Methodology to determine the socioeconomic impact and ecosystem services loss caused by ravines and gullies

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Completing a doctorate is a dream come true, but it also represents the demonstration that access to education and science is the best tool for social transformation. For someone like me, who has worked since childhood, coming from a poor family with few resources, who left home at the age of 14 to study in a big city and support himself, who has witnessed throughout his life the different opportunities available in the world and the challenges of social mobility, I cannot fail to thank my friends, family, professors and many other people who supported me throughout this journey until the end of my doctorate.

The completion of this doctorate does not represent just an academic achievement but rather an act of hope that science and education are the true tools for transforming the world.

Abstract

Gullies and ravines affect human life and the environment in many countries around the world. However, few studies have evaluated the impacts of damage caused by these large linear erosions and clarified their parameters of influence. In this context, the main objectives of this thesis were to identify and systematize the economic impacts and ecosystem services caused by ravines and gullies, aiming to propose a methodology for valuation, in addition to performing an analysis on which erosions should be prioritized for remediation. The methodological path that was adopted consisted of a) a global bibliographic review carried out in the Scopus, Web of Science and Dimensions databases, where more than 120 articles from 27 countries that addressed and evaluated these different types of impacts were identified; b) an analysis of official civil defence records on the impacts of ravines and gullies in Brazil, based on data from the Brazilian Civil Defense Integrated Information System (S2ID), combined with a bibliographic review; c) an application of the valuation methodology in a case study of brownfields caused by ravines and gullies that was conducted in the city of Bauru (Brazil), considering environmental damage, such as costs related to land restoration and erosion control, destruction of infrastructure, losses economic and income losses related to property and urban property taxes; and d) an adaptation of the Tailored Improvement of Brownfield Regeneration in Europe (TIMBRE) method for the analysis and classification of areas affected by linear erosion in the city of Bauru, specifically for erosion analysis to identify priority areas for remediation. Based on the results of the global bibliographic review, the possible types of impacts that can be caused by gullies and ravines and how they can be valued can be systematized. The review also indicated that the greatest impacts are registered in South America, Africa, China and India, related to characteristics of the physical environment, extreme events and disorderly land occupation. In Brazil, civil defence data show an increasing trend in the number of disasters related to ravines and gullies in the last decade (2011-2020), totalling 76 records in this period. However, only 24 of these records contained information on the impacts caused, which added up to an estimated loss of US$54 million. The spatial distribution of disasters related to linear erosion in Brazil suggests a connection between the development of ravines and gullies and the country's agricultural frontier, especially in the North and Midwest regions, including the Cerrado and Amazon Forest biomes, where the greatest changes in land use occurred between the end of the 20th century and the beginning of the 21st century. Based on the methodological proposal that was elaborated considering the global bibliographic review, a case study was conducted in the city of Bauru, Brazil, to carry out the valuation of impacts. The analyses indicate that the total damage in the three analysed areas over two decades exceeded US$ 173 million and was mainly related to losses due to the abandonment of the area. Urban areas affected by ravines and gullies pose problems that are similar to those of brownfields, creating urban voids. Therefore, the TIMBRE method was adapted to analyse areas affected by ravines and gullies, demonstrating a correlation between erosion and urban expansion. With the proposed methodology, the Quinta da Bela Olinda area was identified as the location with the highest scores in the three classifications, being the location with the greatest potential for business development, the most attractive brownfield and the area with the highest environmental risk. This area should, therefore, be prioritized by public management for remediation. Although the implementation of the assessment is challenging due to the large number of different forms of possible impacts related to environmental, economic and social changes, based on the results of this work, it is concluded that the proposed valuation method facilitates the identification and demonstration of the damages. On the other hand, the adaptation of the Timbre Method for ravines and gullies proved to be a great tool that assisted in decision-making about which erosions should be a priority for remediation. The set of results obtained in the thesis can promote management tools for disaster management and land use management in cities, helping public managers and the community to make more assertive decisions regarding the construction of public policies for the remediation of affected areas through ravines and gullies.

Resumo

Voçorocas e ravinas afetam a vida humana e o meio ambiente em muitos países do mundo. No entanto, poucos estudos avaliaram os impactos dos danos causados por essas grandes erosões lineares e esclareceram seus parâmetros de influência. Neste contexto, os principais objetivos desta tese foram identificar e sistematizar os impactos econômicos e nos serviços ecossistêmicos causados por ravinas e voçorocas, visando propor uma metodologia para valoração, além de realizar uma análise sobre quais erosões devem ser priorizadas para remediação. O caminho metodológico adotado consistiu em: a) Uma revisão bibliográfica global realizada nas bases de dados Scopus, Web of Science e Dimensions, onde foram identificados mais de 120 artigos de 27 países que abordaram e avaliaram esses diferentes tipos de impactos; b) Análise dos registros oficiais na defesa civil sobre impactos de ravinas e voçorocas no Brasil, com base nos dados do Sistema Integrado de Informações da Defesa Civil Brasileira (S2ID), aliada a uma revisão bibliográfica; c) Aplicação da metodologia de valoração em um estudo de caso realizado na cidade de Bauru (Brasil), para brownfields causados por ravinas e voçorocas, considerando danos ambientais, como custos relacionados à restauração de terras e controle de erosão, destruição de infraestrutura, perdas econômicas e perdas de renda relacionadas a impostos prediais e prediais urbanos; e d) Adaptação do método Tailored Improvement of Brownfield Regeneration in Europe (TIMBRE) para a análise e classificação de áreas afetadas por erosão linear na cidade de Bauru, para análise de erosões visando identificar áreas prioritárias para remediação. Os resultados da revisão bibliográfica global permitiram a sistematização dos tipos possíveis de impactos que podem ser causados por voçorocas e ravinas e como eles podem ser valorados. A revisão também indicou que os maiores impactos são registrados na América do Sul, África, China e Índia, relacionados a características do meio físico, eventos extremos e ocupação desordenada do solo. No Brasil, os dados da defesa civil mostram uma tendência crescente no número de desastres relacionados a ravinas e voçorocas na última década (2011-2020), totalizando 76 registros nesse período. No entanto, apenas 24 desses registros continham informações sobre os impactos causados, que somaram uma perda estimada de US$ 54 milhões. A distribuição espacial dos desastres relacionados à erosão linear no Brasil sugere uma conexão entre o desenvolvimento de ravinas e voçorocas e a fronteira agrícola do país, especialmente nas regiões Norte e Centro-Oeste, incluindo os biomas Cerrado e Floresta Amazônica, onde ocorreram as maiores mudanças no uso da terra entre o final do século XX e o início do século XXI. Com base na proposta metodológica elaborada considerando a revisão bibliográfica global, foi realizado um estudo de caso na cidade de Bauru, Brasil, para realizar a valoração de impactos. As análises indicam que o dano total em três áreas analisadas ultrapassa US$ 173 milhões em duas décadas e está relacionado principalmente a perdas pelo abandono da área. As áreas urbanas afetadas por ravinas e voçorocas representam problemas semelhantes aos brownfields, criando vazios urbanos.

Portanto, o método TIMBRE foi adaptado para a análise das áreas afetadas por ravinas e voçorocas, demonstrando uma correlação entre erosão e expansão urbana. A metodologia proposta identificou a área da Quinta da Bela Olinda como o local que possui as maiores pontuações nas três classificações, sendo o local com maior potencial para o desenvolvimento de negócios, o brownfield mais atrativo e também a área com maior risco ambiental. Essa área deve, portanto, ser priorizada pela gestão pública para remediação. Embora a implementação da avaliação seja desafiadora devido ao grande número de diferentes formas de possíveis impactos relacionados a mudanças ambientais, econômicas e sociais, os resultados deste trabalho concluem que o método de valoração proposto permite identificar e demonstrar os danos. Por outro lado, a adaptação do Método Timbre para ravinas e voçorocas mostrou-se uma ótima ferramenta para auxiliar na tomada de decisões sobre quais erosões devem ser prioritárias para remediação. O conjunto de resultados obtidos na tese pode fomentar ferramentas de gestão para o gerenciamento de desastres e gestão do uso da terra nas cidades, auxiliando gestores públicos e a comunidade a tomar decisões mais assertivas em relação à construção de políticas públicas para a remediação de áreas afetadas por ravinas e voçorocas.

Zusammenfassung

Spalten und Schluchten beeinträchtigen in vielen Ländern der Welt das menschliche Leben und die Umwelt. Allerdings haben nur wenige Studien die Auswirkungen der durch diese großen linearen Erosionen verursachten Schäden bewertet und ihre Einflussparameter geklärt. In diesem Zusammenhang bestand das Hauptziel dieser Arbeit darin, die wirtschaftlichen Auswirkungen und Ökosystemleistungen, die durch Schluchten verursacht werden, zu identifizieren und zu systematisieren. Ziel war es, eine Bewertungsmethode vorzuschlagen und außerdem zu analysieren, welche Erosionen bei der Sanierung priorisiert werden sollten. Der gewählte methodische Weg bestand aus a) einer globalen bibliografischen Überprüfung, die in den Datenbanken Scopus, Web of Science und Dimensions durchgeführt wurde, wobei mehr als 120 Artikel aus 27 Ländern identifiziert wurden, die diese verschiedenen Arten von Auswirkungen thematisierten und bewerteten, b) eine Analyse der offiziellen Aufzeichnungen des Zivilschutzes über die Auswirkungen von Schluchten in Brasilien, basierend auf Daten des brasilianischen Zivilschutz-Integrierten Informationssystems (S2ID), kombiniert mit einer bibliografischen Überprüfung, c) der Anwendung der Bewertungsmethodik in einer Fallstudie in der Stadt Bauru (Brasilien) für Brachflächen, die durch Schluchten verursacht wurden, unter Berücksichtigung von Umweltschäden, wie z. B. Kosten im Zusammenhang mit der Wiederherstellung von Land und Erosionsschutz, der Zerstörung von Infrastruktur, wirtschaftlichen Verlusten und Einkommensverlusten im Zusammenhang mit Grundsteuern und städtischem Eigentum und d) eine Anpassung der Tailored Improvement of Brownfield Regeneration in Europe (TIMBRE)-Methode zur Analyse und Klassifizierung von Gebieten, die von linearer Erosion in der Stadt Bauru betroffen sind, insbesondere für die Erosionsanalyse, um vorrangige Gebiete für die Sanierung zu identifizieren. Die Ergebnisse der globalen bibliografischen Überprüfung erlauben eine Systematisierung möglicher Arten von Auswirkungen, die durch Schluchten verursacht werden können und wie diese bewertet werden können. Die Überprüfung ergab auch, dass die größten Auswirkungen in Südamerika, Afrika, China und Indien zu verzeichnen sind und mit Merkmalen der physischen Umwelt, Extremereignissen und ungeordneter Landbesetzung zusammenhängen. In Brasilien zeigen die Daten des Zivilschutzes einen steigenden Trend bei der Zahl der Katastrophen im Zusammenhang mit Schluchten im letzten Jahrzehnt (2011–2020), wobei es in diesem Zeitraum insgesamt 76 Rekorde gab. Allerdings enthielten nur 24 dieser Aufzeichnungen Informationen über die verursachten Auswirkungen, was zu einem geschätzten Schaden von 54 Millionen US-Dollar führte. Die räumliche Verteilung von Katastrophen im Zusammenhang mit linearer Erosion in Brasilien deutet auf einen Zusammenhang zwischen der Entwicklung von Schluchten und der landwirtschaftlichen Grenze des Landes hin, insbesondere in den Regionen im Norden und Mittleren Westen, einschließlich der Biome Cerrado und Amazonaswald, wo zwischen dem Ende des 20. und dem Beginn des 21. Jahrhunderts die größten

Veränderungen in der Landnutzung stattfanden. Basierend auf dem methodischen Vorschlag, der unter Berücksichtigung der globalen bibliographischen Überprüfung erarbeitet wurde, wurde eine Fallstudie in der Stadt Bauru, Brasilien, durchgeführt, um die Auswirkungen zu bewerten. Die Analysen zeigen, dass der Gesamtschaden in den drei analysierten Gebieten über zwei Jahrzehnte 173 Millionen US-Dollar überstieg und hauptsächlich auf das Aufgeben der Gebiets zurückzuführen war. Von Schluchten betroffene städtische Gebiete zeigen ähnliche Probleme und führen zu städtischen Leerstand. Daher wurde die TIMBRE-Methode angepasst, um von Schluchten betroffene Gebiete zu analysieren und einen Zusammenhang zwischen Erosion und Stadterweiterung aufzuzeigen. Mit der vorgeschlagenen Methodik wurde das Gebiet Quinta da Bela Olinda als Standort mit den höchsten Bewertungen in den drei Klassifizierungen identifiziert, da es sich um den Standort mit dem größten Potenzial für die Geschäftsentwicklung, die attraktivste Gegend, aber das Gebiet mit dem höchsten Umweltrisiko handelt. Daher sollte dieser Bereich von der öffentlichen Verwaltung bei der Sanierung priorisiert werden. Obwohl die Durchführung der Bewertung aufgrund der Vielzahl unterschiedlicher Formen möglicher Auswirkungen im Zusammenhang mit ökologischen, wirtschaftlichen und sozialen Veränderungen eine Herausforderung darstellt, kommt man auf Grundlage der Ergebnisse dieser Arbeit zu dem Schluss, dass die vorgeschlagene Bewertungsmethode die Identifizierung und den Nachweis der Schäden erleichtert. Andererseits erwies sich die Anpassung der Timbre-Methode für Schluchten als großartiges Hilfsmittel, das bei der Entscheidungsfindung darüber, welche Erosionen bei der Sanierung Vorrang haben sollten, hilfreich war. Die in der Dissertation erzielten Ergebnisse können Managementinstrumente für das Katastrophenmanagement und das Landnutzungsmanagement in Städten fördern und öffentlichen Entscheidungsträgern und der Gemeinde dabei helfen, durchsetzungsfähigere Entscheidungen hinsichtlich der Gestaltung öffentlicher Richtlinien zur Sanierung betroffener Gebiete durch Schluchten zu treffen.

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I. **Kuhn CES**, Reis FAGV, Zarfl C, Grathwohl P (2023) Ravines and gullies, a review about impact valuation. Nat Hazards 117, 597–624. **https://doi.org/10.1007/s11069-023-05874-6**

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II. **Kuhn CES**, Reis FAGV, Lazaretti AF, Zarfl C, Cabral V, Grathwohl P (2023) The record and trends of natural disasters caused by gullies in Brazil. Environmental Earth Sciences 82, 524. **https://doi.org/10.1007/s12665-023-11213-6**

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III. **Kuhn CES**, Reis FAGV, Furegatti SA, Zarfl C, Peixoto ASP **(**2024) Economic impacts of an urban gully are driven by land degradation. Natural Hazards. **https://doi.org/10.1007/s11069-024-06727-6**

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IV. **Kuhn CES**, Reis FAGV, Santos FRP, Zarfl C, Grathwohl P, Cabral V (2024) Adaptation of the TIMBRE methodology for brownfields gully erosion analysis in urban areas. Heliyon 10(13), e32902. **https://doi.org/10.1016/j.heliyon.2024.e32902**

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1. Introduction

Gullies are advanced forms of linear erosion that have been identified since prehistory and the Roman period in Belgium, Poland and Germany and that develop in response to extreme rainfall events and socioeconomic changes (POESEN, 2011; DAGAR, 2018). In countries such as Brazil and the United States, this type of process has also been described since the 17th and 18th centuries in relation to agricultural practices and inadequate construction.

Ravines and gullies occur in all climates, except in permanently ice-covered polar regions (CASTILLO and GÓMEZ, 2016). Several factors can influence the formation of ravines and gullies (Table 1). Topographical, geological and geotechnical soil conditions, along with extreme rainfall events, are some of the main factors (AKGÜN and TÜRK, 2011; CASTILLO and GÓMEZ, 2016; AMORIM, 2017; DAGAR, 2018). However, human action through changes in land use, in general, is the main trigger for the development of accelerated erosion. Deforestation, forest fires, overgrazing, mining, intensive agriculture and urbanization modify the dynamics of surface runoff, favouring the concentration of surface water and the removal of particles through water erosion (BUSNELLI et al., 2006; AKGÜN and TÜRK, 2011; OZER, 2014; CASTILLO and GÓMEZ, 2016; AMORIM, 2017; DAGAR, 2018; GOLOSOV et al., 2018; GUERRA et al., 2018; XU et al., 2019).

Table 1. *List of factors that influence the development of ravines and gullies (KUHN et al. 2023).*

Factor	Description	Influence
Climate	Prolonged droughts followed by heavy rains	Weakens soil structures and facilitates erosion.
	Erosion morphology	Length: Longer if compared to features existing in temperate climate to subtropical and/or tropical; b) Width: Narrower than subtropical, the connection with water table in tropical climates favors lateral evolution; c) Depth: Shallower in tropical climates due to connection and stabilization with the water table; greater in temperate climates than in tropical climates.
	Weathering	The hotter and rainier, the greater the weathering blanket
Rain	Accumulated volume of rain over several days	Saturates the soil
	Extreme rain events in a day	Favor surface runoff
Geomorphology	Slope	The larger, the greater the kinetic energy of the flow
	Drainage basin size	The greater, the greater the flow possible during extreme events
	Strand shape	Can favor accumulated flow
Geology	Rock type	Influences the formation of the soil; in some cases the rock has low cohesion, behaving similar to the soil.
	Aquifers	The characteristics of the rocks influence the characteristics of the local aquifer. The relationship between the local aquifer and erosion is important in tropical regions.
	Uplift of old surfaces	Changes kinetic energy and favors the development of gully systems with a regional dimension.
Soil	Cohesion	Clayey soils are more cohesive, sandy soils less cohesive

	Permeability	Greater infiltration in sandy soils
	Erodibility	Tends to be higher on sandy and loose soils
	Depth	The deeper the soil or loose sediment package, the greater the risk of formation of large linear erosions.
Vegetation	Sediment retention and soil preservation	In semiarid climates, little vegetation favors erosion and hinders recovery; in tropical climates, the frequency of rain favors the insertion of vegetation in the affected area
Anthropogenic changes	Linear structures (trails, roads...)	Favor the surface flow water concentration
	Soil compaction or area waterproofing	Reduces infiltration and favors surface runoff
	Removal of vegetation or burning	Exposes the soil
	Changes in natural runoff	Redirect water flow
	Precarious social conditions	Limit the ability to respond to erosions

Several bibliographic reviews have addressed aspects related to ravines and gullies, such as their causes and forms of erosion control (VALENTIN et al., 2005); evolution of erosion processes (CASTILLO and GÓMEZ, 2016); temporal and spatial mapping and evolution (VANMAERCKE et al., 2016); history and trends of erosion processes, formation process, recovery and containment methods (DAGAR, 2018); methods for rehabilitation of affected areas (ROMERO-DÍAZ et al., 2019); and differences in evolution and morphology in different climates (DUBE et al., 2020), among others.

According to the review carried out by Castillo and Gómez (2016), only 3.1% of studies on gullies addressed urban areas, while 13.2% focused on forest areas and just over 40% examined pastures and plantations. Although rarely studied, ravines and gullies cause significant damage in cities around the world. The evolution of these erosions is responsible for the destruction of houses, streets and bridges, as documented in Nigeria (BALZEREK et al., 2003). Hundreds of ravines are described in Kinshasa, in the Democratic Republic of Congo, where the destruction of housing and infrastructure occurs, as described by Ozer (2014) and Imwangana et al. (2015) (Figure 1). In the city of Comodoro Rivadavia, Argentina, several urban structures and more than 400 houses were destroyed or damaged due to the development of ravines and gullies, as mentioned by Paredes et al. (2020).

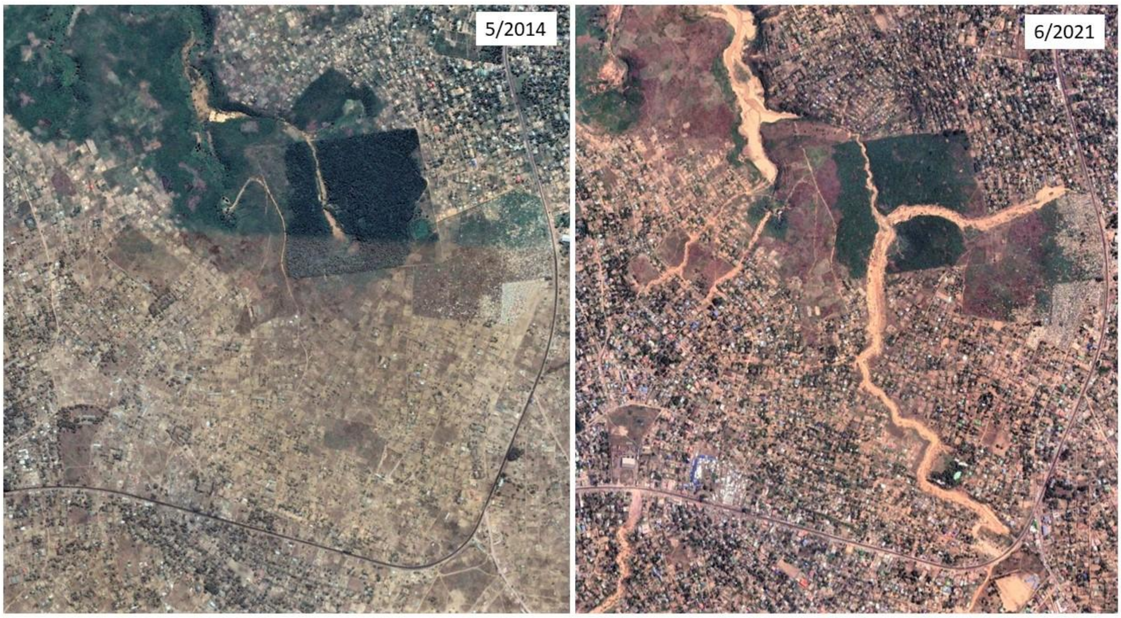

Figure 1. *Comparison of two images of the same area, the first from 2014, where the erosive process development of the ravines is clearly visible between 2014 and 2021, in an area with high population density in Kinshasa, the Republic Democratic Republic of Congo. Images extracted from Google Earth (Lat. 4°30'6.50"S - Log. 15°13'3.67"L).*

Rotta and Zuquette (2014) address the development of ravines and gullies in several cities in Brazil, demonstrating that this process has impacted the city for decades due to the formation of erosion channels. One of the cities with major erosion problems is Bauru, in the state of São Paulo, where at the end of the 1990s, more than 25 ravines and gullies were recorded by Almeida Filho (2000), removing almost 2 million m³ of sediments and contributing to the silting up of dams and rivers. Due to the impacts caused, ravines and gullies are considered by Civil Defense in Brazil as a type of natural disaster (BRASIL, 2012a).

