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Research paper

Soil bioengineering interventions for erosion control in hydroelectric power plant reservoirs

Intervenções de engenharia natural para controle de processos erosivos em reservatórios de usinas hidrelétricas

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ABSTRACT: The banks of water reservoirs are highly susceptible to erosion processes. Thus, interventions to mitigate and control erosion must be performed which are traditionally done using traditional engineering techniques (gabions, riprap, etc.), which have high execution and maintenance costs and high environmental impact. Soil Bioengineering is a viable alternative since it considers technical criteria in dimensioning works and values ecological and environmental factors. The objective of this work is to present a Soil Bioengineering intervention performed to stabilize and control erosion processes in a section of the Itá Hydroelectric Power Plant (Itá HPP) reservoir. The area is located in the Itá HPP reservoir and presents erosion processes with soil loss and transport causing reservoir silting. The section is 169 m long and was divided into subsection 1 (vegetated geotextile wall, vegetated palisades, planting of herbaceous, shrub and tree seedlings), and subsection 2 (vegetated coconut wall, vegetated palisades, planting of herbaceous, shrub and tree seedlings). The project was prepared in June 2020 and the work was performed in June-August 2021. The techniques were then monitored. The plants showed excellent survival and growth rates, the structures did not move or settle, and no erosion was detected. Soil Bioengineering techniques proved to be technically efficient in mitigating erosion processes on the banks of the Itá HPP reservoir. In addition to the technical benefits, the implemented solutions improved ecological and environmental functions, with reestablishment of native vegetation and an increase in floristic and faunal biodiversity.

Keywords: Nature based solutions, shoreline stabilization, land restoration, reservoir siltation.

RESUMO: *As margens de reservatórios de água são muito susceptíveis à ocorrência de processos erosivos. Para mitigar e controlar erosões devem ser realizadas intervenções que tradicionalmente são executadas com técnicas de engenharia (gabiões, enrocamentos, etc.), que têm altos custos de execução, manutenção e alto impacto ambiental. A Engenharia Natural é uma alternativa viável visto que considera critérios técnicos no dimensionamento das obras e valoriza fatores ecológicos e ambientais. O objetivo deste trabalho é apresentar uma intervenção de Engenharia Natural executada para estabilização e controle de processos erosivos num trecho do reservatório da Usina Hidrelétrica de Itá. A área está localizada no reservatório da UHE Itá e apresenta processos erosivos com perda e transporte de solo causando assoreamento do reservatório. O trecho tem comprimento de 169 m e foi dividido no subtrecho 1 (solo envelopado, paliçadas de madeira, plantio de mudas herbáceas, arbustivas e arbóreas) e no subtrecho 2 (parede de biorretentores de coco, paliçadas de madeira, plantio de mudas herbáceas, arbustivas e arbóreas). O projeto foi elaborado em junho/2020 e a obra foi executada em junho-agosto/2021. Na sequência foi realizado o monitoramento das técnicas. As plantas apresentaram excelentes taxas de sobrevivência e crescimento, as estruturas não sofreram movimentações ou recalques e não foram detectadas erosões. As técnicas de Engenharia Natural mostraram-se tecnicamente eficientes para mitigar os processos erosivos nas margens do reservatório da UHE Itá. Além dos benefícios técnicos, as soluções implementadas trouxeram melhorias nas funções ecológicas e ambientais, com restabelecimento de vegetação autóctone e aumento da biodiversidade florística e faunística.*

Palavras-chave*: Soluções baseadas na natureza, estabilização de margens, recuperação de áreas degradadas, assoreamento de reservatórios.*

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INTRODUCTION

Water reservoirs, whether natural or artificial, are highly susceptible to marginal erosion processes. This problem is recurrent worldwide and is even more intensified in countries with tropical and subtropical climates, such as Brazil, due to the uneven distribution of precipitation, with large volumes of rain concentrated in a few months of the year and the presence of soils with well-developed and deep profiles. A combination of these factors favors erosion processes occurring on the banks of water reservoirs in Brazil. In addition, two processes occur in artificial reservoirs, regardless of their size, namely: erosion on the banks and sedimentation on the bottom (Maciel Filho; Nummer, 2014).

