# NATURE-BASED SOLUTIONS AS A STRATEGY FOR URBAN RESILIENCE: IMPLICATIONS FOR LAND USE PLANNING IN DOIS CÓRREGOS (SP)

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**ABSTRACT**– This study analyzes the evolution of an erosive feature associated with the interaction between natural factors and inadequate land use, aiming to evaluate its dynamics and environmental drivers through multitemporal analysis (2010–2023), land use and land cover data (MapBiomas), geological and pedological information (CPRM/SGB), SRTM DEM, rainfall series (2016–2024), and field verification. The findings also show that erosion is not linked to recent urbanization, but to the interaction between physical factors and land use, reinforcing the importance of the watershed scale in territorial planning. Integrated strategies based on Nature-based Solutions are shown to be more effective for erosion mitigation and enhancing socio-environmental resilience.

**Keywords** – Green infrastructure. Soil degradation. Territorial planning. Water erosion.

**RESUMO** – Este estudo analisa a evolução de uma feição erosiva associada à interação entre fatores naturais e uso inadequado do solo, tendo como objetivo analisar sua dinâmica evolutiva e condicionantes ambientais por meio de análise multitemporal (2010–2023), dados de uso e cobertura (MapBiomas), informações geológicas e pedológicas (CPRM/SGB), MDE SRTM, séries pluviométricas (2016–2024) e verificação em campo. Os resultados indicam que a erosão não está ligada à urbanização recente, mas à interação entre relevo, solo, uso do solo e eventos extremos de chuva, que intensificam o escoamento superficial. A análise reforça a importância da escala de microbacia no planejamento e demonstra que estratégias integradas, baseadas em Soluções Baseadas na Natureza, são mais eficazes para mitigação e aumento da resiliência socioambiental.

**Palavras-Chave** – Degradação do solo. Erosão hídrica. Infraestrutura verde. Gestão territorial.

## 1. INTRODUCTION

Erosion processes are a major source of environmental degradation and socioeconomic impacts in both urban and rural areas. Soil dynamics, influenced by factors such as topography, parent material, climate, and land use, directly affect soil susceptibility to erosion (Macedo et al., 2019). Furthermore, inadequate water management, especially in contexts of increasing soil sealing, compromises aquifer recharge and intensifies problems such as flooding and water quality degradation (Yıldız, 2024), highlighting the need for integration between geology, drainage, and urban planning to increase resilience.

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From a theoretical standpoint, resilience can be understood as the capacity of social-ecological systems to absorb disturbances, reorganize, and continue functioning while undergoing change (Folke, 2006), a perspective that situates erosion not as an isolated geomorphological event but as an outcome of the interaction between physical processes and human intervention in the landscape. This interaction has been intensified by global land-use change, which over recent decades has increased pressure on soils, water resources, and ecosystem services worldwide (Foley et al., 2005), reinforcing the relevance of analyzing erosive dynamics through an integrated, multiscale lens.

Gully erosion, in particular, represents one of the most advanced and destructive forms of soil degradation, resulting from the concentration of surface runoff into channels that progressively deepen and widen, frequently as a consequence of land-use change, vegetation removal, and the absence of conservation practices (Poesen et al., 2003). Research reinforces that the rates and impacts of gully erosion tend to intensify under the combined pressure of land-use intensification and rainfall variability, calling for research approaches capable of integrating geomorphological, hydrological, and land-management dimensions (Poesen, 2018).

In this context, the municipality of Dois Córregos (SP) presents conditions favorable to the occurrence of erosive processes, due to the predominance of soils with low permeability, rugged terrain, and agricultural use associated with the absence of conservation practices. Located within the Bauru Aquifer, the municipality requires attention regarding the protection of water resources (Iritani and Ezaki, 2014).

In the district of Guarapuã, these conditions manifest significantly, with the development of erosive features that affect infrastructure and local drainage dynamics. Understanding their evolution, considering geological, pedological, topographical, and land-use factors, is fundamental to informing territorial planning actions.

Given this scenario, the intensification of erosive processes highlights the need for integrated analyses, demonstrating that their occurrence is not restricted to recent urbanization but rather to the dynamics between topography, soil, and extreme events. Within this framework, Nature-based Solutions (NbS), defined as actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively while providing biodiversity and human well-being benefits (Cohen-Shacham *et al*., 2016), emerge as a strategy capable of reconciling erosion mitigation with broader goals of urban and territorial resilience.

