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# Legacy coal mines in Southern Brazil: Actions from National Mining Agency to promote fair mine closure and their transitions to another land-use

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## Abstract

*Issues related to legacy mines and their environmental and social impacts that occur in the coal basin in southern Brazil, in the state of Santa Catarina, Brazil, are described in this paper, as well as actions promoted by the Brazilian government to identify and measure the extent and severity of the impacts. In this region the extraction and processing of coal began in the early 20th century, when the legislation for the activity were not well-established, leading to the abandonment of dozens of mines, exceeding thousands of hectares. These legacy coal mines, with high levels of sulphur and heavy metals, have been causing several environmental impacts over time due to exposure and abandonment of waste rock and tailings from open pits and underground mines. Problems such as generation of acidic drainage as well as water and soil contamination jeopardize the adjacent ecosystems and the public health of local communities. The Brazilian Federal Government, represented by the National Mining Agency (ANM), which is responsible for issuing mine permits, was forced to find solutions for these legacy sites, as well as some companies that still operate. For more than ten years, works have been carried out, with the aim of reclaiming these areas using techniques to minimize the geochemical impacts of coal tailings, as well as to recover affected ecosystems. In this paper, the main technical and regulatory challenges in the Brazilian legacy coal mining industry are presented, as well as the search for solutions to overcome these obstacles. Some examples of reclaimed areas including monitoring data from three river basins are presented, which show the success and failure cases of the techniques used. We address also the main challenges that still need to be overcome so that these areas, public and private, can be returned to the environment and society in a way that provide quality ecosystem services, as well as sustainable future uses, providing a fair transition for stakeholders.*


**Keywords:** *acid drainage, metals, contamination, social impacts, environmental rehabilitation*

## 1 Introduction

Coal is present in several municipalities from the Carboniferous Basin in the south of the state of Santa Catarina/Brazil, having been responsible for a good part of the historical development of the region, with records from 1885. In the 1930s, coal became of strategic importance for Brazil, with the government establishing an obligation for companies to consume national coal by Decree 20089/1931 (Brazilian Government 1931). In 1940, Decree-Law 2667/1940 (Brazilian Government 1940) established the obligation that at least 20% of the coal used in the country should came from national sources, fomenting the activity in the country. The promotion of industry also took place with incentives related to transport and taxes, thus creating conditions for the development, and strengthening of the coal extractive industry in the region (Alexandre 1999).

The Law 1886/54 (Brazilian Government 1954) created the Executive Committee of the National Coal Plan (CEPCAN), which directed its efforts to solve the problems of coal wastes, which had energy potential and no use. The first coal-burning thermoelectric plant in the state was then built. In the 1970s, with the oil crisis, the government increased the number of subsidies for the coal extractive sector, aiming at replacing fuel oil. Mining operations underwent transformations, enabling the operation of large mines and consequently high production rates. The expansion of production rates had harmful effects on soil and water contamination, resulting from the uncontrolled disposal of coal waste rock and tailings containing sulphides, such as pyrite and Marcasite (Gothe 1993; Lattuada 2009; Freitas et al. 2017).

From 1986 to 1997, the Carboniferous Industry lost the incentives granted by the government, and the importation of metallurgical coal was permitted. In 1990 the government, based on the guidelines for the Mineral Coal Policy, promoted the deregulation of the activity with the publication of Ordinance N° 801/90 (Brazilian Government 1990) which established the end of the mandatory consumption of national coal. These actions put the sector in crisis, contributing to the abandonment of mines, inadequate disposal of tailings and intensification of environmental contamination processes.

After the Federal Constitution of 1988 (Brazilian Government 1988), the environmental issues became a pressing matter in the Carboniferous Basin. Faced with large areas already degraded, and the inaction of mining companies to resolve environmental liabilities, the Federal Public Ministry (MPF) in an unprecedented action in the country, initiated Public Civil Action (ACP) or "Coal ACP" as it became known. In 1993, the Federal Public Ministry demanded in court that the coal companies, from the State of Santa Catarina and the Union (represented by Federal Government agencies responsible for mining and the environment), recover the environmental impacts caused by the exploitation of mineral coal in the region. Reaching a favourable decision in March 2000, the defendants were jointly condemned to stop the contamination and recover the degraded areas. In the court order, companies that were still active and had active mineral permits were condemned to recover their areas. In older areas, where the companies that exploited coal no longer had mineral permits, went bankrupt financially or simply no longer existed, the responsibility for rehabilitation rested with the Union.

After the success in court, with the establishment of the sentence that obliged the defendants (private companies and the Federal Government) to stop environmental damage, negotiations, and agreements with the MPF were started. In 2007, the Technical Advisory Group (GTA) was created, comprising technical staff from the Federal Public Ministry, the Federal Government represented by the National Mining Agency (ANM) and the Geological Survey of Brazil (CPRM), mining companies, the Carboniferous Industry Association, and the Hydrographic Basins Committee of the Araranguá, Urussanga and Tubarão rivers. The GTA began to discuss technical issues, establishing criteria and a term of reference for rehabilitation of areas, thus minimizing the number of conflicts to be decided by the Court and initiating work on environmental recovery of abandoned mines.

All areas to be rehabilitated were required to follow the technical rehabilitation criteria established by the GTA (GTA 2015) where the Degraded Area Recovery Plans (PRAD), considering and criteria such as: future use, legal reserve, removal or covering of non-inert tailings and/or overburden, topographic reconstitution, addition of soil capable of supporting growth of a vegetation cover, vegetal cover with native species that do not compromise the infiltration reduction capabilities of the tailings/overburden, reconfiguration of slopes, drainage system, erosion control, monitoring of surface and underground water resources, and monitoring, management and maintenance of vegetation.