For the recovery of areas affected by ravines and gullies, various types of structural and/or vegetative interventions are used in watersheds (ROMERO-DÍAZ et al., 2019; FRANKL et al., 2021). The construction of drainage energy sinks, dams, spillways, accumulation basins, water catchment structures, protection dikes, artificial channels, earthworks, and gabions, as well as the revegetation of areas and planting of grasses, among other measures, can be adopted (ROTTA and ZUQUETTE, 2014; DAGAR and SINGH, 2018). In addition to the cost of implementing actions, other possible impacts include the interruption of economic activities, the cost of maintaining structures and the increase in the cost of labour. The cost of recovering areas affected by erosion may vary according to the biophysical characteristics of each location and the technique applied (DE BRITO GALVÃO et al., 2011; ROMERO-DÍAZ et al., 2019).

Despite the significant impacts, few studies that aim to estimate the economic costs caused by ravines and gullies are found in the literature. Among them, Yitbarek et al. (2012) analysed the cost-effectiveness of the rehabilitation of agricultural areas affected by ravines and gullies in Ethiopia. Quantifying the cost of erosion in the same country was also analysed by Ayele et al. (2015), who considered soil nutrient losses, displacement costs, and the value of lost trees and animals. However, none of these studies included conducting a valuation in urban areas.

Urban gullies and ravines generate problems that are similar to those of brownfields, which, according to Cabernet (2006), are "places that have been affected by previous uses of the site or the surrounding land, are abandoned or underutilized, are mainly in fully or partially developed urban areas, require intervention to bring them back to beneficial use and may present real or perceived contamination problems".

The similarity between brownfields and ravines and gullies can be an opportunity to use the knowledge of support tools and decision support developed in recent decades in countries such as the United States, England, Canada, Germany, China, Italy, Czech Republic, Spain and Australia (LIN et al., 2019; HEPBURN et al., 2019). For tools such as Tailored Improvement of Brownfield Regeneration in Europe (TIMBRE), a set of information in several stages is employed to elaborate the following: 1) Inventory (mapping, identification and analysis of problems); 2) Prioritization (assessment of redevelopment potential and environmental risks); and 3) Marketing (fundraising and search for investors) (NIELSEN and TRAPP, 2014).

Within the state of the art on ravines and gullies, this thesis addresses the following questions:

- What types of economic impacts and ecosystem services are caused by ravines and gullies in the world?
- What economic impacts have been caused by ravines and gullies in Brazilian municipalities in recent decades?
- Is it possible to quantify the economic impacts and ecosystem services caused by ravines and gullies?
- Is it possible to adapt the support and decision support tools created for brownfield analysis to the rehabilitation of ravines and gullies?

Understanding and obtaining answers to the aforementioned questions can contribute to several Sustainable Development Goals (SDGs) and other internationally constructed agendas, which emphasize the importance of soil preservation, the proper management of natural resources and the development of sustainable cities. Accelerated erosion is one of the global challenges affecting many cities, creating significant economic and environmental impacts.

Four articles were elaborated in this research with the goal of finding answers to the presented questions. In Paper I, entitled "Ravines and gullies: A review about impact valuation", a global review of the economic impacts and ecosystem services that can be caused by ravines and gullies, as well as the ways that can be used to calculate each type of impact, was conducted. In other words, an analysis method was proposed.

In Paper II, entitled "An estimate of the economic impacts of ravines and gullies", an analysis of official civil defence data in Brazil was conducted to obtain information on the impacts caused by ravines and gullies. In this article, a critical analysis of the records is performed, in addition to presenting an overview of the development trends of linear erosions in Brazil, suggesting improvements in the database and indicating underreporting problems.

The application of the systematized method in the first article is carried out in Paper III, entitled "Economic impacts of an urban gully are driven by land degradation". In this article, a long-term valuation of the impacts caused by ravines and gullies in three different areas in the municipality of Bauru in São Paulo is carried out.

Finally, in Paper IV, entitled "Adaptation of the Timbre methodology for gully erosion analysis in urban areas", the knowledge constructed for the remediation of brownfields is used to classify ravines and gullies, aiming to identify which would be the priority erosion for remediation.

2. Objectives

The main objective is to develop and apply a methodology for valuing economic impacts and ecosystem services caused by ravines and gullies. Another objective is to develop a way to classify erosions, aiming to identify priority erosions for remediation.

This work has the following hypothesis: the multicriteria analysis of the erosive processes based on the temporal evolution, typology and land use and occupation provides grounds for establishing a method of valuation of socioeconomic impact and for losses of ecosystem services of evolution of ravines and gullies.

The specific objectives are as follows:

- Analyse the main economic impacts and ecosystem services caused by ravines and gullies in different countries;
- Perform a critical analysis of civil defence records and systematize and quantify infractions on the economic impacts of ravines and gullies in Brazil;
- Conduct a case study to apply the developed valuation methodology;
- Develop and apply an adaptation of the Timbre methodology for classifying areas affected by erosion.

This thesis contributes to understanding the impacts caused by ravines and gullies, aiming at their quantification and the classification of erosions to improve territorial management and land use in different places on the planet, thus contributing to the construction of a more sustainable future.

3. Materials and Methods:

The thesis was developed in 5 stages: (Figure 2) global review of economic impacts and ecosystem services caused by ravines and gullies; 2) analysis of civil defence records on the impacts of ravines and gullies in Brazil; 3) analysis of ravines and gullies in the municipality of Bauru, the area chosen for the development of case studies; 4) application of the valuation methodology; and 5) adaptation and application of the TIMBRE methodology for the analysis of areas affected by linear erosion

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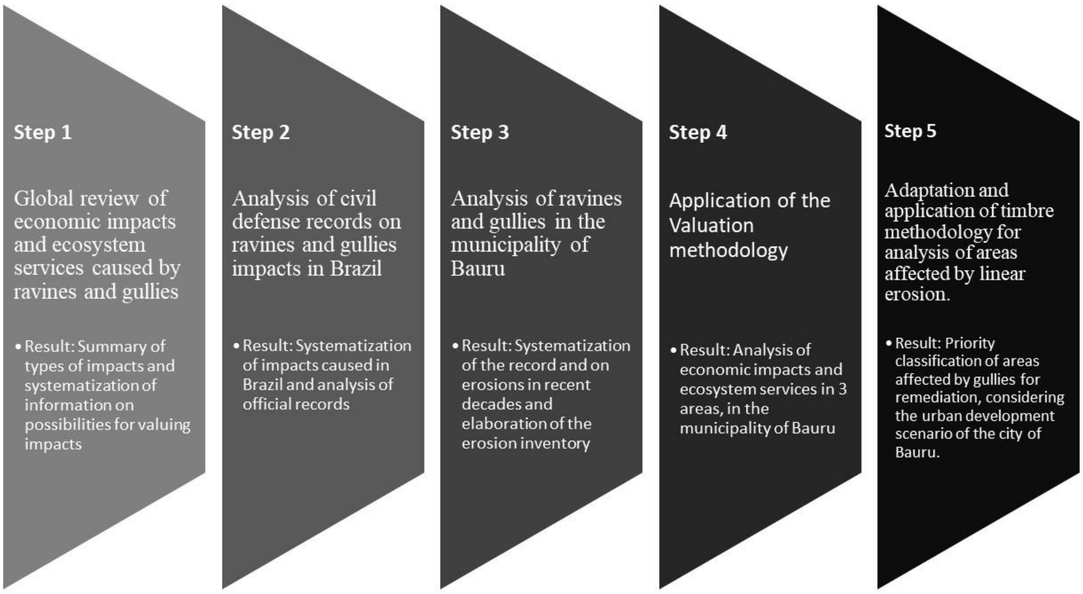
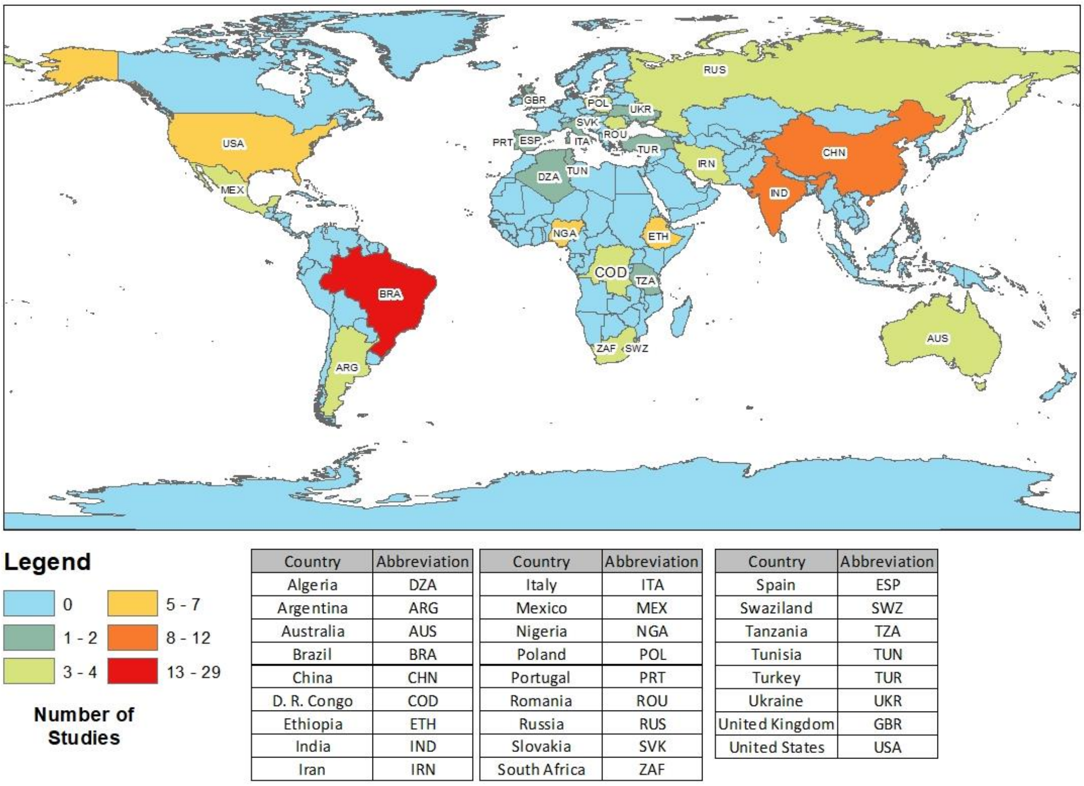


Figure 2. *sequence of the method adopted by the work and results obtained.*

Step 1: The bibliographic search was carried out in the Web of Science, Dimensions and Scopus databases. Several combinations of the following keywords were used: ravines, gully, valuation, natural hazards, invest, soil loss, urban, city, disaster, ecosystem services and linear erosion. After reading abstracts, 124 works from 27 countries were analyzed in full (Figure 3). The criterion for selecting the articles was the existence of results that help to understand the temporal evolution and impacts caused by ravines and gullies and the recovery measures implemented. In addition, the articles published related to Brazil are overrepresented in relation to other countries because the chosen sample is related to research on the valuation of linear erosions in Brazil (additional keyword “Brazil”).

Step 2: Even though records of natural disasters caused by ravines and gullies in Brazil are available since 2003, we analyzed in greater detail the information between January 2013 (implementation of the S2ID, available in: https://s2id.mi.gov.br/) and May 2019 (date on which data acquisition was performed). This time interval was chosen due to a more systematic record of disasters in the S2ID database, covering two levels of detail: a) Occurrence record: location (city and state and basic information), date, type of disaster and estimated number of people affected. b) Complete record: general information on impacts, damages and actions taken.

The latter (b) can be extracted in documents attached to the S2ID, namely the Municipal Declaration of Emergency Action (DMATE) and the Disaster Information Form (FIDE). In FIDE, in addition to basic information, data related to municipal finances are recorded, as well as description of the affected area, causes and effects of the disaster, human, material or environmental damage, and public and private economic losses. The DMATE includes the history of the disaster, information about the municipal disaster management, mobilization and use of material and financial resources. This information is usually accompanied by technical and photographic reports on the affected area. Usually, the occurrence record occurs when the disaster is restricted to a single municipality, while the complete record occurs when the magnitude of a disaster is higher, when there is a need for resources from institutions at a state or federal level.



Country	Abbreviation
Algeria	DZA
Argentina	ARG
Australia	AUS
Brazil	BRA
China	CHN
D. R. Congo	COD
Ethiopia	ETH
India	IND
Iran	IRN

Country	Abbreviation
Italy	ITA
Mexico	MEX
Nigeria	NGA
Poland	POL
Portugal	PRT
Romania	ROU
Russia	RUS
Slovakia	SVK
South Africa	ZAF

Country	Abbreviation
Spain	ESP
Swaziland	SWZ
Tanzania	TZA
Tunisia	TUN
Turkey	TUR
Ukraine	UKR
United Kingdom	GBR
United States	USA

Figure 3. *Map with the distribution of publications analyzed by country.*

Step 3: Theses, dissertations, scientific, peer-reviewed articles, technical reports and other publications were used in the identification of erosional events and estimation of their impacts in Bauru. The work by Almeida Filho (2000) was considered the most complete and was used as a basis for obtaining descriptions of ravines and gullies. Then, Google Earth images taken between 2004 and 2020, for the gully inventory used in the timbre methodology (step 5), and between 2004 and 2021, for the valuation analyzes (step 4). Were we analysed to a) identify changes in the geometry of the channel, b) remeasure the basin for containment or restoration of the area, c) monitor the change in land use and land cover and d) determine the environmental impacts to the region. In addition to the information obtained from the analysis of the images, two field studies were carried out, in December 2020 and in March 2022 to analyse the areas.

The ravines and gullies analysed were classified as follows: a) recovered: the erosion scar area was restored through recovery measures and the social and economic use was resumed; b) stable: erosion was stabilized due to measures aimed at recovering the area, but without fully restoring the use of the area; c) in development: ongoing, gradual increase in the size of the eroded area over time.

Step 4: To identify the impacts of urban ravines and gullies, the classification proposed by Kuhn et al. (2023) was employed. Impacts were classified into a) environmental, considering the cost of replacing soil, nutrients, carbon and pasture; b) costs for recovery and mitigation of erosion in the watershed area; c) destruction of infrastructure, impacts on streets, storm sewers, dams, residences, among others; d) estimated economic losses, which were calculated considering the surface area directly affected by the channels in ravines and gullies, the annual loss of gross domestic product (GDP) per square metre in the affected area in allotments; e) loss of collection of the Property and Urban Land Tax (IPTU); and f) positive impacts after the recovery of areas affected by ravines and gullies.

The analysis time of the estimated economic impacts and tax collection losses was limited to between 2000 and 2021 based on the information sources described in Section 2.1. The cost of the environmental impacts, public infrastructure destruction, and erosion containment and recovery associated with urban gullies and ravines were estimated by considering identified infrastructure close to erosions and descriptions of the channels affected by erosions, that is, all impacts that could be identified from the onset of erosion to the date of the current analysis.

The valuation of the impacts was carried out considering the replacement cost, which is the amount currently paid for the affected items and products (Lillo et al. 2014). The values obtained allow identifying the magnitude of the impacts.

Step 5: The Timbre methodology proposes different levels of decision hierarchies to analyse brownfields, which we adapted for the analysis of areas affected by linear erosions (ravines and gullies). In the adaptation proposed in this work, three stages are used: a) Inventory - in which the gullies are classified according to the activity level of the gullies; b) Prioritization - three classes are used, constituted based on the sum of the scores of the proposed parameters; c) Marketing - where the results are integrated to identify and discuss priority areas for recovery. The urban perimeter of the city of Bauru was chosen for the case study.

4. Results and discussions

4.1. Review on the analysis of the impacts of ravines and gullies

4.1.1. Economic impacts

Among the economic impacts of ravines and gullies are reduced agricultural productivity due to a loss of planting areas and change in soil characteristics; a loss of crops and available land; increases in agricultural costs; increases in agricultural activities workloads due to limitations or difficulties imposed by erosion and the cost of production agriculture and livestock in rural areas; the siltation of reservoirs and their consequential loss of functionality; increases in flooding risks and the subsequent damage to infrastructures situated in areas located near rivers; damage to infrastructure and increases in costs of drains or channel maintenance; and the rapid drainage of aquifers, which lowers the water table and subsequently dries up wells (BALZEREK *et al.* 2003; VALENTIN *et al.* 2005; ROMERO-DÍAZ *et al.* 2019).

In rural areas, several authors have described impacts related to the occurrence of ravines and gullies. Zgłobicki *et al.* (2015a) analyzed the impacts of ravines in eastern Poland. For the authors in some districts where gullies covered more than 2% of the area, where there is a high density of ravines, special management must be carried out to reduce negative economic impacts. According to the authors, the landscape forms developed by ravines are unfavorable to modern agriculture and can become an obstacle to the development of efficient agriculture or to the consolidation of agricultural land.

According to Daba (2003), gullies are expanding in areas of agricultural land in Ethiopia at an accelerated rate. They are considered to be the main cause of silting of lakes (such as Lake Alemaya) and other sources of drinking water and irrigation; in addition, they increase the risk of flooding.

Gullies and ravines reduce the cultivated area, reduce production, hamper the movement of people and livestock, and have other environmental impacts (BELAYNEH *et al.* 2020). Ravine fields cause a permanent loss of agricultural land if recovery measures are not carried out based on government funding (OLSON and MORTON 2012).

Abdo *et al.* (2013) noted that, in Australia, progressive erosion made it impossible to continue farming in areas previously used for agriculture; however, these areas could still be used for fishing, ecotourism and other economic activities. The first step in restoration is to interrupt the evolution of the erosion process and recover the area through engineering works, restrict livestock use, and recover the natural vegetation.

Morokong and Blignaut (2019) analyzed the costs and benefits of reducing soil erosion in the municipality of Mutale, South Africa. The authors identified that an area of 1470 hectares (ha) was affected by soil erosion; in some places, the observed impact was related to the loss of pasture productivity, siltation of rivers and loss of water bodies, as well as the consequent increase in the cost of water, loss in land production capacity, destruction of residential areas and interruption of roads. If considering the opportunity cost lost by unrestored land, the value is estimated at US$10 per hectare and US$56 per hectare for crops. To control erosion, US$ 0.5 million was spent using rock structures for the period 2010-2016, and with this investment, a benefit between US$ 140 thousand and US$ 200 thousand was generated, in other words, a cost–benefit between 0.29 and 0.41.

Pani (2017) determined that of 766 villages in India, 343 are affected by ravines, among which the main effects are the loss of agricultural land, reductions in production, changes in villages, and impacts on infrastructure and subsistence economic activities. Ravines affect access to land and can contribute to changes in the drainage pattern, in addition to affecting the supply of public goods and basic human development structures such as access to health and education.

According to Pani (2016), in the Chambal Valley, India, ravines affected 26.5% of the total agricultural land, but the percentage varied by village. According to the author, 71 families reported the loss of land due to the development of ravines; of this total, 11% were unable to recover the land, 76% partially recovered it and 13% moved to new land.

Busnelli *et al.* (2006) described the silting of an artificial lake in La Angostura, Argentina, where there was a reduction in the depth and loss of surface area of the reservoir, from 23% between 1977 and 2000. They demonstrated the impact of erosion on the useful life of reservoirs.

In urban areas worldwide, the impacts of ravines and gullies are felt. Balzerek *et al.* (2003) noted the destruction of houses, streets and bridges in the State of Gombe, Nigeria. Hudec *et al.* (2005) mentioned that in Nigeria, according to official data, between 1981 and 1994, erosion and other forms of soil degradation caused the country to lose 3.7 million hectares of forests and agricultural land. The authors noted an expenditure of approximately US $ 7.7 million in the state of Imo, with the objective of reducing gullies in the southeast of the country.

The city of Kinshasa (Congo) has the best documented processes of erosion in the literature. Accumulated erosion in the last 50 years in this municipality totaled 308 linear features totaling 94.7 km, that is, an average advance of 2 km annually. The 10 largest gullies had an average width of 57 m and an average depth of 20 m; however, when considering the general average of all gullies, the numbers dropped to 17 m and 6 m, respectively (Imwangana *et al.* 2015). The annual economic impact caused by the destruction of a home is US $ 1.5 million per year, in addition to other expenses such as US $ 10 million for the reconstruction of the Drève de Selembao in 2004 and US $ 7.8 million in 2006 for the recovery of areas affected by gullies in the Mataba district (IMWANGANA *et al.* 2015). Another author who described erosion processes in Kinshasa was Ozer (2014), who, through the observation of images, identified the destruction of more than 60 houses due to the development of a ravine between 2006 and 2011.

Erosions in some cases evolve suddenly due to large storms and occupational use that has not been properly planned, as in the case of Comodoro Rivadavia in Argentina in 2017. After heavy rains, a large number of V-shaped gullies were generated with lengths of up to 870 m and depths of up to 15 m; the event transported over 400,000 m3 of fine to very fine sand and damaged or destroyed more than 400 houses, in addition to urban and industrial infrastructure (PAREDES *et al.* 2020).