Given the above, this study aims to analyze the evolution of an erosive feature in the district of Guarapuã, municipality of Dois Córregos (SP), through multitemporal analysis (2010–2023) integrating land-use and land-cover data, geological and pedological information, topographic

modeling, and rainfall series (2016–2024), in order to identify the environmental and anthropogenic drivers underlying its formation. As a specific contribution, the study seeks to demonstrate the relevance of the micro-basin scale and of Nature-based Solutions as strategies for territorial planning aimed at increasing socio-environmental resilience in erosion-prone areas.

## 2. MATERIALS AND METHODS

The study was conducted by integrating spatial, environmental, and climatic data, using geotechnologies, to analyze erosion dynamics in the Guarapuã district, municipality of Dois Córregos (SP), located within the Areia Branca Stream micro-basin (Tietê-Jacaré Basin). The study is based on the hypothesis that the intensification of erosion processes is associated with the interaction between physical environment characteristics, inappropriate land use, and extreme precipitation events, contributing to increased surface runoff, reduced infiltration, and impacts on the availability and quality of water resources.

The analysis of the evolution of the erosional feature was conducted through multitemporal image interpretation (2004–2023), combined with the characterization of land use and land cover (MapBiomas), soil classes (IBGE), and topographic analysis based on the SRTM Digital Elevation Model (30 m), processed in a GIS environment (QGIS), allowing for the assessment of relief morphology and surface runoff dynamics. In this context, the research seeks to understand how the interaction between natural and anthropogenic factors controls the evolution of erosion and how these dynamics can inform more effective strategies for territorial planning and water management.

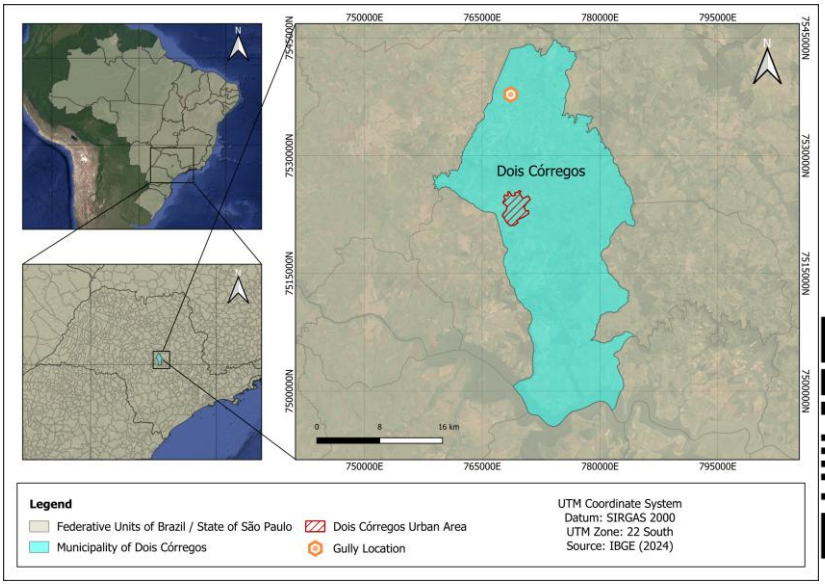
The climate analysis was conducted using rainfall series from 2016 to 2024, obtained from official databases, with data organization, consistency, and processing performed in a GIS environment. Annual totals, historical averages, and percentage anomalies were calculated, allowing for the identification of deviations from expected climate behavior. This integrated approach made it possible to assess the influence of precipitation on surface runoff dynamics, especially in areas with low infiltration, by relating climate patterns to the previously analyzed characteristics of topography, soil, and land use.

## 3 RESULTS AND DISCUTIONS

### 3.1 Characterization of the Municipality of Dois Córregos

The municipality of Dois Córregos is located in the central region of the state of São Paulo, with an area of approximately 633 km² and a population of 24,510 inhabitants (IBGE, 2022). Most of the territory lies within the Tietê-Jacaré River Basin, where agricultural and livestock activities

predominate. The study area is located in the district of Guarapuã, in an urban-rural transition zone, within the Córrego da Areia Branca microbasin (Figure 1).