Basically, the terms of reference used for rehabilitation of the areas consisted of isolating the non-inert coal tailings/overburden in cells, substantially limiting the potential for water and oxygen ingress, thereby limiting oxidation of sulphide minerals and resulting acid mine drainage (AMD). Figure 1 presents a standard schematic profile of how these cells were to be constructed.

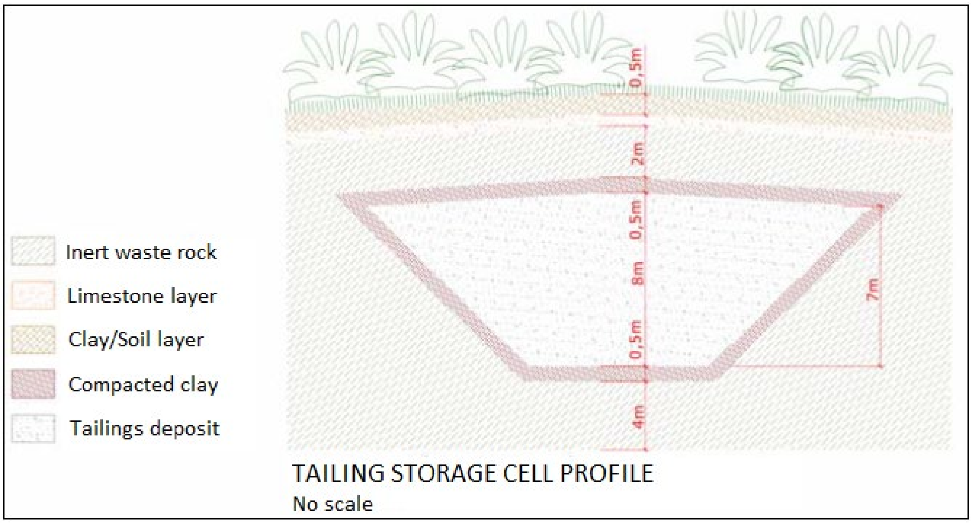


**Figure 1 Schematic profile of the basic system to be used for isolation of non-inert waste. Adapted from IPAT/UNESC, 2005.**

The technique consists of preparing the land with inert overburden, building a layer of 50 cm of compacted clay where the tailings containing sulphides are deposited in layers up to a maximum of 7.0 m, in order to isolate them from contact with atmospheric oxygen and water, and prevent the percolation of rainwater through encapsulated non-inert waste. The cell design also called for placing a layer of 2.0 m of inert waste above the compacted clay, with an overlapping layer of 30 cm of limestone, followed by placing 50 cm of non-compacted clay and/or topsoil to facilitate growth of plant species, which according to the term should be composed only of native grasses, to avoid the growth of large tree species, especially those with deeper root systems.

Therefore, describing the history of coal mining in the southern region of the State of Santa Catarina, the facts that led to the abandonment of numerous mines, the actions that determined the mandatory rehabilitation of these areas, and the basic methodology for rehabilitation, we present below a detailed description of the impacted areas and the rehabilitation actions carried out by CPRM and ANM. The objective is to present the successes and failures of the rehabilitation program, aiming to improve technical and operational knowledge, to contribute to the theme of closure and rehabilitation of abandoned coal mines and their post-closure transitions.

# 2 Methodology

The work was based on a literature review of monitoring reports prepared by the GTA since 2007 (Forum ACP Carvão, 2023). That includes technical reports produced by CPRM on planning and execution of the rehabilitation works, reports and public technical opinions produced by ANM, scientific articles, in addition to data obtained from fieldwork carried out since 2018, with the use of drones for monitoring and dimensioning the impacted areas, in addition to the use of geoprocessing techniques and the use of satellite images.

## 2.1 Description and size of study areas

Coal mining activity in the southern region of the state of Santa Catarina directly affected three watersheds: Araranguá River Basin (BHA), Urussanga River Basin (BHU) and Tubarão River Basin (BHT), which covers an area of 98,929 hectares (Figure 2).

