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Proposal for the Rehabilitation of Erosional Processes within an Urbanized Settlement in Brazil

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Abstract **-** The study site, an informal settlement in Contagem, within the Belo Horizonte metropolitan area, faces severe erosional processes. This degradation stems from urban expansion's profound impact on a landscape characterized by a high density of headwaters. The rapid and intense urbanization has significantly altered natural hydrological pathways, leading to gully formation in preserved areas and ravines in urbanized sectors. Given this critical environmental context, rehabilitation procedures employing nature-based solutions (NBS) were recommended. A model was proposed for the restoration of degraded water channels, stabilization of eroded slopes, and improvement of urban thoroughfares, directly targeting areas most impacted by erosional phenomena. Consequently, a three-tiered restoration framework was established for the site: 1-channel restoration, focused on managing water velocity and flow dynamics; 2-slope restoration, implemented in two stages—physical stabilization via berm construction along contour water lines and biological stabilization through the planting of herbaceous and woody species; 3- street restoration, aiming to enhance hydrological pathways via gutters and collector drains, as well as to boost permeability through rain garden construction.

Keywords**:** Rain Garden, Street erosion, slope erosion, nature-based Solutions, water channel.

1. Introduction

The city of Contagem, located within the Metropolitan Region of Belo Horizonte (RMBH) (Fig. 1A), has a population of 2,315,560 inhabitants [1]. It stands out as a significant industrial hub in Minas Gerais. Throughout the 20th century, particularly from the 1940s forward, Contagem experienced rapid industrialization and urbanization, driven by the establishment of the Cidade Industrial, Brazil's first planned industrial district. This district alone accounts for 621,863 inhabitants [1].

This urban growth, however, occurred in an uncoordinated manner, leading to the formation of peripheral settlements characterized by precarious infrastructure and high levels of socio-environmental vulnerability. The neighborhood of Nova Contagem, with a population of 55,000 inhabitants, exemplifies this reality, accommodating various settlements and a penitentiary. Despite its expansion, the neighborhood faces significant challenges, such as deficient sanitation and the risk of erosive processes, including gully formation [2]. This risk is associated with the presence of an extensive hydrographic network, as the municipality is situated between two major hydrographic basins in Minas Gerais: the Paraopeba River basin and the Velhas River basin (Fig. 1B). The study area, as indicated by the arrow in Figure 1A, is located within the Paraopeba River basin and the Retiro Stream sub-basin.

The invaded settlement area known as Estaleiro is located in a geological sector characterized by Precambrian rocks of the Atlantic Shield, which comprises Archean granites and gneisses. This area also contains numerous headwaters and watercourses, establishing a direct link between local geological conditions and the risk of gravitational slope movements and erosion processes, including landslides and collapses—especially in areas occupied by precarious settlements.

In addition to these geological characteristics—common to many settlement areas in developing countries—the Estaleiro settlement lacks an adequate drainage system and frequently experiences flooding events. These events exacerbate the erosion of roads, footpaths, houses, and urban infrastructure [3].

Soil erosion results from the disaggregation of soil particles followed by their transport and deposition from one location to another. While erosion can be driven by wind, it is primarily caused by water, and its severity is influenced by factors such as soil vulnerability, topography, rainfall intensity, and insufficient vegetation or land cover [4]. Vegetation serves as the primary natural mechanism for preventing erosion and conserving soil and water resources [5].

The canopy shields the soil from wind and raindrop impact, while roots stabilize the substrate. However, the most significant contribution of vegetation lies in the production of recalcitrant organic matter—derived from the decomposition of lignified litter—which promotes the formation of stable soil aggregates, enhancing both stabilization and permeability [6]. Conventional engineering approaches to mitigating water-induced soil erosion and protecting hillslopes typically involve gray infrastructure, such as concrete channeling, gabion walls, concrete piles, geotextiles, anchored triple-torsion wire mesh, and concrete-lined ditches [7].

Nature-Based Solutions (NBS) represent an alternative approach to managing surface runoff, mitigating erosion processes, and reducing flood risks in urban settlements, while simultaneously delivering social and environmental co-benefits [8].