The main factors which trigger erosion on the banks of reservoirs are wave action and fluctuations in the reservoir's operating level, which occur on a daily to annual time scale (Dewes, 2023). The continuous action of waves on reservoir slopes results in two main effects (ASDSO, 2014). The first effect is beaching, where soil erosion occurs and is subsequently transported and deposited on the slope base, in turn forming a very flat area called an abrasion and sedimentation platform with a very steep slope or escarpment upstream (Maciel Filho; Nummer, 2014). These platforms can be large and subject to mass movements. The second effect causes rapid degradation of the protection covering the slopes. Therefore, these protective structures must be frequently monitored and repaired or replaced if damaged (ASDSO, 2014).

Another factor of special relevance in addition to the waves action on the banks is the influence of the annual reservoir oscillation. The waves stress and erode the slopes at the elevation at which the water level is currently located. As the level fluctuates throughout the year, the erosion processes follow this oscillation and erode different sections of the slope located between the maximum and minimum operating levels of the reservoir. The greater the number of oscillations during the year, the greater the number of times the waves will reach different levels and the greater the tendency for the slopes to wear out (Dewes, 2023). Different erosion rates can also occur at different elevations on the slope, depending on how long the water level remains in a given position (Bao *et al.*, 2015; Hampton *et al.*, 2004; Su *et al.*, 2017), as well as the susceptibility of the material to erosion and the geometric characteristics of the slope. Therefore, the banks of reservoirs are highly susceptible to erosion processes which result in loss of stability.

The loss of area related to the strip of riparian vegetation (Permanent Preservation Area) and of neighboring owners (creditors of possible compensation) causes environmental and economic losses which are difficult to quantify considering the numerous factors involved. Another important factor is the great anthropic pressure on the marginal areas of reservoirs, namely agricultural activities, enterprises and leisure spaces. All these associated factors contribute to reduce the useful life of the hydroelectric project due to silting, loss of native vegetation cover, reduced biodiversity, alterations in water quality, eutrophication, among others (Dewes, 2023; Dewes *et al.*, 2021).

Then, in order to mitigate erosion processes and minimize the losses described, the entrepreneur responsible for the reservoir is required to technically intervene to comply with the Environmental Plan for Conservation and Use of the Reservoir Surrounding Area, in addition to maintaining a riparian forest strip that is currently 30 m wide, according to the New Brazilian Forest Code (Brazil, 2012).

Therefore, interventions must be performed to mitigate and control erosion processes

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on the banks of reservoirs, especially in the sections classified as priority areas for erosion monitoring activities in the reservoir. Despite this, controlling and mitigating this erosion is still very incipient, mainly due to the high costs of the works. However, when it is conducted, it is usually done using traditional engineering techniques such as gabions, riprap, concreting, geocells, soil-cements, and geotextiles (among others), which have high execution and maintenance costs (Coppin; Richards, 2007; Sales, 2017; United States Department Of Agriculture (USDA - NRCS), 2014). These techniques have a high environmental impact, since they do not value the ecological and environmental characteristics of the intervention site (Dewes; Sousa; Sutili, 2018). Furthermore, the search for sustainable, low-impact, and economically viable technical solutions has gained prominence in recent years in a context of promoting the green economy, sustainability, and nature-based solutions.

Soil Bioengineering techniques are a viable alternative to traditional techniques, since in addition to taking into account technical criteria in the design of works, they also value ecological and environmental factors (Coppin; Richards, 2007; Sousa; Sutili, 2017). Soil Bioengineering mainly uses living building materials (seeds, plants, plant parts, etc.) which may or may not be combined with inert materials. It can be used as a substitute, but mainly as a useful and sometimes necessary complement to classical Civil Engineering techniques (Schiechtl, 1980). Soil Bioengineering techniques can be applied to solve geotechnical and hydraulic instability problems, and control of surface erosion processes. To this end, the solutions involve designing ecosystems in dynamic equilibrium (Sousa, 2015; Sousa *et al.*, 2020; Sousa; Sutili, 2017).

Biological knowledge of plants is used to give them biotechnical properties for use in interventions to restore degraded areas (Coppin; Richards, 2007; Durlo; Sutili, 2014; Morgan; Rickson, 1995). Thus, plants to be used for Soil Bioengineering interventions are selected based on technical criteria, as well as ecological and landscape criteria (Sousa, 2015). These are techniques which cause low environmental impact (De Antonis; Molinari, 2007; Venti *et al.*, 2003), present more flexible and permeable construction schemes which can be more easily integrated into nature and do not experience soil settlements or movements, and also do not alter the hydraulic conductivity of the soil (Sousa, 2015). Furthermore, Soil Bioengineering offers more economical construction solutions than traditional solutions (Bonatti; Marongiu, 2013; Fernandes; Freitas, 2011; Schiechtl; Stern, 1996; Studer; Zeh, 2014).