This article is available in **Portuguese** via the QR code.

Figure 1 – Location of the municipality of Dois Córregos, São Paulo

### 3.2 Evolution of the erosion process

Multitemporal analysis revealed the progressive development of erosion in the Guarapuã district, with initial signs of rutting and surface instability beginning in 2010, evolving into a well-established gully starting in 2016. The gully is expanding both laterally and longitudinally, associated with the removal of vegetation cover and the concentration of surface runoff.

Between 2021 and 2023 (Figure 2), sporadic establishment of pioneer vegetation is observed, indicating initial regeneration processes. However, the field survey conducted in 2025 reveals the reactivation of erosion, characterized by the exposure of soil horizons, bank instability, and the absence of upstream runoff control structures, indicating that natural stabilization processes are insufficient to contain the erosive dynamics.

The study area is located in an urban-rural transition zone, influenced by unpaved roads, such as the DCR-010 and DCR-313 routes, and agricultural activities, which favor the concentration and channeling of surface runoff, intensifying erosion processes.

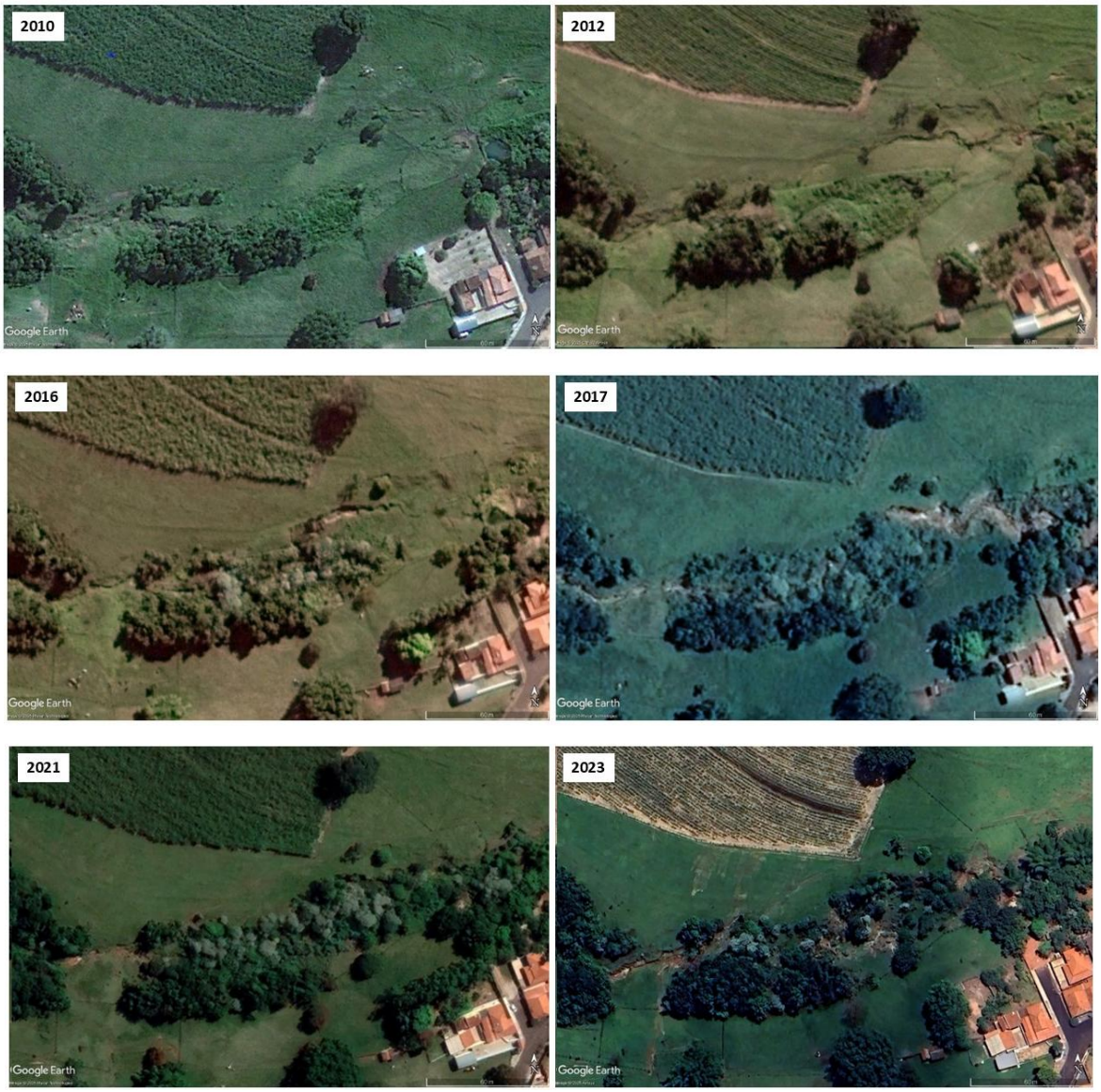



Figure 2 – Erosional features identified at the site

During an on-site visit (Figure 3), active erosion was observed, with exposed soil horizons, including altered material, as well as evidence of collapsed structures, such as fences, indicating bank instability and recent ground movement. There was also a lack of control over surface runoff upstream, resulting in significant soil loss and structural impacts in the area.

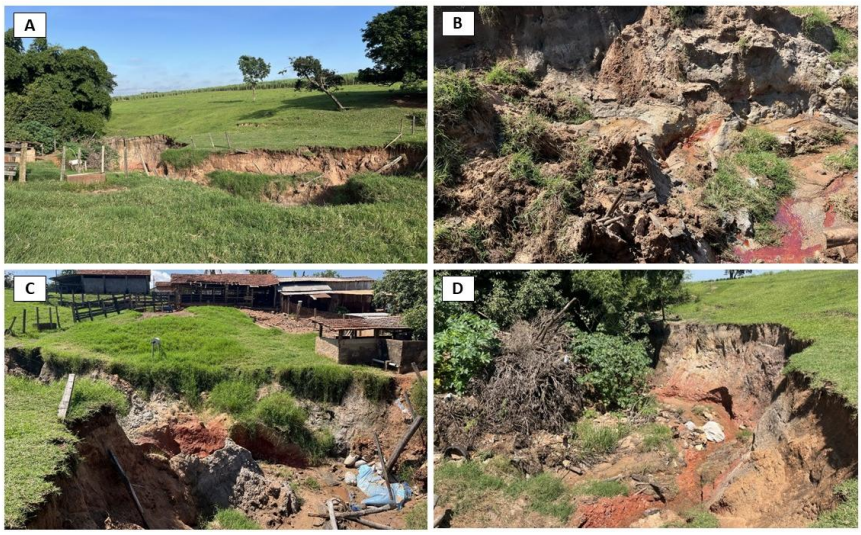