The increase in the cost of maintaining roads and transport routes, or costs with the paralysis of roads, is also another type of existing economic impact of ravines and gullies. Souza *et al.* (2017) stated that their possible impacts on the Malha Paulista railroad in Brazil included the halting of cargo and passenger transportation, the occurrence of accidents involving employees and passengers or even the spillage of flammable cargo, which contaminate soil and water resources. In Algeria, Kouidri (2018) described the impacts of ravines formed after civil works on roads, which included erosion in the fields and the consequent abandonment of production in the area, an increase in the cost of maintaining roads and railways, and impacts on bridges, dikes and water pipes.

The use of gullies and ravines areas after the development process is only possible once the area has recovered. In countries such as Poland, there are geotourism initiatives inside old ravines, but even after stabilization, intensive use can reactivate erosive processes (ZGŁOBICKI *et al.* 2015b).

Despite being cited in several studies, the socioeconomic impacts of Gullies and ravines are not usually detailed. Perhaps this lack of detail influences the focus of the works on typology, spatial evolution of erosion, efficiency of containment processes, among others. However, including a brief description of their impacts, mainly financial ones, can be an important step to demonstrate the losses caused by ravines and gullies and, in this way, demonstrate to society why it is so important to take measures to prevent and contain linear erosions.

Socioeconomic impacts occur in three different areas of the hydrographic basin (Table 2). The first of these is damage caused to the place where erosion occurs, which can mean from a permanent loss of an area that previously could be used for economic activities or a partial or temporary loss, depending on the recovery measures that are established. Among the damages caused are also economic losses in productivity, the destruction of infrastructures and homes, losses of production or animals, the loss of water sources and drying of wells, an increase in production costs and reduction in productivity, and an expansion of the risk of flooding, among others. The second is the downstream impact on the basin, such as an increase in the cost of water treatment and silting up of reservoirs, among others. Finally, upstream impacts may include, for example, the drying of wells or the loss of access routes (Figure 4).

Table 2. *Main economic impacts identified in the literature, classified as follows: impact (0) does not occur; (1) may occur but is not common; (2) occurs but is not predominant; and (3) is predominant.*

Impact	Land-use type		Location in the basin		
	Rural	Urban	Upstream	Erosion area	Downstream
Reduced agriculture and livestock productivity	3	2	3	3	1
Increased workload in productive activities in the affected areas	3	2	2	3	1
Silting of reservoirs	3	3	0	0	3
Increased risk and impacts of floods	2	3	0	0	3
Damage to infrastructure and homes	2	3	0	3	1
Increase in the cost of maintaining drains and channels	1	3	0	3	2
Increase in the cost of road maintenance	3	3	1	3	2
Loss of access to water	1	2	2	0	0
Loss of areas with economic and social use	3	3	1	3	1
Changes in the use of the area	3	3	1	3	1
Change in access to areas	2	2	1	3	1
Abandonment of farmland	2	1	1	3	1
Home abandonment	2	3	1	3	1
Loss of access to land	2	2	1	3	1
Use of reclaimed areas for geotourism	1	1	0	1	0
Development of new economic activities in reclaimed areas	2	2	1	1	1
Expansion of agricultural land in areas of silted dams	2	0	0	0	1
Loss with land tax collection	1	3	1	3	1

4.1.2. Impacts on ecosystem services

In the literature, impacts on ecosystem services are mentioned, such as loss of nutrients from surface layers, reduction in soil productivity, drainage of aquifers, changes in river drainage patterns, loss of soil, loss of moisture and soil cover, increases in surface runoff, increases in adverse events, reductions in aquifer recharge, reductions in carbon sequestration capacity and soil organic matter, changes in the biodiversity of plants and animals, reductions in soil moisture and vegetation cover, increases in floods, contamination of soils and surface and groundwater, wetland dryness, changes in sediment load and impacts on life in rivers, lakes and seas (Balzerek *et al.* 2003; Abdo *et al.* 2013; Rowntree 2014; Rust and Star 2018; Somasundaram *et al.* 2018; Romero-Díaz *et al.* 2019; Paredes *et al.* 2020).

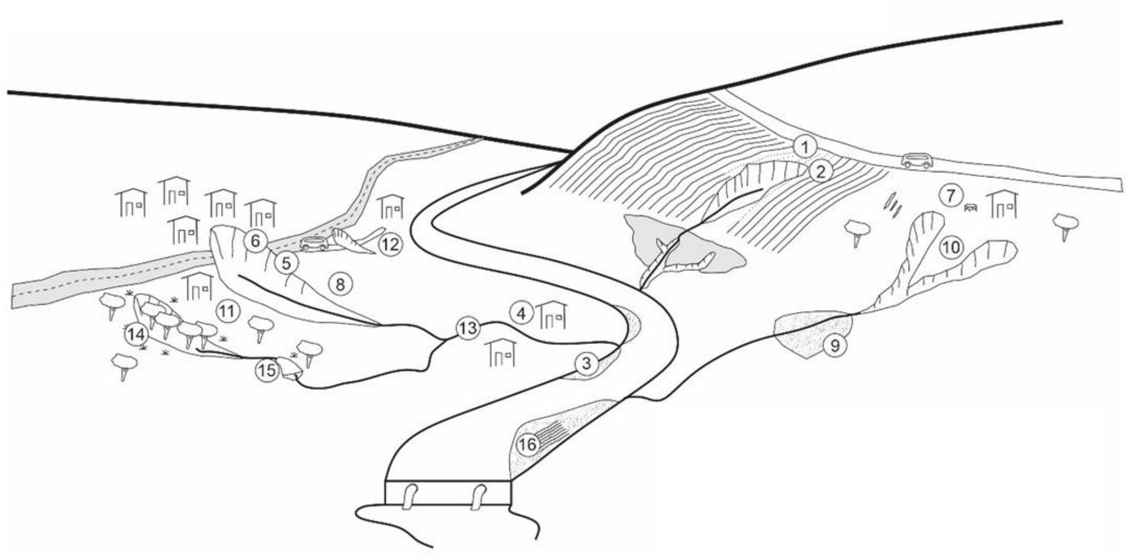


Figure 4. *Schematic spatial distribution of the socioeconomic impacts of ravines and gullies in the hydrographic basin. 1 – reduced productivity; 2 – increased workload; 3 – silting of reservoirs; 4 - increased risk and impacts of floods; 5 – damage to infrastructure and homes; 6 – increase in the cost of road maintenance; 7 – loss of access to water; 8 – loss of areas with economic and social use; 9 - changes in the use of the area; 10 – abandonment of farmland; 11 – home abandonment; 12 – loss of access to land; 13 – increase in the cost of maintaining drains and channels; 14 – use of reclaimed areas for geotourism; 15 – development of new economic activities in reclaimed areas (e.g., fishing); 16 – expansion of agricultural land in areas of sited dams.*

The effects of ravines and gullies impact several fundamental ecosystem services, for example, a) provisioning services: production of food, fibers, fuel and water; b) regulation: climate, natural risks, soil erosion, water cycle and biodiversity and health; and c) support: protection of genetic reservoirs, nutrient cycling and soil formation (ROMERO-DÍAZ *et al.* 2019).

In cases such as in the Peak District (United Kingdom), peat erosion can release lead-contaminated sediment (ROTHWELL *et al.* 2010). According to Shuttleworth *et al.* (2015), truffles are an important carbon stock but can also assimilate heavy metals; thus, truffle erosion in the UK contributes to carbon and pollutant storage. If these systems are affected by erosion, their functions will be modified.

According to Valentin *et al.* (2005), gullies tend to increase drainage and increase the speed of the aridification process in semiarid areas. Morokong and Blignaut (2019) noted among the impacts caused by ravines the compromise of ecosystem water services, in addition to the reduction of carbon sequestration.

Somasundaram *et al.* (2018) considered ravines to be an extreme form of soil degradation and mentioned that in India, this kind of erosion process occupies an area of approximately 10.37 million hectares. For the authors, these areas, if restored, could contribute to carbon sequestration through the adoption of restoration practices such as leveling land, planting perennial trees and sowing legume strips, all of which aim to improve soil quality.

Didoné *et al.* (2014) indicated that erosion problems include changes in the amount of sediment in the water, the loss of fertility, loss of useful area, reduction of water storage in the soil, and remobilization of nutrients and pesticides to water courses, which can increase the cost of water treatment for society.

The impacts on ecosystem services also occur in three different positions in the hydrographic basin (Table 3). Where erosion has developed, loss of soil and removal of the most fertile horizons, loss of vegetation cover, changes in the landscape, reduction of soil biomass, reduction of carbon sequestration, drying of wetlands and reduction of biodiversity have occurred. Downstream from erosion, contamination of watercourses, silting and changes in river drainage patterns can occur, increasing the sediment load, which can impact biodiversity in rivers and coastal regions. Upstream, aquifer drainage can occur (Figure 5).

Table 3. *Main ecosystem impacts, where they occur in the hydrographic basin and to what extent they occur. Impact (0) does not occur; (1) may occur but is not common; (2) occurs but is not predominant; (3) is predominant.*

	Location in the basin			Extent of impact		
Impact	Upstream	Erosion area	Downstream	Permanent loss	Partial when area is reclaimed	Benefits after recovery
Loss of soil nutrients	1	3	1	x		
Aquifer drawdown	3	3	0	x		
Changes in the drainage pattern	0	3	2	x		
Increased runoff	0	3	3		x	
Soil erosion	1	3	1	x		
Reduction of organic material in the soil	1	3	1		x	
Impact on fauna and flora biodiversity	1	3	2	x		
Reduction of vegetation cover	1	3	1			x
Reduction of soil moisture	1	3	1		x	
Dryness of wet areas	0	2	2	x		
Increased sedimentary load	0	1	3			x
Impact on the life of lakes, rivers and seas	0	1	3		x	
Water contamination	0	2	2		x	

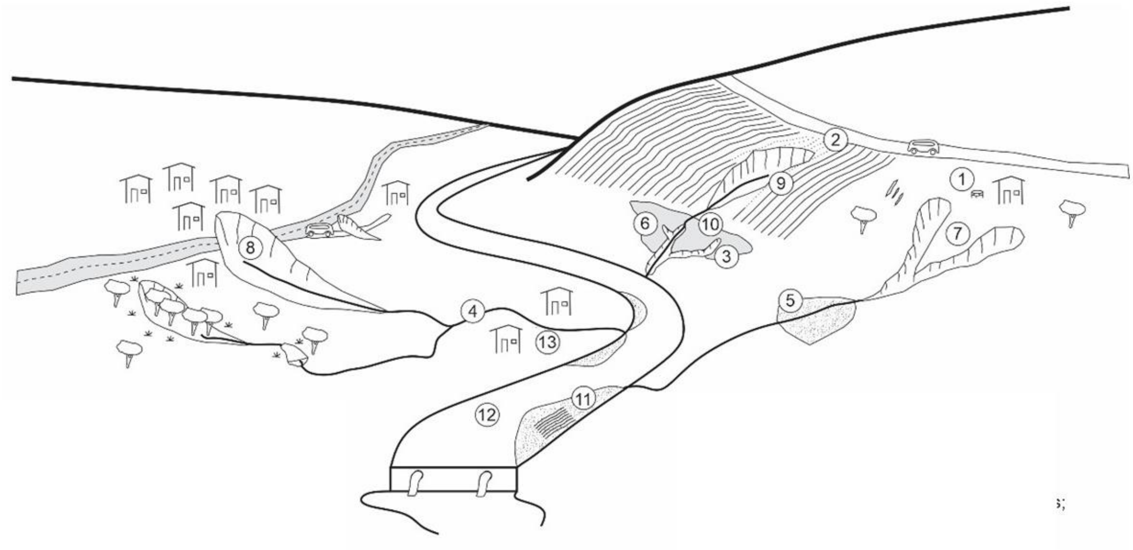


Figure 5. *Schematic spatial distribution of impacts caused by linear erosion on ecosystem services in the watershed. 1 – aquifer drawdown; 2 – loss of soil nutrients; 3 - changes in the drainage pattern; 4 – increased runoff; 5 – reduction of organic material in the soil; 6 – impact on biodiversity fauna and flora; 7 – Reduction of vegetation cover; 8 – soil erosion; 9 – reduction of soil moisture; 10 - drying of wet areas; 11 – increases in sedimentary load; 12 – impact on the life of lakes, rivers and seas; 13 – contamination of water.*

4.1.3 Impact valuation

Few studies have evaluated the impacts caused by ravines and gullies; those that have include Yitbarek *et al.* (2012), Ayele *et al.* (2015) and Rust and Star (2018).

Yitbarek *et al.* (2012) developed a technique for valuing the financial impacts caused by ravines related mainly to soil components. The authors analyzed the cost of 4 erosion events in Ethiopia by analyzing yield loss, the cost–benefit of soil rehabilitation, rehabilitation and personnel costs and the monetization of soil nutrients, based on the price of fertilizers. For the rehabilitation of ravines, structural measures were used, such as loose stones, gabion boxes and other structures of control dams, to reduce the speed of the water and vegetative measures, with the instruction of trees and grasses in the affected area. The soil loss estimate was performed according to dimensions such as mouth width, depth, width of the erosion bed, and length of the ravine. The cost of erosion was obtained based on the loss of income in the area, adjusted by the interest rate of the Central Bank of Ethiopia. Rehabilitation expenses considered from the initial surveys to the final maintenance costs, that is, all expenses with labor, materials, training, equipment in the stages of rehabilitation or maintenance. The cost of nutrient loss considered the conversion of the percentage of lost values of nitrogen (N), phosphorus (P) and potassium (K) and the level of organic carbon (OC) and the replacement cost based on the values of the fertilizers. To calculate the loss of productivity in the area, the period of time since the ravine was formed and the reduction in the cultivated area due to erosion were considered. Werken Gashajagrie, Werken Adura, Eshim Wofena and Tsegur Eyesus, the areas directly affected by each of the ravines in hectares were 2.60, 1.87, 1.51 and 0.95, respectively. For the four erosion events, the damage caused was US$ 4,896, the rehabilitation cost was US$ 24,480 and the replacement of nutrients was US$ 28,320. According to the calculation developed by the authors, the cost of rehabilitation tends to be greater than the future gains from recovery, which makes it difficult for poor farmers to implement these actions.

For Yitbarek *et al.* (2012), if the study had accounted for the monetary value of wood production, grass fodder, carbon sequestration and sedimentation in bodies of water, the benefits of recovery would probably outweigh the costs.

Other authors, such as Ayele *et al.* (2015), also accounted for the cost of erosion in Ethiopia's highlands by counting the loss of soil nutrients (N and P) and the cost of missed opportunities; the value of the daily wage was used to account for the loss of opportunities related to increased travel time due to road interruptions and the value of animal deaths and tree replacements. In the hydrographic basin studied, the cost over two years was US$18,000, which corresponds to US$22 per ha per year, or a value of US$17 per person per year, which represents 19% of the per capita income. According to the authors, although the estimated costs are high compared to family income, they may still be underestimated because the nutrient replacement cost may not reflect the total replacement value. In addition, the estimated values did not consider costs such as the silting of reservoirs, reduction in hydroelectric power generation, impacts on irrigation, and the reduction of water quality, among other types of ecosystem services.

Due to the increase in sediment load in Fitzroy, Australia, and the subsequent changes in the Great Barrier Reef, Rust and Star (2018) carried out a study to analyze the cost of remediation of six gullies, considering measures to decrease stocking rates in pasture, increase revegetation and increase infrastructure construction to contain erosion and earthworks. The calculation of the cost of remediation was carried out by the authors considering the cost of construction, the cost of annual maintenance and the opportunity cost requested, considering a period of 10 years and a discount of 7% per year, in addition to the exclusion of cattle from the site for a period of 18 months. Among the six properties analyzed, the value to prevent erosion of one cubic meter of soil ranged between US$ 78.43 and US$ 604.96 m^3 per year, and the general average was US$ 127.42 per m^3 per year of sediment.

Rust and Star (2018) considered that the study presented a view on the complexity related to the cost of gully remediation measures, as the specific characteristics of each erosion event impact the final cost of recovery. Hence, the construction of policies becomes more difficult.

The works analyzed above in this topic were all carried out in rural regions. The case of changes caused by the increase in sediment load on Australia's reefs is a clear example of impacts outside the area directly affected by erosion. To analyze the socioeconomic impacts and ecosystem services impacts, the three different areas of the hydrographic basin must be considered.

The greater the erosion and/or the longer it takes for measures to contain erosion, the greater the impacts. The estimates proposed by Bartley (2020) of the reduction in sediment load downstream of erosion in a period between 19 and 28 years after the adoption of recovery measures indicate that linear erosion is a problem that requires planning and analysis that consider the results in the medium and long term. The review carried out by Romero-Díaz et al. (2019) indicated that after adopting recovery measures, the positive results increase over the following years.

Considering the economic and environmental impacts described in the previous items, there are complex cases in cities such as the city of Kinshasa in Congo, where in the literature, there is a report of destruction of dozens of houses due to the evolution of only one erosion area (Ozer 2014; Imwangana *et al.* 2015), demonstrating that in urban areas, the costs can be higher. The case of the Comodoro Rivera in Argentina is another example of significant damage in urban areas (Paredes *et al.* 2020). The waterproofing of areas, which changes the natural dynamics of rainwater runoff, the construction of linear structures and the exposure of the soil can favor the rapid development of large erosions. However, none of the analyzed studies assessed socioeconomic impacts or ecosystem services in urban areas.

An analysis of the impacts of erosion must consider the temporal and spatial dimensions of the damage caused, including the direct economic losses at the erosion site, downstream and upstream; the value of the containment or recovery measures; the partial or permanent losses of the productive area, according to the period in which the erosion developed; and the cost of maintaining any containment measures, in addition to accounting for impacts on ecosystem services along the hydrographic basin (Table 4).

Three possible future evolution scenarios may be considered: a) total recovery, that is, where through recovery measures, the affected area can recover all environmental, social and economic functions; b) stabilization, in this case, the recovery measures stabilize the erosion; however, some of the socioeconomic or environmental functions are not recovered or are partially recovered; and c) natural evolution, where no recovery measures are taken, and in this way, erosion continues to grow until is stabilizes naturally.

The calculation of the impact of erosion depends on the variables measured in the affected area. In all cases, the damage caused and/or recovery measures will be carried out in different locations in the watershed area. Some variables will always be linked to the time the impact, damage or cost persisted, such as, for example, the stoppage of economic activities, loss of cultivated areas, and cost of annual maintenance. Other variables, however, generate direct damage that may persist until the item is replaced or rebuilt, such as animal death and infrastructure destruction. Additional variables are linked to local socioeconomic changes, such as increased workloads due to erosion containment and route changes to address road interdiction. Ecosystem services can be monetized by analyses such as replacement cost, as performed by Yitbarek *et al.* (2012), or by other methodologies that allow stipulating the value related to each variable already used for monetization of impacts such as the Contingent Valuation Method (CVM), Willingness to Pay (WTP) and Net Present Value (NPV) (Getzner *et al.* 2017, Maghsood *et al.* 2019, Moos *et al.* 2019), which have been used by the authors to value forests, manage floods under climate change and reduce risks based on the ecosystem provided by the forest. The final calculation of the impacts of erosion will be the result of the sum of the total variables and expenditures made at the site considering the time, the recovery measures, the impacts on ecosystem services and socioeconomic impacts.