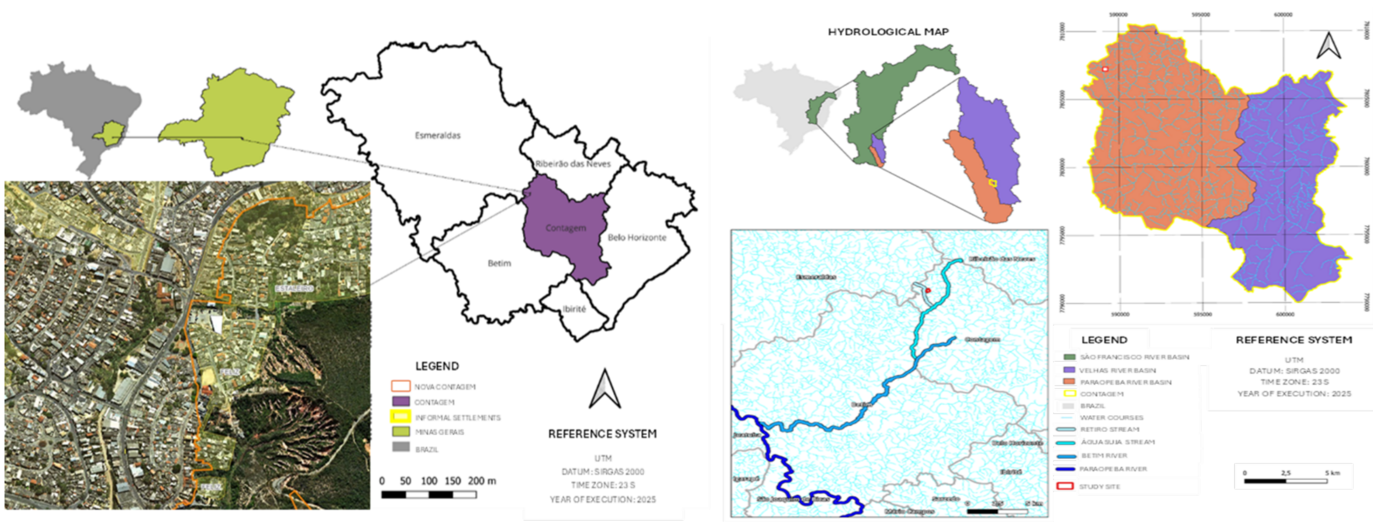

Fig. 1: A Localization map B - Hydrological map. Source: This figure belongs to the authors.

From this perspective, and aiming to remediate erosion processes within the Estaleiro settlement—both in natural drainage areas and along streets and residential zones (Fig. 2)—we propose an alternative model for the stabilization of natural channels and adjacent slopes, as well as the street. This model is designed to be feasible and replicable by municipal governments in small and developing cities.

Fig. 2: Erosive process on the study site. Source: This figure belongs to the authors.

2. Material and Methods

2.1. Study site

The study site is located in the city of Contagem in the state of Minas Gerais. The region is known as Estaleiro, which is an informal settlement in the northwest part of the city. The coordinates of the study site are latitude: 19°49'38.71"S and longitude 44° 8'22.87"W. The study site has been suffering interference from the high-speed pressure of the urban process, which resulted in formation of many informal settlements. Due to the high number of headwaters in the area, the intense urbanization process became a harmful factor to the natural headwater flow which resulted in intensive erosion process in the urban area and gullies in the preserved areas. Considering this context, it is recommended to assure the protection and direction of the water flow.

