively to the East or West of the study area. Most settlements are concentrated in the North, North-East, South, South-West, or South-East directions. This distribution is relevant for understanding potential exposure of local communities to either air or water transport of contaminants.

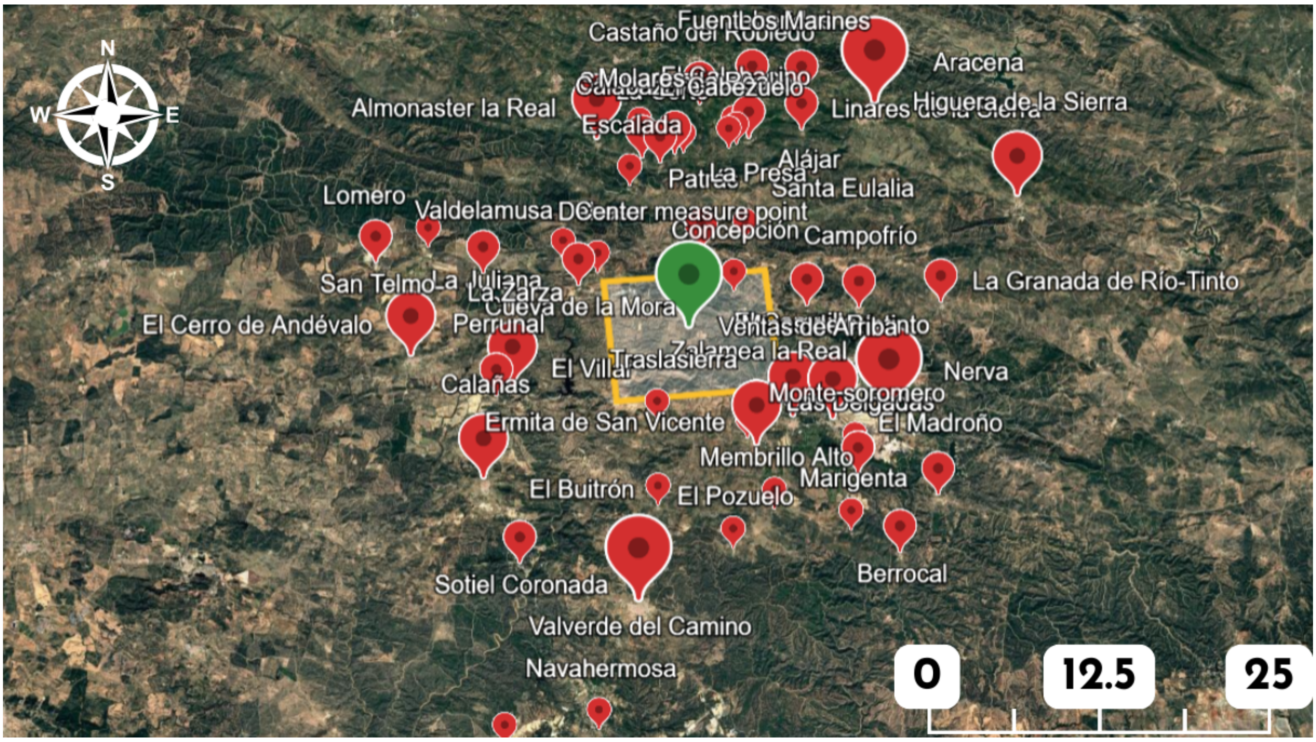


Figure 6.1: Map of the study area with town markers scaled by population size, outlined by a square boundary.The central reference point is indicated by a green marker. Red markers denote local towns and villages, with marker size corresponding to population: small (<100 inhabitants), medium (<1,000), large (<5,000), and extra-large (>5,000). The scale bar provides a visual reference for distance in kilometers.

Table 6.1: Villages located within and around the study area. 'Distance center' refers to the straight-line distance from each village to the center of the study area. 'Distance SA' indicates the shortest distance from the village to the nearest border of the study area. 'Orientation' describes the relative position of each village with respect to the study area. The final column lists the number of inhabitants per village in 2023 [96].

Village/ town	Distance center (km)	Distance SA (km)	Orientation SA	Inhabitants
Concepcion	4.2	0	-	89
Patrás	5.7	1.5	N	139
El Villar	6.6	1.8	S	94
Traslasierra	7.4	1.8	S	37
Dehesa	7.8	0.6	NW	52
Cueva de la Mora	8.5	1.7	W	138
Ventas de Arriba	8.5	2.6	E	36
Zalamea la Real	9.0	3.8	S	2,977
El Campillo	9.7	2.5	S	2,019
Escalada	11.2	6.4	N	52
La Corte	12.1	7.9	N	259
Campofrio	12.1	6.2	E	727
Minas de Ríotinto	12.2	4.4	SE	3,709
El Buitron	12.5	7.9	S	46
Santa Ana la Real	12.7	8.4	N	476
Calabazares	12.8	8.3	N	129
La Zarza	13.2	7.2	W	1,047
Molares	14.0	9.7	N	23
Alájar	14.1	9.0	N	792
El Calabacino	14.1	9.4	N	98
Perrunal	14.5	8.5	W	168
Almonaster la Real	15.0	9.6	N	1,753
Valdelamusa	15.3	8.5	W	306
Nerva	15.5	7.8	SE	5,068
Las Delgadas	15.8	8.4	SE	129
El Pozuelo	15.8	11.2	S	23
Castaño del Robledo	15.8	11.7	N	226
Linares de la Sierra	16.3	10.0	NE	275
Calañas	18.0	11.0	SW	2,757
La Granade de Rio Tinto	18.0	12.0	E	244
Los Marines	18.7	12.5	NE	427
Valverde del Camino	19.9	14.6	S	12,704
El Cerro de Andévalo	20.0	14.2	W	2,267
Aracena	20.0	13.1	NE	8,427
Sotiel Coronada	20.6	13.6	SW	210
El Madroño	21.2	13.8	SE	367
Berrocal	21.9	14.7	SE	288
San Telmo	23.0	16.3	W	245
Higuera de la Sierra	25.0	18.4	NE	1,299
Navahermosa	29.0	23.7	S	61
Fuente de la Corcha	32.3	26.0	SW	61
Total	-	-	-	51,144

As can be seen in 6.1, there are many very small villages present in the study area. To simplify the research, all villages with fewer than 1,000 inhabitants will be excluded from the S-LCA, with the exception of Concepción. Since Concepción lies within the study area, it will be included as a representative location for Zone 1 of the study area. A similar table is constructed only considering villages with more than a 1000 inhabitants and Concepcion in table 6.2.

Table 6.2: Villages located within (Concepcion) and around the study area (with >1000 inhabitants). 'Distance center' refers to the straight-line distance from each village to the center of the study area. 'Distance SA' indicates the shortest distance from the village to the nearest border of the study area. 'Orientation' describes the relative position of each village with respect to the study area. The final column lists the number of inhabitants per village in 2023 [96]. For further research purposes, only the towns in this table will be used.

Village/ town	Distance center (km)	Distance SA (km)	Orientation SA	Inhabitants
Concepcion	4.2	0	-	89
Zalamea la Real	9.0	3.8	S	2,977
El Campillo	9.7	2.5	S	2,019
Minas de Ríotinto	12.2	4.4	SE	3,709
La Zarza	13.2	7.2	W	1,047
Almonaster la Real	15.0	9.6	N	1,753
Nerva	15.5	7.8	SE	5,068
Calañas	18.0	11.0	SW	2,757
Valverde del Camino	19.9	14.6	S	12,704
El Cerro de Andévalo	20.0	14.2	W	2,267
Aracena	20.0	13.1	NE	8,427
Higuera de la Sierra	25.0	18.4	NE	1,299
Total	-	-	-	43,328

6.3.2. Agricultural grounds

Study area

In the area of zone 1, there are several agricultural grounds present, especially farming cattle. Figure 6.2 gives an overview of the locations of these agricultural grounds, pinpointed by the yellow pins. Table 6.3 shows the nearest distance from the mine sites to farmlands present in Zone 1 of the study area.

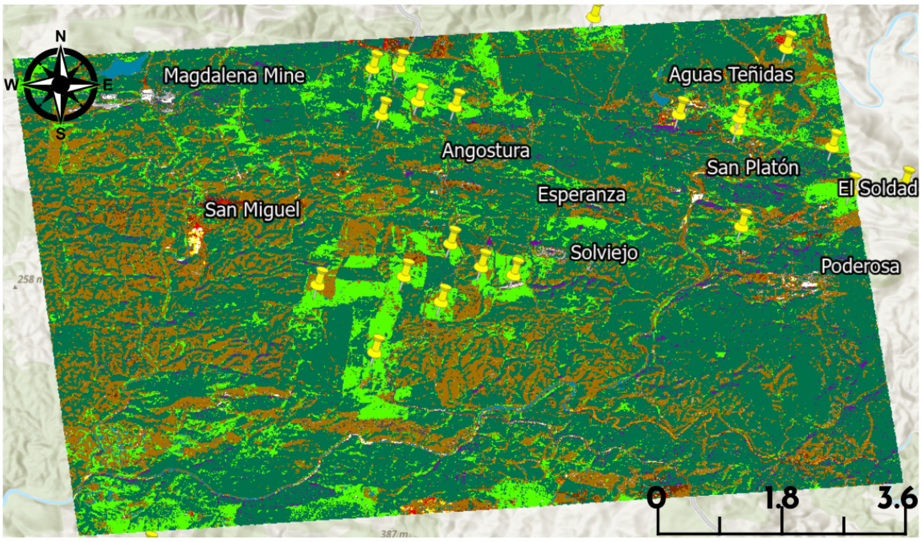


Figure 6.2: Overview of zone 1 with arcgis classification. The identified agricultural grounds in the area are pinpointed by the yellow pins. Image has N-E-S-W orienation. The depicted scale bar is in kilometers.

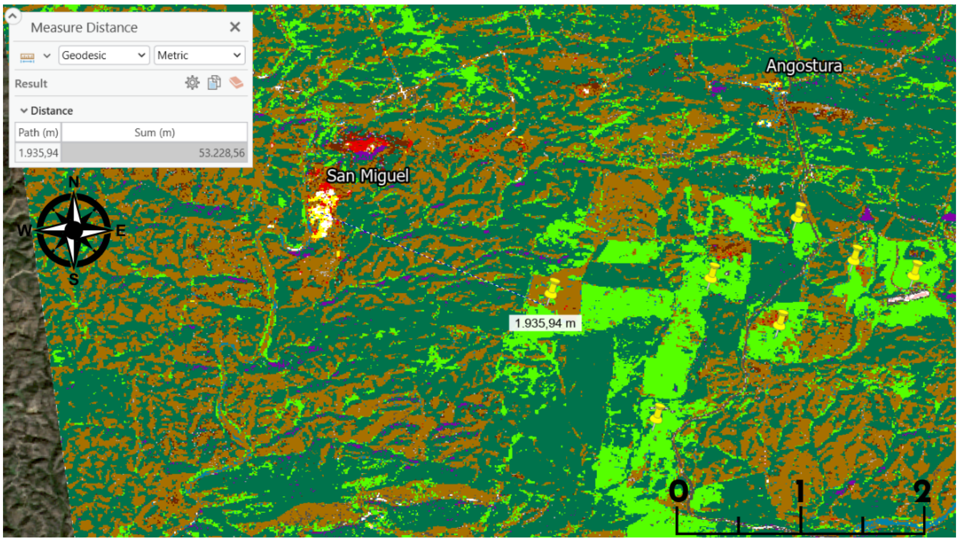


Figure 6.3: Distance measurement to agricultural land using ArcGIS Pro. The depicted scale bar is in kilometers.

6.3.3. Sickness and diseases

The extensive mining operations in the IPB have resulted in the release of large quantities of heavy metals into the environment. As described in section 2.3, the San Miguel mine site in the study area has shown that there are highly elevated levels of metals such as arsenic, lead, and copper present in the study area. Similarly, research indicates that the Huelva estuary, formed by the confluence of the Tinto and Odiel rivers, is heavily polluted due to AMD and industrial discharges, leading to high concentrations of bioavailable toxic metals in sediments [97]. Additionally, research conducted has shown that urban and peri-urban soils in Huelva have been found to contain heavy metal concentrations well above regional screening levels. This poses potential health risks to the local population present in the study area through ingestion, inhalation, and dermal contact, especially since the metal arsenic is commonly known as a highly toxic carcinogenic [98].

Table 6.3: Shortest distances between mine sites and surrounding farmlands as measured by using ArcGIS Pro.

Mine site	Distance to nearest farmland (km)
San Miguel	1.9
Poderosa	1.3
Concepcion	1.2
San Platon	1.3
Angostura	1.3
El Soldado	0.6
Esperanza	1.1
Average	1.3

The ongoing exposure to heavy metals in Huelva has raised concerns about potential health effects. Epidemiological studies have observed higher cancer mortality rates in Huelva compared to other regions. For example, research has linked chronic exposure to metal pollution in the IPB with elevated cancer risks in adults residing in the provinces of Huelva, Seville, and Cádiz [99]. The provinces of Huelva, Sevilla, and Cádiz have therefore been ominously referred to as ’the cancer triangle of death’ (Figure 6.4) due to their highest cancer mortality rates in Spain, with studies pointing to mining and industrialization as key contributing factors [12].

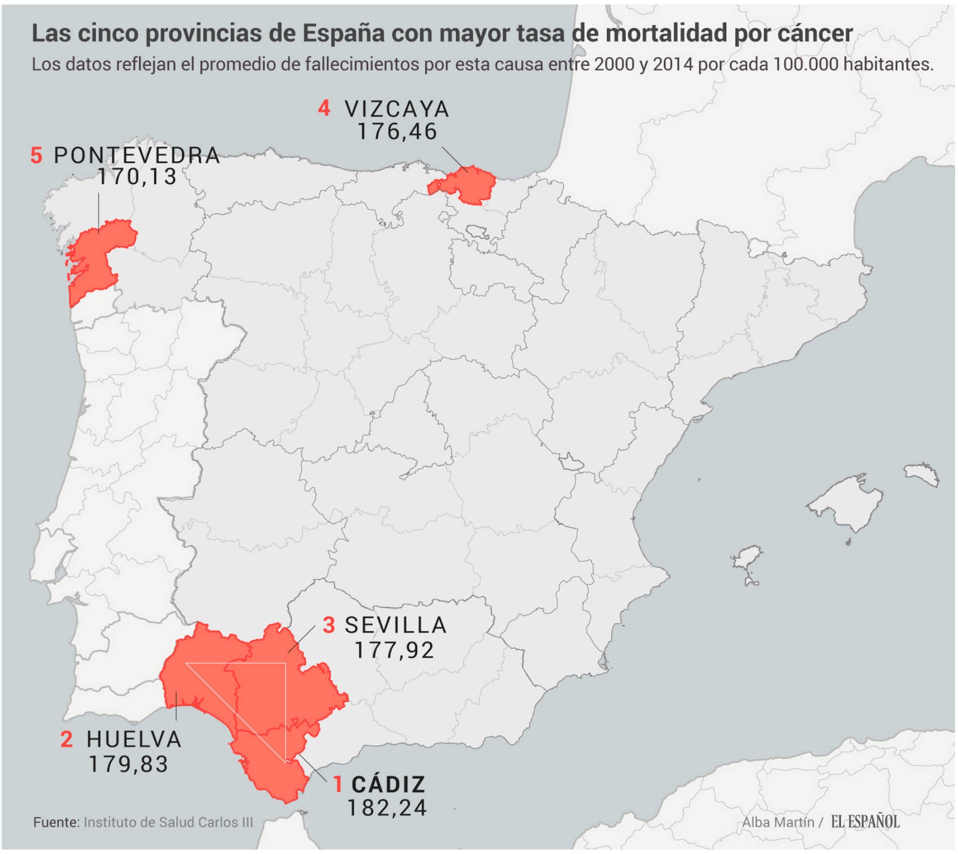


Figure 6.4: Map showing Spain’s five provinces with the highest cancer mortality rates [12].

This is confirmed by a bio-monitoring study published in the Journal of Xenobiotics [100]. The research focused on evaluating the internal cumulative dose of toxic metals among residents of Huelva, using toenail clippings as a biomarker for long-term exposure. Concentrations of 16 different metal(loid)s were analyzed, including well known toxicants such as arsenic (As), cadmium (Cd), lead (Pb), and uranium (U). These metals are common in the study area of this research due to historic and industrial activity, including mining, smelting, and waste storage.

The study found that Arsenic and cadmium, both commonly known as human carcinogens, were highlighted as particularly problematic due to their high present concentrations and strong correlation with cancer outcomes. As well, individuals living closer to the industrial and mining areas had significantly elevated internal levels of these contaminants. More importantly, statistical analysis revealed associations between higher internal metal burdens and increased rates of mortality due to cardiovascular disease and various types of cancer, especially in adults over the age of 60 [100].

A study by Casola et al. [13] demonstrates that municipalities located near mining and industrial sites (e.g. the city of Huelva and the study area) exhibit significantly higher cancer incidence rates compared to other areas within the same province. This is particularly noteworthy given the fact that the province of Huelva already shows one of the highest overall cancer rates in Spain (Figure 6.4). Figure 6.5 presents an overview of cancer relative risk (RR), posterior probabilities (PP) of RR > 1, and spatially interpolated relative risk compared to the provincial average for both men and women in the province of Huelva.