Table 4. *Impacts and measures for the recovery and containment of the affected area and variables and units that can be used to calculate the total cost.*

Socioeconomic impacts	**How to calculate**	**Variable**
Reduced productivity in the affected area	Comparison between previous productivity and the productivity of the area after having been affected	Accumulated losses with time
Increased workload with measures related to erosion	Cost of working hour	Accumulated losses with time
Well drying	Unit cost	Accumulated losses with time
Loss of access to areas	Travel cost and resulting losses	Sum of cost plus per year
Destruction or damage to infrastructure and homes	Infrastructure cost	Accumulated losses over time. For example, monthly rental cost
Loss of area for social and economic use	Area cost	Area productivity
Increased production cost	Added cost	Sum of cost plus per year
Reduced access to water	Cost of measures to re-establish access to water	Maintenance costs or other monthly or annual costs
Increased time spent on moving people, animals and machinery	Work hour cost	Sum of cost plus per year
Loss of crops and animals	Cost of annual crop loss	Sum of cost plus per year
Increased cost of maintenance of transport routes;	Cost of recovery measures	Sum of cost plus per year
Abandonment of urban or rural properties;	Cost of properties and improvements	Accumulated losses with time
Loss of access to water;	Cost of measures to re-establish access to water	Maintenance costs or other monthly or annual costs
Dam silting and loss of functionality;	Cost of measures to reduce the impacts of silting or dam cost	Accumulated losses with time

Increased cost of water treatment;	Difference between the cost of treatment before and after erosion	Sum of cost plus per year
Increased risk and impacts of floods	Difference between costs related to previous and subsequent floods	Accumulated losses with time
Changes in the use of the area	Value per m² prior minus the value per m² after recovery	Difference in values and time estimation
Loss of land tax collection	Calculated by considering the average of the amounts charged for land taxes in the region.	The loss calculation needs to consider the value of the annual fee and the number of years that the area has been affected
Impacts on ecosystem services	**How to calculate**	**Variable**
Lowered aquifer water table	Reduced aquifer volume in cubic meters.	Cost of aquifer recovery (when possible)
Nutrient loss	Amount of nutrients. Replacement cost.	Accumulated losses with time
Soil loss	Volume in cubic meters or tons.	Replacement cost of accumulated losses over time
Wetlands dryness	Environmental changes	Valuation of ecosystem services or analysis with a willing-to-pay method
Reduced carbon sequestration capacity	Amount of nutrients.	Replacement cost of accumulated losses over time
Plant and animal biodiversity impacts	Loss of biodiversity	Valuation of ecosystem services or analysis with a willing-to-pay method
Increased sediment input and water turbidity	Difference in water quality	Valuation of ecosystem services or analysis with a willing-to-pay method
River siltation	Sediment volume	Cost of recovery measures, cost of impact
Drainage pattern changes	Environmental changes	Valuation of ecosystem services or analysis with a willing-to-pay method
Organic soil material reduction	Environmental changes	Valuation of ecosystem services or analysis with a willing-to-pay method
Increased runoff	Damage caused by the new flow dynamics	Accumulated losses with time
Vegetation cover reduction	Environmental changes	Valuation of ecosystem services or analysis with a willing-to-pay method
Water contamination	Changes in water quality	Cost of recovery measures, cost of impact
Cost of recovery or containment measures	**how to calculate**	**Variable**
Measures to control surface runoff and increase soil water retention,	Cost of measurements	Monitoring and maintenance cost
Revegetation,	Cost of measurements	Monitoring and maintenance cost

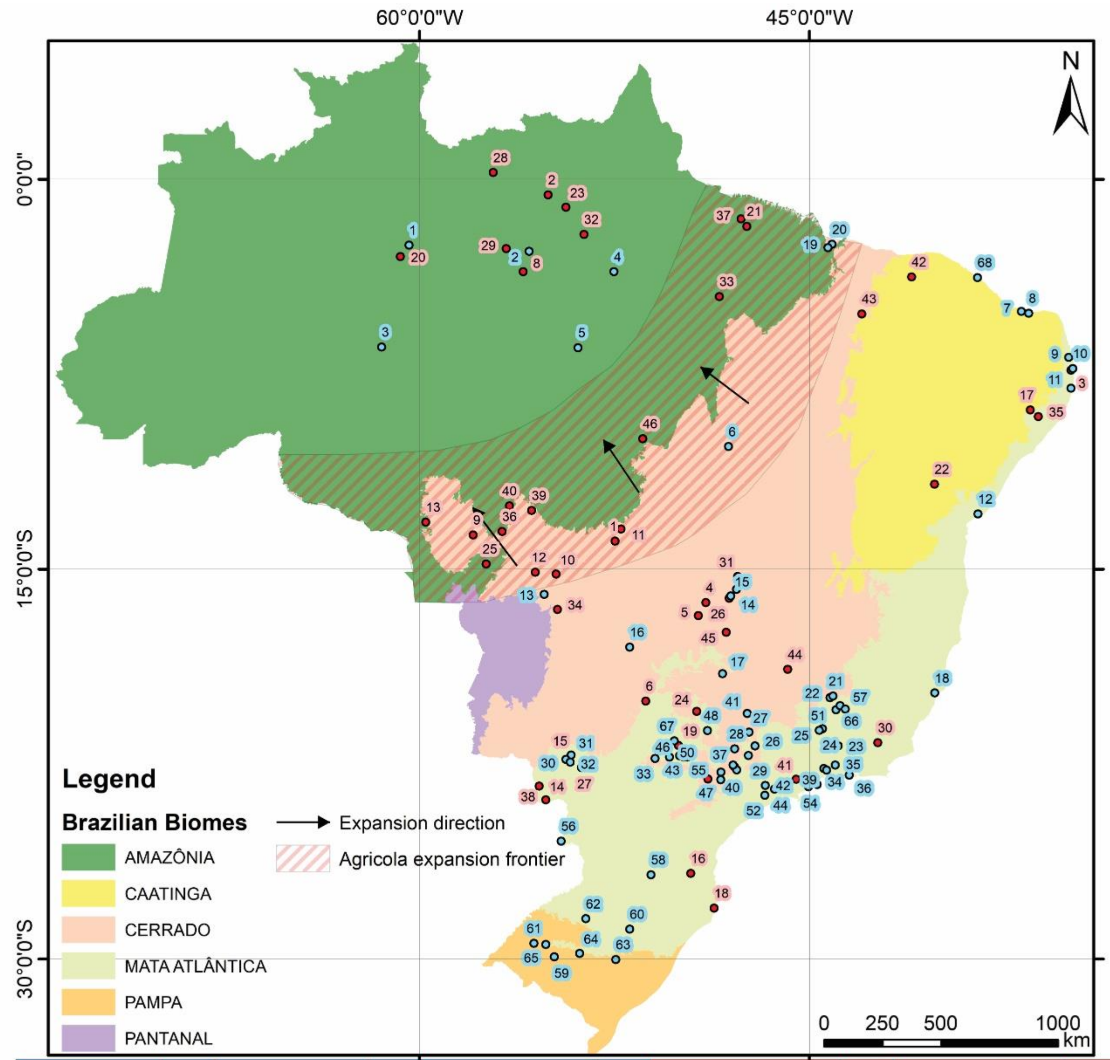
Construction of energy sinks and water storage basins	Cost of measurements	Monitoring and maintenance cost
Construction of structural measures;	Cost of measurements	Monitoring and maintenance cost
Development of revegetative measures;	Cost of measurements	Monitoring and maintenance cost
Erosion grounding;	Cost of measurements	total cost
Terracing and planing areas;	Cost of measurements	Monitoring and maintenance cost
Maintenance of built structures;	Cost of measurements	Monitoring and maintenance cost
Replenishment of nutrients in the soil	Cost of measurements	follow-up cost
Construction of sediment retention dams;	Cost of measurements	Monitoring and maintenance cost
Desilting of water courses.	Cost of measurements	follow-up cost
Cost of other recovery or containment measures adopted	Cost of measurements	Monitoring and maintenance cost
Qualification actions for public agents and farmers	Cost of shares	Sum of cost plus per year
Education actions in affected communities	Cost of shares	Sum of cost plus per year

4.2. Analysis of the impacts of ravines and gullies in Brazil

The data extracted from the S2ID system and the information available in the Scopus database allowed the identification of municipalities with records of impacts related to ravines and gullies (Figure 6). The S2ID database indicated the occurrence of ravines and gullies in 46 municipalities, while the bibliographic analysis indicated their occurrence in 68 municipalities, with a single municipality (Deodápolis) appearing in both analyses (Table 5). Therefore, 113 municipalities have recorded significant impacts related to ravines and gullies.

Table 5. *limitations and contributions of each source of information used in this study.*

Source of information		**Limitations**	**Contributions**
S2ID data base	Occurrence record	- Presents little information about the disaster.	- Allows identifying places where there are relevant cases of ravines and gullies.
	Complete registration	- Information about impacts was no longer updated after completion or state or federal recognition. - information on medium and long-term impacts is not recorded.	- Allows identifying places where there are relevant cases of ravines and identifying the impacts caused up to the date of filling out the forms. - Photographic record. - In general, records are accompanied by technical analyses, carried out by engineers or geologists.
Literature review		- Absence of studies that have previously evaluated impacts.	- Allows identifying places where there are relevant cases of ravines and gullies. - Analyzes typology case studies, containing techniques and other important information to discuss the data obtained in the S2ID. - Provides an overview of the impact of ravines and gullies in Brazil.



County	Code	County	Code	County	Code	County	Code	County	Code
Manaus	1	Conceição Da Barra	24	Pardinho	47	Água Boa	1	Nova Granada	24
Santarém	2	Nazareno	25	Pindorama	48	Alenquer	2	Nova Olímpia	25
Manicoré	3	Casa Branca	26	Piracicaba	49	Alhandra	3	Novo Gama	26
Brasil Novo	4	Cajuru	27	Bacia Rio do Peixe	50	Anápolis	4	Novo Horizonte do Sul	27
Altamira	5	São Carlos	28	Bacia do Rio Maracujá	51	Aparecida de Goiânia	5	Oriximiná	28
Palmas	6	Leme	29	São Paulo	52	Aparecida do Taboado	6	Parintins	29
Porto Do Mangue	7	Fátima Do Sul	30	São Pedro	53	Avaré	7	Pirapetinga	30
Macau	8	Deodápolis	31	Ubatuba	54	Aveiro	8	Planaltina	31
Rio Tinto	9	Glória de Dourados	32	Vera Cruz	55	Campo Novo do Parecis	9	Prainha	32
Conde	10	Rancharia	33	Foz Do Iguaçu	56	Campo Verde	10	Rondon do Pará	33
Recife	11	Paraty	34	Ouro Preto	57	Canarana	11	Rondonópolis	34
Salvador	12	Pinheiral	35	Caçador	58	Chapada dos Guimarães	12	Santana do Mundaú	35
Jaciara	13	Rio De Janeiro	36	Cacequi	59	Comodoro	13	São José do Rio Claro	36
Brasilia	14	Aguas de São Pedro	37	Guaporé	60	Coronel Sapucaia	14	São Miguel do Guamá	37
Gama	15	Arapei	38	Manoel Viana	61	Deodápolis	15	Sete Quedas	38
Bacia de Queixada	16	Bananal	39	Pejuçara	62	Doutor Pedrinho	16	Sorriso	39
Uberlância	17	Botucatu	40	Rio Pardo	63	Garanhuns	17	Tapurah	40
Aracruz	18	Franca	41	Santa Maria	64	Garopaba	18	Taubaté	41
São Luis	19	Franco Da Rocha	42	São Francisco De Assis	65	Getulina	19	Tianguá	42
Paço do Lumiar	20	Garça	43	Itabirito	66	Iranduba	20	Timon	43
Contagem	21	Itaquaquecetuba	44	Alegre	67	Irituia	21	Tiros	44
Betim	22	Jacareí	45	Fortaleza	68	Mairi	22	Urutaí	45
Lima duarte	23	Marilia	46			Monte Alegre	23	Vila Rica	46

Figure 6*. Distribution of the municipalities and regions; in red, municipalities where cases have been reported by the civil defense database and in blue the location of the studies analyzed in the literature review (Scopus); biomes (IBGE 2019) are indicated in colors and the arrows indicate the frontier of agricultural expansion in Brazil.*

4.2.1. S2ID database

A total of 76 cases were registered in the 46 municipalities in the S2ID database. Of this total, 52 contain only “occurrence records”, in which solely the typology of the process is classified and an estimate of the number of people affected is presented. For the other 24 cases, full information was available, which documents describing the impacts caused by the disaster and the inclusion of documents such as the DMATE and FIDE. None of the documents had information about the measures taken after the federal recognition of the disaster.

A total of 296,324 people were affected between 2013 and 2019 and 75% of the recorded events (57) are concentrated in five states: Mato Grosso - MT (19 cases); Pará - PA (16 cases); Goiás - GO (11 cases), Mato Grosso do Sul - MS (9 cases) and Amazonas - AM (7 cases). From 2010 to 2019, a growing trend in the number of annual records of natural disasters caused by ravines and gullies was observed, peaking in the last year with a complete dataset (2018) (Figure 7).

The municipalities with the highest number of records were Oriximiná (PA) with 7, Novo Gama (GO) with 5, Iranduba (AM) with 4, and Canarana (MT), Comororo (MT) and Coronel Sapucaia (MS) with 3 events each. The municipalities with disasters induced by ravines and gullies are among the 50% most populous and/or among the 50% with the best proportion of Gross Domestic Product (GDP) per capita in the country, according to official information from the Brazilian Institute of Geography and Statistics (IBGE, 2020).

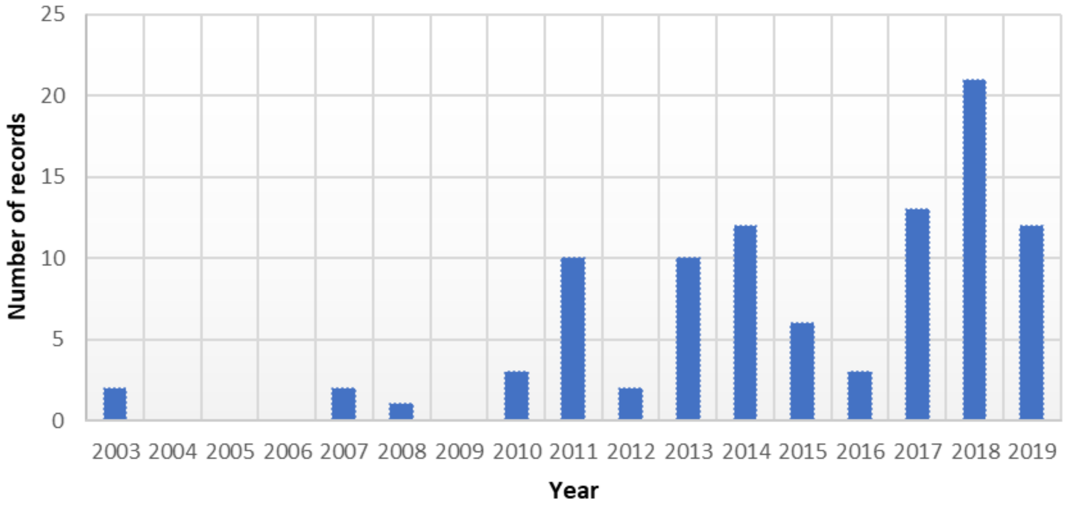


Figure 7. *Number of disasters caused by ravines and gullies per year, based on civil defense data obtained in May 2019.*

4.2.2. Literature review about Brazilian gullies

The Literature review considered 63 publications, which recorded the occurrence of ravines and gullies in 68 municipalities. Published studies are concentrated in the states of São

Paulo (SP), Minas Gerais (MG), and Rio Grande do Sul (RS). The municipality of São Pedro was the most studied area 6 publications, followed by São Luis (4), Nazareno (3) and Marília (3).

4.2.3. Records of damages in the S2iD database

According to the information available in the Disaster Information Form (FIDE) (Table 6), 20 of 24 cases affected urban areas, one of them a rural site and three of them affected both (Figure 8 and Figure 9). Economic impacts were characterized by: 1) material damage causing a total cost of US$26 million covering public infrastructure, residences, public health facilities, public facilities providing other governmental services, and public infrastructure; 2) economic losses in the public and private sector of approximately US$ 17.9 mi, including damage in the sanitary and rainwater system, drinking water supply, medical care, public health and emergency medical care; 3) public losses of U$ 4.73 mi in local and regional transport systems, public security, disinfestation and disinfection of insects, pest and vector control, schools, electricity generation and distribution; 4) private losses of US$ 3.45 mi in the service sector, livestock and industry; and, finally, 5) costs of ongoing actions of US$ 2.55 mi to be covered by the municipal annual budget and municipal extra-budget sources (Table 7). Ravines and gullies in most cases initiated due to atypical rainfall, lack of drainage infrastructure or insufficient urban planning.

Table 6. *Analyzed events in relation to the biomes they are inserted in.*

County	**State**	**Year**	**Biome**
Anápolis	GO	2013	Cerrado
Aparecida de Goiânia	GO	2013	Cerrado
Irituia	PA	2013	Amazon
Novo Gama	GO	2013	Cerrado
Comodoro	MT	2014	Amazon
Novo Gama	GO	2014	Cerrado
Novo Gama	GO	2014	Cerrado
Novo Gama	GO	2014	Cerrado
Tiros	MG	2014	Cerrado
Garanhuns	PE	2015	Caatinga / Atlantic Forest
Novo Gama	GO	2015	Cerrado
Aparecida de Goiânia	GO	2017	Cerrado
Avaré	SP	2017	Cerrado / Atlantic Forest
Pirapetinga	MG	2017	Atlantic Forest
Pirapetinga	MG	2017	Atlantic Forest
Rondonópolis	MT	2017	Cerrado
Timon	MA	2017	Cerrado
Deodápolis	MS	2018	Atlantic Forest
Parintins	AM	2018	Amazon
Rondon do Pará	PA	2018	Amazon
Santana do Mundaú	AL	2018	Atlantic Forest
Urutaí	GO	2018	Cerrado
Getulina	SP	2019	Atlantic Forest
Timon	MA	2019	Cerrado

Figure 8. *Examples of gullies and ravines in Brazil. A and B: Gully located at Rua 14-E, municipality of Aparecida de Goiânia, state of Goiás (Cardoso 2013); C: Unstable areas with imminent risk of landslide. Santana do Mundaú, state of Alagoas (Da Silva 2018); D: Ravine under development, 3 meters from residences, municipality of Timon, state of Maranhão (De Oliveira Filho and Dos Santos 2014) (Source: S2ID system reports).*

Figure 9. *Examples of gullies and ravines in Brazil. A and B: Rural roads affected by erosion in Tiros, Minas Gerais state (Longe 2014); C and D: residence close to erosion and the Cascalheira stream where water is collected for public supply, municipality of Comodoro, state of Mato Grosso (dos Santos 2014) (Source: S2ID system reports).*

Table 7. *Costs caused by ravines and gullies according to the records described in FIDE between January 2013 and May 2019.*

Sectors affected	**Estimated value in millions of US$**
Material damage	
Public infrastructure	18.1
Housing units	6.53
Public health facilities	0.88
Public facilities providing other services	0.36
Public facilities for community use	0.11
Public teaching facilities	0.04
Public and private infrastructure	
Sanitary sewage and rainwater system	16.48
Urban cleaning and waste collection and disposal system	0.82
Drinking water supply	0.41
Medical care, public health and emergency medical care	0.25
Public services	
Local and regional transport	3.68
Public security	0.35
Disinfestation and disinfection of insects, pest and vector control	0.34
Teaching	0.31
Electricity generation and distribution	0.06
Private business	
Service sector	2.02
Livestock	0.96
Industry	0.47
Emergency services	
Municipal anual budget	1.00
Municipal extra-budget	0.91
Other sources (federal or state)	0.65
Total	54.73

The municipality of Novo Gama (GO), with five records, was the municipality with the most affected people (Figure 10). The cases with the greatest material damage were Anápolis (GO) (U$ 6.4 mi); Aparecida de Goiânia (GO) (U$ 5.46 mi) and Novo Gama (GO) (U$ 3 mi). The greatest public and private economic losses were recorded in Aparecida de Goiânia (GO) in 2013 (U$ 5.81 mi) and 2017 (U$ 5.46 mi), followed by Timon - MA in 2019 (U$ 2.37 mi). The largest private economic losses were recorded in Comodoro - MT, related to the livestock sector in 2014 (U$ 0.95 mi) and in the municipality of Novo Gama (GO), in the service sector both in 2013 (U$ 0.87 mi) and 2014 (U$ 0.87 mi).

Although the data available by the S2ID database includes different types of impacts, the total sum US$ 54 million (Table 7), is interpreted as an underestimation. The records do not adequately consider post-impact costs, such as declining economic activities, expenses for land recuperation, changes in the type of economic activity, etc. Another existing shortcoming is that the impacts on the ecosystem are not considered. Environmental impacts are mentioned in FIDE as a percentage of contamination or pollution of water, air and soil, in addition to water reduction or depletion. The reports do not present information on the dimension of environmental impacts in the watershed or even the volume of eroded sediments. Magnitude estimation and a more detailed description of the dimension of the event are important indicators, identifying areas impacted by silting and production losses, thus contributing to the improvement of the economic and environmental impacts records.

The Municipal Declaration of Emergency Action presents information on how the municipality organizes itself in relation to the national policy for civil protection and defense, describing the municipal capacity to deal with adverse events. Out of the 24 cases analyzed, 16 of them occur annually, with only 6 being “first time” records.

Figure 10. *Destruction of public structures and residences in the municipality of Novo Gama, state of Goiás (Pimenta 2015). (Source: S2ID system reports).*

The magnitude of many events exceeded the capacity of the municipal management to deal with the disaster in most cases (21 of 24) and the losses affected the response capacity of the municipal government in 22 cases. In 13 cases, public and private economic losses were separated, and in 20 cases, economic losses caused by ravines and gullies were mentioned. Most municipalities have municipal committees, or a corresponding body structured to monitor disaster situations, in addition to having the support of state agencies and institutions. In 22 of the 24 cases, municipal maps of geological hazard areas already existed.

In most cases, however, there is no provision for programs and projects for actions aimed at tackling the problem in the Multiannual Plan (PPA), which is the document that guides the application of public resources over a four-year period, or in the Budget Guidelines Law (LOA), which approves the city's annual budget. When a disaster occurs, it is necessary to approve extraordinary resources, either from the municipal budget itself or from the National Fund for Public Disasters, Protection and Civil Defense (PNPDEC), which grants resources to municipalities that have an emergency recognized by the federal government, so that they carry out prevention, mitigation, preparation, response, and recovery measures (BRASIL 2010, 2012b).

In Brazil, despite recent advances in the mapping of risk areas in the municipalities of the country by the Geological Service of Brazil, which produced Geological Risk Sectorization maps in 1607 of the 5568 municipalities (CPRM 2021), the incorporation of prevention and mitigation measures has not yet occurred in most of the municipalities analyzed. Complete records of the disasters in the S2ID system can contribute to the analysis of impacts, which is important to convince public managers to develop preventive measures, as well programs that consider the planning and recuperation of areas affected by ravines and gullies. The integration between the technical analysis that is consolidated through maps of risk areas and the evaluation of damage caused by natural disasters can complement each other, demonstrating the potential losses if a disaster occurs and that preventive measure can lessen the socioeconomic impacts.

4.2.4 Integration of the S2iD database and the results of the literature review: an analysis of the economic impacts of ravines and gullies in Brazil

The cases reported in the S2ID system are mainly related to the urban perimeter. Urbanization results in changes in runoff behavior, due to impermeable surfaces (pavings and buildings), and an inadequate urban planning can favor the development of ravines and gullies (DE ALBUQUERQUE et al. 2020). Only 4 of the 24 the impacts recorded in rural areas amount to U$ 0,96 mi damage and are mainly related to livestock in a single event in the state Mato Grosso (Table 2). De Brito Galvão et al. (2011) mention that in the last decades there has been an increase in the number of studies that pursue to understand the impacts of ravines and gullies on agriculture, land conservation and water dams.

Brazilian studies address the impact of ravines and gullies, but in general, they do not measure economic losses, focusing more on the characterization of the process and the qualification of socio-environmental impacts. The few studies that focus on the economic losses are discussed in the following. Guerra et al. (2018) cited that severe erosion poses risk to people in the state of Maranhão. The economic losses reported in Rotta and Zuquette (2014) are related to unsuccessful land recuperation measures in cities such as São Pedro, Franca, São Carlos, Casa Branca and Cajuru, all of them in São Paulo state. The impacts caused by the development of ravines and gullies in railways are mainly interruptions in cargo and passenger transport (SOUZA et al. 2017). Few studies address socioeconomic losses on the country's agricultural frontier and are located in Mato Grosso and in the northern region, where the highest numbers of disasters caused by ravines and gullies are recorded. Although they are mostly described for urban areas, they are not limited to these but can also occur on agricultural land.