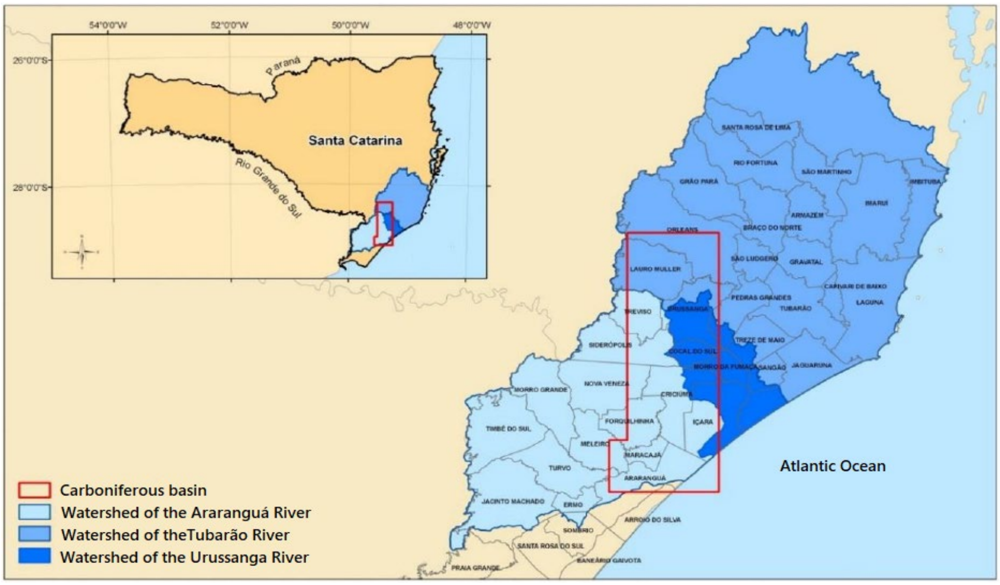


**Figure 2 Location of watersheds with identification of municipalities and delimitation of the coal basin.** Adapted from GTA (2018)

### *2.1.1 Araranguá River watershed*

The Araranguá River Basin (BHA) corresponds to an area of 3,089.1 km$^2$. The Araranguá river is formed by the confluence of the Mãe Luzia and Itoupava rivers, with drain areas of 1,501 km$^2$ and 1,180 km$^2$, respectively, covering a total of 17 municipalities. The Water Resources Plan for the Araranguá River Basin (Government of Santa Catarina, 2014) identified that open-pit and underground mining directly harms the quality of the waters of the Mãe Luzia River and the sub-basin of the Rio dos Porcos; as a consequence, the waters of the Araranguá river that receives them in its lower course, with pH values below 3.0, high concentrations of sulphates, acidity and metals, turning those waters unsuitable for various uses, according to classification defined in the Quality Reference Values of Surface Water Bodies in Brazil (CONAMA, 2005).

### *2.1.2 Urussanga River watershed*

The Urussanga River Basin (BHU) is located between the Tubarão and Araranguá River basins, corresponding to an area of 675.75 km$^2$, covering a total of 10 municipalities. The main river of the basin, the Urussanga, has a length of 43.05 km, reaching its mouth in the Atlantic Ocean (Government of Santa Catarina, 2019).

Based in the State Water Resources Plan of Santa Catarina - PERH/SC (FAPESC, 2017) surface water quali-quantitative balance was evaluated, according to the methodology proposed by the National Water Agency of Brazil - ANA (ANA, 2015). Through the analysis of the ratio between total water demand for consumption and water availability, was concluded that the projection of short (2019), medium (2023) and long-term (2027) demands, regarding the total withdrawal flow (m3/s) and the necessary flow for the dilution of the effluents (m3/s) was classified as very critical for Urussanga River; considering the impacts of the mining activity.

### *2.1.3 Tubarão River watershed*

The Tubarão River Basin (BHT) has an area of 5,959 km$^2$, which includes the Lagoon Complex. The Tubarão river has its source on the slope of Serra Geral and its main tributaries are the Braço do Norte and Capivari de Baixo rivers, and it runs from its sources 120 km to its mouth. The BHT covering a total of 18 municipalities. Studies carried out by Franzen et al (2021), to delimit the areas affected by coal mining in the south of Santa

Catarina, show that BHT is the most environmentally impacted, when considering the total polluting loads generated by mining operations.

## 2.2 Identification and delineation of impacted areas

Due to the lack of environment control in the coal mining process over time, the results of the activity left a legacy of large environmental liabilities, which have direct effects on society, economy, and biodiversity. These liabilities, represented by abandoned mines and inadequate disposal of tailings and overburden generated by the private sector, approximately 4,200 hectares of degraded surface areas have been mapped so far, of which 3,184 ha are private areas and 1,012 ha are public areas (Figure 3).

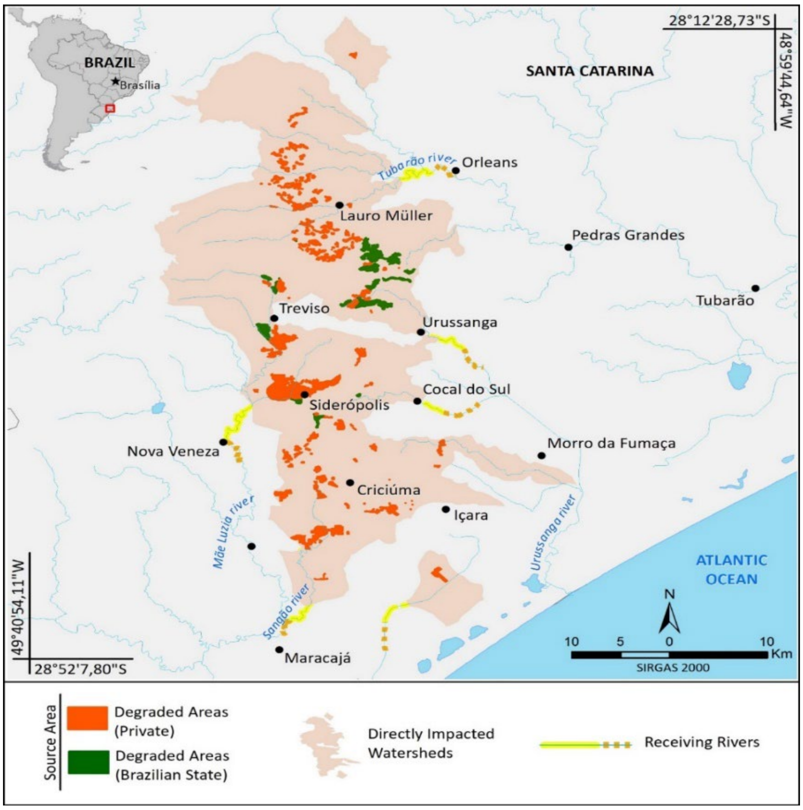


**Figure 3** **Map with affected municipalities, degraded areas, main rivers affected by acidic drainage and delineation of contaminated watersheds.**