Analyses performed in Brazil show that interventions using Soil Bioengineering techniques can cost approximately 50% less than classic interventions (Sousa *et al.*, 2021; Sousa; Dewes; Sutili, 2018). This reduction in execution costs is related to the fact that Soil Bioengineering works normally require less heavy equipment for earthmoving work, and as a result their cost is lower and they have smaller environmental impacts than conventional works (Lewis, 2000). Moreover, the use of natural materials, such as soil, stone, wood and plants (which are normally available at the intervention site) reduces execution costs (Bloemer *et al.*, 2015; Sotir; Gray, 1992; Venti *et al.*, 2003).

The objective of this work is to present a Soil Bioengineering intervention performed to stabilize and control erosion processes in a section of the Itá Hydroelectric Power Plant (Itá HPP) reservoir.

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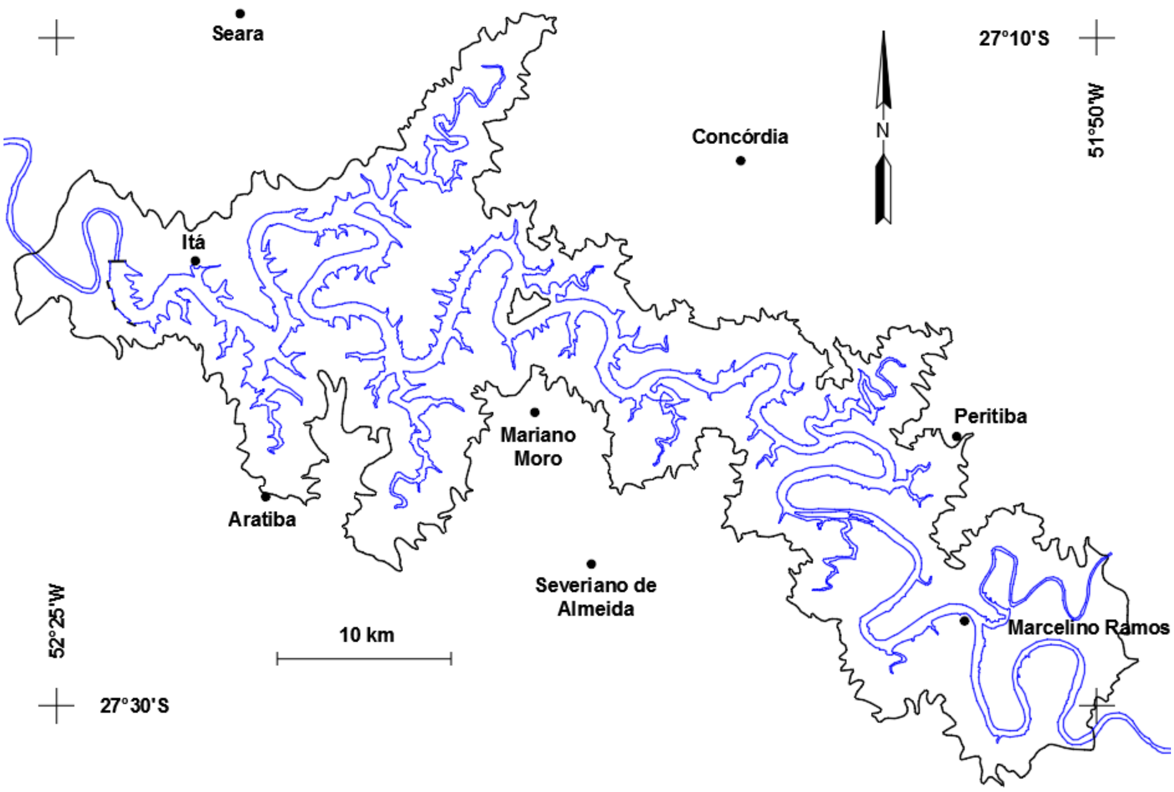
MATERIAL AND METHODS

DESCRIPTION OF THE STUDY AREA

The study area is located in the Itá HPP reservoir. The plant is located in southern Brazil, specifically on the Uruguay River between the states of Santa Catarina (SC) and Rio Grande do Sul (RS). The plant's reservoir has a surface area of 141 km² and a perimeter of 760 km when the level is at its maximum level, as can be seen in **Figure 1**.