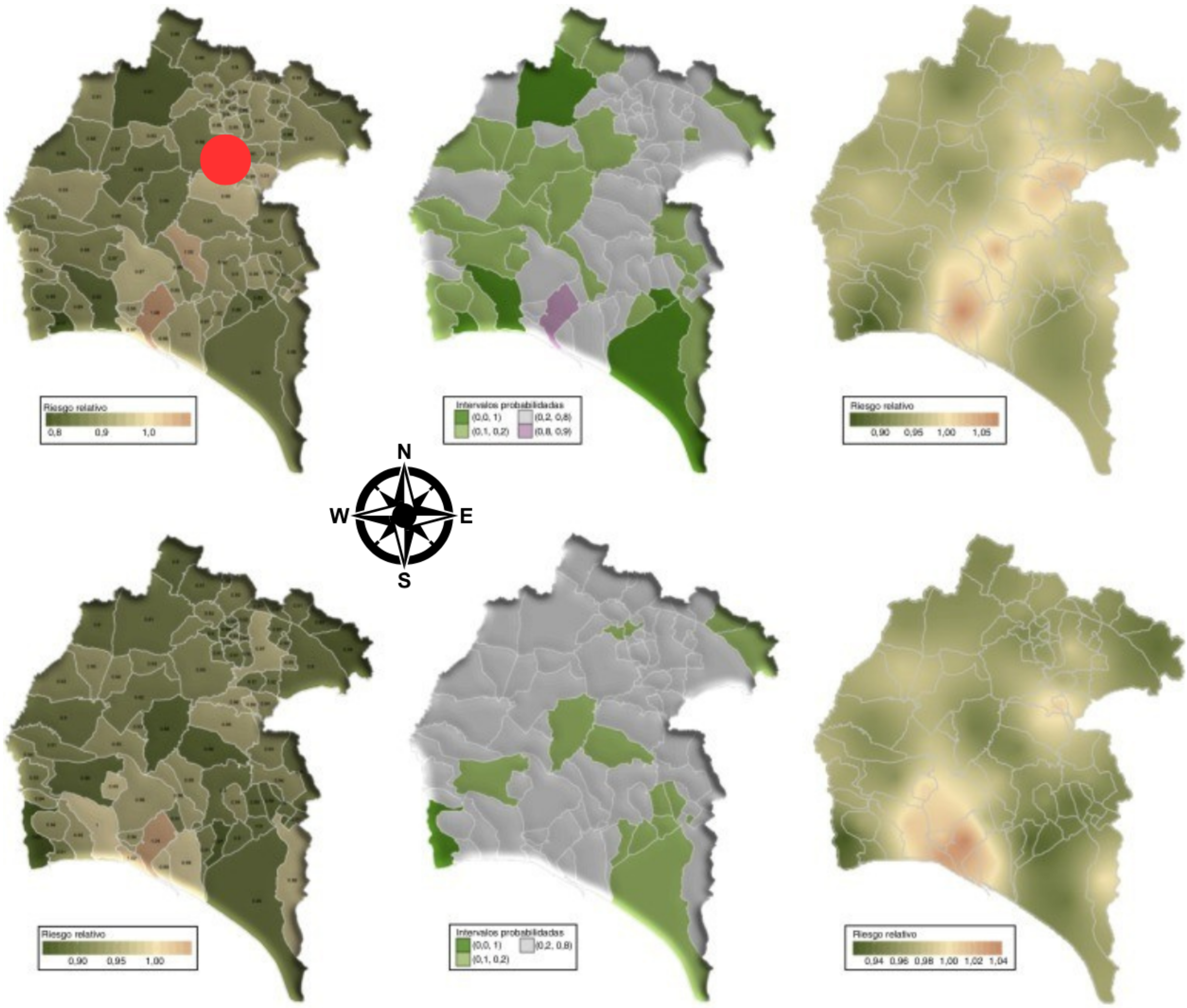


Figure 6.5: Spatial distribution of cancer risk indicators by sex and type of cancer across municipalities in the province of Huelva, the study area is pinpointed by the red dot in the top left image. The top row corresponds to male populations, while the bottom row corresponds to female populations. For each cancer type, three maps are shown (left to right):

1. Choropleth map of estimated Relative Risk (RR) of cancer incidence per municipality.
2. Choropleth map of posterior probabilities (PP) that RR > 1, indicating the credibility of elevated risk of cancer incidence.
3. Isopleth map with kriging interpolation of relative risks of cancer incidence, taking the relative risk of the entire province of Huelva as a reference [13].

This evidence establishes a clear connection between environmental contamination and the health risks faced by local populations in the study area. The findings reveal that exposure is not limited to occupational hazards in the vicinity of the study area, but it shows that in reality it is a daily reality for residents within and around the study area.

6.3.4. Economic dependency

The Iberian Pyrite Belt (IPB) has historically shaped the economic structure of South-West Spain and Southern Portugal. Mining has provided direct employment, infrastructure development, and economic importance and revenues for rural communities, especially in regions where few alternative industries exist. However, the economic consequences of mining, especially after mine closure, show a complex interplay between possible economic opportunities and negative implications for both local communities and the environment.

Active mining operations, such as the active Rio Tinto mines, continue to be important economic drivers in the study area. They offer employment, stimulate local businesses, and contribute to national exports [101]. However, this economic reliance on extractive industries also makes communities vulnerable to the cyclical nature of global commodity prices and eventual resource depletion.

The social and economic aftermath of mine closures often leads to severe local socio-economic disruptions. In many cases, the end of mining operations has resulted in population decline, unemployment, and economic stagnation. A case study of mining communities in Spain shows that the closure of coal mines, similar to the situation of the closure of pyrite mines in the IPB, triggered significant migration, particularly among the youth [102]. The abrupt withdrawal of industrial activity often leaves behind an economy with little capacity to adapt quickly, especially in rural settings such as is the study area.

To counteract this, local and regional authorities have explored strategies to re-purpose former mining infrastructure for alternative (economic) uses. One notable example is the Riotinto Mining Park in Huelva. These forms of tourism not only preserves the historical mining identity of the region, but also generates new income streams and employment, even though it is on a smaller scale compared to the peak of mining activity.

The environmental degradation caused by abandoned mines also has direct and indirect economic consequences. Remediation of contaminated sites, such as leaching of AMD out of tailings dams, requires significant public and private expenditure. A study of several sites across the IPB shows how environmental problems can scare off private investors and make it therefore harder to use the land again for farming or building practices [103]. These impacts impose long term economic burdens on municipalities, especially when there is no viable polluter-pays mechanism due to bankrupt or absentee operators in inactive/ historical mine sites. In some cases, the high cost of environmental cleanup has led to stagnation in economic revitalization plans.

Similarly, spatial inequalities often grows bigger in these regions after mining has stopped. While some areas have managed to integrate mining into broader regional development strategies with some success, others remain isolated and economically marginalized. Historical data show that even during peak mining activity in the 19th and 20th centuries, wealth generated was often exported rather than reinvested locally, adding to the inequality between rural mining regions and urban centers [104].

Impact of employment on mines in the largest cities near the study area

In order to be able to quantify the economic dependency of residents on mines, only villages with more than a 1000 inhabitants will be considered (table 6.2).

The mining sector has long played an important role in several towns and villages across Huelva. Just as can be observed in the study area, extensive mining operations have shaped both the economic landscape and employment dynamics. An overview of these dynamics in the key towns near the study area is presented in table 6.4.

6.3.5. Reclamation impact

Mine site reclamation and rehabilitation aim to mitigate the environmental and social harms caused by mining. When correctly executed, reclamation can lead to substantial improvements in landscape functionality and ecosystem and community health and well being. However, the outcomes of reclamation can vary significantly depending on several factors, such as the methods used, the local environmental conditions, and the degree of community involvement.

Positive Impacts of reclamation

- **Restoration of ecosystems and soil conditions** The reclamation approaches as discussed in chapter 3.3 aim to improve soil conditions and contaminant immobilization, soil fertility, soil stabilization and restore vegetation covers. These changes benefit local communities by limiting their exposure to harmful contaminants as generated by AMD and heavy metal mobilization, as well as enabling agricultural activities and reducing dust and sedimentation that otherwise affect downstream water bodies.
- **Water quality** One of the most pressing environmental issues associated with mining is AMD which affects downstream water systems. The proposed reclamation implementation of SRB with a DAPRB, such as suggested in section 3.3, aims to mitigate or improve the current AMD and heavy metal pollution issue of the surface and groundwater near the mining sites. This reduces the transport of heavy metals and acidity to nearby rivers and aquifers, thus positively influencing downstream local communities and ecosystems, which might be dependent on water sources for drinking, agriculture or aquaculture.
- **Biodiversity** The revegetation and phytostabilization aspect of the reclamation plan aims to use native plants which do not have invasive features. An overview of the plants to be used is given in section 3.2.4. The revegetation and phytostabilization approach ensures ecological restoration in the study area, which enhances regional biodiversity . Communities downstream or adjacent to reclaimed sites often benefit from reduced health risks and increased environmental quality.
- **Health and safety** As discussed in Section 6.3.3, there is substantial evidence that the elevated concentrations of lead and arsenic in and around the study area are having adverse health effects on local communities. This concern is particularly important, given that the region exhibits the highest cancer mortality rate in Spain. Reducing the mobilization and concentrations of toxic heavy metals at the mine sites could therefore positively contribute to public health by limiting their exposure to local residents, potentially increasing both the health and life expectancy of local residents.

Negative or uncertain impacts of reclamation

- **Incomplete remediation** The proposed reclamation plan aims to improve the current conditions of the study area and nearby communities in the IPB. However, the approach may fail to address long-term subsurface contamination or degradation due to a lack of data. For local, upwind and downstream communities, this means continued exposure to polluted water or soil.
- **Dust generation** As outlined in Section 3.2.5, the use of heavy machinery and soil reshaping during the installation of an DAPRB with SRB and geo-membranes can mobilize fine particles from exposed tailings and overburden, leading to increased dust emissions. This is particularly problematic in arid climates or during dry seasons, both of which is relevant for the study area. Elevated dust levels can degrade air quality, increase respiratory risks for nearby communities, deposit pollutants onto soils and water bodies, and reduce visibility [85]. In the reclaimed sites that previously processed sulfide ores, dust may also contain hazardous metals in high concentrations, such as the findings showed (sections 2.4.2 and 2.3), posing chronic health risks to both workers and local residents [85]. Fortunately, except the village Concepcion, the study area is not that closely inhabited (table 6.1).

- **Noise pollution** The reclamation process involves use of heavy machinery for the installation of a DAPRB and the placement of geo-membranes. Heavy machinery can contribute to noise pollution in the area. As was mentioned before, besides Concepción, the area of Zone 1 is sparsely inhabited, however, disturbance to the village Concepción and local farmers near the selected mine sites for reclamation will probably occur (table 6.2). This can lead to reduced quality of life and potential hearing health effects for workers and community members, especially where reclamation activities occur over extended time periods [116]. As well, stress or displacement of local wildlife might occur, which may interfere with the intended ecological recovery of the study area [117].

6.4. Life Cycle Impact Assessment

The LCIA phase builds on the LCI data to evaluate the potential social impacts associated with the rehabilitated and historical mine sites present in Zone 1. Using the S-LCA framework, this phase links specific inputs and activities to social outcomes across defined stakeholder groups.

6.4.1. Study area

First, the LCIA will be performed considering only key stakeholder groups in Zone 1 of the study area. A scoring matrix has been developed to evaluate how severely stakeholders are impacted per relevant impact category. This social impacts are evaluated of active & historical mining activities and the impact of reclamation across four key categories: Health & Safety (H&S), Local Employment (LE), Cultural Heritage (CH), and Environmental Degradation (ED).

The scores range from 1 (low impact) to 5 (high impact) and reflect each stakeholder's degree of exposure or involvement in relation to the study area. The key stakeholders for the study area can be divided into residents, employees (mining), tourism, mining companies, local authorities (local/regional), authorities (national), NGO's and the agriculture sector. There will be differentiated between two impact scenario's in table 6.6 and 6.7, namely: (1) the impact of local and historical mining and (2) reclamation efforts.

Note: It is important to keep in mind that in Zone 1 of the study area itself, there are currently 2 active mines present (Magdalena mine and Aguas Teñidas mine, table 2.5) and the study area is in close proximity to the active Rio Tinto mining operation.

Due to limitations in time and available resources, the LCIA was conducted based on the author's interpretative analysis of the available demographic data and literature reviewed during the LCI phase (Section 6.3).

6.4.2. Impact of active and historical mining on Zone 1

The impact of active and historical mining on the key stakeholders is taken into consideration. A scoring matrix (Figure 6.6) based on the interpretation of the available spatial data and literature has been established. A distinction was made between positive and negative impact scores, acknowledging that certain influences may affect key stakeholders both positively and negatively, depending on context. An explanation of the scoring matrix per relevant stakeholder is given in Section 6.4.2.

- Impact score 5: positive
- Impact score 4: positive
- Impact score 3: positive
- Impact score 2: positive
- Impact score 1: positive
- Impact score 1: negative
- Impact score 2: negatuve
- Impact score 3: negative
- Impact score 4: negative
- Impact score 5: negative

Stakeholder	H&S	LE	CH	ED	Cummulative
Residents	5	4	4	5	18
Employees mining	4	5	2	3	14
Tourism	2	2	5	1	10
Mining companies	3	5	2	5	15
Local Authorities	4	2	3	4	13
Authorities	3	1	1	3	8
NGO's	4	1	3	4	12
Farmers	5	3	1	5	14
Cummulative	30	23	21	30	102

Figure 6.6: Scoring matrix showing the impact of active and historical mining on key stakeholder groups in the study area. H&S: Health & Safety, LE: Local Employment, CH: Cultural Heritage, ED: Environmental Degradation.

Scoring matrix explanation

- **Residents** Scored negatively high for both Health & Safety (5) and Environmental Degradation (5) due to long-term exposure to contaminated soils, dust, and water near former mining areas. Local Employment (4) reflects historical reliance on mining for income. Cultural Heritage (4) is rated high as well, as mining is important to the local and cultural identity of the area.
- **Employees (mining)** Received the highest positive Employment score (5) given their direct dependence on mining jobs historically en presently in the study area. Environmental exposure (4) and H&S risks (3) are also notable, though slightly lower than residents due to present environmental regulations of active mines (e.g. minas de Riotinto) and health & safety guidelines at mine sites itself. Cultural Heritage (2) is moderate, it entails the strong workplace identity but is limited to broader cultural connection.
- **Tourism** Tourism scores lower than the other two stakeholders but receives the highest score (5) for cultural heritage, as it promotes mining heritage through trails, and the Riotinto Mining Park. While locals may work in tourism, the number of jobs created is limited, resulting in a moderate employment score (2). Health and safety must be ensured for tourists, but this has limited direct impact, also scoring a 2. Tourism is only

weakly linked to environmental degradation, thus scoring 1.

- **Mining companies** High Employment (5) and Environmental Degradation (5) scores reflect their historical role as employers and main contributors to land and water impacts. H&S (3) is lower, as they are not directly exposed to hazards, however, they have to ensure that H&S guidelines are closely followed and implemented by their employees. Cultural Heritage (2) is low, as companies in general rarely engage in preservation beyond regulatory compliance. However, cultural heritage preservation by the opening of e.g. the Rio Tinto mining park contradicts this, resulting in the final score for CH being (2) and not (1).
- **Local authorities** Scored moderately to high across most categories. They are involved in minimizing the negative impacts of mining legacies (ED = 4), public health (H&S = 4). As they are not directly responsible for local employment of the historical and present mining efforts, they score relatively low for LE (2). Cultural Heritage (3) reflects their role in preserving the mining identity of the towns in and near the study area by supporting walking trails and tourism in the area.
- **Authorities** The national authorities are more distanced and score thus relatively lower compared to regional authorities. However, they still have an important regulatory and policy setting role regarding health & safety standards for active & historical mining sites and environmental degradation. Therefore, they score for H&S and ED both 3. Because they are not directly linked to local employment and cultural history in the area, they score only 1 in those aspects.
- **NGO's** NGOs are strong advocates for environmental and public health (ED = 4, H&S = 4), and have often played a key role in exposing health risks. They score low for employment (1) due to their indirect influence and relatively moderate to high for Cultural Heritage (3), as many are involved in cultural landscape preservation and advocacy.
- **Agriculture** Farmers and agricultural actors are significantly impacted by Environmental Degradation (5) due to contamination of soils and water. H&S (5) is also elevated due to exposure through land use. Employment (3) reflects loss or reduced agricultural productivity near mines. Cultural Heritage (1) is low, as farming traditions persist but are not directly related to mining heritage narratives.

6.4.3. Impact of reclamation on Zone 1

The impact of the proposed rehabilitation plan of the study area on the key stakeholders, namely: residents, employees of the mining sector, tourism, mining companies, local authorities, national authorities, Non-Governmental Organizations (NGO's) and farmers, has been estimated. A scoring matrix (Figure 6.7) based on the interpretation of the available spatial data and literature has been established, thereby visualising the impact of factors, such as Health and Safety and Environmental Degradation, on key stakeholders. A distinction was made between positive and negative impact scores, acknowledging that certain influences may affect key stakeholders both positively and negatively, depending on context. An explanation of the scoring matrix per relevant stakeholder is given in Section 6.4.3.