Figure 3 – On-site photographic record (A – panoramic view; B – spring outcrop; C – structural damage; D – loss of vegetation)

### 3.3 Environmental constraints

The soil identified near the erosion area is a dystrophic Red Argisol (Figure 4), characterized by the presence of a textural B horizon, with a marked increase in clay content compared to the surface horizon, low base saturation (<50%), high acidity, and low natural fertility (SANTOS *et al*., 2018). Its genesis is associated with intense leaching processes, which promote the accumulation of clay in the subsurface horizon (Bt), resulting in textural discontinuity that reduces water infiltration and favors surface runoff (EMBRAPA, 2018a, 2018b). These characteristics make this soil highly susceptible to water erosion, especially in sloping areas and under inadequate management, with removal of vegetation cover (SANTOS et al., 2018).

Rainfall analysis for the period from 2016 to 2024 indicated a historical average of 1,385.64 mm, with significant interannual variability. The year 2022 had the highest total precipitation, with values 36.58% above the average, coinciding with reports of structural damage in the municipality of Dois Córregos and indicating a strong potential for intensification of erosive processes. In contrast, 2024 had the largest deficit, with precipitation 22.52% below the historical average.

In the context of water erosion, positive precipitation anomalies increase erosion potential, especially in areas with exposed soil or low vegetation cover (GALDINO *et al*., 2015; CARDOSO *et al*., 2022). On the other hand, dry periods reduce the immediate occurrence of erosion but can promote the degradation of vegetation cover, increasing soil susceptibility to subsequent erosive events.