Figure 1. Perimeter of the Itá HPP reservoir (blue) and directly affected area (black)



Source: Dewes, 2019.

This perimeter is the result of the region's rugged and jagged terrain, forming large adjacent arms and numerous lateral extensions to the main body of the reservoir. The reservoir's maximum normal operating level is 370 m above sea level. The water level oscillation amplitude is approximately 6 m, with the minimum operating level being 364 m above sea level (Dewes, 2023).

The slope stability analysis performed during the feasibility studies of the project showed that the soil thickness along the reservoir is reduced, generally varying up to a maximum of 10 m in depth, although it can reach up to 15 m (CNEC, 1989). The safety factors obtained for different points around the reservoir classify 30% of the slopes as stable ($\alpha < 15°$); 30% as likely to present instability ($15° \leq \alpha \leq 20°$); and 40% as unstable or potentially unstable ($\alpha > 20°$).

The soils commonly found here have low permeability with a clayey composition,

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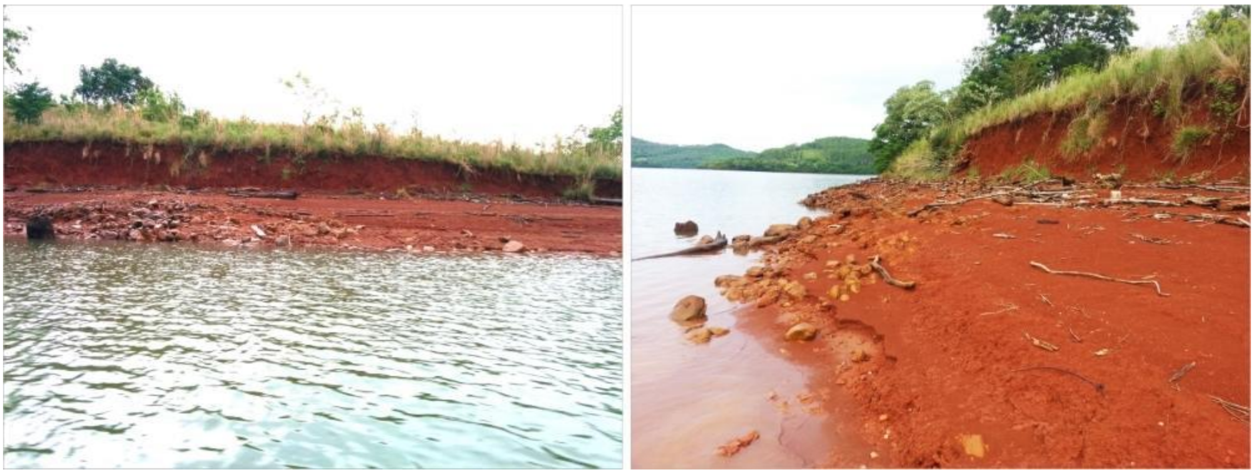
which often present blocks of rock immersed in the morphological profile (Dewes, 2023).

The study area is part of the subtropical Cfa climate according to the Köppen climate classification, being temperate, rainy, humid environment with large variations in average temperatures throughout the year. The average annual temperature is above 18ºC and the average temperature of the hottest month (January) exceeds 22ºC. The coldest month (July) has an average in the range of 3ºC - 18ºC. The average annual precipitation remains between 1600 mm and 1900 mm (Alvares *et al.*, 2013).

The intervention section is 169 m long, has an upper slope with a variable inclination between 38° and 60° (average of 46.8° ± 9.3°) and a variable height between 0.8 m and 3.5 m (average of 1.9 m ± 1.2 m). The lower slope has an average inclination of 7.5° ± 0.9°, with a maximum inclination of 9° and a minimum of 7°. The intervention section, represented in **Figure 2**, was monitored for the presence of erosion processes, with two topographic monitoring sections installed. Small landslides and bank retreat caused by soil loss from the upper slope were observed at the site, as well as deepening of the lower slope, indicating soil loss and transport into the reservoir, causing silting.

Figure 2. Conditions of the intervention section with occurrence of erosion processes



Source: Rita Sousa and Junior Dewes, 2017 and 2018 (personal file).

There are no plants in the area influenced by the oscillation of the reservoir's operating level in the study section. This is due to the constant action of the waves which do not allow plant fixation and development, since they promote continuous soil removal. This condition can be observed in **Figure 2**.