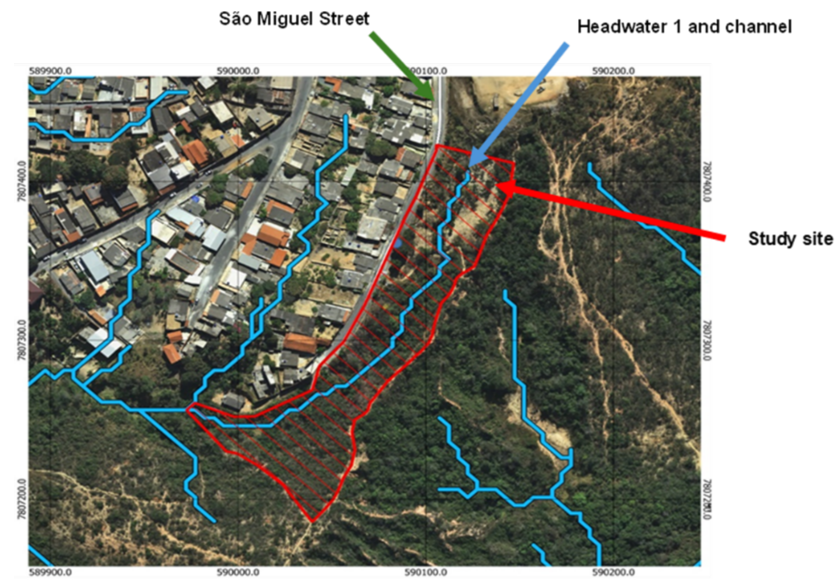

Fig. 3A: Study site. Source: This figure belongs to the authors.

2.2. Channel restoration

To reconstruct the natural drainage channel (Fig. 3), contour lines were used to identify the headwater point, which was located near the 900-meter elevation mark. To determine the dimensions of the conduit channel, it was necessary to calculate the terrain slope (%).

To estimate the average flow rate, the Retiro Stream basin was evaluated. Using rainfall data from the Retiro meteorological station, the flow rate in the channels designed along the gully slopes was calculated using the IDF equation (Intensity, Duration, and Frequency – Equation), which is commonly used to estimate extreme rainfall events. For this analysis, a return period (RP) of 20 years and a rainfall duration of 10 minutes were adopted. The local parameters k, a, b, and c required for the IDF equation (equation 1) were obtained using Pluvio 2.1 software (Federal University of Viçosa).

$$i=(k \cdot t_r^c)/(t+b)^a \qquad (1)$$

Where i = intensity (mm/h), tr = return time (years), t = rainfall duration (minutes), k = 833.45 (local parameter), a = 0.173 (local parameter), b = 7.174 (local parameter) and c = 0.701 (local parameter)
To estimate the maximum flow, the “Rational Method” was used equation 2:

$$Q=(C \cdot i \cdot A) /3.6 \qquad (2)$$

Where Q = flow (m^3/s); i = rainfall intensity (mm/h); A = area (km^2); C = Surface runoff coefficient of the Rational Method. An average flow rate of 0.32 (m^3/s) was estimated for the study site.

Using the SisCCoH software System for Calculating Hydraulic Components (Department of Hydraulic Engineering and Water Resources at the Federal University of Minas Gerais – UFMG, 2019), it was possible to verify the hydraulic dimensioning of the channels designed to adapt the average flow rate to 0.32 m^3/s.

2.3. Slope Recovery

Figures 3A and 3B present essential information on the slope stabilization measures, which were divided into three sections composed of varying numbers of berms or steps. Each 1-meter berm or step will be stabilized with a 40 cm high strip of stones at its base (Fig.4 A and 4B). Following physical stabilization, the slope will undergo biotic stabilization through the planting of native woody and herbaceous species.

2.4 Street Recovery

To stabilize São Miguel Street, the construction of roadside gutters parallel to the sidewalks were proposed, both on the left and right sides, totaling 300 meters of length on each side. Each gutter will measure 0.20 meters in width and 0.20 meters in depth. These gutters will be interconnected by six transverse collector drains (Fig. 5), each measuring 6 meters in length, 0.30 meters in height, and 0.20 meters in width, filled with 2.0 cm diameter stones. Each transverse drain will discharge into a stair-step drain on the slope, where each step will measure 0.5 m x 0.5 m x 0.25 m. Additionally, three rain gardens will be built on the first berm, each measuring 10 m x 1.4 m x 1.50 m.