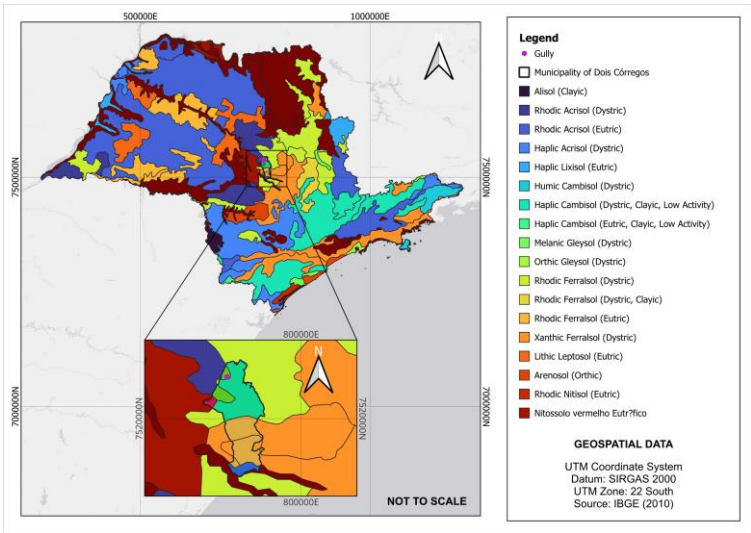



Figure 4 – Soil map of the study area

### 3.4 Land use and land cover

The MapBiomas analysis indicates that anthropogenic land use predominates in the municipality, accounting for 83.9% of the area (53,032 ha), with agricultural and livestock use accounting for 82.2%. Of this total, 62.74% corresponds to agriculture, 10.55% to pasture, 1.77% to forestry, and 24.94% to mixed-use areas. Natural vegetation occupies 16.1% of the area (10,151 ha), with 11.5% consisting of forest formations and 0.8% of non-forest natural areas, as shown in Figure 5.

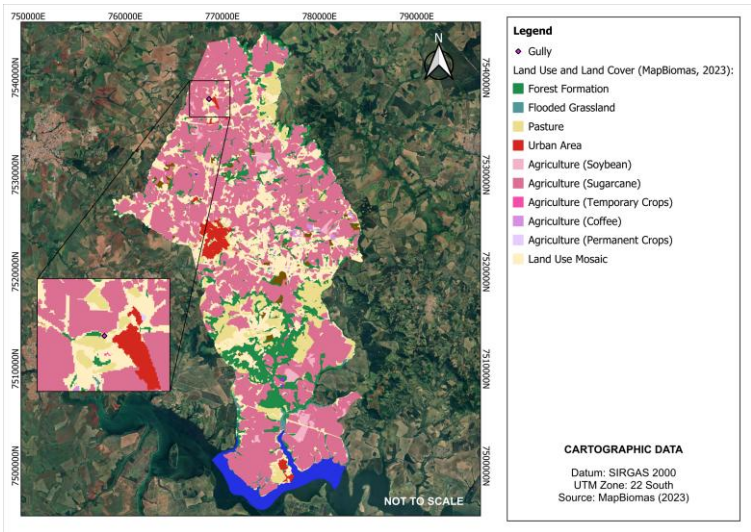



Figure 5 – Land use and land cover in the study area

A multitemporal analysis of land use and land cover indicates that the area already exhibited consolidated urban development in 2004, with no significant expansion in recent years (Figure 6). Permanent Preservation Areas (APPs) remain largely intact, suggesting that erosion is not directly

associated with the removal of riparian vegetation. As shown in Figure 7, the area is situated at an altitude of approximately 700 m, in a micro-basin characterized by the convergence of flows from adjacent slopes. This configuration favors the concentration and increase in the energy of surface runoff, intensifying erosive processes. The topography indicates that the site acts as a natural drainage outlet, where waters from different slopes converge, contributing to the evolution of the gully. Thus, the occurrence of erosion cannot be attributed exclusively to urban expansion, but rather to the interaction between natural conditions and human interventions.