As illustrated in Figure 3, the areas impacted by acidic drainage from exposure and open pit abandonment of overburden and coal mining tailings were classified into one of three categories: (a) source areas; (b) directly impacted watersheds; and (c) receptor rivers. The source areas correspond to the degraded places where the overburden and coal waste were deposited at open pits without control or treatment of the effluents. To delineate the directly affected areas, the region of the three watersheds that drain the areas was considered in this study. And finally, the receiving rivers are those that receive the contaminated effluents, drained by the rivers of the directly affected areas. The main receiving rivers are Tubarão, Urussanga, Sangão and Mãe Luzia.

The areas with the greatest impact include old abandoned coal mines (most with acidic drainage) (Figure 4), pits exposed by open pit mineral exploration, acid lakes, and places with irregular disposal of tailings from coal processing. These areas are close to several urban centres, and some of them are in the process of rehabilitation or rehabilitated. In addition to the mining activity, there is an interface with different sources of pollution such as livestock (pig farming), agriculture, domestic and industrial waste. (Franzen et al, 2021).

**Figure 4 Aerial image shot by a drone of an abandoned area with open pit coal tailings disposal, partially rehabilitated and source of acidic drainage.**

# 3 Data, Results and Discussion

## 3.1 Main environmental impacts that occur in the region

The main environmental impacts that occur in the region are directly related to abandoned mines. On the surface, there are areas where tailings and overburden are disposed of at open pits, under the direct influence of atmospheric conditions. In these cases, the main impact stems from the presence of high concentrations of pyrite associated with tailings and overburden, with the generation of acid mine drainage (AMD), in addition to the presence of heavy metals whose mobility and toxicity are enhanced by the decrease in pH resulting from the AMD process (Mendes et al 2012, Lattuada et al 2009, Netto et al 2013).

Data from monitoring programs maintained by government agencies in Brazil such as CPRM and ANM demonstrate that several drainage courses, generally represented by small streams, which later flow into the main rivers, are strongly affected by these geochemical processes. There are currently 143 surface water monitoring points in the region, including 69 in the Araranguá River Basin, 37 in the Urussanga River Basin, and 37 in the Tubarão River Basin. At these monitoring points, water parameters such as: flow rate, pH, electrical conductivity, dissolved oxygen, total acidity, sulphate, Fe, Mn, and Al were evaluated (GTA, 2022).

About 72.4 % (14,624.8 km) of the river running through the three watersheds are monitored by one of the 143 monitoring points, of which 6.1% (1,241.3 km) of the river receives contributions from areas impacted by coal mining and 66.3% of this amount does not receive these contributions. The stretches of rivers that are outside the limits of the coal basin and/or far from the impacted areas are classified as not monitored and correspond to 27.6% (5,568.2 km).

The stretches of rivers with pH <4.5 represent 63% (781.7 km) of the total extent impacted, so the development of aquatic organisms is not expected in these stretches. Only 12% (143.9 km) of the river stretches show an intermediate condition, with the possibility of the development of some aquatic organisms, and 25% (316.3 km) show good quality (result of pH ≥ 6.0). The values of the river stretch, in percentage, considering only the stretches that are influenced by coal mining (impacted = 1,241.3 km), in relation to the pH parameter are shown in Table 1 and Figure 5.

**Table 1 Quantification of stretches of rivers affected by drainage from abandoned coal mines in the monitored watersheds. Source: GTA (2022).**

| pH range | BHA | | BHU | | BHT | | Total | |
|---|---|---|---|---|---|---|---|---|
| | Length (km) | % | Length (km) | % | Length (km) | % | Length (km) | % |
| IMPACTED | 474 | 8.2 | 265.6 | 17 | 501.3 | 3.9 | 1,241.30 | 6.1 |
| pH < 4.5 | 335.3 | 5.8 | 123.0 | 7.9 | 323.4 | 2.5 | 781.7 | 3.9 |
| 4.5 ≤ pH < 6.0 | 45.0 | 0.8 | 85.5 | 5.5 | 13.3 | 0.1 | 143.9 | 0.7 |
| pH ≥ 6.0 | 94.6 | 1.6 | 57.1 | 3.7 | 164.6 | 1.3 | 316.3 | 1.5 |
| NON-IMPACTED | 2,807.3 | 48.7 | 1,181.1 | 75.9 | 9,395.1 | 73 | 13,385.5 | 66.3 |
| Total Monitored | 3,281.3 | 56.9 | 1,446.7 | 92.9 | 9,896.8 | 76.9 | 14,624.8 | 72.4 |
| Total No Monitored | 2,487.4 | 43.1 | 111.3 | 7.1 | 2,969.4 | 23.1 | 5,568.2 | 27.6 |
| Total length | 5,768.1 | 100 | 1,558.0 | 100 | 12,865.2 | 100 | 20,193.0 | 100 |