3. Results and Discussion

The conduit channel was dimensioned based on its flow capacity, as shown in Table 1. The results indicate that the channel has a low slope, which contributes to water retention and inhibits natural drainage. This supports the hypothesis that erosion in the area is primarily due to water stagnation. Therefore, increasing the channel's flow capacity by modifying its dimensions is recommended (Table 1, Fig. 3).

B

C

Fig. 3: B - Flow direction of headwater 1 and C - Slope of São Miguel Street. Source: This figure belongs to the authors.

Table 1: Basic information for the collector channel restoration on São Miguel Street. Source: This table belongs to the authors.

Channel sections	Length (m)	Width (m)	Depth (m)	Decline (%)	Flow (m^3/s)	Velocity (m/s)
1	133	0.5	0.3	8	0.22	1.5
2	83	0.5	0.4	8	0.32	1.62
3	58	0.4	0.4	7	0,3	1.52

Table 2: Basic information for slope restoration on São Miguel Street. Source: This table belongs to the authors.

Slope sections	Length (m)	Width mean (m)	Height (m)	Decline (%)	Berms (number)	Width/ berm
1	133	22.78	11.0	8	11.0	2.07
2	83	10.39	7.0	8	9.0	1.15
3	58	5.94	4.0	7	4.0	1.5
Total	274.0	25.0	20.0	7		

For slope stabilization, two strategies were proposed:

1- Physical stabilization involves the construction of stepped slopes with berms anchored by rockfill, integrated with drainage channels and stair-step drain (Fig. 4A and 4B) to ensure proper conduction of rainwater and runoff from São Miguel Street.

2- Biological stabilization, through the planting of native herbaceous and tree species (Fig. 4C). To enhance soil aggregation and slope stability, we recommend inoculation plants with arbuscular mycorrhizal fungi (AMF), as supported by literature [9].

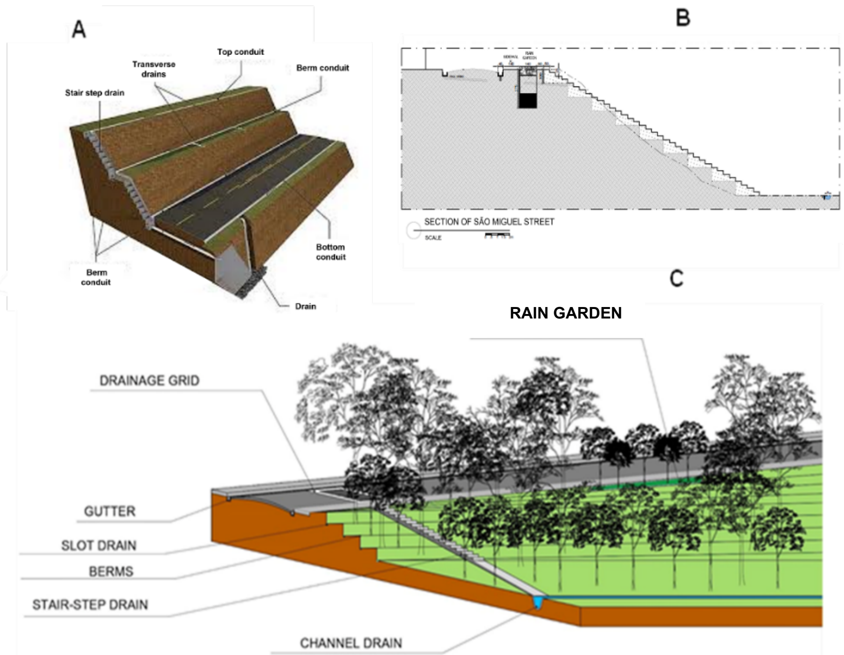

Fig. 4: A: Schematic drawing of the slope with verges and water ladder. Source: LEOBIANCO. (2016, 23 de march). SECÇÃO TRANSVERSAL – RODOVIAS. B: Schematic drawing of the verges with rain garden on the upper verge. C: Schematic drawing of the street, rain garden and planted slope. Source: These figures B and C belong to the authors.