- Impact score 5: positive
- Impact score 4: positive
- Impact score 3: positive
- Impact score 2: positive
- Impact score 1: positive
- Impact score 1: negative
- Impact score 2: negatuve
- Impact score 3: negative
- Impact score 4: negative
- Impact score 5: negative

Stakeholder	H&S	LE	CH	ED	Cummulative
Residents	4	3	4	5	16
Employees mining	3	2	2	3	10
Tourism	3	3	4	3	13
Mining companies	3	2	2	4	11
Local Authorities	4	2	3	4	13
Authorities	3	1	1	4	9
NGO's	4	1	4	5	14
Farmers	5	3	1	5	14
Cummulative	29	17	21	33	100

Figure 6.7: Scoring matrix showing the impact of reclamation on key stakeholder groups in the study area. H&S: Health & Safety, LE: Local Employment, CH: Cultural Heritage, ED: Environmental Degradation.

Explanation of scoring matrix

- **Residents** Reclamation improves living conditions, especially by reducing contamination and improving visual landscape quality. Health & Safety (4) improves due to reduced exposure to toxic dust, polluted water and mobilization of toxic heavy metals in surrounding soils and surfaces. However, as the reclamation efforts can only positively improve and not completely solve the contamination and the area, a score of (4) and not (5) is attributed. Environmental Degradation (5) decreases as ecosystems recover, especially because of efforts such as revegetation. Local Employment (3) scores moderately, reclamation creates temporary jobs but not long term stability. Cultural Heritage (4) stays high, as some projects integrate mining heritage into restored landscapes.
- **Employees (mining)** Reclamation may offer some job continuity post closure (LE = 2), especially for workers involved in site rehabilitation. However, many jobs are temporary or outsourced. H&S (3) is maintained due to active monitoring on post mining sites. ED impact improves (3), particularly when workers contribute to land restoration. Cultural Heritage (2) remains relatively low, as identity shifts away from active mining.

- **Tourism** Tourism benefits from reclamation, particularly when restored areas are incorporated into mining trails or heritage parks. Cultural Heritage remains high (4), as reclamation often supports the valorisation of the local mining history in the area. Local Employment (3) improves slightly, not directly, from reclamation activities, but through the potential growth of the tourism sector driven by safer, more accessible and environmentally improved areas. Health & Safety (3) increases as reclaimed sites pose fewer risks to visitors. Environmental Degradation (3) also improves, reflecting the enhanced landscape quality and suitability for recreational use.
- **Mining Companies** Mining companies may be required to lead or finance reclamation efforts, improving their H&S (3) and ED (4) scores through remediation obligations. Cultural Heritage (2) may rise slightly if companies support heritage related reclamation. LE (2) drops compared to active phases, reflecting reduced direct employment roles.
- **Local Authorities** Reclamation enables authorities to meet sustainability and public safety goals, scoring high on both ED (4) and H&S (4). LE (3) increases modestly with job creation during rehabilitation projects oversight in the area and administrative roles. CH (4) improves as authorities often integrate heritage conservation into spatial planning (e.g., trails, signage).
- **Authorities** National/regional governments support and oversee reclamation policy, scoring moderately across categories. H&S remains (3) and ED increases to (4), given their role in enforcing environmental remediation laws. LE (1) and CH (1) remain low due to limited direct involvement.
- **NGOs** NGOs benefit from reclamation as it aligns with their environmental and public health goals. ED (5) and H&S (4) scores reflect their advocacy and oversight roles. CH (4) increases due to involvement in heritage protection initiatives. LE (1) stays low, as their employment influence remains indirect.
- **Agriculture** Reclamation significantly benefits agriculture by restoring soil quality and reducing toxic runoff. ED (5) and H&S (5) reflect improved conditions, especially whereas farmers are directly exposed to (pre-reclamation) polluted soils and ED has a direct impact on their agricultural products. LE (3) remains moderate, with potential for increased farmland productivity whereas soils and agricultural products are safer. CH (1) remains low, as reclamation typically doesn't affect farming traditions or cultural heritage.

6.4.4. Impact of active and historical mining on communities in proximity of Zone 1

In line with the previously conducted S-LCIA for stakeholders in Zone 1, the impact of active and historical mining on local communities located North-East (downwind) [10] and South (downstream) [11] of the site was also considered. For simplicity, only towns and villages with more than 1000 inhabitants were included, with the exception of Concepción. Despite its smaller size, Concepción was included as a representative settlement for Zone 1, where the actual reclamation efforts will take place. An overview of the selected towns and villages is presented in Table 6.2.

The impact of active and historical mining is taken into consideration just as has been done before in Section 6.4.2. However, the towns as listed in Table 6.2 are identified as the key stakeholders. A scoring matrix (Figure 6.8) based on the interpretation of the available spatial data and literature has been established, thereby visualizing the impact of factors, such as Health and Safety and Environmental Degradation, on key stakeholders. Just has has been done before in Section 6.4.2, a distinction was made between positive and negative impact scores, acknowledging that certain influences may affect key stakeholders both positively and negatively, depending on context. An explanation of the scoring matrix per relevant stakeholder is given in Section 6.4.4.

The impacts on both active and historical mining evaluated in this section are restricted to those originating within Zone 1 and close proximity of Zone 1 to the remaining of the study area. As such, the magnitude of social benefits (particularly in terms of health and environment) diminishes with increasing distance from the active and historical mine sites. Additionally, spatial orientation relative to the study area affects exposure: towns to the south are more affected by groundwater contamination due to dominant southward flow, while towns to the North-East are more exposed to airborne pollutants via dust transport, following the prevailing wind direction.

Once more it is emphasized that, due to limitations in time and available resources, the LCIA was conducted based on the author's interpretative analysis of the available demographic data and literature reviewed during the LCI phase (Section 6.3).

- Impact score 5: positive
- Impact score 4: positive
- Impact score 3: positive
- Impact score 2: positive
- Impact score 1: positive
- Impact score 1: negative
- Impact score 2: negatuve
- Impact score 3: negative
- Impact score 4: negative
- Impact score 5: negative

Town	H&S	LE	CH	ED	Cummulative
Concepción	5	4	4	5	18
Zalamea la Real	4	5	4	4	17
El Campillo	4	5	4	4	17
Minas de Riontito	4	5	4	4	17
Nerva	4	5	4	4	17
La Zarza	3	4	3	3	13
Almonaster la Real	3	4	3	3	13
Calañas	3	4	3	3	13
Valverde del Camino	3	4	3	3	13
El Cerro de Andévalo	3	4	3	3	13
Aracena	2	2	2	2	8
Higuera de la Sierra	2	2	2	2	8
Cummulative	40	48	39	40	167

Figure 6.8: Scoring matrix showing the impact of active and historical mining on Concepción and larger villages. H&S: Health & Safety, LE: Local Employment, CH: Cultural Heritage, ED: Environmental Degradation.

Scoring matrix explanation

- **Concepción**
  Minas de Concepción has been exploited since Roman times, reaching significant copper production by the mid-19th century. With the construction of a railway in 1906, the mine became a central economic driver until operations ceased in 1987. Today, Concepción lies less than 500 meters from the active Aguas Teñidas mine operated by Sandfire Matsa, making it exposed to both legacy and ongoing mining activities (Table 6.4). As a result, Health & Safety (5) and Environmental Degradation (5) are rated high. Employment (4) is relatively significant, considering the village's past reliance on mining and potentially emploiment in the Aguas Teñidas operation. Cultural Heritage (4) is actively preserved, with restoration efforts aimed at valorising the area's mining past.

- **Zalamea la Real, El Campillo, Minas de Riotinto, Nerva**
  These towns are historically linked to the Río Tinto mining complex and have undergone several mining booms, particularly in the 19th and 20th centuries. Mining has played a critical role in their development and remains part of their economic and cultural identity (Table 6.4). Employment (5) is rated high, while H&S (4) and ED (4) reflect legacy pollution and associated health concerns. Cultural Heritage (4) is strong due to the valorisation of mining history by initiatives such as the Riotinto Mining Park.

- **La Zarza, Almonaster la Real, Calañas, El Cerro de Andévalo, Valverde del Camino**
  These towns have more recent or intermittent mining histories. La Zarza is undergoing renewed exploration; Almonaster and Calañas host currently active mines (Aguas Teñi-

das and Sotiel). Valverde del Camino and El Cerro have future mining potential (e.g., Masa Valverde, Table 6.4). Employment (4) is moderately high, with active or planned mining operations playing a role. H&S and ED are scored at 3, while CH (3) reflects modest but present mining identity.

- **Aracena, Higuera de la Sierra**
  Limited data on mining-related employment leads to a lower Employment score (2). H&S and ED (2) are also lower due to greater distance and reduced historical exposure. CH (2) remains minimal given the lack of strong mining heritage presence (Table 6.4).

6.4.5. Impact of reclamation efforts on communities in proximity of Zone 1

In line with the previously conducted S-LCIA for stakeholders in Zone 1, the impact of rehabilitation efforts on local communities located North-East (downwind, dust pollution [10]) and South (downstream, AMD and heavy metal pollution [11]) of the site was also considered. For simplicity, only towns and villages with more than one thousand inhabitants were included, with the exception of Concepción. Despite its smaller size, Concepción was included as a representative settlement for Zone 1, where the actual reclamation efforts will take place. An overview of the selected towns and villages is presented in Table 6.2.

The impact of active and historical mining is taken into consideration using these towns as the key stakeholders. A scoring matrix (Figure 6.9) based on the interpretation of the available spatial data and literature has been established, thereby visualizing the impact of factors on key stakeholders. A distinction was made between positive and negative impact scores, acknowledging that certain influences may affect key stakeholders both positively and negatively, depending on context. An explanation of the scoring matrix per relevant stakeholder is given in Section 6.4.5.

The reclamation impacts evaluated in this section are restricted to those originating within Zone 1 of the study area. As such, the magnitude of social benefits (particularly in terms of health and environment) diminishes with increasing distance from the reclamation sites. Additionally, spatial orientation relative to the study area affects exposure: towns to the south are more affected by groundwater contamination due to dominant southward flow, while towns to the North-East are more exposed to airborne pollutants via dust transport, following the prevailing wind direction.

- Impact score 5: positive
- Impact score 4: positive
- Impact score 3: positive
- Impact score 2: positive
- Impact score 1: positive
- Impact score 1: negative
- Impact score 2: negatuve
- Impact score 3: negative
- Impact score 4: negative
- Impact score 5: negative

Town	H&S	LE	CH	ED	Cummulative
Concepción	4	3	4	5	16
Zalamea la Real	4	2	4	4	14
El Campillo	4	2	4	4	14
Minas de Riontito	4	2	4	4	14
Nerva	4	2	4	4	14
La Zarza	3	1	3	3	10
Almonaster la Real	3	1	3	2	9
Calañas	3	1	3	3	10
Valverde del Camino	3	1	3	3	10
El Cerro de Andévalo	3	1	3	3	10
Aracena	2	1	2	2	1
Higuera de la Sierra	2	1	2	2	7
Cummulative	39	18	39	39	135

Figure 6.9: Scoring matrix showing the impact of reclamation efforts on Concepción and larger villages. H&S: Health & Safety, LE: Local Employment, CH: Cultural Heritage, ED: Environmental Degradation.

Scoring matrix explanation

- **Concepción**
  As the only village located within the study area and directly adjacent to the reclamation sites, Concepción receives the most significant benefits. Health & Safety (4) and Environmental Degradation (5) improve due to the stabilization of mine tailings and remediation of contaminated soils. Employment (3) is moderately boosted through restoration, monitoring, and tourism potential. Cultural Heritage (4) is actively supported through the potential valorisation of the historical Minas de Concepción by making the area safe for tourists to visit (Table 6.4).
- **Zalamea la Real, El Campillo, Minas de Riotinto, Nerva**
  These towns, located south and southeast of the study area, are likely influenced by both the historical contamination and its mitigation through groundwater pathways. While they are located outside the direct reclamation Zone 1, their relative proximity and hydrological connection ensure that they obtain moderately high scores for H&S and ED (both 4). LE (2) reflects limited local employment opportunities generated by reclamation due to the close proximity to the study area. CH (4) remains strong due to continuous heritage promotion (Table 6.4).
- **La Zarza, Calañas, El Cerro de Andévalo, Valverde del Camino**
  Located to the west and southwest of the study area, these towns are moderately distant but may experience some groundwater improvements following reclamation, as groundwater flow generally moves southward, potentially reducing contamination in these areas.

Health & Safety (H&S) and Environmental Degradation (ED) are scored moderately (3), reflecting marginal indirect benefits. Local Employment (LE) scores low (1), since monitoring and maintenance activities are not directly linked to these towns; instead, communities closer to the mining sites—such as Concepción, Zalamea la Real, El Campillo, Minas de Riotinto, and Nerva are more likely to benefit from such efforts. Cultural Heritage (CH) holds a moderate score (3), maintained through the indirect valorization of the shared mining heritage across the region (Table 6.4).

- **Almonaster la Real**
  Located north of the study area, Almonaster la Real is primarily subject to windborne/ dust pollution as a result of the study area. Therefore, the reclamation efforts will slightly improve the H&S (3) conditions in the area. Environmental degradation is,however, more impacted by groundwater flow and not airborne pollution, therefore it will have limited influence on ED (2). The reclamation efforts does not have a direct link to the LE of Almonaster la Real, therefore LE=1. Cultural heritage holds a moderate score (3), maintained through the indirect valorization of the shared mining heritage across the region (Table 6.4).

- **Aracena, Higuera de la Sierra**
  Located North-East and at greater distances (13–18 km), these towns are primarily subject to windborne exposure but benefit only marginally from study area reclamation. H&S and ED (2) are scored low. LE (2) and CH (2) reflect low relevance to ongoing remediation or mining heritage promotion (Table 6.4).

6.5. Interpretation

6.5.1. Study area

The two SLCA tables clearly show that the social impacts of mining in the study area vary significantly depending on the phase of activity: active/historical mining versus reclamation efforts. The results reveal a strong contrast in how stakeholder groups are affected, particularly across the categories of Environmental Degradation (ED) and Health & Safety (H&S).

Under active and historical mining (Table 6.6), the highest scoring categories are ED (30) and H&S (30), highlighting the considerable negative impact mining has had on the landscape and public health. Residents, farmers, and mining companies each score 5 in ED, reflecting widespread environmental contamination of soils and water. Similarly, H&S scores are elevated, especially for residents and farmers, who are directly exposed to pollutants and dust. In this scenario, Local Employment (LE) also scores relatively high (23), particularly for mining companies and employees, who were traditionally dependent on mining for income. Cultural Heritage (CH), on the other hand, scores the lowest (21), indicating that, while mining history is present in the region, it does not necessarily mean that there is a strong or uniformly appreciated cultural identity for all stakeholder groups.

By contrast, the reclamation phase (Table 6.7) shifts the impact profile. Environmental Degradation (ED) again receives the highest cumulative score (33), but this time as a positive impact: it is generally assumed that stakeholders perceive reclamation efforts as significantly improving landscape quality and reducing environmental risks. Similarly, H&S (29) remains high, now reflecting enhanced safety and public health due to containment of pollution sources and restoration activities. Cultural Heritage (CH) scores the same as in the mining scenario (21), suggesting that reclamation often incorporates heritage valorisation, especially through tourism initiatives and spatial planning, however, the exact magnitude of positive increase in cultural heritage efforts is hard to determine on beforehand. Local Employment (LE), however, drops notably to 17, showing the limited job creation associated with reclamation efforts compard to the active mining phase. Created jobs due to reclamation tend to be temporary and less labor-intensive compared to active mining activities.

When comparing stakeholder groups across both scenarios, residents consistently receive high cumulative scores (18 during mining, 16 during reclamation), emphasizing their central role and vulnerability in the region. Farmers/agriculture and NGOs also score relatively high under reclamation (both 14), benefiting from improved environmental conditions and public health outcomes. Tourism, meanwhile, sees a notable increase in CH and H&S scores under reclamation, pointing to opportunities for growth through the development of safe and accessible mining heritage trails or intitiatives such as the Rio Tinto mining park.

Employees in the mining sector and mining companies see a sharp decline in their LE scores during reclamation, which indicates the economic downside of mine closures. However, their H&S and ED scores either improve or remain stable, as these stakeholders often remain engaged in or responsible for remediation tasks. Authorities and local governments show relatively consistent patterns, with improved scores in environmental and safety domains, though their influence on employment and cultural aspects remains limited.

In conclusion, active and historical mining in the study area has had a strongly negative impact on Environmental Degradation and Health & Safety. This is reflected by the high scores in these categories in the first table. Reclamation, generally generates positive outcomes in the same categories, suggesting that environmental and health legacies can be partially mitigated through targeted restoration efforts. However, reclamation does not significantly ensure long-term employment. As well, its effect on cultural heritage depends on the extent to which heritage is actively integrated into the actual reclamation efforts. These results show the importance of incorporating both environmental remediation and socio-economic transition strategies into post-mining development plans to support sustainable regional futures.