DESCRIPTION OF THE INTERVENTION TECHNIQUES

The intervention section has a total length of 169 m and was divided into two sub-sections according to their geometric characteristics. Sub-section 1 is 57 m long and the following Soil Bioengineering techniques were specified: vegetated geotextile wall, vegetated palisades, herbaceous, shrub and tree seedling planting, as can be seen in **Figure 3**.

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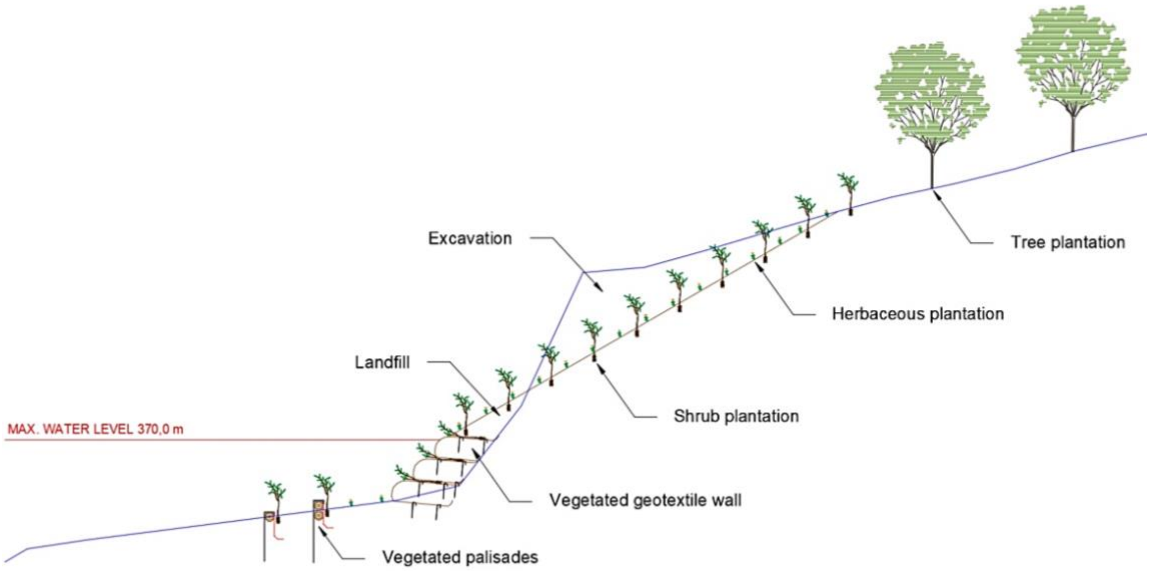
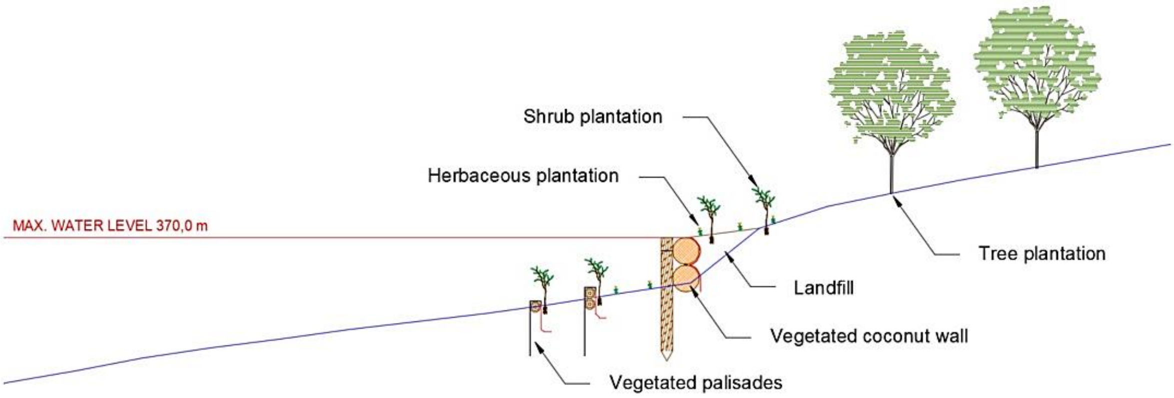
Figure 3. Soil Bioengineering techniques designed for sub-section 1



Subsection 2 has 112 m of intervention, and the following techniques were specified: vegetated coconut wall, vegetated palisades, herbaceous, shrub and tree seedling planting, as can be seen in **Figure 4**.