S2ID presents raw data with important information about disasters and the impacts caused throughout the national territory. This database can be an important source of information to indicate potential areas for scientific research, which can study and understand the most significant disasters, seeking to strengthen the protection and civil defense policy in Brazil. In addition, transforming database information into scientific publications is a way of validating existing information.

To reduce underreporting and expand information on existing disasters in the country, the federal government and the civil defense could establish the obligation that public concessionaires, be they highways, gas pipelines, sanitation infrastructure, transmission lines etc..., have to report cases of ravines and gullies in the S2ID. This type of action would allow recording small-scale impacts. Another gain that could be achieved with this measure is the identification of areas where problems with ravines and gullies are recurrent, which is essential for public institutions to be able to identify the environmental sensitivity of areas with low population density, such as the agricultural frontier of Brazil.

In some cases, as in the cities of Novo Gama (GO) in 2014 and Pirapetinga (MG) in 2017, the existence of two or more different processes in the same year, may indicate duplication of registration, or register damage caused due to the evolution of the same erosion at different times. In order to improve the analysis on the recording of natural disasters, it is necessary to add information describing the evolution processes that caused the disaster. In addition, it is necessary that a new event can be linked to the previous one, creating a documentary timeline of the impacts and actions carried out.

The fact that disaster records only exist in municipalities with Gross Domestic Product (GDP) per capita among the 50% largest in the country, and/or in municipalities among the 50% most populous, suggests that smaller and poorer municipalities can experience difficulties carrying out disaster cataloguing. The increase in the number of recorded events after 2012 may represent a growth trend or an improvement in reporting due to changes in the civil defense system and the structuring of public policies related to the disaster database in the country (KUHN et al. 2022).

The significant number of disasters in the states of Mato Grosso, Mato Grosso do Sul, Pará, Amazonas and Goiás suggests a relationship between the expansion of the agricultural frontier in Brazil and accelerated erosion processes due to changed land use. The formation of ravines and gullies are directly connected to the release of high sedimentary loads, which may contribute to the silting of rivers and changes in water dynamics. The data related to deforestation in Brazil demonstrate that in the Amazon biome between 1988 and 2020 most accumulated deforestation was with 157 667 km² in the state of Pará and with 147 926 km² in the state of Mato Grosso, corresponding to more than 66% of the biome's total deforestation (INPE 2021). In the Cerrado Biome, between 2001 and 2020, 4 878 192 km² were deforested inMato Grosso, followed by Goiás with 4 586 154 km² (INPE 2021). These changes occurred mainly due to the growth of agricultural and livestock activities.

The S2ID data showed that in 22 of the 24 cases analyzed, the municipalities had maps of risk areas in the municipalities. Although the ravines and gullies are considered a common process in 16 of the 24 cases analyzed. In most municipalities, there are no permanent programs or resources foreseen in government budget instruments for erosion prevention or control. This indicates that although the risk areas are known, most municipalities have not developed measures to prevent and contain ravines and gullies.

In rural areas, the production of erosion susceptibility maps has been simplified due to technological development, especially GIS software. Remote sensing methods combined with artificial intelligence were used in the Brazilian Cerrado (Minas Gerais), for automatic classification of optical images to identify ravines and gullies with high precision (VRIELING et al. 2007). Image analysis through remote sensing thus is an important tool to quantify the size, volume, downstream silted areas and affected infrastructure. Furthermore, the use of drones can provide more quantitative information related to estimates of economic and environmental impacts.

The existing data in the bibliography review indicates that in several places in the world the control of ravines and gullies is part of a regional strategy, with costs that in general exceed the municipal capacity to deal with this process of the physical environment alone. Therefore, the help of regional and national governments is needed for better management and financial support.

In addition to accounting the direct impacts of ravines and gullies, it is necessary to expand the studies to consider the cost of land recuperation and the losses related to halting the economic activity. Romero-Díaz et al. (2019) analyzed 26 documented cost actions to control ravines and gullies and indicate that costs could vary by a factor of 100, e.g., between US $ 100 and US $ 10,000 per hectare. While the annual maintenance costs for 50% of cases are less than US $ 100 per hectare, for the other 50% it can be as high as US $ 1000 per ha. According to De Brito Galvão et al. (2011) traditional methods of movement of large volumes of soil and measures of revegetation works, while drainage infrastructure is more expensive. While bioengineering methods tested by the author such gully revetment with blankets and re-vegetation works and partial grading of the gully and cheaper drainage system works. These large inconsistencies in costs reported demonstrates the need to carry out further research and studies in search of cost-efficient solutions to contain ravines and gullies in diverse climate and geological-geotechnical settings.

4.3. Ravines and gullies in Bauru, Brazil

4.3.1 History of studies on ravines and gullies in Bauru

Several studies, such as Salomão (1994), Almeida Filho (2000), Da Silva and Barbieri (2004); Corghi (2008), Santos (2008), Ide et al. (2009) and Thomazini and da Cunha (2012) have been carried out to understand the evolution of erosion in the municipality of Bauru (Figure 11).

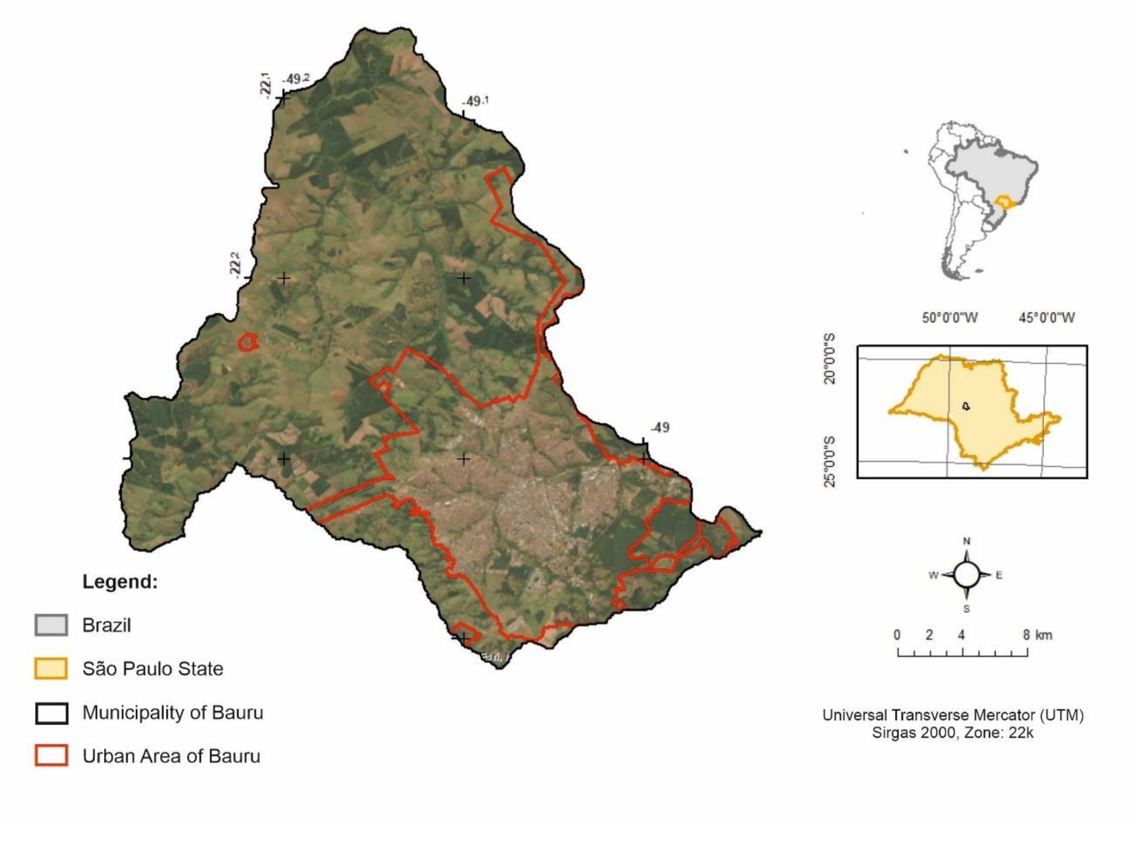


Figure 11. *Location map of the municipality of Bauru.*

Salomão (1994) carried out an analysis of aerial photographs from 1972 and identified a total of 516 ravines and 409 gullies in the region, most of which formed in drainage headwaters after deforestation due to changes in hydrological conditions related to increased surface runoff. Some were also formed due to the impacts of deepening and widening of river channels.

The most impressive case recorded in the municipality occurred between November 1992 and April 1993. The month of February 1993 was atypical, with the monthly rainfall exceeding 450 mm, approximately 250 mm above the usual amount. The gully formed was 800 m long, with an average width of 26 m, a maximum width over 50 m and a depth ranging from 15.5 to 28 m, removing a volume of approximately 360,000 m³ of sediment (Almeida Filho 2000). According to Santos (2008), there was one death related to the development of the gully.

Almeida Filho (2000) described in detail the 25 areas affected by ravines and gullies in the late 1990s (Table 8). The survey of erosion evolution in the municipality of Bauru between 2004 and 2021 identified 7 features in the recovered class, 7 in the stable class and 11 in the in-development class. In some regions, such as Quinta da Bela Olinda, although the main gully has not shown reactivations in the last 20 years, new large-scale erosion has appeared, increasing the impact on the basin.

In the municipality of Bauru, ravines and gullies caused the following impacts: silting of watercourses and reservoirs (Figure 12 A); destruction or clogging of the storm sewer network (Figure 12 B); soil loss, destruction and breakdowns in the water and sewer system; expansion of floods; dispersion of pollutants; isolation of housing or neighbourhoods; social and economic damage caused by flooding; increase in the cost of maintaining streets, canals and sewers; environmental changes caused by siltation (Figure 12 C and D); depreciation of real estate value; discouragement of new investments; decrease in water potential; loss of agricultural areas; increased cost of production and increased cost of water treatment (ALMEIDA FILHO 2000, DA SILVA and BARBIERI 2004, THOMAZINI and DA CUNHA 2012). Another type of impact cited is decreased urban mobility (CUNHA 2020). For Santos (2008), among the problems triggered by erosion is the fragmentation of the city and the creation of urban voids.

Bauru is located in the Western Plateau of São Paulo, located within the Tiete watershed. The Bauru and Ribeirão do Campo Novo River subbasins are composed of wide hills. The Ribeirão da Água Parada area is composed of 85% wide hills and 15% medium hills. In the Batalha River subbasin, 66% of the area are wide hills, 9% are medium hills, 8% are elongated hills and spires and 7% are slopes furrowed by subparallel valleys (ALMEIDA FILHO 2000). According to Salomão (1994), the local relief favours the concentration of rainwater.

In addition to the relief in Bauru being composed of wide hills, and the thick, loose and sandy soils favour soil erosion. According to Salomão (1994), the changes in water conductivity and porosity between different soil horizons and between different soil types, added to ruptures in the topography, favour the development of the piping phenomenon. This occurs because in the higher positions of the slope, the more developed soil facilitates water infiltration, while in the lower positions, in addition to the natural tendency of the water table to be closer to the surface, the less developed soil contains more clay and the few, generally non-communicating macropores increase pressure and percolation forces (SALOMÃO 1994).

Table 8. *Current situation of erosions described by Almeida Filho (2000).*

Erosions recovered between 2000 and 2021						
Erosion name	Year	Classification	Length (m)	Average depth (m)	Average width (m)	Volume (m^3)
Jardim América paulista	1995	Gully	600	13	30	234000
Jardim Ouro Verde	1999	Gully	200	3	4	2400
São Geraldo	1997	Gully	800	7	20	112000
Distrito Industrial	1993	Gully	500	4	18	36000
Conj. Habitacional 16	2000	Ravine	500	5	15	37500
Jardim das Orquídeas	1998	Gully	150	5	16	12000
Vila São Paulo	1995	Gully	400	6	30	72000
Erosions that showed significant changes between 2000 and 2021						
Erosion name	Year	Classification	Length	Average depth	Average width	Volume
Vila Ipiranga	2000	Gully	450	4	25	45000
	2021	Gully	390	6	60	140400
Jardim Grama - Fepasa	2000	Gully	240	5	15	14400
Jardim Grama - IBC	1999	Gully	600	8	36	172800
Jardim Grama (Fepasa and IBC)	2021	Gully	1.271	6	29	221154
Cohab 16 – Eucaliptos	1995	Gully	200	5	15	15000
	2021	Gully	250	5	15	18750
Parque Bauru	1993	Gully	800	15	30	360000
	2000	Gully	150	4	20	12000
	2021	Gully	300	5	11	16500
Conj. Habitacional 2000	2000	Gully	150	6	40	22500
	2022	Gully	291	6	25	43650
Núcleo Popular	2000	Ravine	70	6	4	1680
	2021	Gully	500	5	15	37500
Cohab 16 - Fepasa	1995	Gully	120	6	10	7200
	2021	Gully	480	6	9	25920
Stable erosions between 2000 and 2021						
Erosion name	Year	Classification	Length	Average depth	Average width	Volume
Jardim da Grama – Tapeçaria Chic	2000-2021	Gully	120	5	15	9000
Santa Edwirges	1998-2021	Gully	230	6	25	34500
Jardim Vânia Maria	1995-2021	Gully	300	4	14	16800
Parque União	2000-2021	Gully	200	6	20	24000
CESP	1999-2021	Gully	1000	10	50	500000
Pousada da Esperança II	2000-2021	Gully	300	5	15	22500
Pousada da esperança I	2000-2021	Gully	200	5	15	15000
Otávio Rasi	2000-2021	Gully	570	6	10	34200

Horto Florestal-Codasp	2000-2021	Gully	300	6	10	18000
Clube do Recreio da Prefeitura	2000-2021	Ravine	150	5	30	22500
Conj. Habitacional I	2000-2021	Gully	150	5	20	15000
Jardim Guilherme	2000-2021	Gully	1000	10	25	250000
Quinta da Bela Olinda	1999-2021	Gully	500	5	16	40000

Figure 12. *A) Erosion process at the valley bottom, where the lowering of the channel upstream and the silting and drying of wetlands downstream occur; B) ravine at Quinta da Bela Olinda, developed due to problems in stormwater sewers; C) silted-up area in the region of Quinta da Bela Olinda; D) soil profile, indicating lowering of the channel and drying of wetlands.*

Some erosions have affected large areas in the urban perimeter since the 1970s, as is the case for erosions located in the Jardim Grama region, which have been reactivated more than three times over the last 50 years, mainly related to years with atypical rainfall events or due to changes in land use in the watershed in areas close to the erosion process. Another problem is that the adopted structural measures are often inefficient or may lose efficiency due to the advancement of erosion or to the lack of periodic maintenance (Figure 13 A and B). The solutions adopted are, in general, palliative and do not resolve the causative factors, with inefficient measures that prioritize the channel of the formed feature, without considering the processes within the watershed as a whole.

Analyses of the evolution of land use and occupation between 2004 and 2021 also illustrate the dispute for urban space. The urban voids caused by ravines and gullies in development were the result of occupation by low-income communities in search of sites to build homes. Conversely, other areas, such as the erosion of Jardim América, were fully recovered, returning to the conventional social and economic use, because of its good location in the urban perimeter and appreciation of the area, which enabled the construction of a high-end condominium.

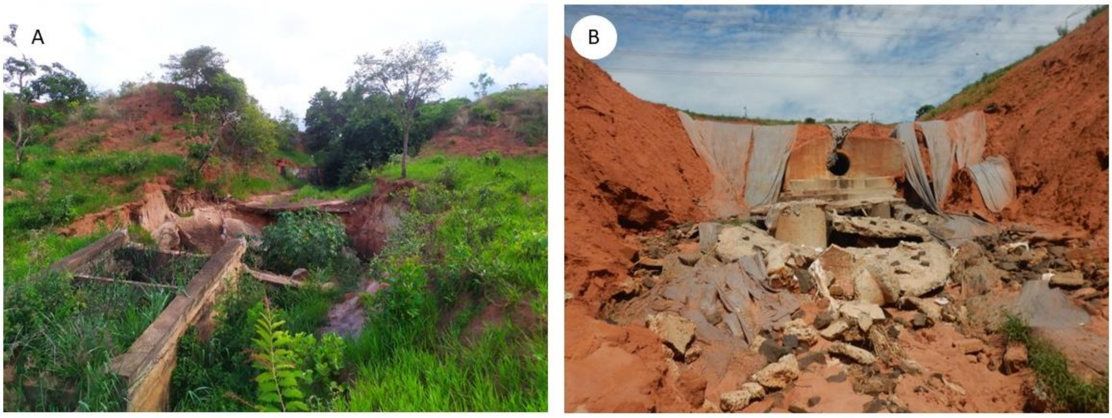


Figure 13. *Erosion containment structures damaged by lack of maintenance or sizing errors: a) Jardim Grama; and b) Quinta da Bela Olinda.*

Although Brazilian law currently prohibits it, Almeida Filho (2000), Da Silva and Barbieri (2004), Corghi (2008) and Ide et al. (2009) cite the use of areas affected by erosion, such as ravine and gully channels for the disposal of urban waste and even hospital waste, as is the case of Vila Garcia, Pousada da Esperança II, Jardim Paulista, Jardim Colonial, Vila Jussara, Vila Santista, Cohab 16 and Quinta da Bela Olinda. In places such as Parque Bauru (Figure 14 A) and in the gully of Vila Ipiranga (Figure 14 B), garbage disposal, including of construction and organic waste, was observed during the field stage. These residues can contaminate the channel with leachate and pollute the environment through the release of gases, transforming these areas into areas of disease outbreaks and creating other types of problems related to soil and water contamination. According to Santos (2008), the use of technogenic materials, without performing technical analyses, aims at reducing costs for companies and may increase environmental impacts due to contamination of the soil and aquifers.

Figure 14. *a) Use of the area affected by erosion for urban waste disposal (pruning, organic and construction waste); b) waste disposal in the gully channel in Vila Ipiranga.*

Some erosions have been fully or partially recovered. In the CESP gully, part of the area was recovered for the construction of an avenue. The erosion of the industrial district was recovered for the construction of industrial warehouses. In Jardim Ouro Verde, the erosion area was recovered for the construction of a soccer field. In Jardim América, the area was transformed into a high-end condominium.

In Núcleo Mary Dota, an allotment built over a buried gully, several houses have cracks, demonstrating the technical difficulty of recovering the affected areas (SANTOS, 2008). The problems can be aggravated because in some cases, companies do not follow the technical suggestions for works in areas affected by ravines and gullies. In some cases, there are changes in the drainage regime and migration of watercourses (SANTOS, 2008).

The lack of an official technical record in areas affected by erosion made it difficult to build a detailed history of actions taken to analyse the related costs and technical solutions adopted.

3.3.2. Gullies inventory

The inventory step includes the mapping, identification and analysis of ravines and gullies. The identification of scars of ravines and gullies was performed using images from Google Earth from 2004 and 2020, extracting the location and size of the area affected by the channel on the two dates analysed. The use of aerospace images for erosion analysis is a common method in many studies (DABA et al., 2003; OZER 2014; MESSIAS and FERREIRA 2017; GOLOSOV et al., 2018). Ravines and gullies were classified into a) "recovered areas", which represent areas that were recovered between 2004 and 2020; b) "stable areas", where no further evolution of erosion in images in the period between 2004 and 2020 was visible (e.g., consolidated by vegetation; and c) "active areas", where erosion progressed visibly in satellite images (vegetation not consolidated and siltation occurred in channels or in downstream locations).

The inventory of linear erosions (Figure 15) demonstrated that in 2004, 175 gullies existed in the urban area occupying an area of more than 64.1 hectares. In 2020, the number of erosions had increased to 189, with an affected area of 62.5 hectares (Table 9).

Table 9. *Number of linear erosions and affected area in 2004 and 2020. Stable areas, where no further evolution of erosion during the analysed time interval; and active areas where erosion progressed visibly in satellite images.*

Classification		**Erosion number and percentages of total**		**Affected area m^2 percentages of total**	
Erosions in 2004	stable	145	82,9%	472.425	73,6%
	active areas	30	17,1%	169.043	26,4%
Total in 2004		175		641.468	
Erosions in 2020	stable	139	73,5%	466.400	74,5%
	active areas	50	26,5%	159.527	25,5%
Total in 2020		189		625.927	

Table 10). Most recovered erosions were already stable with vegetation inside the erosion channel. However, the area affected by the 13 active erosions that were recovered represented approximately 2/3 of the area recovering (Figure 16). Large areas affected by ravines or gullies were recovered during this period, generally for residential use or for the construction of urban infrastructure.