6.5.2. Communities in proximity of the study area

The assessment of social impacts on communities located in proximity to the study area reveals variations in results of the S-LCA related to the spatial variability of the towns. Two key phases—active/historical mining and post-mining reclamation affect these communities differently, with the most impportant factor being the proximity of the towns to Zone 1 of the study area. As was to be expected, the closerby the towns are located, the most impact rehabilitation and active/ historical mining practices have on these areas.

Active and Historical Mining Communities such as Concepción, Zalamea la Real, El Campillo, Minas de Riotinto, and Nerva have been historically intertwined with mining operations. Their higher added up scores (17–18) for (H&S) and (ED) show a prolonged exposure to contaminated soils, groundwater, surface water and dust, thereby having the highest impacts for both active/ historical mining and rehabilitation efforts alongside the socio-economic dependency developed through decades of mining employment in these towns. Cultural heritage (CH) in these towns is also rated highly due to preserved mining landmarks and active valorisation initiatives, such as the Parque Minero de Riotinto.

Reclamation Efforts Reclamation benefits are spatially concentrated, decreasing with distance from the to be rehabilitated Zone 1 of the study area. Concepción, located within the study area and adjacent to active remediation sites, gains the most from reclamation (score of 16), particularly in improved environmental conditions and reduced health risks.

Towns to the south and southeast, such as Zalamea la Real, El Campillo, Minas de Riotinto, and Nerva, experience indirect and therefore slightly smaller improvements (score of 14), mainly due to Southward (downstream) groundwater flow that reduce contamination. Their persistent cultural heritage score (CH = 4) suggests continued emphasis on preserving mining identity even in the post-mining phase.

Western and southwestern towns (e.g., Calañas, El Cerro de Andévalo, La Zarza, Valverde del Camino) receive marginal environmental and health benefits (score of 10), while employment impacts remain minimal. Their historical mining identity sustains a moderate cultural heritage score.

Communities to the North-East (e.g., Aracena and Higuera de la Sierra) are primarily exposed to airborne dust pollution; hence, reclamation yields limited improvements (score of 7–8), as the dominant reclamation efforts target soil and groundwater remediation.

Comparative Analysis Overall, proximity plays a central role in determining the magnitude of social impact. Concepción consistently ranks highest across both mining and reclamation phases, being located within the study area and thus gaining the most benefits of reclamation efforts of adjacent, inactive mine sites. More distant communities receive only secondary benefits, and their scores remain lower, especially in terms of local employment generated by remediation.

6.5.3. Assumptions and Uncertainties

The Social Life Cycle Assessment (S-LCA) conducted in this study is based on a set of assumptions and is subject to several uncertainties that may influence the interpretation of results. These are outlined below:

1. Stakeholder groups. The selection of stakeholder groups (residents, employees, tourism, mining companies, authorities, NGOs, agriculture) is based on a general understanding of actors in the study area and their expected involvement with mining activities and reclamation efforts. However, the composition of actual stakeholders and their influence may vary within the region, and some groups may have been underrepresented or simplified in this analysis.

2. Scoring subjectivity. The scoring system (1–5) reflects an estimation of relative social impact per category. These scores are subjective and based on the author's interpretation of available satellite data and literature insights. Therefore, the lack of quantitative social data introduces uncertainty into the exact impact magnitude, whereas no actual stakeholders have been involved in the development of the scoring matrix.

3. Temporal scope. Some effects of reclamation (e.g., improved soil health or new job creation) may take years to materialize, while the negative impacts of historical mining may be ongoing or even worsen due to weathering and acid mine drainage. This temporal dimension is not taken into consideration due to time constraints and lack of relevant data.

4. Geographic scope. Although the analysis focuses on the defined study area, the proximity of other active mines (e.g., Rio Tinto) may influence perceived impacts. Cross-boundary effects, such as regional tourism or external regulatory pressures, have not been fully incorporated.

5. Reclamation quality. The positive impacts attributed to reclamation efforts of the study area assumes that these projects are well executed and environmentally effective. In reality, success of reclamation can vary enormously depending on factors such as funding and implementation quality. Failed or poorly managed reclamation could result in lower benefits than assumed here.

6. Employment assumptions. Local employment impacts were estimated based on assumed job creation potential in mining and post mining phases. The actual employment impact of reclamation depends mostly on tourism development and local engagement. This has not been taken into consideration due to time constraints and lack of relevant data.

7. Cultural heritage interpretation. Cultural Heritage scores reflect assumptions about how stakeholders value and engage with mining heritage. These values can differ greatly depending on age, background, and economic interest. No formal survey was conducted to validate cultural perceptions in the local community.

8. Policy dynamics. The assessment assumes relatively stable institutional engagement and support for both mining operations and reclamation efforts. Political shifts, funding gaps, or regulatory failures could affect the impact of stakeholders significantly.

6.6. Discussion

The S-LCA reveals that multiple social groups, especially farmers and local residents, are significantly affected by ongoing pollution from both active and inactive mine sites in and around Zone 1 of the study area.

Public health, especially in communities located downwind (North-East) and downstream (South) of the mine sites, is a critical area for improvement. Reducing airborne particulates and contaminated runoff could lower the incidence of respiratory illnesses. In addition, transforming hazardous landforms into forested or vegetated zones not only reduces exposure risks but also improves the visual landscape, which can indirectly benefit mental health and overall quality of life.

The presence of cattle within a radius of 0.6 to 1.9 km from the inactive mine sites in Zone 1 further suggests that local populations may be affected not only by direct exposure to heavy metals, via groundwater, surface water, air, and soil contamination, but also by consuming contaminated meat or other agricultural products. Reducing environmental contamination in the area would therefore have a substantial positive effect on the health and safety of local residents and communities.

Environmental degradation is also directly addressed by efforts to immobilize heavy metals, limit AMD, and improve erosion control through revegetation and phytostabilization. As such, it is no surprise that the categories of Health & Safety and Environmental Degradation stand to benefit the most from the proposed rehabilitation measures in the area.

6.7. Conclusion

This chapter conducted a S-LCA to evaluate the social and socio-economic impacts of legacy and ongoing mining activities, as well as the projected outcomes of the proposed rehabilitation efforts in Zone 1 of the Iberian Pyrite Belt. The assessment focused on four main social impact categories: Health & Safety (H&S), Local Employment (LE), Cultural Heritage (CH), and Environmental Degradation (ED) across key stakeholder groups such as residents, farmers, employees, local authorities, and so on. By applying a matrix scoring based approach grounded in the interpretation of available literature and spatial & demographic data, the analysis enabled a structured comparison of impacts before and after rehabilitation, both within the study area and in its surrounding communities.

The S-LCA contributes a critical social dimension to the thesis's overall objective of developing a sustainable and scalable rehabilitation strategy for legacy mine sites in the IPB. Whereas earlier chapters focused on geochemical contamination (Chapter 2), and technical remediation options and strategy design (Chapter 3), this chapter integrates those physical interventions into a broader human context. In doing so, it highlights how environmental degradation and rehabilitation are not only scientific or engineering challenges, but also a deeply social challenge, whereas it does not only affects health,but also livelihoods and, especially in and near the study area, the regional historical identity.

The S-LCA shows that historical and active mining have mostly affected local residents, farmers in terms of health and environmental degradation. Conversely, reclamation improves outcomes especially in those same domains, especially for communities closest to Zone 1 (e.g., Concepción). The use of spatial demographic data and semi-quantitative scoring represents a novel approach within a data-limited context, evaluating a social risk assessment in the absence of field interviews or formal surveys by the personal interpretation of the author on available literature and spatial-demographic data. Notably, the analysis reveals that while environmental and health conditions can improve with proper rehabilitation, local employment generation remains relatively limited unless supported by long-term economic diversification strategies, such as tourism related initiatives. Cultural heritage benefits depend on how actively reclamation integrates the local mining identity present in the area into spatial planning and reuse.

This chapter is restricted by several methodological limitations, most notably the absence of direct stakeholder consultation and reliance on literature and proxy-based scoring. The applied social indicators, while grounded in research, are not validated through participatory methods, and employment impacts are estimated rather than empirically measured. Additionally, the assumed success of reclamation activities may not fully reflect real-world implementation variability, and long-term social effects such as demographic changes, land use transitions, or public perception shifts lie outside the current temporal scope. The subjectivity inherent in the author's interpretation and reasoning, based on available literature and spatial data used in the scoring matrix, highlights the need for future assessments that incorporate local perspectives by e.g. surveying or conducting interviews with key stakeholders.

The insights gained from this S-LCA highlight the importance of accounting for social impacts on local communities and stakeholders when planning rehabilitation or mine closure activities. These findings directly contribute to the development of rehabilitation strategies that are both socially responsive and practically viable.

Table 6.4: Employment significance of mining in towns with >1000 inhabitants in a radius of maximum 25 kilometers from the study area.

Town	Employment significance
Concepcion	Minas de Concepción has been exploited since Roman times, reaching significant copper production by 1853 and expanding further with a railway link in 1906. Mining ended around 1987 after the operator went bankrupt. Today, restoration efforts focus on environmental recovery and promoting industrial heritage tourism [105]. Nowadays, it lies very close <500m to the active Sandfire Matsa Aguas Teñidas mine.
Zalamea la Real	In the 19th century, tensions over toxic fumes from the Río Tinto mines led to a major uprising by farmers and miners, resulting in a deadly military crackdown on a protest. During the 20th century, the area experienced a population boom driven by agricultural development, livestock farming, and continued mining activity due to the Rio Tinto mines [106].
El Campillo	Located near the Río Tinto mines, El Campillo experienced rapid population growth at the end of the 19th century due to the large scale exploitation of copper resources. This lasted until the 1980s, when the closure of the copper line led to a sharp decline in mining related employment. In response, the town reinvented itself by shifting its economic focus to citrus cultivation [107].
Minas de Riotinto	Mining remains a major economic driver, with the Rio Tinto mines employing in total 2,355 workers in 2021, representing 1.2% of total employment in Huelva [108]. As well, the town is home to Parque Minero de Riotinto, featuring a mining museum, train rides, and historical sites, generating more employment in the tourist sector of the Rio Tinto mines [109].
La Zarza	Historically, the La Zarza mine has been exploited since the mid 19th century until it's closure in 1991. From 2004 to 2012, exploration has been performed, indicating a significant presence of copper and gold in the silicate ore. Currently, Tharsis Mining is investing in R&D and exploration drilling in order to reactivate the historic mining operations, possibly generating future jobs locally in the mining sector [110].
Almonaster la Real	Mining influences the employment rate in Almonaster la Real, whereas Sandfire Matsa currently has the Aguas Teñidas and Magdalena mines in active operation in the district. Discovered in the 1980s, the Aguas Teñidas mine began operations in 1997 but closed in 2001 due to falling metal prices. Commercial production resumed in 2009, and the site has since expanded its processing capacity and infrastructure [111].
Nerva	Historically, mining activity in the area dates back to Roman times with silver production. In modern times, mining continued to drive employment, especially with the Peña del Hierro mine, which is now part of the Rio Tinto Mining Park. The village's population peaked in 1940 with nearly 15,000 residents, reflecting a mining driven employment boom. Though the population has since declined, mining heritage remains a foundational element of local identity and economic activity [112].
Calañas	The reopening of Sotiel Mine has played a significant role in revitalising employment opportunities in the Calañas district. A mining site since Roman times, Sotiel had been closed since 2001 due to low metal prices and poor ore grades. Its reopening in 2015 by Sandfire MATSA brought renewed economic activity to the area, creating jobs in both mining and supporting sectors [113].
Valverde del Camino	The Masa Valverde project, developed by Atalaya Mining, is set to significantly boost local employment. Once operational, it is expected to create around 157 direct and +/- 600 indirect jobs, offering long term opportunities across not only mining, but also across infrastructure, environmental management, and logistics. With a projected lifespan of 20 years, the project is expected to provide economic benefits to the local population [114].
El Cerro de Andévalo	The village was surrounded by mines extracting e.g. pyrite, which provided jobs to many inhabitants until the mining crisis of the 1960s led to mine closures. Despite economic challenges, mining remained a key source of livelihood for the community. Over time, the decline in mining forced the village to diversify, but its mining past still influences the identity and economic history of El Cerro de Andévalo [115].
Aracena	Historically associated with mining, but today limited information is available regarding the impact of mining employment in this town.
Higuera de la Sierra	Limited information is available regarding mining employment impact in this town.

7

General Recommendations for Zones 2–4: Rehabilitation and Monitoring

7.1. Introduction to Zones 2–4

Zones 2, 3, and 4 of the study area in the IPB comprise a mixture of active and inactive mining operations. There are various inactive mines present in Zone 2, such as the La Zarza mines [118], Mina del Perrunal [119] and in Zone 3 Minas de la Buitron [120] and Mina Tinto Santa Rosa [121]. All of these inactive mine sites correspond to VMS deposits.

Sandfire MATSA's Aguas Teñidas and Magdalena mines are active underground VMS operations near Almonaster la Real, exploiting copper–zinc–silver deposits with a central paste tailings facility and integrated water management systems [111] [54]. Minas de Riotinto, continuously mined for pyrite and copper since roman times, remains a cornerstone of the Huelva province's economy and also hosts an industrial heritage park, the Rio Tinto Mining Park, managed by the Rio Tinto Foundation [122].

Unlike Zone 1, where rehabilitation efforts are deeply detailed in this thesis, Zones 2–4 fall outside the scope of site specific interventions. However, due to their geographical and geological similarity and close proximity to Zone 1, it is assumed that general recommendations can be provided based on the methods, findings, and strategies developed in previous chapters, particularly Chapters 3 and 4.

The following sections sets out general guidance for these zones, separated into **active** and **inactive** mine categories, focusing on environmental monitoring, rehabilitation, and closure planning.

7.2. Inactive Mines: General Rehabilitation and Monitoring Guidance

The inactive mine sites in Zones 2 and 3, including La Zarza, Mina del Perrunal, Minas de la Buitron, and Mina Tinto Santa Rosa, are characterized by their history of VMS exploitation and subsequent abandonment. Although no site-specific fieldwork was conducted in these zones, their mineralogical and geological similarity to Zone 1, justifies extrapolation of general rehabilitation and monitoring principles.

7.2.1. Recommended Rehabilitation Approaches

As these sites exhibit characteristics similar to those of the San Miguel cluster, therefore, the rehabilitation strategy proposed in Chapter 3 serves as a relevant baseline. The following recommendations are provided:

- **Stabilization through Phytostabilization and Revegetation:** Implement a vegetation based cover system using native or adapted plant species to immobilize contaminants by using phytostabilizing properties to immobilize contaminants, reduce erosion through root system development, and a reduction of direct water infiltration. Whereas Zones 2-4 are in close proximity to Zone 1, the same selection of plant species for both revegetation and phytostabilization purposes will be advised as for Zone 1 (Table 3.8).
- **Passive AMD Mitigation:** Utilize SRB and other passive treatment approaches (Section 3.2.5) in areas with confirmed or suspected AMD, especially near old tailing ponds and barren mine waste surface covers.
- **Surface Sealing with Low-Permeability Barriers:** Employ geo-membranes (Section 3.2.1) which limit the leaching of AMD and heavy metals to surrounding soils and water bodies.

7.2.2. Monitoring Priorities

Chapter 4 outlines the key environmental parameters necessary for long-term monitoring in post-mining landscapes. The same framework can be adopted for these inactive sites:

- **Water Quality:** Perform regular sampling of surface water and groundwater for pH, electrical conductivity [83], and concentrations of arsenic, lead, and copper as identified in Chapter 2 as major contaminants.
- **Soil Quality:** Monitor heavy metal accumulation in topsoil, especially in areas near waste deposits or downstream agricultural and inhabitated zones (Section 4.0.2, [84]).
- **Air Quality and Dust Dispersion:** Measure airborne PM concentrations and assess the geochemical composition and metal content of dust, particularly during dry seasons when dust emissions are high (Section 4.0.3, [85]).
- **Biodiversity Baselines:** Establish biodiversity benchmarks through periodic flora and fauna surveys, focusing on indicator species sensitive to heavy metal toxicity (Section 4.0.4, [87]).

7.3. Active Mines: Early-Phase Environmental Safeguards and Closure Planning

The active mining operations in Zones 2 and 4 (Sandfire MATSA's Aguas Teñidas and Magdalena mines, as well as Minas de Riotinto), are active underground and open pit VMS deposit mines, with on-site processing infrastructure and tailings management systems present. These active mines offer a chance to put environmental protections in place early on and to link closure planning with rehabilitation efforts right from the start.

7.3.1. Proactive Mitigation and Site Design

While these operations generally follow contemporary best practices, the following strategies should be reinforced according to the findings from this thesis:

- **Progressive backfilling and landscape integration:** Adopt progressive backfilling (if geo-technically and economically feasible) during underground development and apply site contouring techniques (see Appendix B and C) to support future landform stability and enable reforestation.

- **Geochemical waste characterization:** Routinely classify mine and process waste into acid-generating and non-acid-generating categories in order to accurately implement separation and remediation methods during the active mining phase and upon mine closure.
- **Seepage management:** Build upon existing integrated water management systems by incorporating predictive hydrogeological modeling and AMD risk simulations during dry–wet cycle transitions (Section 4.0.1).
- **Tailings engineering:** Employ geo-membranes to minimize leachate generation and enhance physical stability, particularly in seismic or erodible terrain (Section 3.2.1).