To stabilize São Miguel Street, the system of parallel gutters and transverse collector drains is designed to efficiently direct surface runoff to the main collector channel (Fig. 5 and Fig. 6A and 6B). These transverse drains will be covered by a protective grid (Fig. 6A and Fig. 6B). At the end of each transverse conduit drain, where it meets the right-side gutter, a stone stair-step drain will be built to guide the water down to the main conduit channel (Fig. 4C and Fig. 5). From the third transverse drain onward, due to the steep slope, three rain gardens will be implemented on the first slope edge (Fig. 5, Fig. 6C and Fig. 6D). The purpose of these rain gardens is to mitigate the excessive surface runoff on São Miguel street, reducing the urban flooding as well as the erosion slope risks.

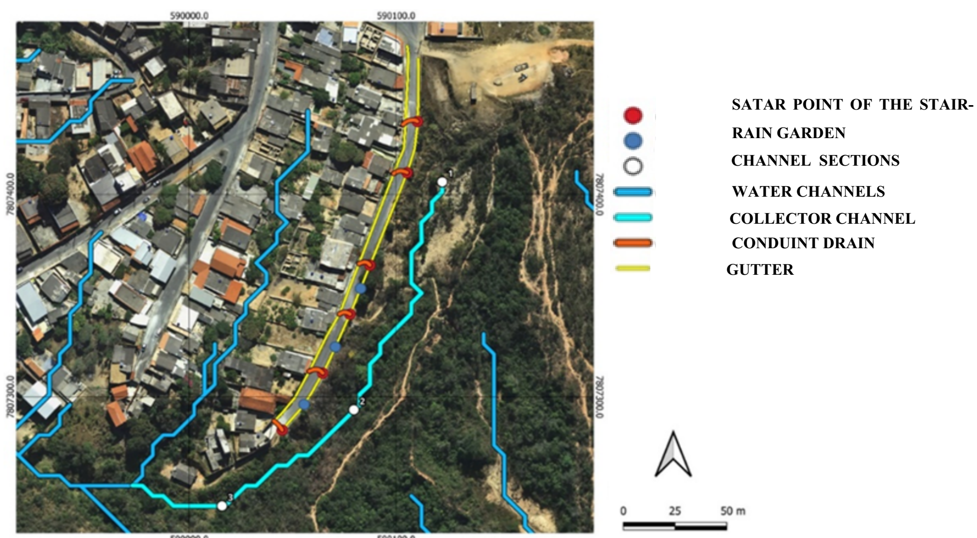

Fig. 5: Positioning of the interventions to stabilize São Miguel Street. Source: This figure belongs to the authors.

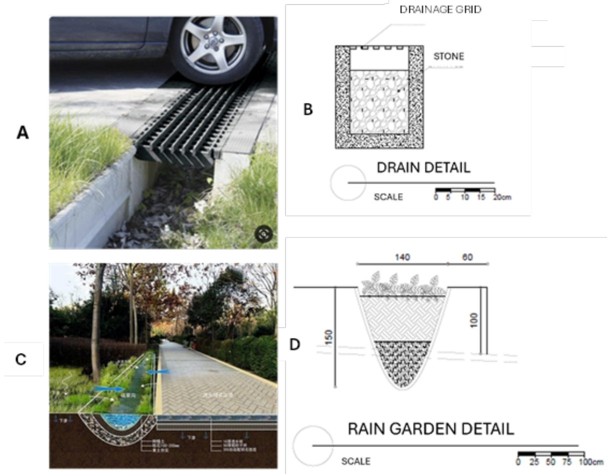

Fig. 6: A- Drain grid on the street. Source: Protección de la biodiversidad (I): Pasos para anfibios. (2013, june). B- Schematic drawing of the collector channel protected with grid. Source: This figure belongs to the authors. C- Rain garden. Source: archmili.com Architecture and Life (2025, June) D- Schematic drawing of the rain garden. Source: This figure belongs to the authors.