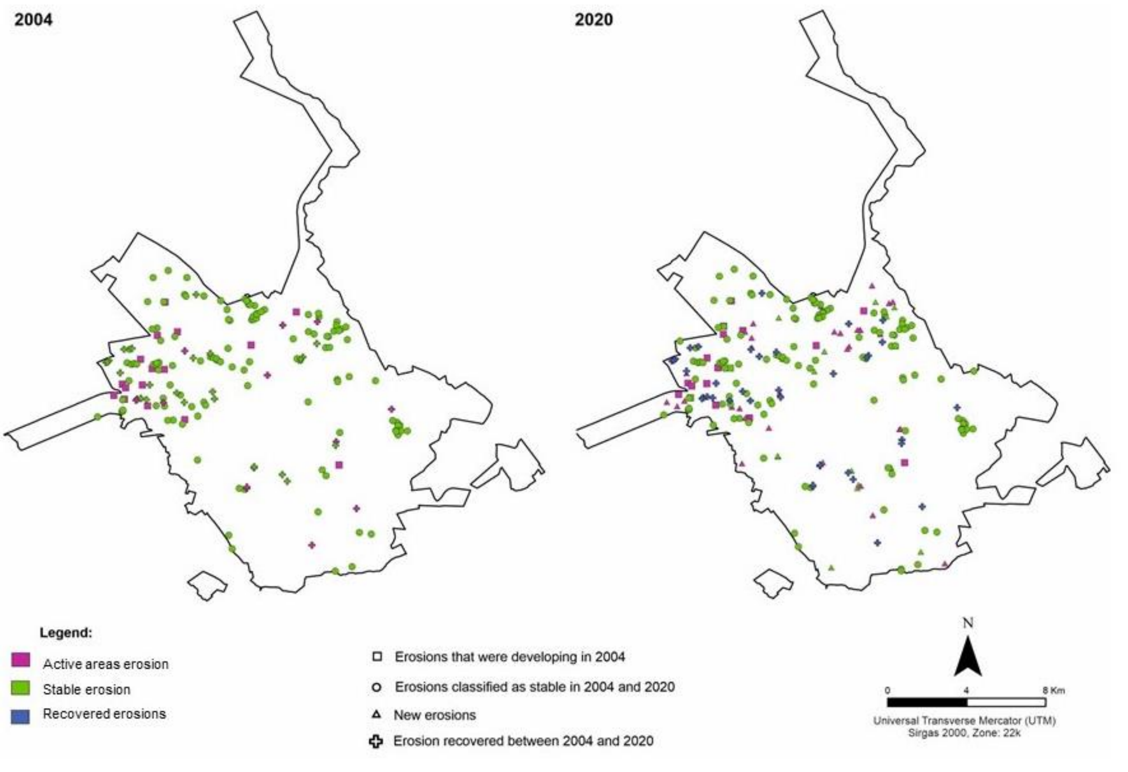


Figure 15. *Linear erosion inventory in 2004 and 2020.*

Table 10. *Areas where erosions were recovered between 2004 and 2020.*

Erosions recovered between 2004 and 2020	**Number and percentages**		**Affected area m² percentages of total**	
Classified as "stable" in 2004	24	64.9%	21.420	34,1%
Classified as "active areas" 2004	13	35.1%	41.410	65,9%
Total	37		62.830	

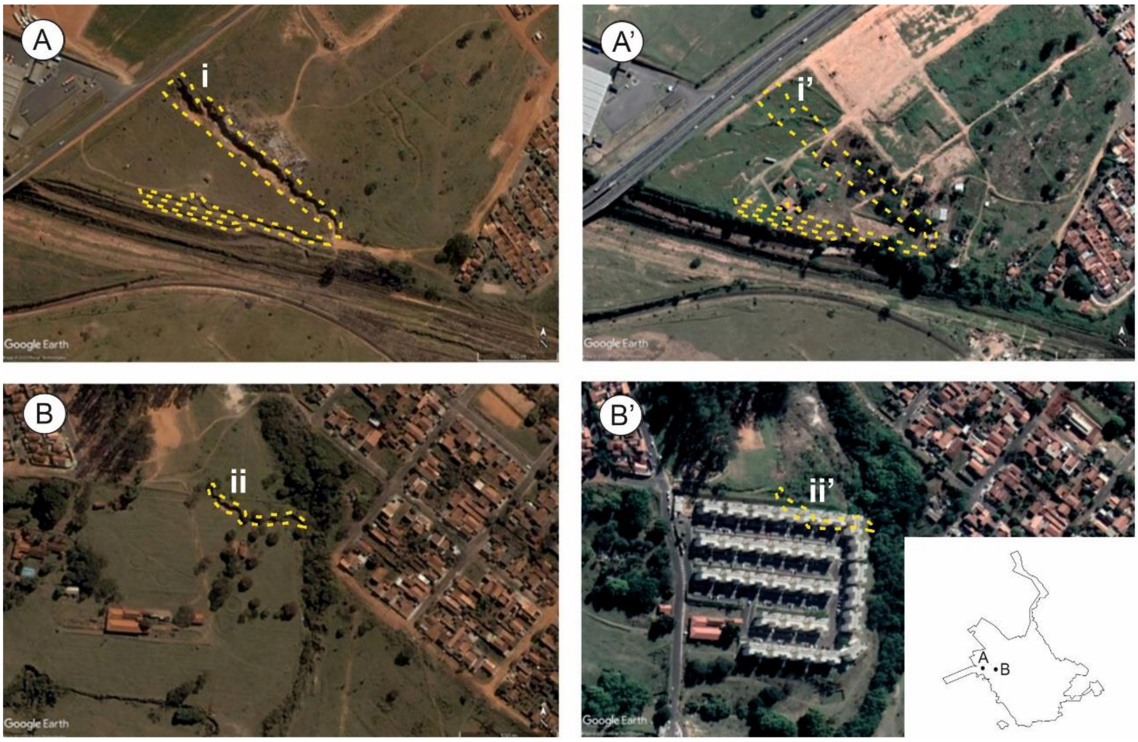


Figure 16. *(A) large ravine (i) active in 2004; (B) after remediation channel covered (i') and reintroduction of the area in the urban environment; (C) gully channel (ii) connected to a watercourse in 2004; (D) area with social use recovered in 2020, after remediation of the area affected by erosion and the construction of residential buildings (ii').*

Between 2004 and 2020, 51 new erosions (Figure 17) were identified, most of which were already active in 2020. However, the number of new gullies and gullies is greater than the number of recovered erosions. The new erosions are smaller than the erosions that were recovered, which contributed to the reduction in the area affected by erosions. Most erosions that were not stabilized in 2004 showed changes in channel development in 2020. The area affected by erosion by 2020 is lower than the area affected in 2004, but the number of existing erosions is higher (Table 11).

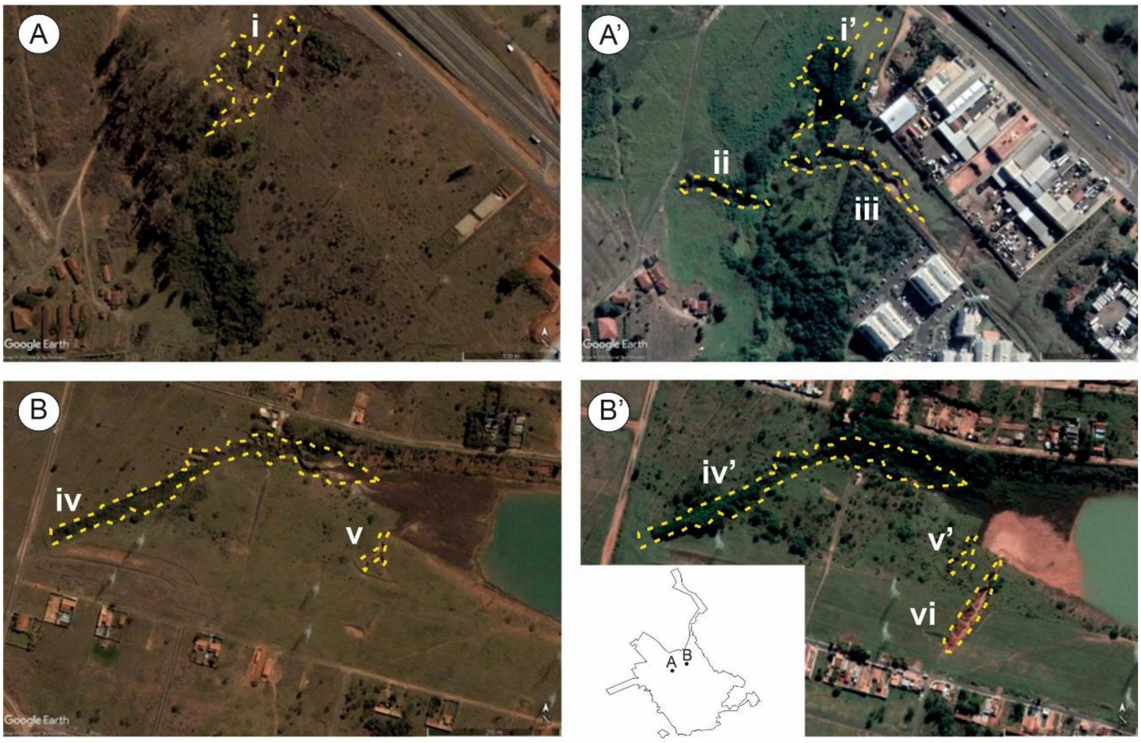


Figure 17. *Some areas affected by new erosion between 2004 and 2020; (A) area with stable erosion (i) in 2004; (B) erosion channel development near residential condominium (iii) in 2020; (C) Quinta da Bela Olinda: area with two (iv and v) stable erosions in 2004; (D) Quinta da Bela Olinda in 2020: area with two stable erosions (iv' and v') and a newly developed erosion (vi).*

Table 11. *Existing erosions in the study area in 2020.*

Classification		**Erosion number and percentages of total**		**Affected area m² percentages of total**	
Erosions that emerged between 2004 and 2020	stable	16	8.5%	11,077	1.8%
	active areas	35	18.5%	33,265	5.3%
Erosions classified as stable in 2004 and 2020		121	64%	451,005	72%
Situation in 2020 of erosions classified as under development in 2004	stable	2	1%	4,318	0.7%
	active areas	15	8%	126,262	20.2%
Total		189		625,927	

4.4. Valuation of impacts in Bauru

Three areas were selected to assess the economic and environmental impacts. The areas were chosen for the following reasons: i) Quinta da Bela Olinda, an area where there are ravines and stable and developing pits; ii) Jardim América, as it represents a place where social and economic use has been fully recovered; iii) Parque Bauru, w one of the erosions that is partially recovered.

4.4.1. Valuation method applied

To identify the impacts of urban ravines and gullies, the classification proposed by Kuhn et al. (2023) was employed. Impacts were classified into a) environmental, considering the cost of replacing soil, nutrients, carbon and pasture; b) costs for recovery and mitigation of erosion in the watershed area; c) destruction of infrastructure, impacts on streets, storm sewers, dams, residences, among others; d) estimated economic losses, which were calculated considering the surface area directly affected by the channels in ravines and gullies, the annual loss of gross domestic product (GDP) per square metre in the affected area in allotments; e) loss of collection of the Property and Urban Land Tax (IPTU); and f) positive impacts after the recovery of areas affected by ravines and gullies.

The analysis time of the estimated economic impacts and tax collection losses was limited to between 2000 and 2021 based on the information sources described in Section 2.1. The cost of the environmental impacts, public infrastructure destruction, and erosion containment and recovery associated with urban gullies and ravines were estimated by considering identified infrastructure close to erosions and descriptions of the channels affected by erosions, that is, all impacts that could be identified from the onset of erosion to the date of the current analysis.

The valuation of the impacts was carried out considering the replacement cost, which is the amount currently paid for the affected items and products (LILLO et al. 2014). The values obtained allow identifying the magnitude of the impacts.

Because current replacement cost values and impact dimensioning were used, inflationary updates were not performed, as it is understood that these values are already considered in the current cost. To convert the value from Brazilian real to U.S. dollar, the reference value of 5.30 reais to 1 U.S. dollar (as of November 14, 2022) was used.

3.4.1.1. Environmental impacts

For soil-related environmental costs, such as loss of vegetation, information from the Anuário da Pecuária Brasileira [Brazilian Livestock Yearbook] (ANUALPEC 2022) was used. The previous standard vegetation was considered pasture and semi-intensive. According to the yearbook, pasture is worth US$ 756.68/ha.

The loss of nutrients—nitrogen (N), phosphorus (P) and potassium (K)—and of organic carbon (OC) in the soil caused by ravines and gullies were monetized considering the replacement cost, as previously done by Yitbarek et al. (2012). For the analysis of replacement of soil nutrients (NPK), data from Radam Brasil (BRASIL 2018) were considered for up to 1 m of soil depth, according to analyses carried out on the Pederneiras-Bauru Road. A reference value of 1.4 t/m^3

of soil was adopted. The total value of nutrient loss per square metre (Table 12) was calculated according to the market price of the fertilizer sector statistical yearbook (ANDA 2022) for 2021.

For the analysis of the carbon stock, data from Sobral et al. (2014), who reported that the carbon stock in the region ranges from 49.2 to 221.0 Mg ha^{-1}, with 96.5 Mg ha^{-1} of C being stored in undisturbed vegetation types; thus 9.65 kg/m² was adopted as a reference value for the region. According to the Power BI platform (2022), the average price paid for carbon stocks is $32.37 per ton (22/10/2022). Thus, the value of 9.65 kg/m² proposed by Sobral et al. (2014) represents a corresponding stock of $0.31 of carbon per square metre.

Table 12. *Amount of nutrients per square metre and replacement cost.*

Nutrient	Amount to be replaced, in kg/m³, in the soil up to 1 m deep	Concentration used for replacement	Required quantity of product	Cost per kg of product used for replacement (US$)	Cost of nutrient loss per kg/m³ (US$)
P_2O_5 fertilizer	0.22 kg/m³	20%	1.2 kg/m³	0.35	0.42
Potassium chloride	0.26 kg/m³	53%	0.501 kg/m³	0.59	0.30
Nitrogen (Urea)	0.32 kg/m³	45%	0.711 kg/m³	0.63	0.45
Total					1.16

Source: Fertilizer sector statistical yearbook (Anda 2022).

3.4.1.2. Erosion recovery and containment and public infrastructure destruction

To estimate the costs of containment works and recovery of the affected areas and destruction of homes and infrastructure, the National Research System of Civil Construction Costs and Indices (SINAPI), the System of Reference Costs of Works (SICRO) and Civil Construction Union (Sinduscon) were used for cost analysis of engineering works in Brazil (Sinapi 2021, Sicro 2021, Sinduscon 2021) according to the compositions elaborated in Table 13:

3.4.1.3. Estimated economic impacts

To estimate the economic losses caused by the impacts of urban ravines and gullies, an analysis of the GDP per square metre was also carried out, according to official information available from the Brazilian Institute of Geography and Statistics (IBGE 2019, 2022). The value of the municipal GDP is US$ 2,891,432,319, divided by an area of 667,684,000 m², which represents a GDP/m² of US$ 4.33 per year. Estimates of economic impacts were carried out considering a time interval of 20 years between 2000 and 2020.

The loss of useful area of urban space was calculated by the average of the existing values in Municipal Law No. 7,510/2,021 (BAURU 2021), which corresponds to US$ 72.88/m². The costs of the affected area were calculated based on the market price available on online sales sites. The following average values were used: a) US$ 72.57 per square metre for unused lots on paved streets; b) US$ 36.28 per square metre for unused lots on unpaved streets.

Table 13. *Compositions used to calculate impacts, according to data from SINAPI (2021), SICRO (2021) and SINDUSCON (2021).*

Composition	Item	Form of valuation	Unit	Unit value (US$)
1	Excavation of an area for the construction of a contour line or a containment basin or dam or weir	Cost of machinery for excavation 1 m³/m². Reference codes in SINAPI (2021) used for valuation 100973, 100574 and 96386.	m³/m²	4.02
2	Replacement of eroded soil	Value for removal, transport and reallocation of soil on site, considering an estimated transport distance of 10 km. Reference codes in SINAPI (2021) used for valuation 100973, 100574 and 96386. 10x95877 and 00006079 (I)	m³	19.81
3	Destruction or unfeasibility of a paved street with an urban structure	It is estimated that the cost of a kilometre of highway today is in the range of 1.5 to 2.5 million, including the support structures. Estimated value according to average construction cost.	m	377.36
4	Destruction or unfeasibility of paved, unpaved, or unstructured street	Cost of machinery for opening the street. Estimated value according to average construction cost.	m	188.68
5	Destruction of rainwater pipes	Construction cost. Reference codes in SINAPI and SICRO used for valuation 102279, 0804037 (SICRO) and 93367.	m	149.26
6	Hydraulic ladder construction	Construction cost. Reference codes in SINAPI used for valuation 100973, 100574, 96386 and 91070	m	28.92
7	Implementation of a drainage system in streets parallel to the gully with corrugated steel pipes, with one of the lines being 0.80 m or 1.20 m, with a collection system through manholes	Excavation, sand cradle, installation, backfill and drainage pipe compaction. Reference codes in SINAPI used for valuation 102279, 804029, 93367.	m	122.64
8	Mixed underground drain built with hollow tube and upstream. Approximately 600 m of plumbing. The plumbing system is 5 m away. Erosion has been buried in these pathways.	Excavation, sand cradle, installation, backfill and drainage pipe compaction. Reference codes in SINAPI used for valuation 102280, 804037, 93372.	m	157.61
9	Popular housing	Cost per square metre of popular housing according to the SIDUSCON table is R$ 1278.90 m². For calculation purposes, an average area of 50 m² for houses was considered.	house	12,065.09

Source: National System for Surveying Civil Construction Costs and Indices (SINAPI 2021) System of Reference Costs for Works (SICRO 2021) and Civil Construction Union (SINDUSCON 2021).

3.4.1.4. Urban Property and Land Tax (IPTU)

Municipal losses or gains from tax collection were calculated using the information available in Municipal Law No. 7,510/2,021. The calculation considered the following equation as the Urban Land Tax (IPTU) value: 1% of the value resulting from the multiplication of the average land value per square metre (US$ 72.88) by the size of the affected area and the number of years that erosion has affected the site (Bauru 2021, 2022). Estimates related to gains or losses in IPTU collection performed considering a maximum time interval of 20 years.

The calculation was carried out considering the lots indicated in the Google Earth images or estimates made based on the existing streets in the area; that is, areas used for streets, sidewalks, green areas and other infrastructure were not considered.

3.4.1.5. Data presentation

The data obtained in the analysis are presented in spreadsheets, considering the values obtained in the impact analysis considering the number of units and the total value of the impact. For impacts that are continuous, such as Urban Property and Land Tax (IPTU) and estimated economic impacts, the value over 20 years was considered.

3.4.2. Quinta da Bela Olinda

The area of Quinta da Bela Olinda is located in the urban expansion zone. In this location, 5 linear erosions were identified (Table 14 and Figure 18), four of which (1, 2, 3 and 4) remained stable between 2004 and 2021, but in this period, ravine number 5 appeared due to problems in a rainwater pipeline. Despite attempts to stabilize the process, erosion has been growing at an accelerated rate (Figure 19 A and B). The largest gully in the area is stable, with vegetation in the channel and its surroundings and the development of a water source inside it (Figure 19 C). Other erosions, although stable, predominate the pasture, with few trees (Figure 19 D).

Table 14. *Existing erosions in the Quinta da Bela Olinda area.*

Erosion name	Year	Classification	Length (m)	Average depth (m)	Average width (m)	Volume (m³)
Quinta da Bela Olinda 1	1999-2021	Gully	500	5	16	40,000
Quinta da Bela Olinda 2	1999-2021	Ravine	80	4	8	2,560
Quinta da Bela Olinda 3	2004-2021	Ravine	66	5	15	4,950
Quinta da Bela Olinda 4	2004-2021	Ravine	60	5	10	3,000
Quinta da Bela Olinda 5	2021	Ravine	180	7	25	31,500

Despite several attempts to stabilize ravine 5 (Figure 18) by carrying out engineering works in the channel, including the implementation of barriers at contour lines, placement of rainwater drainage pipes and construction of gabion walls, erosion advanced in an accelerated manner after November 2017, causing a risk to homes and infrastructure located upstream. The works implemented thus far have proven to be palliative and ineffective in containing the advance of erosion.

Da Silva et al. (2004) note that the development of gullies made unfeasible a housing complex that already had a water distribution structure, sewage collection network, and asphalt and rainwater drainage system ready. According to the authors, part of this structure was destroyed. In the analysis of aerial images, it is possible to identify elements of the affected urban infrastructure, such as isolated and abandoned paved streets due to the development of erosion processes.

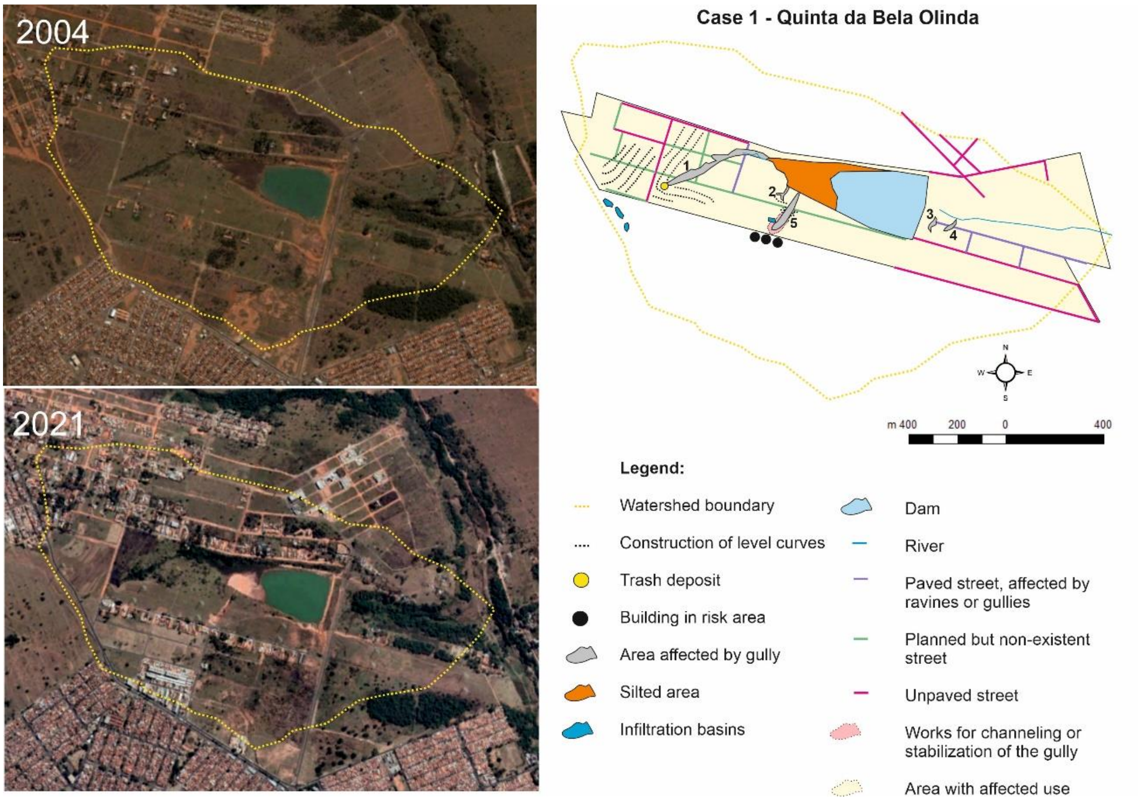


Figure 18. *Quinta da Bela Olinda area and identified impacts.*

Table 15 and Figure 19 show the impacts identified in the Quinta da Bela Olinda area, namely, soil erosion, loss of carbon stock, loss of pasture, loss of soil nutrients (NPK), destruction of storm drain pipelines, silting of the dam, destruction of streets, isolation of paved streets, unfeasibility of lot construction due to lack of access, unfeasibility of social and economic use of urban areas, loss of municipal tax collection, economic losses due to non-social use and economic impact of the areas surrounding the erosions. The following measures taken to control and stabilize erosion were identified: construction of contour lines, infiltration basins, hydraulic ladders, energy sinks and canalization of part of the erosion channel.