7.3.2. Integrated and Adaptive Monitoring Programs

Unlike legacy sites, operational mines can use and apply real-time monitoring technology:

- **Automated monitoring:** Deploy in-situ sensors for water quality (pH, EC, redox) (Section 4.0.1), dust monitoring stations (Section 4.0.3), and drone-based aerial surveys for real-time plume and erosion tracking [83].
- **Tailings dam and waste rock surveillance:** Use tools, e.g. piezometers, inclinometers, and satellite-based InSAR to monitor structural stability and catch early signs of ground movement [83].

7.3.3. Closure Planning and Transition Pathways

Given the scale and legacy of mining in the IPB, mine closure planning must begin well in advance of the actual closure time:

- **Closure modeling:** Develop and update closure scenarios that account for long-term chemical stability, water quality targets, and social impacts, in accordance with the Zone 1 rehabilitation approach.
- **Social transition mapping:** Integrate the results from the S-LCA (Chapter 6) to anticipate and mitigate socio-economic disruptions during and after mine closure, especially focusing on limiting the negative and harmful effects on residents and farmers.
- **Heritage valorization:** In sites such as Rio Tinto, where industrial heritage and tourism go hand in hand, rehabilitation should focus not only on cleaning up the environment but also on preserving the cultural and historical landscape.

7.4. General Implementation Recommendations for Rehabilitation for Comparable VMS Sites Worldwide

This thesis presents a detailed rehabilitation plan for Zone 1 of the San Miguel mine and lines out a scalable model for similar VMS sites worldwide. For successful implementation, future stakeholders, such as environmental agencies, mining companies, and researchers, should consider the following recommendations:

1. **Define Key Performance Indicators (KPIs):** Establish site-specific KPIs to track the environmental recovery (e.g., reduced contamination, vegetation cover), as well as monitoring public health improvements, and socio-economic outcomes such as job creation and stakeholder engagement.

2. **Establishment of clear success criteria:** Define when rehabilitation is considered successful after certain rehabilitation benchmarks haven been met. Benchmarks can be defined and measured by indicators such as ecosystem recovery, improved living conditions, or productive post-mining land use. Involve local communities in setting these benchmarks.
3. **Set realistic timeframes:** Adopt phased implementation for the total rehabiliation proposal, focusing on short-term (e.g. waste stabilization), and long-term (sustainable land use or even tourism) goals.
4. **Evaluate economic benefits:** Quantify benefits of rehabilitation (e.g., increased land value, tourism potential) and avoided costs (e.g., health care, infrastructure damage). Future studies should include a more detailed and in depth cost-benefit analysis.
5. **Highlight Societal and Infrastructural Co-Benefits:** The focus should also be on how successful rehabilitation can lead to better public health, more resilient infrastructure, and a stronger sense of community identity.

7.5. Conclusion

The mines in Zones 2–4 reflect the full spectrum of challenges across the mining life cycle, from abandoned legacy sites to fully operational modern mines. While inactive sites should align closely with the Zone 1 rehabilitation framework after rehabilitation efforts have proved to be successful, active mines should use the opportunity to ensure sustainability of their mining practices through early-phase rehabilitation planning, real-time monitoring of potential contamination and environmental hazards, and stakeholder engagement . Applying the findings from Chapters 3 and 4, This chapter outlines practical steps for reducing environmental risks, improving social conditions, and supporting long-term resilience across the broader zones of the study area, namely for zones 2-4. It aims to provide clear guidance that can be adapted to different situations within the region.

8 Discussion

8.1. Introduction

This chapter discusses the scientific validity, applicability, and limitations of the findings presented in this thesis. By integrating geochemical analysis, GIS-based extrapolation, rehabilitation planning, and a S-LCA, this study proposes a multi-layered framework for the sustainable rehabilitation of legacy mine sites in the arbitrarily chosen study area of the IPB. The discussion begins with a critical interpretation of the results and continues with an assessment of their theoretical and practical implications, particularly in the context of scaling findings to other zones. Key methodological limitations are then reviewed, followed by a set of concrete recommendations for future research and practical implementation.

8.2. Interpretation

8.2.1. Contaminant Characterization and Sampling Scope

One of the key pillars of this thesis is the use of portable X-ray fluorescence (XRF) to assess heavy metal concentrations in various mine waste types at the San Miguel site. While the study employed a color-based classification of the mine waste present in the area (yellow, brown, red, grey, white, and soil) to sample visually distinct materials, the spatial and temporal representativeness of these samples remains a limitation, especially whereas only samples for the San Miguel site have been evaluated and no samples from the other inactive mine sites present in Zone 1. Arsenic, lead, and copper were consistently present at concentrations exceeding safe limits, which affirms the environmental urgency of intervention.

All samples were collected during a single dry-season field campaign (June 2024), meaning that temporal variability, particularly during a more wet season, when AMD intensifies, could not be captured. In regions like the IPB, where hydrological and geochemical processes are seasonally driven, this is a significant limitation. Evaporite formation, transient salt crusts, and seasonal vegetation growth may alter metal mobility and bioavailability over time.

8.2.2. Spatial Extrapolation and Representativeness

Geospatial extrapolation using ArcGIS Pro and Sentinel-2 satellite imagery played an important role in scaling localized sample data of the San Miguel mine to the remaining inactive mine sites present in Zone 1. The supervised classification algorithm differentiated surface types based on visible spectral signatures. However, this classification only operates at a resolution of 10 meters and cannot detect small subsurface variations or differentiate between chemically distinct but visually similar materials.

Additionally, Sentinel-2's spectral bands are limited in their ability to distinguish between geochemically relevant classes (e.g., Fe-oxides vs. Mn-oxides), which may lead to classification errors, particularly in zones where mineralogical heterogeneity is present. While the assumption of lithological and mineralogical similarity across Zone 1 is supported by regional geological maps and literature, this remains an assumption and may not hold true at finer spatial scales.

As such, the extrapolation of results to the entirety of Zone 1, let alone other zones, should be interpreted as indicative, rather than deterministic. Follow-up field sampling in each inactive mine site present in Zone 1 would be required to validate these assumptions and generalizations.

8.3. Theoretical and Practical Implications

8.3.1. Scalability of Rehabilitation Strategies

The rehabilitation strategy, comprising LLDPE geo-membranes, phytostabilization, revegetation, and passive SRB treatment, is tailored to address both AMD, soil- and groundwater contamination and surface dust contamination.These methods were selected as the re-extraction of metals from the mine waste was deemed economically unfeasible. For inactive sites in Zones 2 and 3 (e.g., La Zarza, Tinto Santa Rosa), the strategy of rehabilitation is assumed to be largely transferable due to similar (VMS) deposit types and the sites being in close proximity the San Miguel site of Zone 1. The comparable geological profiles and pollution patterns therefore support a similar rehabilitation combination of geo-membranes, revegetation & phytostabilization, and passive SRB treatment.

The rehabilitation plan is designed for a 25-year timeframe. However, if the implemented methods prove sufficiently successful, it may be possible that by the end of this period, the site conditions are adequately restored, eliminating the need for further rehabilitation interventions while still maintaining environmental monitoring. However, the possibility of this is fairly limited by uncertainties regarding future site conditions and the efficiency of the proposed rehabilitation plan.

8.3.2. Integration into Active Mines

In Zones 2 and 4, active operations such as Aguas Teñidas and the Rio Tinto mines present different limitations. Here, the proposed measures are only partially applicable due to the sites still being actively mined. Real-time water quality monitoring, early segregation of acid-generating tailings, and progressive rehabilitation plans aligned with the established mine closure timelines are more appropriate interventions. Still, lessons from Zone 1 can guide long-term planning and inform regulatory requirements for closure.

8.3.3. Social and Ecological Outcomes

The Social Life Cycle Assessment demonstrated that moderate environmental improvements in Zone 1 would yield significant health and economic benefits for nearby communities. Reduced airborne dust and improved water quality have direct implications for public health and land usability for agricultural practices. This shows that ecological restoration can also bring real social benefits, as well for smaller rural mining communities.

8.4. Limitations

There are, however, notable limitations. For instance:

8.4.1. Sampling and Data Resolution

A critical limitation is the reliance on only obtained surface samples during a single season. Subsurface conditions, for instance redox gradients, were not assessed. Similarly, metal speciation and bioavailability were not determined, limiting the ecological relevance of the reported contaminant concentrations in the top surface layer for subsurface layers.

8.4.2. Extrapolation Uncertainty

The assumption that San Miguel can serve as a proxy for all Zone 1 sites brings some uncertainty, whereas it doesn not capture differences such as the variety in waste materials or changes in local terrain and geology. Also, the ArcGIS extrapolation depends on the idea that surface types have similar spectral properties, which might not be true in areas with mixed materials.

8.4.3. Monitoring Plan Constraints

The monitoring strategy outlined as has been outlined in Chapter 4 is based on several assumptions: it relies on consistent long-term funding, reliable and effective monitoring performance over long periods of time by using e.g. satellite data and sensors, and unlimited access to the site without any constraints of potential land owners. However, it doesn't take into account key geotechnical factors, for instance slope stability, which could have a major impact on erosion rates, vegetation growth, and the overall stability of features such as the proposed geo-membranes.

8.4.4. Cost Modelling and Engineering Assumptions

The cost estimates used in this study are drawn from various literature sources and are simplified compared to real-world conditions. Values from different reviews are used as a baseline for total costs, with the geo-membrane approach based on U.S. dollar figures from American case studies. However, these estimates do not account for several important factors, such as site-specific transport logistics, Spanish labor costs (except for excavation), varying terrain preparation requirements, regulatory compliance expenses, or unforeseen project circumstances.

8.5. Recommendations and Future Research

8.5.1. Research Recommendations

- **Prevention of AMD**:As a first step in future recommendations, it is advised that further research be conducted into the causes of AMD and heavy metal pollution at comparable mine sites of VMS deposits, both within and beyond the Iberian Pyrite Belt. This could help prevent contamination and reduce the need for costly rehabilitation efforts in the first place.
- **Development of a comprehensive remote sensing plan**: In the current research, the development of a comprehensive, remote sensing monitoring plan was outside of the scope. For future research, it would be advised to implement this as a crucial part of the research.
- **Scalability**: This research relies on several assumptions, literature sources, and interpretation of the acquired data. However, its scalability to other regions has not been thoroughly assessed; the recommendations are primarily limited to comparable mine sites within the immediate study area. Therefore, future research should focus on clearly identifying the key parameters that control the applicability of this framework and systematically evaluate how the findings can be effectively scaled to other, comparable VMS

sites worldwide.

8.5.2. Field and Laboratory Improvements

- **Seasonal sampling**: Conduct sampling during both dry and wet seasons to assess dynamic pollutant mobility, especially for arsenic and sulfate leaching.
- **Depth profiling**: Use methods such as coring to assess the subsurface conditions regarding contaminant distribution, redox state, and AMD generation potential.
- **Sampling distribution**: Collect and analyze surface and subsurface samples from mine sites in Zone 1, excluding San Miguel, to assess the extent and nature of existing pollution.

8.5.3. Methodological Enhancements

- **Pilot Trials**: Implement small-scale tests of the proposed rehabilitation methods (e.g. geo-membranes, phytostabilization, and DAPRB SRB systems) at selected Zone 1 sites to validate effectiveness under local conditions.
- **Remote Sensing Expansion**: Integrate higher-resolution satellite data or drone-based multispectral imaging to improve surface classification, NDVI and erosion monitoring.
- **Geo-technical Inclusion**: Future plans should explicitly model slope stability and incorporate drainage infrastructure, particularly for geo- membrane covered mine ponds.

8.5.4. Social and policy Recommendations

- **Scalable frameworks**: Development of rehabilitation guidelines that distinguish between active, inactive, and abandoned sites while aligning with Spanish and EU policy.
- **Local participation**: Encourage local participation in simplified, low-cost monitoring protocols, such as visual AMD scoring of fluvial systems in the study area.
- **S-LCA Refinement**:Conduct an empirical social study within the research area by interviewing the stakeholders referred to in Section **??**, in order to more accurately assess the social impacts of rehabilitation efforts, as well as those of both active and inactive mining operations in the region.

Concluding Remarks

This thesis offers a structured yet scalable indicative strategy for addressing legacy mine pollution in the Iberian Pyrite Belt. While grounded in field data, literature, and the author's own interpretation, the approach is constrained by temporal and spatial limitations. Nonetheless, its multidisciplinair perspective, spanning geochemistry, GIS, remediation engineering, and social impact, can serve as an indicative and replicable foundation for both academic and policy oriented work in similar mining regions worldwide. =

9 Conclusion

9.1. Research Problem and Objectives

Legacy mine waste poses a significant and persistent environmental threat in the IPB, particularly due to heavy metal contamination and AMD. The objective of this thesis was to assess the environmental and social impact of such contamination in Zone 1, using the San Miguel mine as a case study, and to propose a scalable, cost-effective rehabilitation strategy. These results were further extended to encompass Zones 1 through 4, consisting of both active and inactive mine sites, offering general recommendations for rehabilitation and long-term monitoring practices. Furhtermore, Zones 1 to 4 are intended to serve as representative examples of other VMS deposit sites within the IBP and comparable mining regions worldwide.

9.2. Summary of Key Findings

This thesis presents a multidisciplinary approach to an environmental impact assessment and rehabilitation planning for the arbitrarily chosen Zone 1, being used as a case study and representation of comparable VMS mine sites within the IBP, encompassing the inactive mines of San Miguel, Poderosa, Concepción, San Platón, Angostura, El Soldado, and Esperanza. While only San Miguel was sampled, its geological and mineralogical consistency with the others justified spatial extrapolation of the findings to the remaining inactive VMS deposit mine sites in Zone 1.

The findings reveal critical pollution levels, particularly of arsenic (a known carcinogenic), lead (neurotoxic), and copper (disruption of nutrient cycles in soils), therefore demanding urgent remediation. A site-specific rehabilitation strategy was developed, thereby combining phytostabilization, revegetation, and the application of geo-membranes to prevent leaching and mobilization of heavy metals out of mine ponds and passive AMD treatment by using SRB. These methods were selected especially for their cost effectiveness, low environmental impact, potential for long-term stability and compatibility with the geochemical and mineralogical composition of Zone 1. Rather than aiming for complete decontamination, the objective is to significantly improve environmental conditions in a way that benefits local ecosystems, agricultural practices and local communities, particularly those downstream and downwind.

For the inactive mines in Zones 2–4, the same rehabilitation approach proposed for the inactive sites in Zone 1 is recommended. However, this is only the case if the interventions in Zone 1 have first been tested and proven effective under local conditions. This recommendation is based on the assumption that these sites, like those in Zone 1, are VMS deposits with similar geochemical and mineralogical characteristics. For the active mines in Zones 2–4, general closure guidance is provided to support long-term planning. Additionally, it is strongly emphasized that during the operational phase, monitoring, maintenance, and the mitigation of AMD and heavy metal mobilization must be treated as urgent and ongoing responsibilities. The thesis also integrates a S-LCA to underscore the social implications of environmental recovery due to carried out rehabilitation efforts.

Overall, this research presents a practical and adaptable methodology for assessing contamination and guiding the rehabilitation of legacy VMS mine sites and their surrounding landscapes. The focus lies on achievable improvements rather than idealized solutions, while emphasizing the integration of both environmental and social aspects of sustainability in rehabilitation proposals. For future research, the recommendations outlined in Section 8.5 should serve as a foundation for further refinement of the rehabilitation proposal.

Research Questions

RQ1: What are the dominant pollutants in the San Miguel mine waste, and how severe is their environmental impact when extrapolated to the broader Zone 1?

The dominant polluting metals identified at the San Miguel site include arsenic, lead, copper, and arsenic. These levels significantly exceed environmental thresholds and thereby pose long-term ecological and health risks, particularly through AMD, heavy metal mobilization and airborne dust. Using supervised classification in ArcGIS Pro based on Sentinel-2 imagery, these findings were spatially extrapolated across Zone 1. The spatial modelling confirmed that similar surface waste types are widespread in the remaining inactive mine sites of Zone 1, indicating that the environmental impact observed at San Miguel is representative of a broader contamination issue in the study area.

RQ2: What are the most suitable, cost-effective, and sustainable rehabilitation strategies for Zone 1, considering the geological characteristics and pollution severity?

A rehabilitation strategy was developed encompassing three main approaches: (1) The rehabilitation plan includes the excavation of mine ponds, installation of geo-membranes to contain and prevent leaching out of heavy metals and AMD within the mine pond, and subsequent backfilling to restore site stability, (2) phytostabilisation and revegetation using native species for heavy metal immobilization, erosion and dust control, and (3) passive AMD treatment using SRB with a DAPRB in localized hotspots of inactive mine sites present at or in the vicinity of a fluvial system. These techniques were selected for their low maintenance requirements, compatibility with the semi-arid climate, low environmental impact and proven effectiveness in comparable post-mining environments. The strategy has been proposed for a 25 year timespan and balances technical feasibility with affordability and long-term sustainability, and is scalable to comparable VMS deposits within the IPB and worldwide.