Figure 4. Soil Bioengineering techniques designed for sub-section 2



The project included reshaping the upper slope and limestone application in both subsections prior to implementing the techniques.

The vegetated geotextile wall and the coconut wall aim to protect and stabilize the upper slope base from erosion processes caused by wave action and fluctuations in the reservoir's water level. Thus, the structures function as living physical barriers which prevent the erosion process from progressing and consequently the banks from receding and loss of the Permanent Preservation Area. The vegetated geotextile wall consists of overlapping several soil layers wrapped or "enveloped" by a geotextile, with seedlings arranged between these layers. The coconut wall consists of applying two 100% coconut fiber rolls superimposed and applied longitudinally along the reservoir shoreline.

Wooden palisades act as a protective element against wave action and aim to retain

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sediments transported by surface erosion of the natural terrain and the upper slope. They consist of the longitudinal application of wooden logs combined with geotextiles along the reservoir shoreline.

All techniques must be combined with an application of shrub seedlings, which increases their stabilizing action as the root systems of the plants develop.

Herbaceous and shrub seedlings were planted in order to cover and superficially protect the exposed soil resulting from the slope re-enhancing in both intervened sections. Planting tree seedlings aims to promote increased biodiversity in the riparian zone through enrichment of native forest species.

The species used in the interventions were produced in the Botanical Garden of the Itá Hydroelectric Power Plant. All the species specified are autochthonous to the Upper Uruguay River region and were observed naturally recolonizing areas of the Itá HPP (on the banks of the reservoir and downstream of the main dam). Therefore, the shrub species used were: *Phyllanthus sellowianus* (Klotzch) Müll Arg. (white sarandi), *Gymnanthes schottiana* Müll Arg. (red sarandi), *Mimosa pigra* L. (giant sensitive tree), *Sesbania virgata* (Cav.) Pers. (wand riverhemp) and *Calliandra brevipes* Benth. (pink powderpuff); and the herbaceous species used were *Sphagneticola trilobata* (L.) Pruski (yellow creeping daisy) and *Arachis repens* Handro (creeping peanut). The following tree species were also used: *Bauhinia forficata* Link (brazilian orchid tree), *Eugenia involucrata* DC. (cherry of the Rio Grande), *Eugenia uniflora* L. (pitanga), *Inga marginata* Willd. (guabilla), *Inga vera* Willd. (river koko), *Psidium cattleyanum* Sabine (cattley guava) and *Schinus terebinthifolius* Raddi (brazilian peppertree).

RESULTS AND DISCUSSION

The team from the Soil Bioengineering Laboratory (*Laboratório de Engenharia Natural - LabEN*) at UFSM prepared the project during the month of June 2020 for the treatment of a 169 m stretch of the Itá HPP reservoir shoreline. At the beginning of 2021, the entrepreneur responsible for the operation of the Itá HPP hired the executing company, the work began in June 2021 and its completion occurred in August 2021, with a duration of approximately 2 months.

Figure 5 and **Figure 6** show the evolution of subsections 1 and 2, respectively, considering the situation after the work in September 2021 until December 2022, approximately 16 months after its execution.

An inspection was performed immediately after the interventions to verify the compliance of the techniques. It was found that the Soil Bioengineering techniques were well executed and the construction materials met the specifications determined in the project.