Table 15. *Estimate of the impacts of erosion identified in the Quinta da Bela Olinda area.*

Type	Impact description	Number of units	Unit	Unit cost (US$)	Amount (US$)	Value in 20 years (US$)
Environmental, per replacement cost	Loss of carbon stock in the area of 14405 m² (Erosion 1, 2, 3, 4 and 5)	14,730	kg	0.31	4566.30	4530.17
	Loss of nutrients in the soil (NPK) in the area of 14405 m² (Erosion 1, 2, 3, 4 and 5)	14,730	m³	1.16	17086.80	17086.80
	Erosion of 82010 m³ of sediments, including 40000 m³ (Erosion 1), 2560 m³ (Erosion 2), 4950 m³ (Erosion 3), 3000 m³ (Erosion 4) and 31500 m³ (Erosion 5)	82,010	m³	19.81	1624726.42	1624726.42
	Loss of pasture area in the area of 14405 m² (Erosion 1, 2, 3, 4 and 5)	14,730	m²	0.76	11144.77	11144.77
Erosion recovery and containment	Construction of an infiltration basin: area of 247 m² (Erosion 5), area of 800 m² (Erosion 1)	1,047	m²	4.02	4213.68	4213.68
	Construction of the contour line: 2260 m (Erosion 1), 200 m (Erosion 2) and 80 m (Erosion 5).	2,540	m	4.02	10222.30	10222.30
	Hydraulic ladder, shackles and sink (Erosion 5)	100	m²	28.92	2891.89	2891.89
Infrastructure destruction	Destruction/impairment of 1023 m of paved street with urban structure.	1,023	m	377.36	386037.74	386037.74
	Destruction/unfeasibility of 1614 m of unpaved, paved or unstructured street	1,614	m	188.68	304528.30	304528.30
	Destruction of 800 m of rainwater pipes (Erosion 5)	800	m	149.26	119409.81	119409.81
	Dam silting. The structure has 263 m, with a width of 80 m. Approximate value of the volume of soil used in the construction of the 105,200-m² dam. Considering that the dam has already lost 1/3 of the original water surface area, this proportion was applied in relation to the total value, considering the cost of 34716 m³ for calculation purposes.	34,716	m³	4.02	139715.52	139715.52
Estimated economic losses	Value of unused lots on the upstream paved street (13 × 20) – 103 lots	103	unity	18867.92	1943396.23	1943396.23
	Value of unused lots on the downstream paved street (13 × 20) – 51 lots	51	unity	18867.92	962264.15	962264.15
	Value of unused lots on unpaved streets (13 × 20) – 171 lots	171	unity	9433.96	1613207.55	1613207.55
	Annual GDP loss per square metre, in the area with affected social-economic use of 51 ha along the watershed (Erosion 1, 2, 3, 4 and 5)	807,000	PIB/m²	4.15	3349811.32	66996226.42
	Surface directly affected by the scar caused by ravines and gullies, 14405 m². (Erosion 1, 2, 3, 4 and 5)	14,730	m²	72.88	1073511.28	1073511.28
Municipal tax collection losses	Annual loss of municipal tax collection (annual IPTU of land made unusable by erosion), 325 plots of 13 × 20 m	84,500	m²	0.73	61541.51	1230830.19
Total					11628275.57	76443943.21

The impacts of erosion at Quinta da Bela Olinda are estimated at US$ 76.4 million, including US$ 17,300 in erosion recovery and containment, US$ 1.65 million in environmental impacts, US$ 72.5 million in estimated economic losses, US$ 1.23 million in lost municipal tax collection, and US$ 949,600 in infrastructure destruction.

Figure 19. *a) top view of ravine 5, the implemented works already have some of their functionality damaged, b) top view of ravine 5, where it is possible to observe grooves demonstrating the concentration of surface runoff into the ravine channel; c) gully 1, which shows water flow in the channel and vegetation composed of trees in the surroundings; d) ravine 2, with pasture and small trees inside and around the channel, indicating stability of the feature.*

3.4.3. Parque Bauru

Erosion in Parque Bauru developed mainly in February 1993 (Figure 20 A). To contain erosion in Parque Bauru, in February 1993, four works were carried out in the area: dams and infiltration basins upstream and works to divert and conduct rainwater downstream, in addition to the implementation of drainage systems in streets parallel and transverse to the gully. In October 1993, three more works were carried out: earth dikes with underground drainage with sewer networks (Figure 20 B), mixed underground drain and erosion embankment with slope abatement (ALMEIDA FILHO 2000). Due to the large volume of eroded soil, the gorge impacted the downstream drainage basin, causing the silting of the river and dams such as the one at Bauru Country Club (Figure 20 C and D).

Despite these emergency and subsequent works, in 2000, an accelerated erosion process from downstream to upstream was observed, compromising the works already carried out, with the destruction of 100 m of drainage pipes (ALMEIDA FILHO 2000).

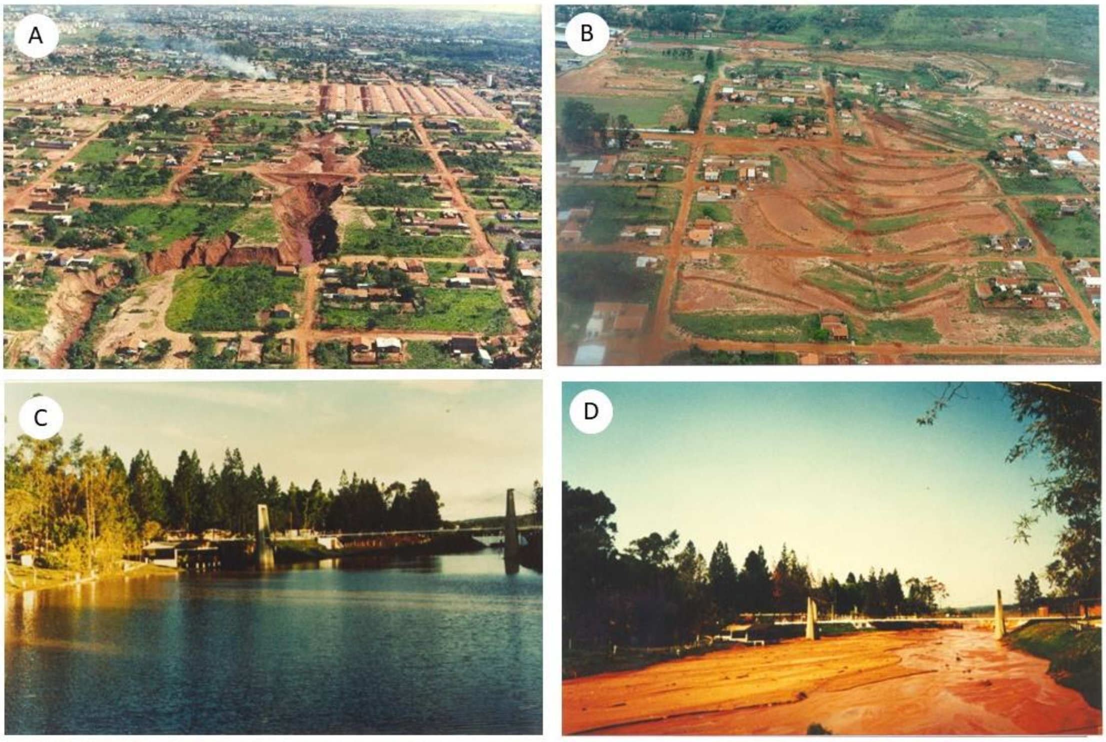


Figure 20. *A) gully of Parque Bauru in 1993; B) emergency works to mitigate erosion; C) Bauru Country Club dam before the development of erosion; D) silting of the Bauru Country Club dam due to the development of erosion upstream in 1993 (Photos: Nariaqui Cavaguti).*

In 2010, reports mention that erosion continued to cause problems. Because of this, in 2011, emergency works were carried out in Parque Bauru to recover the streets. To contain erosion on Maria de Lourdes Almeida Street, 65 trucks filled with dirt and debris were used. Other works, such as the construction of new sewers and paving, were carried out around the area affected by erosion in 1993. In 2016, a hole 3 m long and 4 m deep caused the partial collapse of a house. City Hall carried out new recovery works for sewers in the streets of Parque Bauru neighbourhood (MELLO 2018).

Although it is not possible to identify all the impacts caused due to changes made in the area and the lack of adequate records, the erosion in Parque Bauru has caused recurrent problems in the area since its formation in 1993. The image analysis and field work allowed us to identify the following impacts (Figure 21): loss of soil, loss of nutrients (NPK) and carbon stock, silting of the dam of the former Bauru Country Club, destruction of houses and public structures, construction of erosion channels, making social use unfeasible, economic impact to the urban area, loss of pasture, loss of municipal tax collection, and economic losses due to the social and economic non-use of the areas surrounding the erosions (Table 16). The case of the gully in Parque Bauru demonstrates the partial recovery of an area affected by ravines and gullies, but part of the impacted area has continued to have no social use since 1993, in addition to causing damage to infrastructure and homes in the region.

Table 16. *Estimate of the impacts of erosion identified in the Parque Bauru area.*

Type	Impact description	Number of units	Unit	Unit cost (US$)	Amount (US$)	Value in 20 years (US$)
Environmental, per replacement cost	Sediment erosion volume at least 376000 m^3	360,000	m^3	19.81	7132075.47	7132075.47
	Loss of carbon stock in the area (Surface affected by erosion in 1993, 24,000 m^2)	24,000	m^2	0.31	7440.00	7381.13
	Loss of pasture area	24,000	m^2	0.76	18158.49	18158.49
	Soil nutrient loss (NPK) in the area (Area affected by erosion in 1993, 24,000 m^2)	24,000	m^2	1.16	27840.00	27840.00
Erosion recovery and containment	Construction of at least 3 infiltration basins on empty land, upstream, in the contribution basin, totalling an area of 275 m	275	m^3	4.02	1106.75	1106.75
	Construction of 1650 m of level curve	1,650	m^3	4.02	6640.47	6640.47
	Construction of rainwater channels, on Lucio Luciano Ave, with the aim of diverting and directing rainwater, which caused a lateral branch to the right; estimated area of 50 m.	50	m^3	4.02	201.23	201.23
	Implementation of a more complete drainage system on the two streets parallel to gully, with corrugated steel and concrete pipes, one of the lines measuring Ø = 0.80 m, and the other measuring Ø = 1.20 m, with a storm drain collection system on the parallel streets, grills on Lucio Luciano Ave. and dissipation system with rock blocks. 1300 m of estimated construction.	1,300	m	102.16	132803.58	132803.58
	Earth dike with underground drainage downstream of the second erosion curve. Approximately 200 m, 3 m deep and 6 m wide	3,600	m^3	4.02	14488.30	14488.30
	Earthmoving to land erosion in an area of 600 m by 30 × 5.	90,000	m^3	4.02	362207.55	362207.55
	Mixed underground drain, built with hollow pipe and upstream. Approximately 600 m of 2 × 2 piping. The plumbing system is 5 m away.	2,400	m^2	157.61	378253.58	378253.58
	Erosion embankment with slope abatement, movement of half of the eroded volume (188000 m^3).	188,000	m^3	4.02	756611.32	756611.32
Destruction of infrastructure	Destruction of 1 house	1	unit	12065.09	12065.09	12065.09
	Silting of the dam built by Bauru Country Club, 8670 m^2 of area, depth of 2 m.	17,340	m^3	4.02	69785.32	69785.32
Estimated economic losses	Surface affected by erosion in 2022, of 9700 m^2	9,700	m^2	72.88	706928.68	706928.68
	Possible use for directly and indirectly affected area. Use of 144 lots of 12 × 28	144	m^2	18867.92	2716981.13	54339622.64
	Annual loss of GDP per square metre, in the area with social-economic use. Area of 100200 m^2	100,200	m^2	4.15	415924.53	8318490.57
Municipal tax collection losses	Annual loss of municipal tax collection (annual IPTU of land made unusable by erosion), 144 plots of 12 × 28 m	48,384	m^2	0.73	35238.16	704763.17
Total					12794749.66	72989423.35

The impacts of the sinkhole in Parque Bauru are estimated at US$ 72.98 million, with US$ 1.65 million related to erosion recovery and containment, US$ 7.18 million to environmental impacts, $ 63.3 million to estimated economic losses, US$ 704,700 to lost municipal tax collection, and US$ 81,800 to infrastructure destruction. The damage caused by this erosion was not greater because the works carried out in 1993 allowed the control of erosion and the occupation of the area around and even under the old channel in the areas close to the head of the erosion.

The impacts caused by the erosion of Parque Bauru could be even greater, but the works carried out in 1993 allowed an area of 51,000 m² affected by erosion to be reinserted into the urban space in 1993; currently, this area houses more than 77 buildings (Figure 21).

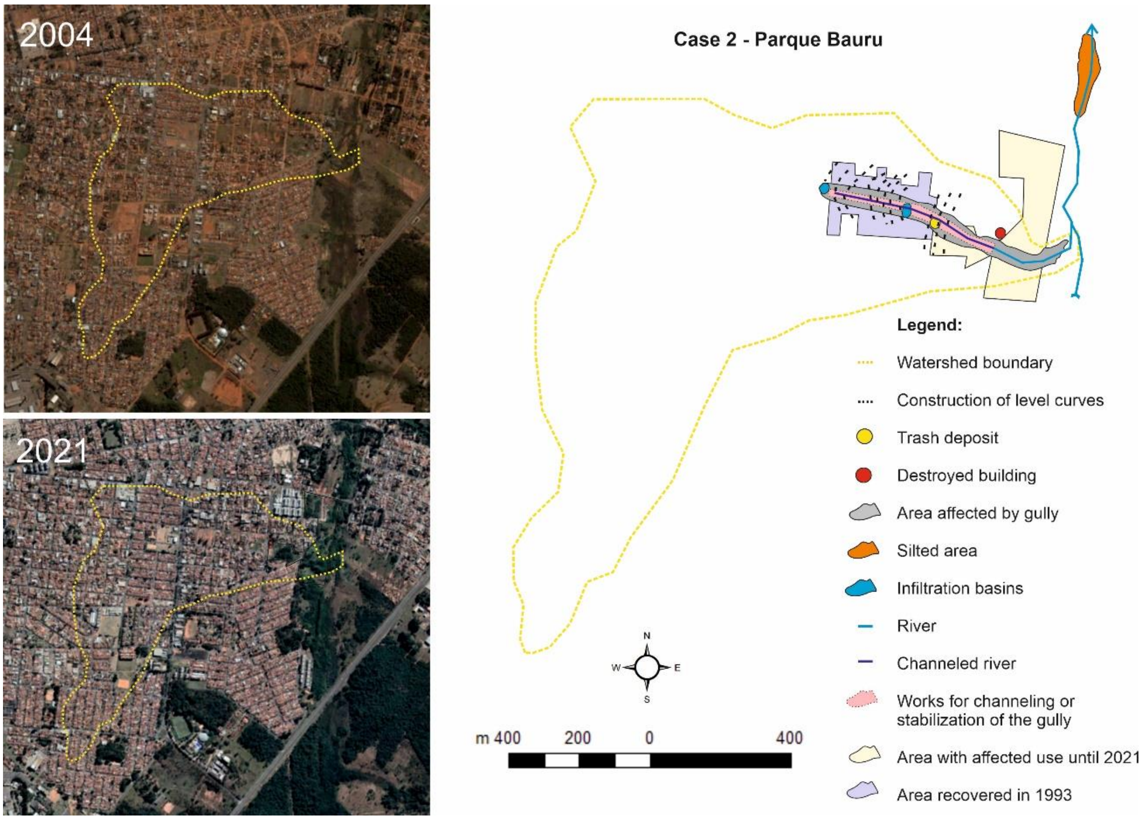


Figure 21. Parque Bauru area and identified impacts.

3.4.4. Jardim América

The Jardim América gully emerged between 1987 and 1988 and, since then, has been used for garbage disposal (ALMEIDA FILHO 2000). In 1993, City Hall implemented a drainage system inside the erosion with a network of sewers and a landfill with rubble. Erosion was completely recovered between 2004 and 2010, and a gated community with high-standard housing was constructed on the site. This case demonstrates that areas affected by ravines and gullies, if recovered with appropriate techniques, can be reinserted into the urban space, returning to social and economic use.

Among the impacts identified in the area until its recovery were soil erosion, loss of nutrients (NPK) and carbon stock, unfeasibility of social and economic use of the urban area, loss of municipal tax collection, economic losses due to the non-social and economic use of areas surrounding the erosion, and loss of pasture (**Figure 22**). In the areas, the containment and recovery measures identified were construction of contour lines, infiltration basins, drainage systems and sewer networks and landfill in the affected area (**Table 17**). After the recovery of the area, the value of a square metre of land increased to more than US$ 188, demonstrating a significant appreciation of the area. This change also increases the municipal tax collection.

The negative impacts of the Jardim América sinkhole are estimated at US$ 23.2 million, of which US$ 110,000 is related to erosion recovery and containment, US$ 4.67 million to environmental impacts, US$ 17.32 million to estimated economic losses, and US$ 1.16 million to lost municipal tax collection. In contrast, after the recovery and occupation of this area, the minimum estimated gains are US$ 19 million, with US$ 3 million from municipal tax collection after recovery of the area and US$ 16 million in estimated economic gains based on GDP per square metre.

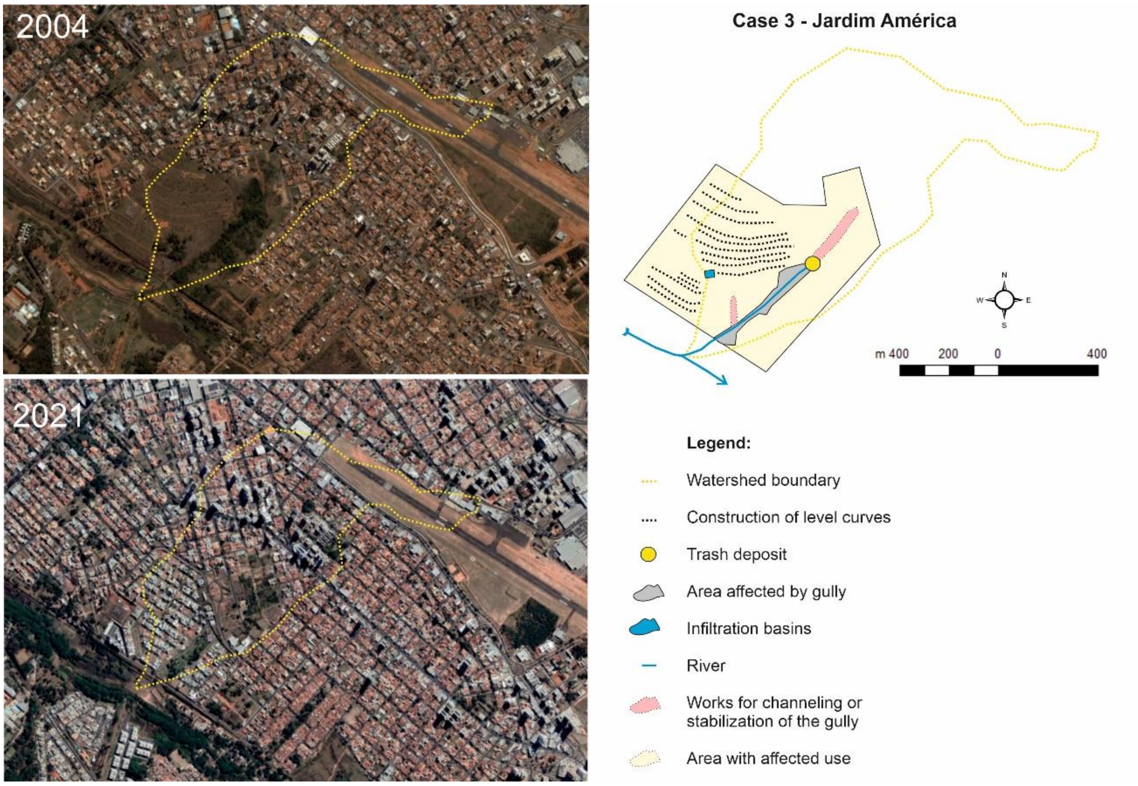


Figure 22. *Jardim América area and identified impacts.*

Table 17. *Estimate of the impacts of erosion identified in the Jardim América area.*

Type	Impact description	Number of units	Unit	Unit cost (US$)	Amount (US$)	Value in 20 years (US$)
Environmental, per replacement cost	Sediment erosion volume of at least 234000 m^3	234,000	m^3	19.81	4635849.06	4635849.06
	Loss of carbon stock in the area	18,000	m^2	0.31	5580.00	5535.85
	Loss of nutrients in soils (NPK) in the area	18,000	m^2	1.16	20880.00	20880.00
	Loss of pasture area	18,000	m^2	0.76	13618.87	13618.87
Erosion recovery and containment	Construction of 3948 m of level curve	3,948	m^3	4.02	15888.84	15888.84
	Construction of an infiltration basin with an area of 1179 m^2	1,179	m^3	4.02	4744.92	4744.92
	In 1993, City Hall implemented a drainage system inside the erosion with a 600 m sewer network of 1 m pipe and a landfill with rubble	600	m	149.26	89557.36	89557.36
Estimated economic losses	Affected area of 18000 m^2	18,000	m^2	72.88	1311826.42	1311826.42
	Annual loss of GDP per square metre in the area with social-economic use. Area of 385700 m^2 between the 2000s and 2010s	385,700	m^2	4.15	1601018.87	16010188.68
Municipal tax collection losses	Annual loss of municipal tax collection (annual IPTU of land made unusable by erosion), approximately 380 plots of 12 × 35 m, considering the equivalent value of 1% of the average IPTU.	159,600	m^2	0.73	116236.98	1162369.81
Total negative impacts					7815201.30	23270459,79
Gains from municipal tax collection after recovery of the area	Gains from land tax collection (approximately 380 plots measuring 12 × 35 m), considering the equivalent value of 1% of the IPTU of the current land R$ of 1000 m^2.	159,600	m^2	1.89	301132.08	3011320.75
Estimated economic gains	Annual GDP gain per square metre after recovery of the area with social-economic use.	385,700	m^2	4.15	1601018.87	16010188.68
Total positive impacts after recovery					1902150.94	19021509.43

3.4.5. Discussion about valuation data

The impacts of the three areas represent significant amounts spent by the government. Regarding costs with recovery and construction of containment structures, the highest estimated value was estimated for Parque Bauru, which exceeded US$ 1.65 million. With regard to environmental impacts, analysed by replacement cost, the highest value was estimated for soil replacement, which, due to the large volume of eroded material, can represent values of US$ 7.1 million in cases such as Parque Bauru if a complete replacement of the area affected by erosion were to be carried out with soil extracted from another location. Considering the three areas analysed, the cost of replacing the eroded soil is estimated at US$ 13.3 million.