RQ3: How would these rehabilitation efforts affect the surrounding ecosystems, agriculture, and communities, particularly those downstream (South) and downwind (North-East)?

The proposed rehabilitation strategy is anticipated to generate significant benefits for both local communities and surrounding ecosystems within and near the study area. The S-LCA showed that reduced dust and AMD & havey metal leachate emissions could improve air and water quality in vulnerable villages located South and North-East of the San Miguel cluster. These improvements would benefit already existing agriculture practices due to improved soil conditions, reduce health risks while simultaneously improving environmental degradation. Although no quantitative health risk modeling was conducted, the combination of spatial demographic analysis and literature review supports the conclusion that remediation efforts would lead to improved social and public health outcomes.

RQ4: What general recommendations can be made for active mines (Zones 2–4) and for long-term monitoring beyond Zone 1?

Inactive mines in Zones 2 and 3 can adopt the Zone 1 strategy with minor adaptation, particularly with regard to surface stabilization and passive AMD control.Active sites like Aguas Teñidas and Rio Tinto should prioritize interventions during their operational phases, including geochemical waste segregation and real-time environmental monitoring. Additionally, they should develop a comprehensive rehabilitation plan well before closure to ensure effective site management. Across all zones, long-term monitoring should focus on water and soil quality indicators (e.g., pH, conductivity, heavy metal concentrations), airborne particulate matter, and ecosystem recovery using biodiversity indices. The thesis emphasizes that while methods are scalable, site-specific restrictions must be assessed before implementation.

9.3. Broader Significance

This research advances the field of environmental remediation by demonstrating how targeted field data, geo-spatial tools, and literature based rehabilitation planning can be combined into a scalable framework for legacy mine management. It offers practical guidance not only for local rehabilitation in the IPB, but also for other VMS mining districts with similar climate and pollution profiles worldwide. In policy and industry contexts, this thesis highlights the importance of integrating environmental and social considerations into mine closure planning, emphasizing both cost-effective and long-term rehabilitation strategies that support both ecosystems and local communities.

9.4. Closing Statement

This thesis proposes a multidisciplinary framework for assessing and rehabilitating legacy VMS mine sites in the Iberian Pyrite Belt, using the arbitrarily chosen Zone 1, and specifically the San Miguel mine, as a representative case. Despite limited sampling at only San Miguel, geological consistency of the remaining mine sites in Zone 1 supported the spatial extrapolation of contamination findings, thereby revealing critical levels of arsenic, lead, and copper present in surface covers of the study area. A rehabilitation strategy was developed, prioritizing practical, low-impact measures such as phytostabilisation, geomembranes, and passive AMD SRB treatment to improve conditions for both ecosystems and local communities. The inclusion of a S-LCA highlights the broader societal relevance of mine rehabilitation in the IBP and supports the development of scalable, sustainability-focused closure strategies for comparable VMS deposits worldwide.

By integrating geochemical data, spatial analysis,literature, economic benchmakrs, and social considerations, this work offers a practical and indicative framework for restoring post mining landscapes for VMS deposits in comparable setting worldwide. While focused on the Iberian Pyrite Belt, the methods and lessons from this study can be applied to other regions facing similar environmental challenges, thus contributing to more sustainable mining closures around the world.

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A

Samples

(a) Soil sample of the San Miguel Area, sample number: SM24-G3-18.

(b) Soil sample of the San Miguel Area, sample number: SM24-G2-28.

(c) Soil sample of the San Miguel Area, sample number: SM24-G2-26.

(d) Soil sample of the San Miguel Area, sample number: SM24-1-19.

(e) Soil sample of the San Miguel Area, sample number: SM24-G1-09.

(f) Soil sample of the San Miguel Area, sample number: SM24-G1-05.

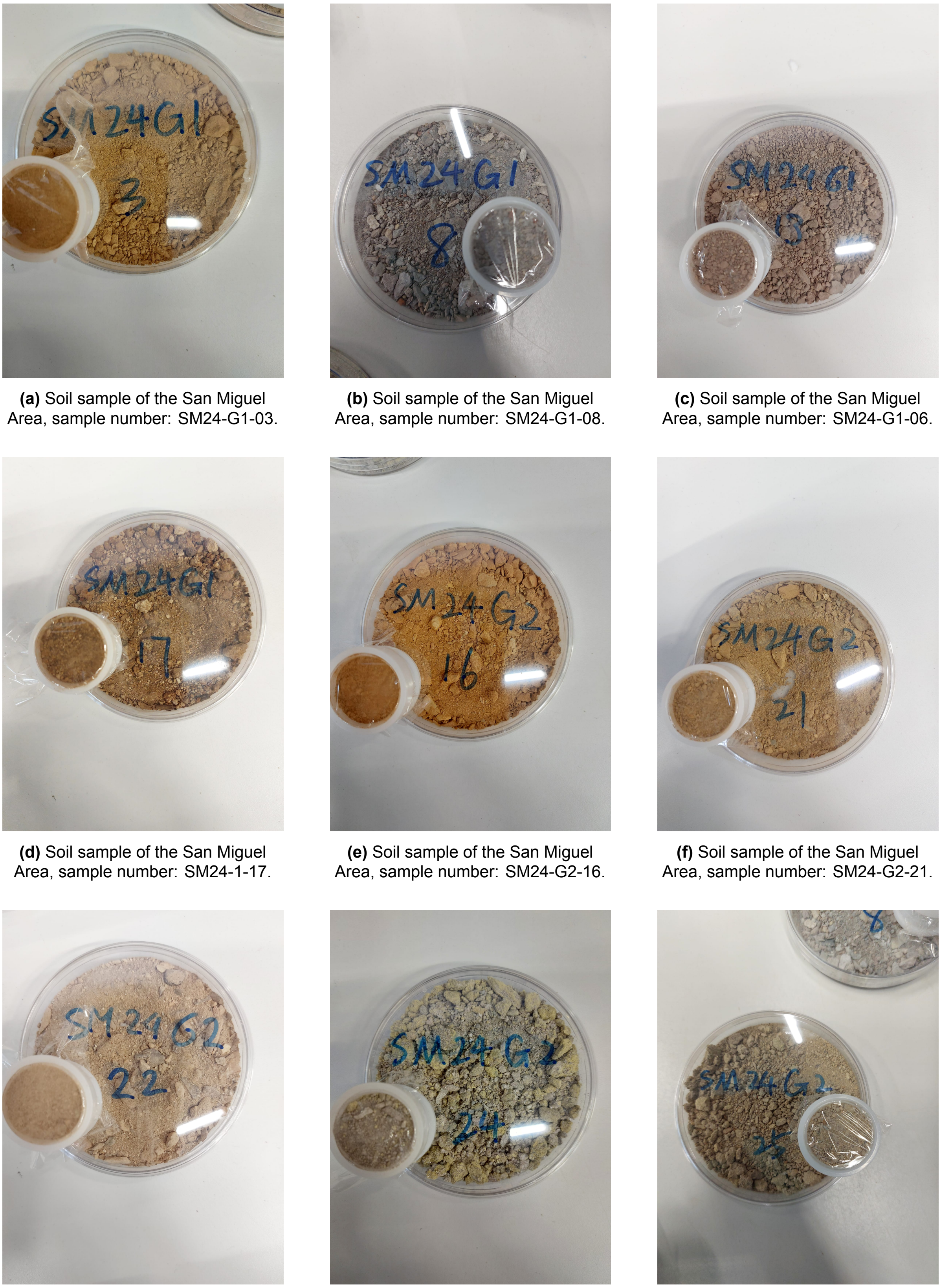
(g) Soil sample of the San Miguel Area, sample number: SM24-G3-01.

(h) Soil sample of the San Miguel Area, sample number: SM24-G2-08.

(i) Soil sample of the San Miguel Area, sample number: SM24-G2-11.

(j) Soil sample of the San Miguel Area, sample number: SM24-G2-21.

Figure A.1: Overview of soil samples collected from the San Miguel mining area for XRF analysis.



(a) Soil sample of the San Miguel Area, sample number: SM24-G1-03.

(b) Soil sample of the San Miguel Area, sample number: SM24-G1-08.

(c) Soil sample of the San Miguel Area, sample number: SM24-G1-06.

(d) Soil sample of the San Miguel Area, sample number: SM24-1-17.

(e) Soil sample of the San Miguel Area, sample number: SM24-G2-16.

(f) Soil sample of the San Miguel Area, sample number: SM24-G2-21.

(g) Soil sample of the San Miguel Area, sample number: SM24-G2-22.

(h) Soil sample of the San Miguel Area, sample number: SM24-G2-24.

(i) Soil sample of the San Miguel Area, sample number: SM24-G2-25.

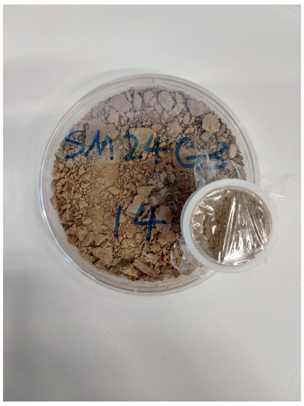
Figure A.2: Overview of soil samples collected from the San Miguel mining area for XRF analysis.

(a) Soil sample of the San Miguel Area, sample number: SM24-G3-02.

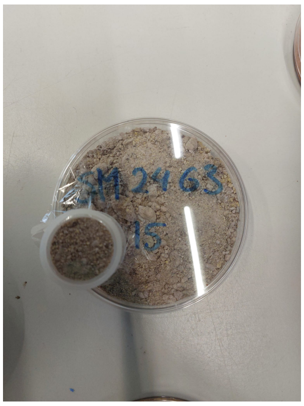
(b) Soil sample of the San Miguel Area, sample number: SM24-G3-03.

(c) Soil sample of the San Miguel Area, sample number: SM24-G3-05.

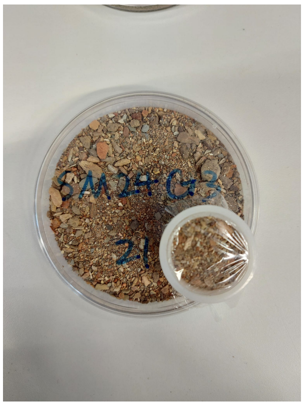
(d) Soil sample of the San Miguel Area, sample number: SM24-G3-10.



(e) Soil sample of the San Miguel Area, sample number: SM24-G3-14.

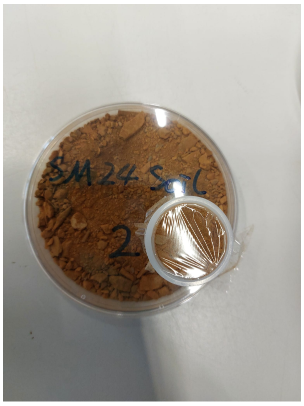


(f) Soil sample of the San Miguel Area, sample number: SM24-G3-15.

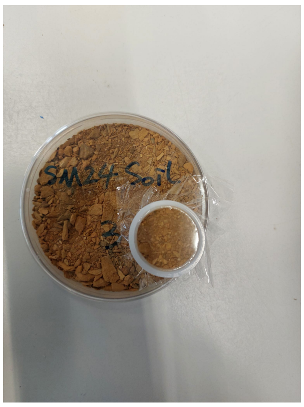


(g) Soil sample of the San Miguel Area, sample number: SM24-G3-21.

(h) Soil sample of the San Miguel Area, sample number: SM24-Soil 1.

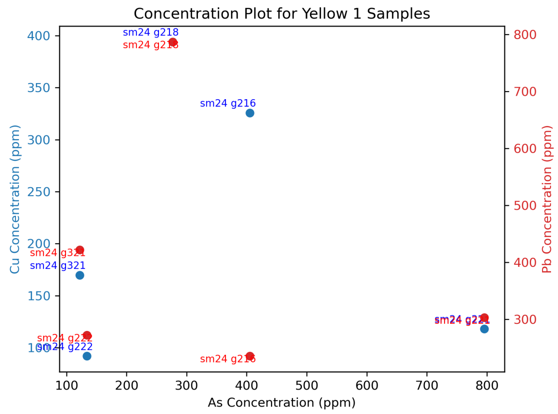


(i) Soil sample of the San Miguel Area, sample number: SM24-Soil 2.

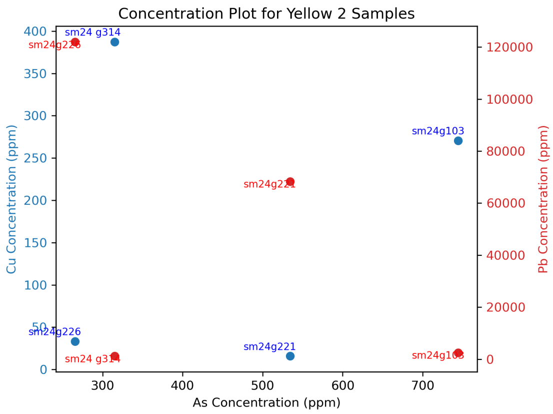


(j) Soil sample of the San Miguel Area, sample number: SM24-Soil 3.

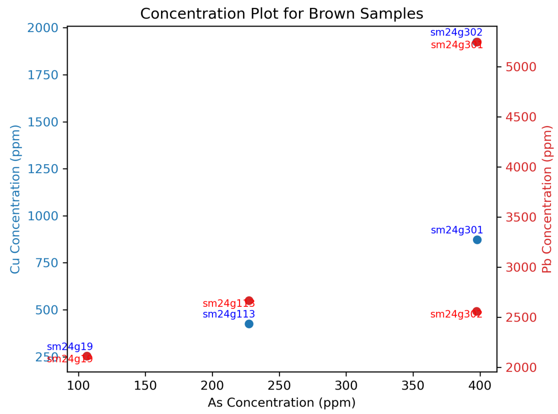
Figure A.3: Overview of soil samples collected from the San Miguel mining area for XRF analysis.



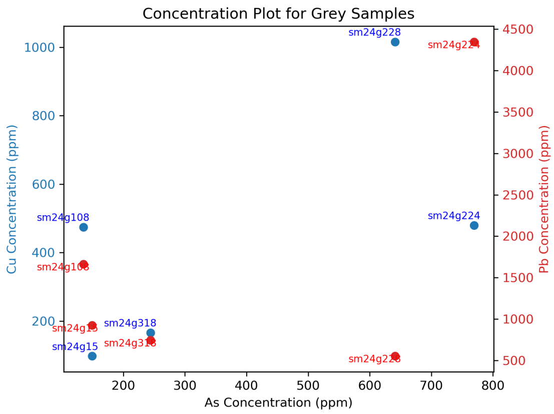
(a) Plot showing the concentrations for lead, arsenic and copper for all samples identified as type ’yellow type 1’.



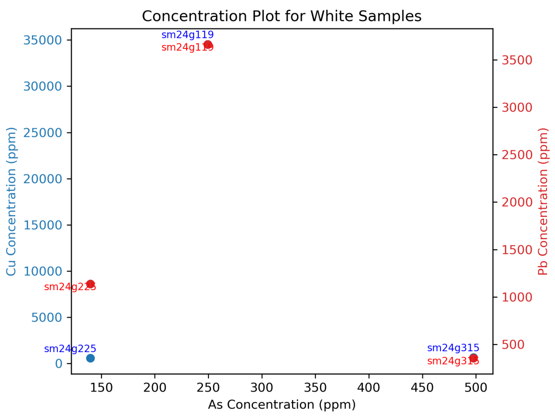
(b) Plot showing the concentrations for lead, arsenic and copper for all samples identified as type ’yellow type 2’.



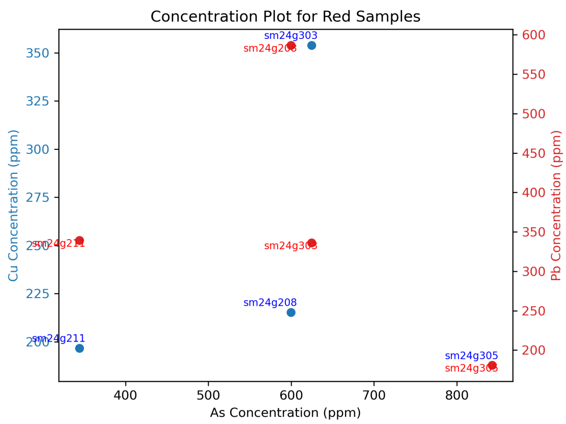
(c) Plot showing the concentrations for lead, arsenic and copper for all samples identified as type ’brown’.



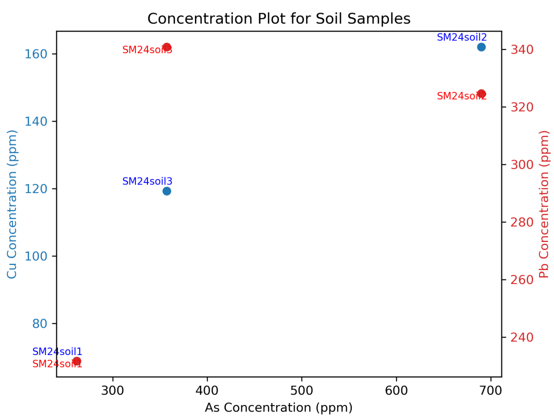
(d) Plot showing the concentrations for lead, arsenic and copper for all samples identified as type ’grey’.