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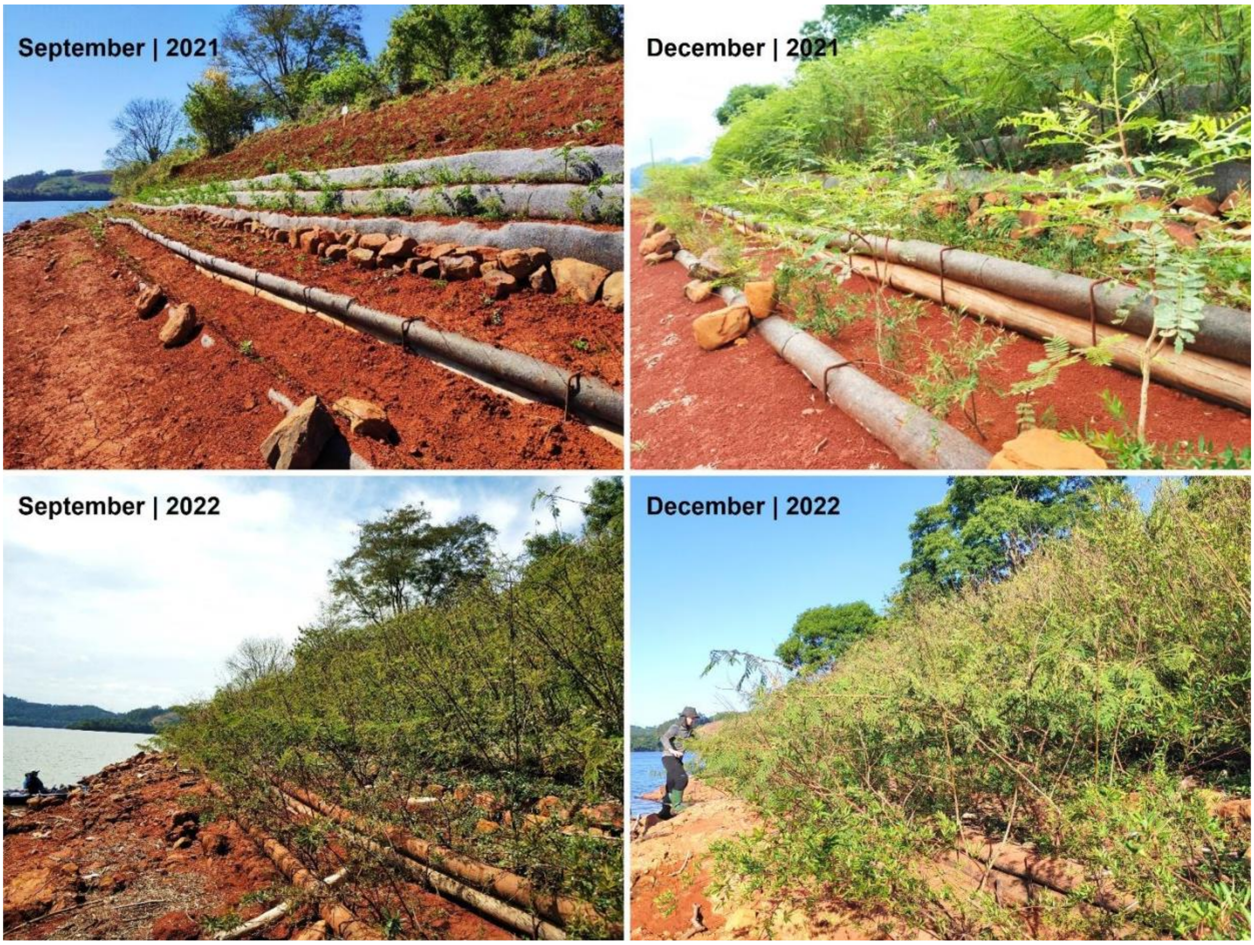
Figure 5. Evolution of Soil Bioengineering techniques consisting of vegetated geotextile wall and palisades combined with seedlings in subsection 1 between 2021 and 2022



Source: Rita Sousa and Junior Dewes, 2021 and 2022 (personal file).

The techniques were visually monitored in the following months. It was found that the herbaceous, shrub and tree seedlings presented excellent survival and growth rates, as can be seen in **Figures 5** and **6**, and the structures did not undergo movement or settlement. No erosion processes were also detected.

Therefore, the Soil Bioengineering techniques proved to be technically efficient in mitigating erosion processes on the banks of the Itá HPP reservoir. In addition to the technical benefits, the implemented solutions provided improvements in ecological and environmental functions, with reestablishment of autochthonous vegetation and an increase in flora and fauna biodiversity. Since Soil Bioengineering interventions have increasing technical efficiency over time, it is expected that they will continue to meet the criteria for which they were designed.