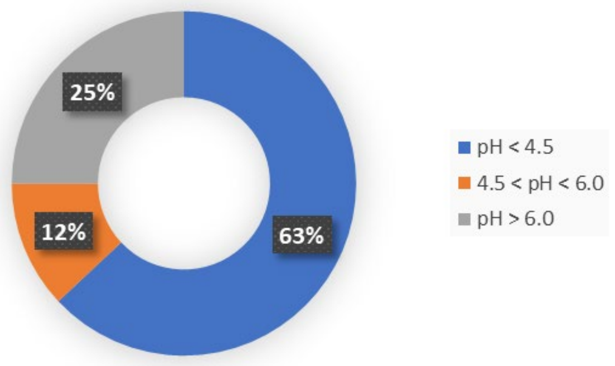


**Figure 5 Percentage of impairment of rivers under the influence of abandoned coal mining areas in relation to pH values. GTA (2022).**

The results of the 2022 monitoring show that most rivers and water courses in the region are highly impacted by acidic drainage, mainly coming from orphaned areas. Furthermore, as demonstrated by Lattuada et al (2009), analyses carried out at Mãe Luzia River, one of the main tributaries of the Araranguá River, showed high levels of Cr, Mn, Fe, Ni, Zn and Cd. The authors corroborate the results of the monitoring, concluding that in several points of the river, mainly in those located close to the abandoned areas, the concentration of metals in sediments and water were found at toxic levels for the bioindicator used in the study (*Daphnia magna*).

The abandoned mines have been causing significant environmental impacts to the aquatic and terrestrial ecosystems over the past several decades. In Figure 6, it is possible to observe in an orbital image the change in the appearance of the water in the Mãe Luzia River downstream of the discharge of effluents from areas that are sources of acidic drainage. The typical reddish aspect of acid drainage in the stream that carries the contaminated effluent from an orphaned mine is noteworthy. Upstream, it is possible to observe that the colour of the water's river is darker (natural colour of river water), becoming more yellowish after the entry of effluents, caused by the presence of dissolved or suspended metals (mainly Fe and Mn oxides). Figure 7 shows in detail the tributary that flows into the Mãe Luzia river causing contamination by acidic waters.

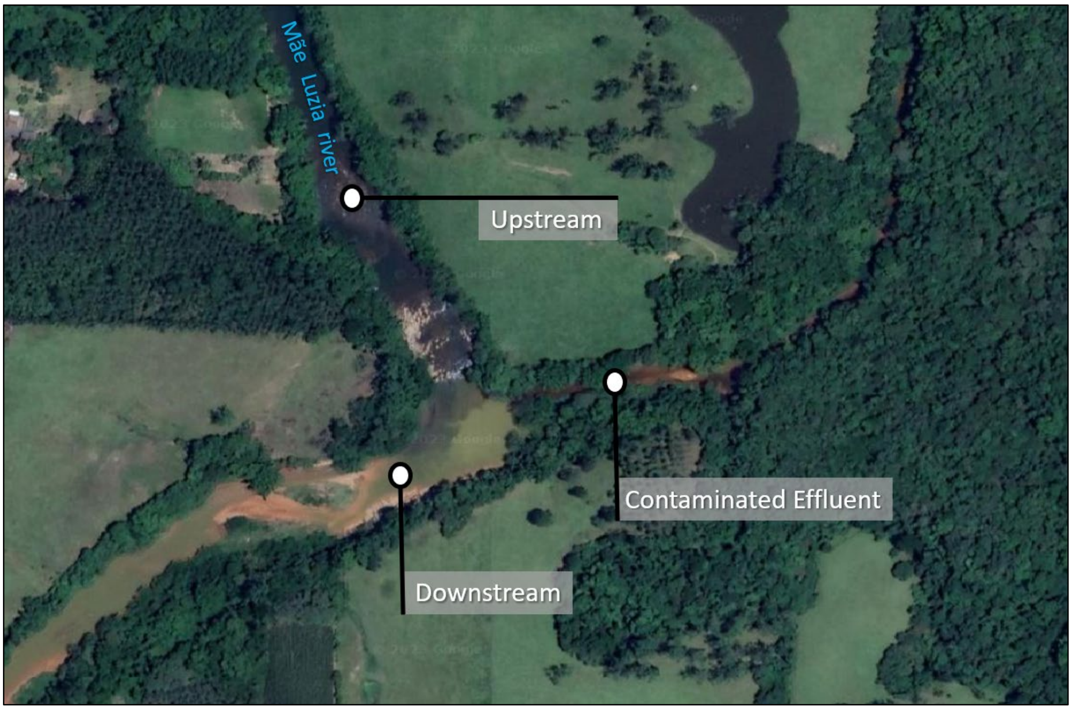


**Figure 6 Confluence of contaminated effluents with the Mãe Luzia River.**

**Figure 7 Aspect of water bodies affected by acidic drainage in orphaned coal mining areas.**

## 3.2 Main social impacts that occur in the region

Social impacts result from deterioration of the water within the three watersheds, which consequently affect activities such as agriculture, public supply, as well as risks for the communities that live close to these water bodies, due to the health risk that these waters can cause. In many cases, these rivers pass through cities and communities, which further increases the likelihood of exposure of the local population to acidic waters. The adjacent soils of abandoned mines and rivers also show a loss of quality; mainly in the chemical and biological aspects, related to the strong decrease in pH, excess of metals such as Fe, Al and Mn, in addition to other heavy metals, which affects the vegetation and biodiversity (Netto et al, 2013).