(e) Plot showing the concentrations for lead, arsenic and copper for all samples identified as type ’white’.



(f) Plot showing the concentrations for lead, arsenic and copper for all samples identified as type ’red’.



(g) Plot showing the concentrations for lead, arsenic and copper for all soil samples.

B

Literature review: Remedial Work Plan

This chapter provides an in depth literature review of remediation techniques applicable to legacy mine sites, such as the ones present in Zone 1 of the Iberian Pyrite Belt. The review consists of both passive and active remedial strategies. The main focus is on methods that are technically feasible for mitigating the harmful impacts of heavy metal contamination and AMD.

Remediation techniques reviewed include:

- In situ approaches: phytostabilization, biochar amendments, technosols.
- Passive AMD treatment: sulfate-reducing bacteria (SRB), constructed wetlands.
- Ex situ methods: soil excavation and containment, chemical immobilization, encapsulation.

The goal is to identify strategies compatible with the field results presented in Chapter 2 and adaptable to the physical and socio-economic context of Zone 1.

B.1. In situ: soil amendments, erosion control & enhancing soil water retention

B.1.1. Soil amendments

Soil amendments refers to material added to the soil to improve its physical and/ or chemical properties. The soil amendments itself can be divided into two subcategories: organic and inorganic [57].

Organic

Organic amendments are rich in carbon. These materials are able to improve the soil structure, as well as enhancing nutrient availability and an increase in the microbial activity. There are several commonly used organic amendments in mine site rehabilitation [57]:

- **Biochar:** Biochar is produced through pyrolysis of organic biomass. It is a carbon rich material, which is able to enhance soil aeration, water retention and contaminant adsorption. It's application is very useful for stabilizing heavy metals by promoting their sorption and precipitation onto soil particles.
- **Compost and manure:** Compost and manure increases the microbial biomass, asl well as improving soil aggregation and enhancement of nutrient cycling.

- **Biosolids and sewage sluds:** Biosolids and sewage sludge contain high concentrations of organic matter and nutrients, but the application of these materials requires monitoring to prevent the introduction of additional contaminants, such as heavy metals and pathogens [57].

Inorganic

Inorganic amendments are mainly used for neutralization, and therefore improve the chemical properties of acidic soils. Some of the primarily used inorganic amendments include:

- **Lime:** Lime is used to neutralize acid generating mine waste by raising the pH. This increase in pH results into the precipitation of toxic metals as insoluble hydroxides,carbonates and phosphates. However, it must be taken into consideration that their long-term effectiveness can be limited if acid generation persists due to e.g. ARD.
- **Phosphate amendments:** Phosphate amendments are used to reduce the bioavailability of metals, such as lead, by reacting with these metals and forming insoluble phosphate minerals.
- **Metal oxyhydroxides:** Metal oxyhydroxides have large surface areas with strong sorption capacities, which allow them to effectively immobilize metals through adsorption and co-precipitation

Usually, a combination of organic and inorganic amendments are used to address the complex contamination issues of mine site pollution [57].

B.1.2. Technosols

Technosols is an ecotechnology used in mine site rehabilitation which develops soils from waste. These soils contain at least 20% of the waste artifacts in their volume. The development of Technosols integrates knowledge of waste properties and natural soil functions. The application rates of each amendment must be modified to the conditions of the specific degraded mining site or soil.

Technosols improve mine soil conditions at chemical, physical, and biological levels. They are able to immobilize potentially harmful elements (PHEs) through processes such as adsorption, precipitation, ion exchange and redox reactions, reducing their environmental mobility. Unlike composting, Technosols contribute to lower greenhouse gas emissions by reducing carbon and nitrogen losses [57].

B.1.3. Mulch

Mulching can be used to control erosion and enhance soil water retention by covering the soil surface with a thin layer of plant based materials. This thin surface cover is used to maintain soil moisture by reducing evaporation and erosion control. For this, there are several materials which can be used, for instance: wood chips, or shredded leafs. Over time, the plant cover will start to degrade and as well provide organic phosphate and carbon to the soil, leading to an improved plant cover and soil conditions [57].

B.2. In situ:physical, biological and chemical treatment

B.2.1. Physical

Physical remediation methods focus on the direct removal or containment of contaminated soils. One of the most commonly used approaches is soil excavation and replacement, which involves physically removing polluted soil and replacing it with uncontaminated material. This technique provides an immediate solution, however it is costly, and requires proper disposal or further treatment of the removed soil. Another comparable strategy is soil isolation, where impermeable barriers, such as clay liners, are used to prevent the migration of metals into groundwater or surrounding areas [58].

Copper

Electrokinetic remediation is another physical technique that applies an electric field to mobilize copper ions within the soil. The ions move toward collection electrodes, where they can be extracted from the soil matrix. This method is particularly effective for fine-grained soils with a high moisture content, but its efficiency depends on the soil's pH and electrical conductivity. In cases where copper is present in large concentrations, thermal desorption can be used to heat the soil, causing the contaminants to evaporate and to be collected for treatment. Although this method is mainly used for organic pollutants, it can sometimes be combined with other remediation techniques for heavy metals [58].

AMD

Once AMD is generated, the mitigation costs increase significantly. The most cost effective approach might therefore be to limit the exposure of sulfide minerals to air and water, and neutralize acidic conditions before they develop. An overview of techniques to mitigate the harmful effects of AMD is given as follows [6]:

- **Surface water diversion**: in order to reduce and limit the volume of contaminated runoff, surface water can be diverted away from mine waste. This is typically done by using impermeable perimeter channels, which re-direct clean water away from sulfide rich materials.
- **Mine galleries and shaft sealing** Sealing abandoned mine galleries and shafts prevents oxygen and water entry, thus reducing potential sulfide oxidation. Concrete plugs or cement injections are commonly used to seal mine galleries. However, this method requires careful hydrogeological assessments to avoid unintended water table rise and potential failures.
- **Dry cover**: by placing a low permeability layer, such as clay, over mine waste, water infiltration and oxygen diffusion will be limited. These covers may incorporate vegetative layers to promote stability and reduce wind erosion. The effectiveness of dry covers depends on local climatic conditions and the material's physical properties.
- **Wet cover**: for fine grained mine tailings, flooding sulfide bearing mine waste under water will prevent oxygen exposure. However, in order fot the method to be efficient, long term water level stability must be ensured to prevent seasonal exposure and renewed AMD formation due to oxygen exposure.
- **Micro-encapsulation**: Microencapsulation involves coating sulfide minerals with inert substances to prevent oxidation. Laboratory studies have explored various coating agents, including silicates, phosphates, and metal hydroxides. While promising, actual field scale applications are limited, and issues such as long term stability remains a concern.
- **Alkaline addition**: blending fly ash or limes with mine waste neutralizes acidity and reduces therefore AMD generation. In cases where AMD has already developed, periodic reapplication may be necessary, making the method a costly and unsustainable approach for Zone 1 of the study area [6].

B.2.2. Chemical

AMD

In AMD chemical treatment, a division can be made between active and passive systems. Active systems involve the addition of neutralizing chemicals, such as calcium oxide (lime), sodium carbonate, calcium carbonate, magnesium oxide and/ or sodium hydroxide. The addition of alkaline matter accelerates chemical oxidation of ferrous iron, thereby increasing the pH of the AMD and facilitates precipitation of metals as carbonates and hydroxides [123].
Passive systems are in general slower compared to active systems, however, they are more cost-effective and use naturally occurring processes to treat AMD. Chemical passive treatments include:

- **Limestone ponds:** Water passes through the limestone layers, the limestone dissolutes and reacts with the acidic water. As a result, the pH increases. This system is recommended for treating water with low dissolved oxygen and no Aluminum and Iron.
- **Open limestone channels:** AMD water flows through channels lined with limestone, which reacts and dissolved and thus to neutralises acidity.
- **Anoxic limestone drains:** Sealed systems where water flows through a drain filled with limestone gravel or other carbonated material in the absence of oxygen, allowing for efficient neutralization of AMD without iron precipitation. The circulation of water through the drain causes the dissolution of limestone that generates alkalinity and raises the pH of the water [123].

Arsenic

There are several methods to remove arsenic from water, with one of them being biosorption. Biosorption uses biosorbents, which is a nonliving inactive biomass which bind and removes arsenic from water by reactions such as chelation, precipitation, and adsorption.Adopting biosorption offers several advantages: it does not require additional nutrients, is relatively low-cost, allows for the recovery of valuable metals due to its relevance in industrial applications, and it can be reused across multiple treatment cycles.
Biosorbents contain several varying functional groups, such as carboxyl (-COOH), amino (NH_2), phenloic, hydroxyl (-OH), sulfydryl (-SH), ester and alcoholic groups. Arsenic biosorption involves various mechanisms, such as (1) ion exchange, (2) ligand exchange, (3) surface precipitation and (4) diffusion processes [44].

- **Ion exchange** is a reversible, stoichiometric process where one counter ion on the biosorbent surface is replaced by another to maintain electroneutrality. Arsenic binds to the biosorbent through electrostatic interactions, but the presence of other anions such sulfate and nitrate, which also strongly bind to anion resins, can lower the overall removal efficiency.
- **Ligand exchange** occurs when arsenic ions replace surface-bound ligands such as OH^- on the biosorbent. This exchange leads to a saturated solution where ions remain in equilibrium.
- **Surface precipitation** happens when arsenic forms insoluble compounds on the biosorbent surface over time, lowering its total concentration in the surrounding surface and ground water.
- **Diffusion** This refers to the process by which arsenic moves from the solution into the biosorbent. It starts with fast adsorption on the surface, followed by a slower movement

into the deeper pores of the material—a process that can take months to fully reach equilibrium [44].

The effectiveness of biosorption is influenced by the initial arsenic concentration, the pH, contact time, pH and the presence of anions and cations in water [44].

Copper
Chemical remediation methods rely on reactions that either extract copper from the soil or reduce its bio-availability and environmental mobility. Soil washing is a widely used chemical technique that involves applying chemical solutions, such as chelating agents, acids, or surfactants, to dissolve the present copper ions from soil particles. The copper-rich liquid is then separated and treated. Soil washing is highly effective, but costly and environmetnal disruptive, method for heavily contaminated sites. However, it requires a careful selection of chemical agents to prevent further soil degradation [55].

Stabilization and immobilization techniques focus on reducing the mobility of copper in the soil. This is usually done by adding chemical amendments such as lime, phosphates, biochar, or other stabilizing agents, which bind with copper and convert it into less soluble forms. By doing so, these techniques prevent copper from leaching into water sources or being absorbed by plants. Another chemical approach, precipitation and adsorption, involves introducing substances that react with copper to form insoluble precipitates. These precipitates remain trapped in the soil, reducing copper's environmental impact. Adsorption techniques use materials like activated carbon, clay minerals, or bio-based adsorbents to capture and immobilize copper ions [58].

Lead
Various methods, as have already been discussed for copper and arsenic, can be implemented for the remediation of lead in soils, for instance soil washing and phytoremediation [55].

B.2.3. Biological

AMD
Biological treatments can be divided into active and passive treatments. Active treatments include the following:

- **Rotating Biological Contactors (RBCs):** This approach utilizes rotating discs coated with biofilm to enable the biological precipitation of metals, thereby enhancing metal removal from wastewater.
- **Sulfidogenic bioreactors:** Utilisation of bacteria which reduce sulfate to generate hydrogen sulfide. The bacteria react with the metals present in the AMD waters, precipitating them as metal sulfides. Simultaneously, the acidic water is neutralized by the increase in pH. Active systems work relatively fast compared to passive systems, however they require continuous addition of organic carbon sources and energy input, such as pumping and mixing, to enable the process [123].

Passive biological treatments include the following list:

- **Fixed-bed and iron-oxidizing bioreactors:** These systems contain acidophilic microorganisms immobilized on solid supports, thereby forming biofilms that oxidize ferrous iron (Fe^{2+}) into ferric iron (Fe^{3+}), which in turn precipitates as iron hydroxide.
- **Sulfate reducing bacteria (SRB):** Oxidation of organic matter and reducing sulfate to sulfide by using SRB. This process forms highly insoluble metal sulfides that are precip-

itated. The process basically involves AMD passing through organic substrates, which removes oxygen and promotes microbial sulfate reduction. Metals are precipitated as sulfides, as the resulting alkalinity neutralizes the water, making it less harmful to the environment. The approach can be implemented in wetlands or Diffusion Active Permeable Reactive Barriers, thus making the process passive [123]. There are several factors which influence the efficiency of this approach. So is the choice of organic substrate important for long term reactor performance. Readily biodegradable sources such as ethanol, lactate, and molasses can rapidly stimulate SRB activity, whereas materials, such as sawdust and straw, provide slow and continuous carbon release over extended periods. Most of the systems utilize a combination of both to balance immediate and long-term treatment needs. As well, there needs to be sufficient contact time between the AMD and the reactive media to allow for the process of sulfate reduction to happen, and thus neutralization and metal precipitation [81].

Arsenic, lead & copper

Biological remediation methods use living organisms, such as plants, bacteria, and fungi to detoxify or remove heavy metals from contaminated soils. One of the most sustainable and cost-effective approaches is phytoremediation, in which plants extract or stabilize heavy metals by trapping them in their root system. Phytoextraction involves hyperaccumulator metal tolerant plants. These hyperaccumulator plants absorb heavy metals such as copper, arsenic and lead through their roots, and store it in their stems and leaves. Phytostabilization is closely linked to phytoextraction in which, once mature, these plants are harvested to remove the accumulated heavy metals from the site. In contrast, phytostabilization does not extract heavy metals but instead immobilizes its spread by trapping it within the root zone, and stabilizing the soil structure. Rhizofiltration, another plant-based technique, uses plant roots to absorb metals from contaminated water sources, thereby reducing its concentration in surrounding contaminated environments [58].

Microbial remediation, also known as bioremediation, utilizes microorganisms to alter the chemical state of metals, either by enhancing its bioavailability for plant uptake or by immobilizing it within the soil. Bioleaching employs bacteria, such as Acidithiobacillus ferrooxidans, which produce acids that dissolve metla sand minerals, making them easier to extract. Biosorption and bioaccumulation involve the natural absorption of copper by fungi and bacteria in their cells, effectively removing it from the environment. Additionally, biostimulation and bioaugmentation techniques can improve microbial activity by introducing specific nutrients or engineered microorganisms to accelerate copper degradation or stabilization [58].

While biological methods are environmentally friendly and cost-effective, they typically require longer timeframes to achieve significant results compared to (active) physical or chemical techniques. However, their ability to restore soil health, are environmentally friendly and minimize secondary pollution makes them an attractive option for large-scale and long-term remediation projects [58].

B.3. Ex situ treatment

Ex situ remediation methods for mine sites entail the excavation of contaminated soil from the original location on the site, and treating it somewhere else. However, as contaminated soils contain a variety of pollutants, usually more than one remediation technology is necessary to reduce the present pollutant concentration to an acceptable level. For arsenic polluted soils, such as is the case in the study area, soil washing and solidification are the commonly applied remediation techniques.

B.3.1. Soil washing

Soil washing entails the mixing of a washing agent with the contaminated soil. In this particular process, contaminants from the soil minerals are dissolved and separated as the leaching waste liquid, which contains the pollutants, can be separated from the soil through solid-liquid separation [124].

There are two types of soil washing, they can be subdivided into a (1) chemical extraction method and (2) a physical water washing separation method. The latter uses the difference in the physical properties (e.g. particle size, magnetic properties, and density) of the soil to separate pollutants from the soil. The chemical extraction method relies on the effectiveness of the washing agent. There are several types of washing agents, such as alkalis, salts, acids, surfactants and organics [124].

Acidic or near neutral solvents are less effective in order to extract heavy metals such as arsenic from soil minerals. This is because, under acidic conditions, the oxygen anion of As tends to be reabsorbed by positively charged soil particles. In contrast, phosphoric acid is generally considered more effective in de-sorbing arsenic from soil due to the competitive adsorption between arsenate (AsO_4^{3-}) and phosphate (PO_4^{3-}). Similarly, the use of phosphate in soil washing is based on the competition between AsO_4^{3-} and PO_4^{3-}. Alkaline washing agents also have proven to be effective washing agents, whereas hydroxide ions have a stronger affinity than other anions, thereby preventing the re-adsorption of arsenic oxyanions [124].

Combined washing methods aim to maximize extraction efficiency by combining multiple washing agents. The key advantage of soil washing is its rapid restoration time, with most cases being completed within 12 hours. This method also demonstrates high efficiency and tolerance to elevated arsenic levels in soils. However, ex situ soil washing requires extensive excavation, leading to significant costs and disturbance of the ecosystems present in the excavated soil. Additionally, the large quantities of washing agents used may alter the soil's original properties [124]. Therefore, ex-situ approaches such as soil washing are unsuitable for the rehabilitation propsal of the study area, whereas the proposal aims to employ environmentally friendly and cost-effective methods to mitigate the harmful effects of ongoing lecay mine site pollution in the area.