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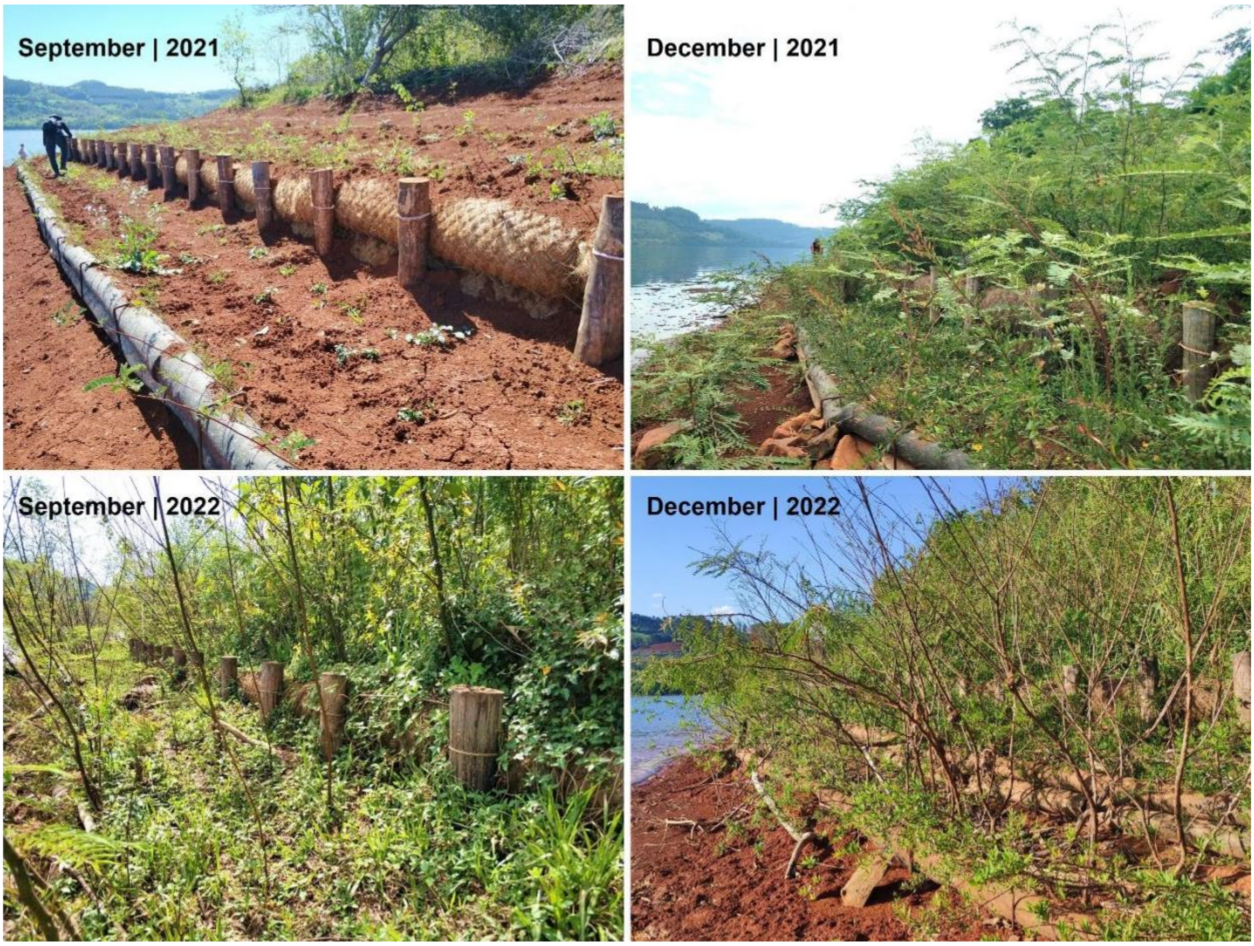
Figure 6. Evolution of Soil Bioengineering techniques consisting of vegetated coconut wall and palisades combined with seedlings in subsection 2 between 2021 and 2022



Source: Rita Sousa and Junior Dewes, 2021 and 2022 (personal file).

CONCLUSION

The use of Soil Bioengineering techniques in reservoirs aims to mitigate erosion processes on the banks which contribute to silting and reducing the useful life of the reservoir.

The specified solutions aim to cover and protect the banks with native rheophyte species which occurred naturally on the river slopes of the Uruguay River before construction of the Itá HPP.

Reintroducing original flora is essential since it favors spontaneous colonization of the reservoir banks, as well as downstream of the plant due to the creation of new areas that are sources of propagules.

The combination of inert materials with the plants aims to protect and provide structural support for their establishment and development. Without this initial support, these new areas would not be able to establish themselves due to the constant adverse action of the waves and the operating regime of the reservoir.

Finally, it is important to highlight that the Soil Bioengineering techniques used at the Itá HPP provided innovative and technically viable solutions for recovery projects in areas

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surrounding hydroelectric plant reservoirs and can be used independently or in addition to traditional engineering techniques. In addition, their use provides ecological, economic, environmental and aesthetic advantages.

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