Another strong social impact resulting from abandoned mines is not visible to the commonwealth. Considering that activity has taken place since the beginning of the 20th century, there are many abandoned underground mine workings, and considering the disorderly exploration at the time, nowadays there is no mapping of these workings. With this, the occurrence of subsidence of houses is frequent, which makes the inhabitants live under constant tension. In addition, on many occasions, tailings from coal mining were used as gravel for paving streets and land, and considering the high sulphur content in this material, there have been cases of spontaneous combustion of the material, causing fires in homes built above this material (Figure 8).

**Figure 8 Houses with subsidence caused by underground mine workings within the urban area of the municipality of Criciúma, and houses built over tailings affected by spontaneous combustion.**

As seen, the abandonment of mines as well as the inadequate disposal of tailings, associated with the disorderly expansion of underground mines and abandoned mine shafts, cause recurrent inconvenience to the local communities. So, it is urgent to establish remediation programs and adequate future uses, which bring a minimum of security both from a structural as well as from a health point of view for the people that are directly or indirectly affected.

## 3.3 Case study I – Area successfully rehabilitated

As explained above, the problems faced by both the local communities and those responsible for rehabilitation of the impacted areas are neither few nor small. Considering the size of the areas, only joint and coordinated work will make the rehabilitation actions of these mines successful. It is clear, therefore, the complexity of the works to be developed in the region, illustrated by the presentation of three cases of rehabilitation, where one has been successful, and the other two have encountered some problems, where the rehabilitation process has not resulted in the desired outcomes.

The rehabilitation case considered successful used the techniques defined in the Term of Reference. In this case, tailings were isolated in compacted clay cells, covered with organic soil and sowed with a mix of grasses. To date, this technique has proved successful in substantially limiting water infiltration and oxygen entry, preventing the oxidation of sulphides in the tailings and consequently the generation of AMD. However, for this technique to be efficient, strict control and management of the species succession at the site is necessary, because the presence of arboreal species, especially those with pivoting roots, has the potential to penetrate the protective layers of the cell, allowing increased water and oxygen ingress.

In the case of this area, periodic maintenance of the vegetation is carried out to limit the development of deeper rooting tree species. Another important action carried out in the rehabilitation works of this area was the construction of a collection channel around the perimeter, which allows contact waters to be collected and directed to a treatment facility. In this way, there is both the rehabilitation of the landscape and the control of impacted waters from leaching, minimizing the off-site release of acidic and contaminated water (Figure 9).

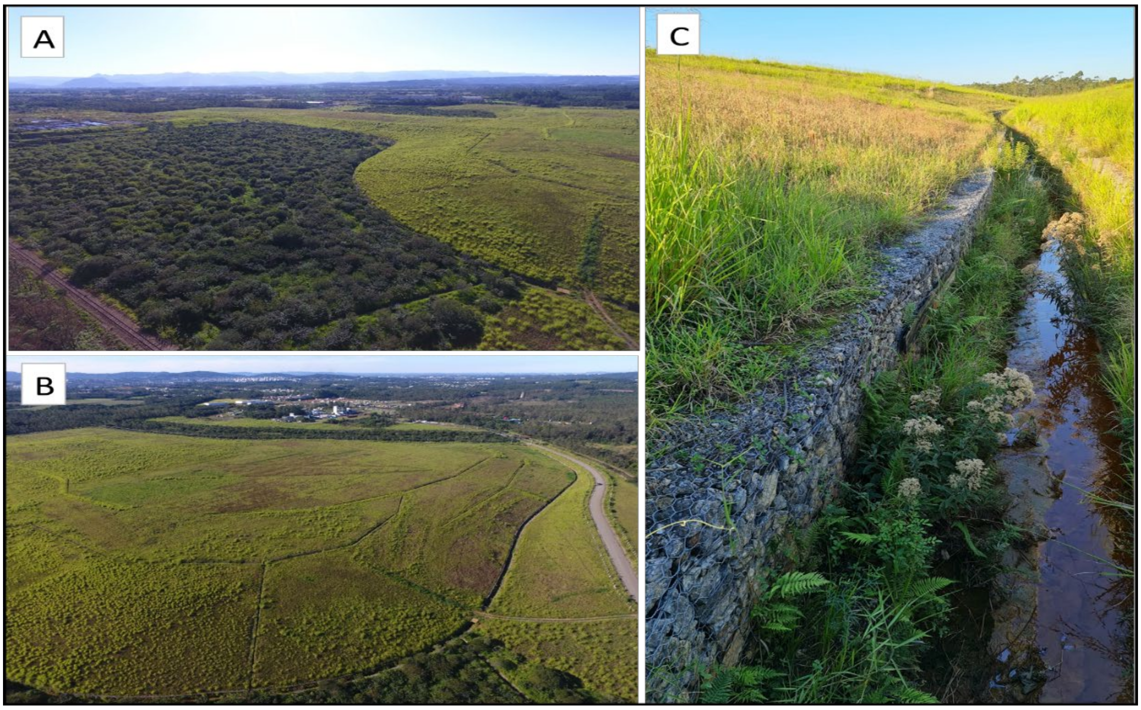


**Figure 9 A and B - Aerial images of the tailing's cells covered by vegetation with grasses and, C - Detail of the channel built in rockfill to collect and direct contact waters to a treatment facility.**

## 3.4 Case study II – Rehabilitated area with not so successful outcomes

The second case study presented here was also rehabilitated using the same Terms of Reference; however, some flaws in the planning, execution and maintenance resulted in poorer outcomes. In this case, the same technique was used: encapsulating the waste in compacted clay cells, covering with 50 cm of limestone, and overlapping with organic soil and peat to allow plant growth. The sowing was done only with grasses; however, natural succession quickly came into play, with the growth of tree species, which likely penetrated the clay cell, resulting in higher rates of water and oxygen ingress. In this case, although the landscape has been rehabilitated, there has some groundwater drainage downstream of the rehabilitated area, which flow acidic waters directly into the adjacent river, negatively impacting the water quality (Figure 10 and 11).