B.3.2. Solidification and stabilization

Soil stabilization is an in situ remediation strategy, which aims to immobilize heavy metals by decreasing their leachability and bioavailability, rather than physically removing them. This technique involves the application of soil amendments to the soil cover, that interact with inorganic and organic components through adsorption, complexation, and precipitation. Common stabilizing agents include organic materials, such as biosolid compost, manure, vermicompost, and biochar, which enhance the soil's cation exchange capacity (CEC) and facilitate the formation of stable metal complexes. Organic amendments, particularly biochar and sewage sludge derived compost, have shown high efficiency in long-term Pb immobilization due to their large surface area, functional groups present (carboxyl and hydroxyl), and nutrient content. However, while stabilization effectively reduces Pb bioavailability, it does not decrease the total metal content in contaminated soils. Therefore, it is most effective when applied as a complementary technique rather as one remediation approach.

Combining soil stabilization with soil washing has been shown to be highly effective in mitigating heavy metal contamination in soils. Soil washing serves as a pre-treatment, significantly reducing total heavy metal concentrations, while stabilization is applied as a post-treatment to control residual Pb bioavailability and restore soil health.

Generally, Solidifcation and stabilization technologies achieve an immobilization efficiency exceeding 80%, with a relatively short treatment duration (usually less than a month). These methods have demonstrated strong stabilization effects, even in mine soils with severe heavy metal contamination. However, the application of this process is costly, irreversible and can cause subversive damage to soil properties [124] by using both soil washing and soil stabilization, thereby making it unsuitable for the environmentally friendly approach of the rehabilitation proposal of the study area of the IPB.

[55].

B.4. Assumptions and uncertainties

- Scalability: Techniques deemed effective in pilot or lab-scale studies are assumed scalable to Zone 1 of the study area. In reality, this might not be the case due to logistical, biological, or climatic constraints.
- Transferability of case studies: Many reviewed remediation projects are located outside of Spain. Climatic and soil differences (e.g. rainfall, pH, organic matter) affect thereby the outcomes of the proposed rehabilitation efforts.
- Uniform pollution profile: Assumes similar contaminant behavior across Zone 1 by using the San Miguel mine site as a proxy. However, actual concentrations, mineralogical composition and geochemical mobility may differ per site in Zone 1.
- Sustainability assessment: Life-cycle impacts of certain methods (e.g. imported amendments) were not always accounted for in literature, thereby making certain methods in reality potentially less sustainable than is assumed.
- Time horizons: Few studies provide long-term monitoring data, which limits yhe assessment of durability and recontamination risks of the proposed 25 year time-scale of this research.

B.5. Summary and conclusion

Moving forward, the remediation strategy for the study area in the IPB should focus on a combined approach utilizing phytostabilization for heavy metals and a passive SRB approach for limiting AMD.

Phytostabilization is a suitable technique for managing arsenic, copper, and lead contamination, as is the case in the study area of the IPB. By using metal-tolerant plant species, this method can immobilize these pollutants in the soil, thereby significantly reducing their mobility and bioavailability. This will help prevent leaching as well as limiting exposure risks, and stabilize mine tailings. This is critical in the region's highly acidic and heavy metal contaminated environment.

For AMD, the passive implementation of SRB provide an effective solution by enabling sulfate reduction, leading to an increase of the pH and the simultaneous precipitation of insoluble metal sulfides, which are more stable and less bioavailable. SRB-based treatments can be integrated into passive remediation systems, such as DAPRB or constructed wetlands, to control the release of dissolved metals into nearby water systems.

C

Literature review: Morphological Recovery Plan

C.1. Introduction
This chapter reviews morphological recovery strategies relevant to legacy mining landscapes with severe surface degradation, such as those present in Zone 1 of the study area. Emphasis is placed on approaches that can be integrated with ecological restoration plans as discussed in Chapter 3.

C.2. Backfilling & site contours
The extraction of large VMS deposits in the study area has resulted in the formation of numerous structures, including slag heaps and mine ponds as a byproduct of mining and metallurgical processes. These mine ponds are filled with tailings: a watery sludge composed of medium to fine grained material, containing heavy metals and minerals such as pyrite. These ponds serve as reservoirs, however, they also act as contributors to AMD due to the oxidation of sulfides present within the tailings when the sulfide minerals are exposed to oxygen [3]. As a result, mine ponds in Zone 1 of the study area pose a significant environmental concern, especially when they are abandoned and no monitoring system is in place [125].

C.2.1. Cemented paste backfill
Cemented Paste Backfill (CPB) technology basically entails the disposal of mining waste back into the undeground mines, thereby also contributing to the stability of underground mines. CPB is produced by mixing dewatered mineral tailings (70%-85%), with water, and a binder (3%-7%), which is typically cement or another binding agents. When combined, a thick paste is created. This paste can then be transported to underground voids, mine ponds or mined-out areas, where it hardens to provide structural support.

Flocculation
The cementation of fine particles in mine tailings using polymeric flocculants depends on a sequence of processes. It starts with the adsorption of polymers onto particle surfaces. These flocculants, which are long-chain synthetic polymers, are transported to the mineral surfaces by convection or diffusion. Once at the surface, the polymers adsorb to the tailings through various interactions, such as hydrogen bonding and electrostatic attractions.

After adsorption is succesful, the polymer chains can take on different conformations. Which conformation exactly depends on several factors, such as polymer stiffness and interactions with water and solids. These conformations influence the efficiency of flocculation.

The strength and performance of CPB are influenced by a combination of material properties, mixing procedures and curing conditions. Homogeneous mixing of CPB components is essential, as uneven particle distribution can significantly affect unconfined compressive strength (UCS).

Incorporating CPB into the morphological plan of the study area has several advantages:

- **Minimizing environmental risk** The use of CPB helps to reduce the environmental impact of tailings by preventing their exposure to oxygen and water. By filling back mine voids and ponds with a stable, hardening paste, the CPB encapsulates sulfide-rich materials, effectively reducing the risk of potential future AMD formation. This is especially important for abandoned inactive mine sites, where tailings have the potential to leach heavy metals and acid into surrounding ecosystems if left untreated.
- **Structural stability** CPB not only addresses environmental concerns but also contributes to the structural integrity of the mine site. The paste hardens over time, thereby providing support to underground voids and preventing ground subsidence or surface deformation. This contributes to the long-term stability of the site, which is critical for ensuring that the rehabilitation efforts are sustainable.
- **Reduction of the volume of tailings** By backfilling mined out areas with CPB, the overall volume of tailings stored on site can be reduced. This makes the rehabilitation process more efficient and minimizes the need for large tailings storage facilities, which are often associated with long-term environmental hazards. The consolidation of tailings into a stable, non-reactive form ensures that the site can be restored to a more natural state, enhancing its potential for future land use.

Cemented paste backfill could be a viable solution for the study area, however, such an implementation method would be very costly as the cement used for backfilling would need to be imported. As well, it might result in more subsurface damage by filling the cemented tailings back into the voids [56], therefore making it an unsuitable approach for the rehabilitation of Zone 1 of the study area.

C.3. AMD leakage mitigation

As an example and relevant to the study area, one of the mine ponds of Mina Concepción (part of Zone 1), failed in their remediation efforts in the past.

Recent studies have indicated that there is leaking present of this pond to the outside, thereby still contributing to the ongoing AMD generation in the Rio Odiel. Therefore, the Mina Concepción mine pond would need an improvement in waterproofing and a monitoring plan for the future to ensure that the pond does not pose anymore environmental harm [82].

The partial failure of the Mina Concepción reclamation provides valuable insights for the rehabilitation of the San Miguel mine. Despite initial efforts to stabilize and revegetate the site, the persistence of AMD highlights shortcomings in waterproofing of the mine pond. Therefore, there are currently problems with the drainage control. The paper states that this failure probably could have been detected and mitigated earlier by real-time and long-term monitoring of the area. Addressing these issues proactively can enhance the effectiveness of reclamation of the mine ponds at San Miguel, Mina Concepcion, Angostura, Solviejo, Esperanza and Magdalena, and prevent similar environmental risks, highlighting the need for a well thought out monitoring plan for the future [82].

- **Improving waterproofing measures** One of the critical failures at Mina Concepción was the inadequate sealing of the mine pond, allowing acidic water to seep into surrounding watercourses. For the remaining mine sites in Zone 1, it is essential to implement an impermeable lining system for mine ponds to prevent the leaching of AMD. Additionally, a robust monitoring system should be in place to ensure continuous water coverage over the tailings, thereby preventing oxygen exposure [82]. This can be achieved through the use of e.g. geosynthetic liners such as geomembranes. Geomembranes will be more discussed in section C.3.1.
- **Optimizing drainage systems** While Mina Concepción incorporated collector pipes and an overflow channel, these proved insufficient to fully control acidic water discharge. A well-designed drainage system at the inactive mine sites of Zone 1 should include properly maintained lateral drainage ditches, sediment control structures, and possibly constructed wetlands to passively treat leachates before they reach natural water bodies. Additionally, the use of alkaline amendments in the drainage system could help neutralize acidity before water exits the site [82].
- **Long-term monitoring** The delayed recognition of AMD leakage at Mina Concepción emphasizes the need for continuous monitoring. At Zone 1, a robust monitoring program should be implemented from the start of rehabilitation efforts, including regular water quality assessments (pH, conductivity, heavy metal concentrations) and geophysical surveys to detect potential seepage pathways [82].

C.3.1. Geo-membrane

Geo-membranes are thin polymeric sheet materials used primarily as liners or barriers to control fluid migration in various applications. In the context of tailings management in inactive mine ponds, geo-polymers can serve as an effective protective layer for mine tailings ponds to contain hazardous waste and prevent leaching and thus contamination of soil and water. Legacy mine ponds should be excavated, lined with geo-membranes, and subsequently backfilled to mitigate future risks associated with AMD and heavy metal mobilization.

Challenges

The use of geo-membranes in mine ponds presents several challenges. One significant concern is the potential for defects and wrinkles that can occur during construction. These defects can lead to uncontrolled fluid migration through the geo-membrane, compromising its effectiveness as a barrier against AMD.

Another challenge is the mechanical and thermal stresses that geo-membranes may experience over time. Factors such as differential settlement and stress concentrations can lead to tears or holes in the geo-membrane, further increasing the risk of fluid transport and leachate generation. Additionally, geo-membranes may be subjected to degradation due to environmental fluctuating conditions such as temperature or climatic fluctuations, which can affect their flexibility and overall durability [63].

Composition

Geomembranes are primarily composed of thin polymeric sheet materials, with polyolefins being the most commonly used types. The specific polymers include high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), polyvinyl chloride (PVC), flexible polypropylene (fPP), ethylene propylene diene terpolymer (EPDM), and chlorosulphonated polyethylene (CSPE) [59].

Best practices

Several best practices can be implemented during the design, installation, and monitoring of geo-membranes in mine pond liners:

- **Use of Reinforced Geomembranes** Utilizing reinforced geo-membranes can help mitigate the risks associated with thermal expansion and differential settlement. These materials are less prone to wrinkle formation and therefore provide more resistance to mechanical stresses.
- **Lateral Drainage Systems:** Installing a lateral drainage system beneath the geo-membrane liner helps to prevent water accumulation, thereby lowering the pore water pressure. As a result, the likelihood of failure and leakage through the geo-membrane will be reduced.
- **Monitoring** Continuous monitoring of the geo-membrane's condition can help identify issues and challenges early on, limiting the total negative impact due to failure [59].

Geo-membrane liners will be an useful method to beimplemented in the study area to prevent the leaching of polluting elements, such as heavy metals, from the legacy mine ponds present in the area.

C.4. Revegetation

Revegetation is a key part of the larger reclamation process that involves the restoration of disturbed lands, such as mine tailings, to a stable, self-sustaining ecosystem. Revegetation mainly focuses on soil stabilization and the establishment of a vegetative cover. Soil stabilization occurs because the roots form a subsurface network that increases soil cohesion, thus preventing erosion. Morevoer, surface cover (e.g. grasses or bushes) reduce the impact of water infiltration, as well as creating a more aesthetically pleasing landscape [62]. There are two approaches to revegetation, namely:

1. **Non-direct revegation**
   Non-direct revegetation involves the establishment of vegetation on top of a protective layer (e.g. coarse rock, soil) that is placed over the mine tailings. This approach minimizes oxygen and water penetration and supports plant growth by providing a more hospitable environment. As well, it prevents the upward migration of toxic substances such as acids and metals from the tailings.
2. **Direct vegetation**
   In the direct vegetation approach, vegetation is planted directly on the surface of the mine tailings without a protective cover. This approach could be more cost effective compared to indirect vegetation, however it is challenging due to several unfavorable conditions found in mine tailings, such as: low organic matter & nutrient levels, poor physical structure that inhibits plant root growth, and high toxicity and low pH due to contaminants and heavy metal presence in the soil. However, several amendments are often used to address these issues, such as the application of lime to neutralize the acidic conditions. Organic matter can be added to improve the soil structure and microbial activity, whereas fertilizers are used to provide the necessary nutrients for vegetation establishment [62].

Plant growth-promoting rhizobacteria (PGPR) play an important role in enhancing plant growth and development through various direct and indirect mechanisms. These beneficial bacteria colonize the rhizosphere, the region surrounding plant roots, where they influence plant health by triggering immune responses. As a result, it helps regulate hormonal balance and protect against pathogenic organisms. PGPR can be classified based on their functions: some act as biofertilizers by increasing nutrient bioavailability, while others serve as phytostimulators by releasing phytohormones that promote plant growth. Their interactions with plants can lead to an improvement of nutrient uptake, an increase in biomass, and enhanced tolerance to environmental stresses [126]. The key mechanisms can be described as follows:

- **Nitrogen Fixation** PGPR can convert atmospheric nitrogen (N_2) into ammonia, a form that plants can utilize.
- **Phosphorus Solubilization** PGPR can solubilize phosphorus from organic and inorganic forms in the soil, making it thereby more available for plant uptake.
- **Production of Phytohormones** PGPR synthesize phytohormones, such Indole-3-acetic acid (IAA), cytokinins, and gibberellins that promote root development and enhance nutrient absorption [126].

C.5. Assumptions and Uncertainties

- **Topographic data limitations:** Subsurface stability and internal drainage conditions remain unverified due to time constraints and lack of relevant data.
- **Hydrological sealing performance:** It is assumed that pond liners are properly installed and remain intact, although they could fail over time due natural processes such as differential settling, punctures, or root penetration.
- **Uniform ground conditions:** Geo-technical properties such as compaction, shear strength, and porosity are not taken into consideration due to a lack of relevant data, meaning local variations are not taken into consideration and are therefore not captured in the study area.
- **Climatic suitability:** Erosion control measures and vegetation plans are designed with the local Mediterranean climate in mind, but intense summer droughts or unexpected rainfall could affect their success.
- **Vegetation growth rates:** Assumptions about revegetation density and speed are based on existing literature. In practice, growth could be slower due to local factors and conditions, such as poor soil quality or water stress.
- **Site accessibility:** The plan assumes machinery and materials can be brought to all relevant areas for earthworks. Steep slopes or rough terrain may make this more difficult in practice.

C.6. Summary

The morphological rehabilitation approach to be implemented in Zone 1 of the study area is the installation of geo-membrane liners in legacy mine ponds and revegetation of degraded surface areas.

Geomembranes are thin sheets made of synthetic polymers, commonly used as liners or barriers to prevent the movement of liquids in a range of settings. To reduce future risks of AMD and heavy metal leaching, legacy mine ponds should be excavated, lined with geomembranes, and then refilled. When applied to tailings management at inactive mine sites, these membranes act as a protective layer to contain hazardous materials and stop contaminants from leaking into the surrounding soil and water.

Revegetation plays an important role in the broader process of land reclamation. It aims to restore the disturbed mine face surface areas into stable, self-sustaining ecosystems. Root systems reduce the risk of erosion by increasing the soil cohesion, while vegetation on the surface, such as grasses or shrubs, helps limit water infiltration and enhances the visual appearance of the landscape.

A combination of both geo-membranes and revegetation will therefore be applied in the rehabilitation proposal of Zone 1 of the study area.

D

Portable XRF results of 10 representative samples

Table D.1: Highest metal concentrations measured in 10 representative samples from the San Miguel mine using portable XRF.

Sample ID	As (ppm)	Cu (ppm)	Fe (ppm)	Pb (ppm)	Ti (ppm)	V (ppm)	Zr (ppm)
SM24-G3-18	243.94	165.93	136226.09	745.03	4286.40	445.85	170.05
SM24-G2-28	641.13	1105.99	113440.14	552.37	4718.04	1569.84	147.88
SM24-G2-26	265.57	416.52	112988.40	450.44	3304.46	839.51	200.45
SM24-G1-19	424.571	85.15	52324.71	1638.55	5362.36	938.97	211.07
SM24-G1-09	106.27	253.51	67955.41	2113.02	5004.65	520.89	176.76
SM24-G1-05	149.22	97.35	88545.95	923.47	4933.48	327.88	149.77
SM24-G3-01	420.71	949.67	281068.57	5811.90	4091.81	1310.33	151.33
SM24-G2-08	652.76	233.29	121000.63	654.83	5059.00	518.61	173.82
SM24-G2-11	344.28	196.63	103382.67	339.14	4742.20	243.47	167.15
SM24-G2-21	534.31	92.10	68361.65	205.77	4046.01	184.43	125.98
Average	378.28	350.61	119539.43	1343.47	4554.74	689.98	170.30