Figure 6 - Comparison of land use and land cover in the study area in 2004 and 2023

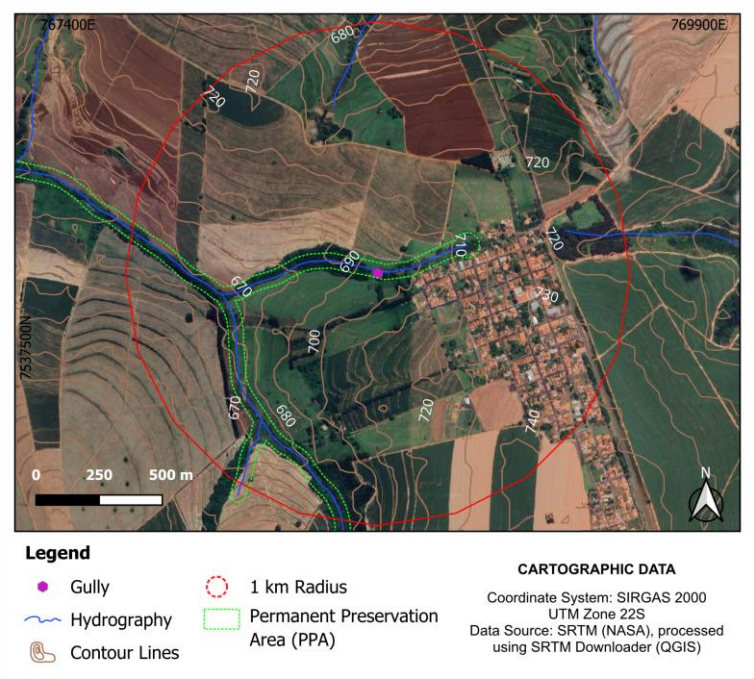



Figure 7 - Elevation map of the study area

### 3.5 Implications for nature-based planning and strategies

The results show that erosion dynamics are influenced by the interaction between physical and anthropogenic factors, and are intensified by extreme weather events and inappropriate land use, underscoring the need for integrated approaches in land-use planning. This pattern aligns with warnings from the IPCC (2014) and UNISDR (2015), which highlight the combination of land use, extreme events, and lack of infrastructure as key drivers of erosion-related disasters.

In the local context, the results are consistent with studies conducted in Dois Córregos, which demonstrate the potential of Nature-Based Solutions (NbS) to reduce surface runoff, increase infiltration, and stabilize the soil (SILVA *et al*., 2025; FILHO *et al*., 2025). In the present study, this effectiveness is reinforced by the identification of the area as a flow convergence zone, indicating that interventions aimed at water retention and infiltration tend to be more efficient when applied at the micro-basin scale.

In this sense, the mitigation of erosive processes depends on the adoption of integrated strategies, including conservation practices (such as contour lines, terracing, and vegetation cover), runoff control measures (small dams and sustainable drainage), land-use planning, and water management tools, such as rainfall monitoring and Payments for Environmental Services (PES). Such actions, combined with governance and social participation, are fundamental to promoting socio-environmental resilience.

Thus, the study demonstrates, at the local scale, that the interplay between physical constraints, land use, and hydrological dynamics is essential for guiding the effective application of NBS, especially in areas of stream convergence, contributing to territorial planning and adaptation to extreme events.

## 4. CONCLUSIONS AND RECOMMENDATIONS

The hypothesis was confirmed, showing that increased erosion results from the interaction between physical environmental factors, land use, and rainfall events, which increase surface runoff. Erosion dynamics are controlled by the convergence of flows in the micro-basin, a key factor for land-use planning and water management.

The results indicate that erosion is not associated solely with urbanization, but with the combination of natural conditions and inadequate soil management, constituting a systemic process. Extreme events, such as those in 2022, act as triggering factors, intensifying degradation in areas with low infiltration and a lack of runoff control.

The importance of the micro-basin scale is highlighted, demonstrating that isolated interventions are largely ineffective. In this context, SBNs prove to be more effective, especially when combined with water retention and infiltration and appropriate land use.

As a contribution, the results supported projects funded by the State Water Resources Fund (FEHIDRO), totaling over R$ 770,000, aimed at erosion control using NBS techniques and the improvement of rural roads, highlighting the coordination between diagnosis, planning, and financing.

It is emphasized that the integration of water management, territorial planning, and public policies, combined with social participation, is essential for the effectiveness of interventions; thus, the adoption of integrated management tools, the strengthening of governance, and the continuous monitoring of implemented actions are recommended.

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