Figure 11 shows the anticipated flow path for shallow groundwater from the rehabilitated area to the adjacent river, and in detail shows one of the points where acidic drainage has been observed discharging into the river. In this location, there is still the possibility that there may be sources of basal groundwater flow, which may be causing the saturation of the tailings cells from bottom to top, which may also cause the oxidation of pyrite present in the tailings. However, more detailed studies still need to be done to confirm or reject this hypothesis.

**Figure 10 Image of the rehabilitated area where it is possible to observe the presence of tree and shrub species that may have penetrated the 50 cm layer of compacted clay that isolates the tailings.**

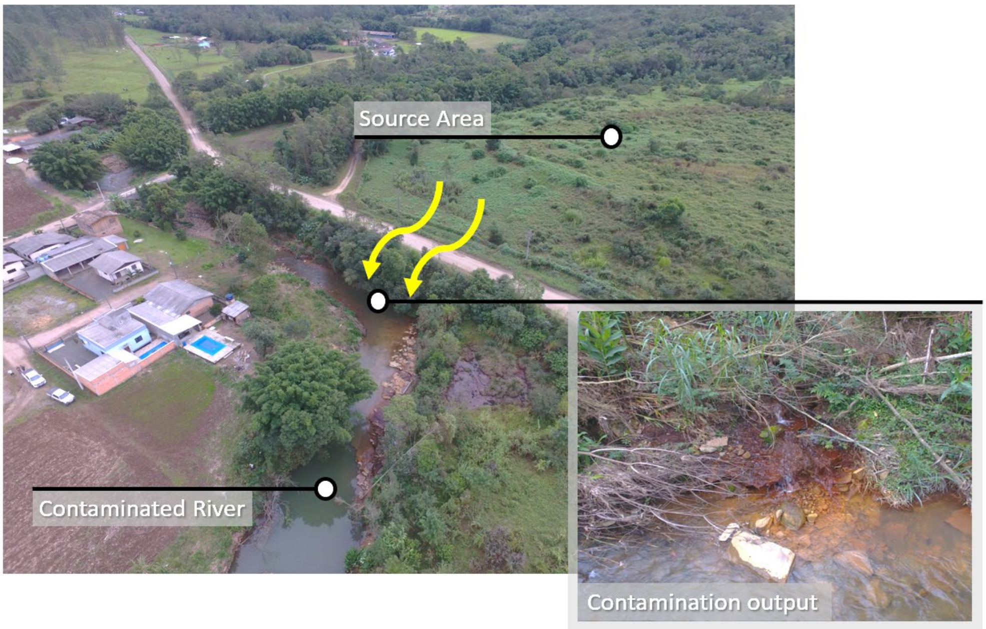


**Figure 11 Emergence of acidic drainage in an area where remediation measures through capping with compacted clay and planting of grasses was unsuccessful, due to emergence of tree species.**

## 3.5 Case study III - Area under rehabilitation that did not adopt the terms of reference

A good example that demonstrates an area that, at first, did not follow the techniques established in the Terms of Reference, is where the tailings were isolated in depth and covered with a layer of non-compacted clay/topsoil of approximately 50 cm in surface, with subsequent planting of *Eucalyptus grandis* (Figure 12). In this area, the clay/soil on the surface was not compacted and the system is not adequate for several reasons. First, *E. grandis* is not a native species in Brazil and therefore is not recommended by the control agencies for the environmental recovery of areas. Second, because it is a pivoting root and fast growth plant, with a strong potential for penetrating the isolation cells, it does not take long for roots to enter the buried waste.