The urban impervious surfaces promoted by asphalt seal the soil layers and cause surface runoff, which leads to urban flooding. The rain garden is a bioretention system composed of layers of high permeability materials as stones and layers of stabilizing organic matter to also increase infiltration. In a rain garden the top layer is formed by native vegetation composed by herbaceous, shrubs and woody species which act as filters and soil stabilizer elements through soil aggregates formation [10].

These interventions aim to stabilize both São Miguel Street and the adjacent slope along the headwater's main conduit channel. Moreover, they ensure the efficient conveyance of stormwater to the gully conduit drain (Fig. 7), which ultimately connects to the Retiro Stream. This restoration approach is based on nature-based solutions and integrates key ecosystem functions into the design.

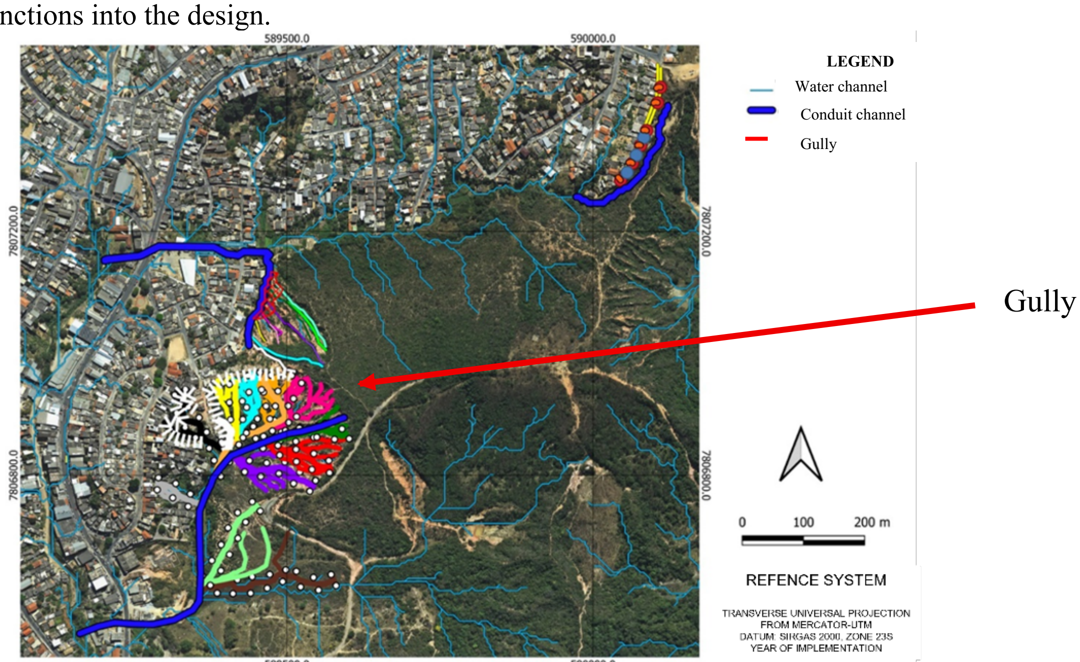

Fig.7: Direction and net connections of the water flow of the head waters of the study area. Source: This figure belongs to the authors.

4. Conclusion

The advanced process of erosion has significantly impacted a low-income urban settlement, leading to substantial destabilization of both street infrastructure and adjacent slopes. This environmental degradation critically compromises the structural integrity of residential dwellings. Given the confluence of high environmental risk and precarious socio-economic conditions within the affected community, the implementation of restoration measures necessitates cost-effective solutions that align with the fiscal limitations of the local municipality. Nature-based solutions (NBS) emerge as the most efficacious and sustainable approach for remediation. Specifically, proposed interventions include fluvial channel restoration, to mitigate hydraulic energy and regulate water flow velocity. Concurrently, slope stabilization will integrate a combination of green and grey reinforcement techniques. Furthermore, street infrastructure restoration will focus on re-establishing appropriate hydrological pathways and enhancing surface permeability through the strategic deployment of green infrastructure, such as rain gardens, to facilitate effective stormwater management.

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