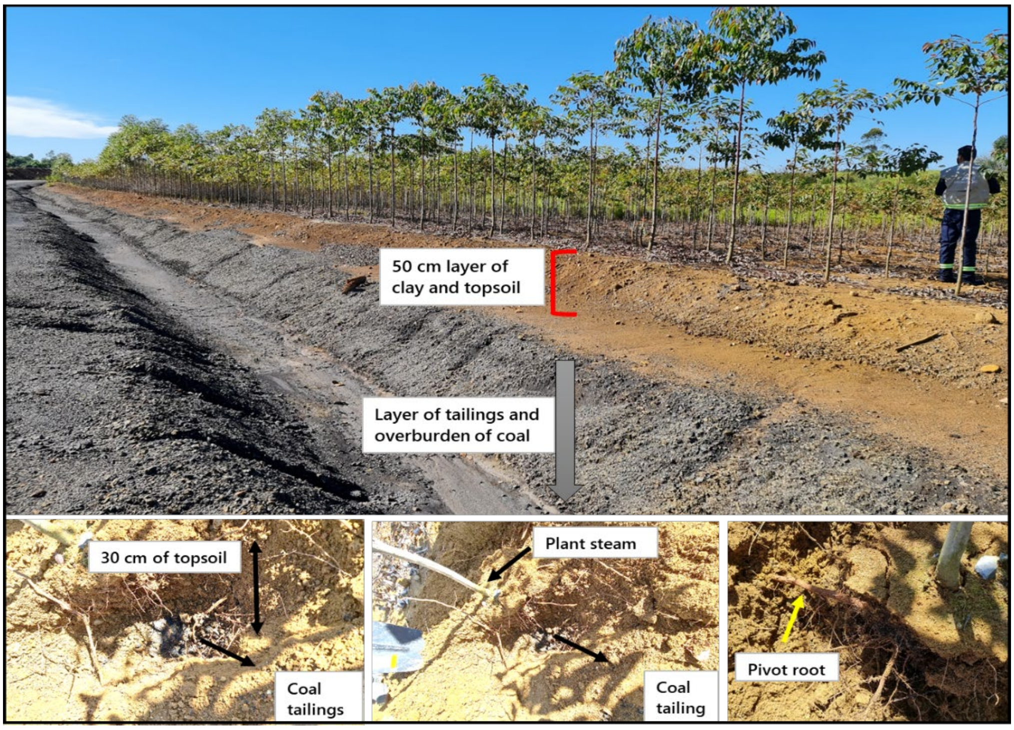


**Figure 12 Rehabilitation of an area with coal tailings covered with 50 cm of clay and topsoil. In detail, the eucalyptus pivoting root coiling, avoiding contact with the tailings.**

An important field observation is the behaviour of *E. grandis* roots. The trees were planted between 1 and 2 years ago and what was observed is that the roots avoided entering the layer where the tailings are located. Figure 12 clearly shows a root movement in the 50 cm layer of clay, indicating that, despite the good resistance of the specie to acidic soils, the plant seeks strategies to keep away from the inhospitable conditions provided by the tailings.

In this case, there is an initial establishment of plants, with a specific rehabilitation of the landscape. However, does not tackle the geochemical problem of the acidic drainage, which could both suppress plant growth and produce acidic and toxic leachates generating both superficial and underground runoff. Therefore, continuous monitoring of the area will be carried out to assess whether the species will only maintain their roots in the 50 cm layer of clay/topsoil, which will probably affect the growth and development of the plants, or whether in fact they will penetrate the layer of tailings, and what will be the behaviour if this occurs. Will the plant withstand the limiting conditions of the tailings layer? Will it tolerate the inhospitable conditions of this layer? Time will provide answers to these questions.

## 3.6 Main challenges to be overcome for future rehabilitation and future uses

As demonstrated, there are several challenges that still need to be overcome so that the actions of the ANM and CPRM become more effective for rehabilitation and adequate post-closure of the numerous areas that still need to be rehabilitated. We consider that only the first steps have been taken, with establishment of a first Terms of Reference to give “a guide” for rehabilitation of the areas. However, with the beginning of the works we were able to verify that this first set of guidelines does not seem to be so effective and sustainable over time. Initially the isolation of non-inert waste in compacted clay cells was adequate, but with time and the development of ecosystem succession with larger species, problems with root penetration of the barrier layers occur, leading to increased rates of water and oxygen ingress. These are great examples that there is no ‘one-size-fits-all’ solution and each case needs to be diagnosed in detail before proposing solutions

A new approach that has been studied by the ANM and CPRM, as an alternative to the initial Terms of Reference, is the removal of pyrite from coal tailings before their discharged. Several studies have demonstrated the feasibility of treating coal tailings, either to accelerate the oxidation kinetics of pyrite with ozone and hydrogen peroxide, aiming to decontaminate the tailings (Gomes et al. 2022), or for separation by density using bromoform, with subsequent leaching with water and acetone (Oliveira 2016) or lithium heteropolytungstate (Ghedin et al. 2022).

It would be more economical to use inert waste materials for rehabilitation of abandoned and degraded areas. In these case they could even be used as components of Technosols, associated with other materials such as organic compounds, other types of inert waste, which could, over time and through pedogenetic processes to become healthy soils, which would allow the restoration of ecosystems, giving more sustainability to the rehabilitation processes of mined areas. This may facilitate the use of abandoned mines for agriculture, forestry, creation of parks and leisure areas without worrying about the issue of acidic drainage and contamination of water and soils. Recovering not only the local landscapes, but also the quality of life for local community members.

# 4 Conclusions

The challenges for rehabilitation of areas affected by abandoned coal mines, as well as promoting a fair post-closure transition in the southern region of the state of Santa Catarina are considerable given the size of the areas that still need be rehabilitated. The solutions require a collaborative effort considering regulatory, judicial, technical, and operational matters. The Union has been making efforts to build viable alternatives, which can provide guidelines not only for the Union's areas of responsibility, but also for the areas whose responsibility for rehabilitation is that of private companies. It is therefore necessary to recognize and replicate the measures that were successful, as well as having the humility to learn from mistakes, as well as establishing partnerships with national and international organizations for the application of best global practices. One of the main actions carried out by the ANM was the publication of Resolution nº 68/2021 (ANM 2021), which established the mandatory preparation and execution of Mine Closure Plans by all companies operating mining areas, which will certainly reduce the number of abandoned mines not only in the coal region, but throughout the country. However, the areas that remain abandoned will continue to be monitored and inspected by the ANM. With the techniques of tailings decontamination to remove pyrite, combined with the creation of healthy soils from these tailings (such as technosols), it is expected that will be possible to conciliate the rehabilitation of these areas with gradual decontamination of the water courses and soils. The main purpose in to enable to return these areas to the local communities in a healthier condition, which will allow an adequate and sustainable future use considering the environmental, social, and economic aspects.

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