The loss of soil nutrients, although having lower values, also exceeded US$ 27,800 in the case of Parque Bauru and US$ 17,000 in Quinta da Bela Olinda. These high values are the result of the large surface area affected by erosion channels.

The loss of carbon in the soil represented US$ 17,300 when adding the three areas analysed. According to Somasundaram et al. (2018), ravines are fragile ecosystems, and the recovery of carbon stocks is a slow and long-term process that requires continuous input of biomass into the soil. Thus, the recovery of these areas requires adequate conditions for a long period.

Quinta da Bela Olinda was the area where the value of infrastructure destruction was more relevant, as the damage exceeded US$ 949,000. The main cause for this value is the destruction of public infrastructure built for the development of the subdivision, such as paved streets, sidewalks and rainwater drainage systems.

The highest values found correspond to estimated economic impacts and losses municipal land tax collection.

Ravines and gullies in Bauru have created large urban voids. When calculated, the annual economic losses exceed values US$ 4.4 million in Quinta da Bela Olinda. This value is explained by the large unused area due to the development of erosion and the non-construction of the lots planned for the area, which was made unusable by erosion, despite the entire urban structure built. Likewise, the loss with municipal land tax collections between 2000 and 2010, considering the average IPTU value, exceeds US$ 113,000 per year in areas such as Jardim América. In this particular case, a comparative analysis of tax values can be performed for before and after recovery of the area affected by erosion. After 2010, a high-standard condominium was built on the site, where the value per square metre land exceeds US$ 188 dollars; thus, the IPTU value in the area, currently collected by the City Hall, is at least approximately US$ 300,000 a year. This change in value in the area after recovery is yet another strong argument for calculating losses in municipal taxes and the average value of GDP per square metre in analyses of impacts of erosion in urban areas.

If the impact from 2000 to 2021 is considered, Quinta da Bela Olinda had a municipal loss of US$ 76.4 million, Parque Bauru had a municipal loss of US$ 73.2 million, and Jardim América had a municipal loss of US$ 23.3 million up to the beginning of recovery, while after recovery the economic gains, including with municipal taxes, were at least US$ 15.8 million in Jardim América. Of this total, more than US$ 3.5 million was lost with IPTU collection in the three areas. In the Jardim América area, in the period between 2010 and 2021 alone, the gain in revenue after the recovery of the site exceeded US$ 3 million.

Among all the erosions described by Almeida Filho (2000), the recovery of areas affected by ravines and gullies occurred mainly for the development of public works, transport or leisure, or private undertakings related to subdivisions and condominiums. This is explained by the ease with which a large enterprise manages to dilute the cost of recovery among the gains provided by the reintroduction of social use to the area. The difference in recovery measures also results from the position of the erosion in the urban perimeter. In Jardim América, which is located in an upscale neighbourhood, the surroundings were occupied while leaving the feature area as a vegetated area with public squares and other spaces. In Parque Bauru, which is a popular neighbourhood, houses are being built on top of the channelled and buried feature, increasing the risk in this case.

The emergence of new ravines and gullies can increase the impact of these areas. This is the case for ravine 5 in Quinta da Bela Olinda, which, due to rapid growth, is getting closer every year to houses and other public infrastructure located upstream. The reactivation of erosion in periods of atypical rainfall or due to changes in land use is another factor that requires attention from City Hall and owners in areas affected by erosion or people who live in the surroundings.

Both the development of containment works and the recovery of areas affected by erosion need to be well documented to build a history of the measures taken in the area, so that it is possible to carry out cost analyses and more easily solve any future geotechnical problems.

Valuations carried out in rural areas by Yitbarek et al. (2012) and Ayele et al. (2015) calculated the values for variables similar to those analysed in this work, such as the cost of recovering the area, loss of nutrients, and cost of missing opportunities.

Yitbarek et al. (2012) quantified the costs of ravine erosion and the costs and benefits of rehabilitation in an area in Ethiopia. The authors used as a reference the cultivated area yield lost by farmers and calculations of rehabilitation costs, considering the cost of labour, materials and equipment at each level of rehabilitation or maintenance, in addition to the monetization of soil nutrients (NPK) and organic carbon (OC). The study indicated that ravine rehabilitation may be economically viable in some cases. The average cost of investment in gully rehabilitation per hectare was calculated at US$ 24,412. In the analyses carried out by the authors, the rehabilitation nutrient benefit generally exceeds the rehabilitation establishment cost by up to 25% more, as is the case for the Eshim Wofena gully, where the cost of erosion was estimated at approximately € 7,000, the rehabilitation nutrient benefit at € 57,100 and rehabilitation establishment cost at € 41,400.

Ayele et al. (2015) quantified the cost of erosion in Ethiopia in a watershed for two years and concluded that the cost of erosion was at least US$ 18,313, with US$ 7,848 related to loss of soil nutrients, US$ 7,204 to missed job opportunity cost, US$ 1,208 to animal losses, US$ 243 to eucalyptus wood losses, and US$ 1,810 to *Rhamnus prinoides* losses. According to the authors, the cost per ha per year was US$ 22, or US$ 17 per person per year, a figure that represents 19% of per capita income. The loss of nutrients in the soil and the cost of lost opportunities were the main impacts identified.

In rural areas, where the function of the land in general is related to agricultural production, the cost of ownership is much lower per square metre, and the ease of replacement of the area is greater. In urban areas, however, competition for land and the value per square metre are greater due to the proximity to numerous economic activities and public structures. The use of variables such as GDP per square metre was a simplified way of considering the economic complexity involved in urban space.

According to Lall and Deichmann (2012), the risk posed by ravines and gullies in cities should increase in the coming decades due to population growth and land scarcity. According to these authors, in cities such as Caracas, Venezuela or Rio de Janeiro, Brazil, poor families occupy land in risk areas to enter the urban labour market. In Bauru, the analysis of images taken between 2004 and 2020 demonstrates that areas affected by erosion are a frequent focus of irregular occupations for the creation of slums.

In cases of the use of engineering works for containment and control of ravines or gullies, long-term impact analyses need to account for the resources used to restore the functionality of infrastructure. In Bauru, at Quinta da Bela Olinda and other places such as Jardim Grama and Parque Bauru, several infrastructures such as hydraulic ladders have been partially or completely destroyed, suggesting that the works may have been poorly sized or that the solution was insufficient because it focused on the consequence, not the process. For Bartley (2020) and Frankl et al. (2021), the key to recovering areas affected by erosion is vegetation, as engineering works have a high failure rate. In this sense, Romero-Díaz et al. (2019) suggest that works built to stabilize ravines and gullies be checked annually after the season with the highest rainfall.

The use of urban waste to fill in gully areas can further aggravate the impacts of these processes. In areas of ravines and gullies, where garbage has been disposed of without any type of waterproofing, it is likely that in addition to the problem caused by erosion, there will also be problems with soil and groundwater contamination. The disposal of garbage in erosions also occurs in other cities of São Paulo. Rotta & Zuquette (2014) cite this practice in an erosion area in São Carlos. This suggests that urban ravines and gullies can also become contaminated areas and a source of contamination in the basin.

For Santos (2008), in addition to the problems in the area directly affected by erosion, ravines and gullies cause the devaluation of the land in the surroundings. According to the author, it is difficult to sell lots in closed subdivisions such as Chácara Odette and Jardim Tavano, and price dropped in areas close to the gully in Jardim Jussara.

Rotta and Zuquette (2014), when analysing areas affected by ravines and gullies in several cities in Brazil, presented examples of erosion that affected land development for decades. In São Pedro, gullies started in 1972 and were recovered with the construction of open channels after the advance of urbanization between 1995 and 2000. This allowed reinserting this area into the urban space with the construction of homes and public structures.

The problems and impacts caused by ravines and gullies in urban areas have many similarities with contaminated areas classified as brownfields. According to Cabernet (2006) brownfields are sites affected by previous use which are abandoned or underutilized due to real or perceived problems of contamination, occur mainly in urban areas, and require intervention so that the area can be used again for beneficial use. Ravines and gullies favour the creation of urban voids, where recovery measures aiming at the reinsertion of these areas into the urban space have a high cost. Contamination caused by garbage disposal in erosion channels brings the concept of brownfields even closer to the scenario created by large erosions in the urban perimeter.

Studies carried out for the recovery of brownfields demonstrate methodological paths that may be applied to the recovery and analysis of areas affected by ravines and gullies. The recovery of brownfield areas requires analysis of environmental, economic, social, time, uncertainty aspects and user friendliness of a sustainable site remediation (Huysegoms & Cappuyns 2017). Thus, the recovery of these areas involves risk assessment, land use planning and the selection of the best remediation methods and technologies (Hammond et al. 2021). Instruments, such as the Timbre Brownfield Prioritization Tool, that use multicriteria tools can help identify priority areas for remediation (Pizzol et al. 2016). If tools such as this are adapted, they can also be used for the analysis of ravines and gullies.

However, ravines and gullies are also a form of natural disaster. Thus, governmental and land planning aimed at reducing the risk of danger is essential. Gully erosion susceptibility maps are an important instrument in land planning and in the development of erosion control and mitigation measures (ARABAMERI et al. 2019). Monitoring the temporal evolution of erosion can be an important geoindicator (BUSNELLI et al. 2006), as urban development can affect hydrological connectivity, change natural flow routes (GUDINO-ELIZONDO 2018), and promote erosion in areas with lower natural susceptibility.

The use of remote sensing can help in valuation analyses, as was the case with the use of Google Earth images in this study. The analysis of spectral images allows the identification of land cover changes (PANI 2017). Automatic identification through the use of remote sensing is an alternative to area monitoring (VRIELING et al. 2007). Municipalities with a high susceptibility to ravines and gullies can use this type of technology as an initial diagnostic tool. The early identification of areas with ravines and gullies at an early stage of development can facilitate a quick response to contain the process, thus avoiding greater environmental and economic damage.

Unmanned aerial vehicles (UAVs) and terrestrial laser scanners (TLSs) are other tools that can be used in the precision analysis of erosion (Julian and Nunes 2020). These methods can provide better results when monitoring the evolution of erosion processes, since two images from different dates are needed to carry out an impact analysis.

In places such as Erosion 1 at Quinta da Bela Olinda, where there is already a recovered erosion with dense vegetation and a watercourse in the interior, the development of a geotourism itinerary or educational itineraries aimed at explaining to students the processes that operate in the formation of ravines and gullies, as well as their economic and environmental impacts, can be an alternative use for these areas. Ravines are used for this purpose in other countries such as Poland (ZGŁOBICKI et al. 2015b).

Although natural conditions influence susceptibility and City Hall has an important role in land planning, the development of ravines and gullies is driven by human action. In this sense, the valuation process is also important in identifying those responsible for triggering accelerated erosion. The impacts of ravines and gullies can cause environmental, social and economic damage to several points of the watershed, including upstream, downstream and surrounding areas.

For other types of disasters, an increasing number of studies address their disasters and the value of remediation strategies. For example, Logar and Van Den Bergh (2013) examined the methods available to assess all types of drought costs, considering direct, indirect and nonmarket costs. Montaña et al. (2016) calculated the natural capital value of forests in Saldaña related to mitigating the risk of landslides. Additionally, Semenova et al. (2013) calculated the cost of wildfires in California. Valuing the impact of erosion is a way of following the same trend, whether to measure the impact for management purposes or for accountability purposes or to trigger any insurance that covers losses.

The method proposed in this study made it possible to carry out an analysis of the short- and long-term costs of urban erosion, considering important factors for understanding the problem, the cost of erosion recovery and containment, environmental impacts, estimated economic losses, loss of revenue from municipal taxes, and losses with infrastructure destruction, in addition to also demonstrating the positive impacts of remediation of these areas. Although the values of losses from erosion and gains due to the reinsertion of these areas can be calculated using the same variables, they need to be calculated separately. The different types of economic and environmental impacts can be identified following the proposal by Kuhn et al. (2023), while the loss of opportunity in the urban space can be determined considering the municipal GDP per square metre. The methodology used in this study can be replicated in other countries around the world, as long as local values are used to determine reference values for replacement or infrastructure costs.

The method proposed in this study allows the valuation of the impacts of ravines and gullies, considering the short-, medium- and long-term losses. The analysis of losses in urban areas, based on the calculation of GDP per square metre, is a simplified way to consider the impact of making areas unfeasible for use in cities, thus creating a way to account for the complexity of the urban environment. The results showed that the application of the replacement cost of items affected by ravines and gullies allows the valuation of items related to damage to infrastructure and ecosystem services performed by the soil. The method to be applied in other countries needs to use local reference values due to variations in the cost of products and services.

4.5. Analysis of which gullies are priorities for recovery.

Based on the analysis performed in the inventory, the existing erosions in 2020 were classified according to “local potential for business development”, “attractiveness and marketing”, and “environmental risks”.

4.5.1. Prioritization

Prioritization was based on the analysis of land use and occupation according to the Master Plan (BAURU 2021a). Thematic maps were used to obtain information on urban infrastructure, population density, education and sanitation infrastructure, characteristics of soil use, transport structures, health services, development areas for new enterprises and proximity to watercourses. For development of the index of geological risks, erosion magnitude and activity, the results from the inventory stage were used. Land value was calculated based on the territorial taxes charged per square metre by the municipality (BAURU 2021b). The proximity of erosions in built areas was defined based on a map composition of spectral bands produced with the use of Landsat 8 orbital images extracted from the Portal of the National Institute for Space Research (INPE).

The priority classes were defined as follows: 1) Class 1: “local potential for business development” comprising land value, population density, educational index, entrepreneurial activity, periphery and transportation connections (Table 18); 2) Class 2: "attractiveness and marketing potential" considering specific location, previous use, infrastructure, and expected regeneration costs (Table 19); and 3) Class 3: "environmental risks" accounting for erosion magnitude, activity (stable or dynamic) of the erosive process, location with respect to urban zonations and proximity to built areas (Table 20). The priority parameter was evaluated on a scale score from 0 to 4.

Table 18. *Classification of "Local potential for business development"*

Parameter	**Method for calculation**	**Score**	**Description**
Land value per square metre	land value per square metre provided by the municipality of Bauru	0	Properties located in rural or urban area with value of up to US $ 6 per square metre
		1	Properties located in urbanized or periurban regions, in neighbourhoods with low to medium standards and values between $ 6 and $ 60 per square metre
		2	Properties located in urbanized regions with values between $ 60 and $ 160 per square metre.
		3	Properties located in urbanized regions, in neighbourhoods with medium to high standards with values of over US $ 160 per square metre.
Population density	Heatmap on housing density	0	Up to 500 inhabitants per km²
		1	From 500 to 2,500 inhabitants per km²
		2	Between 2,500 and 5,000 inhabitants per km²
		3	Above 5,000 inhabitants per km²
Educational indices	Distance to an educational unit (schools and university)	1	Areas without availability of educational units within a radius of up to 1.5 km
		2	Areas with one educational unit within a radius of 1.5 km
		3	Areas with two or more educational units up to 1.5 km distance
Sanitation	Distance from water networks and sewage collection	1	Area without sewage and water and distant to 200 meters of the municipal road network
		2	Area without sewage and/or water and far less than 200 meters of the municipal road network
		3	Area with complete sanitation and water structure within the municipal road network
Land use	Use of the areas indicated in the Master Plan	1	Non-urbanized area
		2	Area in urbanization, urban voids and green area
		3	Areas located in urbanized regions.
Transportation connections	Distance from the main access roads	1	More than 100 metres from some street and over 500 metres of avenues and highways.
		2	Less than 100 metres from some street or less than 500 metres of avenues and highways.
		3	Less than 100 metres from some street and less than 500 metres of avenues and highways.
Health structures	Heatmap considering the distance from health facilities	1	Areas without availability of health units within a radius of up to 1.5 km.
		2	Areas with low concentration of health units within a radius of 1.5 km
		3	Areas with high availability of health units within a 1.5 km-distance

"Local potential for business development" was quantified by summing the scores attributed to each parameter (e.g., Land value per square metre + Population Density + Educational Indices + Sanitation + Land use + Transportation connections+ Health Structure).

Table 19. *Attractiveness and marketing potential*

Parameter	**Method for calculation**	**Score**	**Description**
Infrastructure	Calculated according to the availability of asphalt infrastructure, water and sewage network, distance from schools and health units	1	No sanitation structure, asphalt, education network and consolidated health network.
		2	With sanitation structure, asphalt, education network, health network, water in consolidation.
		3	With sanitation structure, asphalt, education network, health network, available water.
Potential of future residential use	Calculated as used in the Municipal Master Plan, considering the possibilities of use for homes.	0	Areas not indicated for residential use
		1	Areas indicated for single -family residential use
		2	Areas indicated for horizontal or/and single -family multifamily use
		3	Areas indicated for single -family, horizontal and vertical multifamily residential use.
Possibilities of future uses for trade	Calculated as used in the Municipal Master Plan, considering the possibilities of use for trade	0	Areas not indicated for commercial use
		1	Areas where compatible or tolerable activities can be developed to the residential neighbourhood (e.g. residential galleries, hotels, retailers)
		2	Areas where compatible and tolerable activities occur to the residential neighbourhood (e.g. retail trade, gas stations, bank branches)
		3	Areas where compatible, tolerable and uncomfortable activities occur to the residential neighbourhood (e.g. carriers, wholesale trades of fuel storage.)
Possibilities of future uses for industry	Calculated as used in the Municipal Master Plan, considering the possibilities of use for the industry.	0	Areas not indicated for industrial use
		1	Areas where industrial activities can be developed compatible by the residential neighbourhood (e.g. manufacturing of food products)
		2	Areas where compatible and/or tolerable industrial activities can be developed by the residential neighbourhood (e.g. manufacturing of wood products).
		3	Areas where compatible, tolerable and/or uncomfortable industrial activities can be developed to the residential neighbourhood (e.g. cosmetics manufacture and cleaning products)
		4	Areas where compatible, tolerable, uncomfortable and incompatible industrial activities can be developed to the residential neighbourhood (e.g. metallurgy, slaughterhouses and refrigerators)
Expected regeneration costs	Calculated according to the size of the area of each scar of ravine or gully.	1	Erosion with an area larger than 10000 m²
		2	Erosion with area between 2001 and 10000 m²
		3	Erosion less than 2000 m²
Ease of developing	Calculated considering restrictions on use and	0	Green area or special use where the building of houses, installation of industries or commerce is not allowed

new enterprises	the size of the surrounding areas. The larger the unused area the better the score, because the cost of giving recovery is more easily diluted in areas that can be used by large enterprises.	1	Consolidated urban area
		2	Allotment with low occupation, controlled occupation zone or areas in the Vale Fund in the region of Urban Area Consolidated
		3	Areas where urban voids predominate
Drainage	Consider whether erosion is in a natural drainage area. There are restrictions on Brazilian law for the development of enterprises in areas of drainage or source.	0	Erosion positioned in the valley bottom with natural drainage
		2	Erosion positioned in the slope

“Attractiveness and marketing potential” was quantified by summing up the scores attributed to parameter infrastructure, expected regeneration costs, ease of developing new ventures and drainage. The possibilities of future uses can be considered according to municipal planning (residence or commercial or induction).

Table 20. *Environmental risks*

Parameter	**Method for calculation**	**Score**	**Description**
Erosion area size	The higher the size of the erosion the higher the risk	1	Erosion with an area of up to 2,000 m²
		2	Erosion with an area of between 2.001 and 10,000 m²
		3	Erosion with an area larger than 10,001 m²
Erosive Process activity	Score according to stability of the area of erosion.	2	Stable Ravines or Gullies
		3	Ravines or Gullies Development
Zoning	Calculated according to the proximity to urban infrastructure, being considered the highest grade for areas without structure and close to the urban perimeter.	1	Urbanized area, with control of rainwater surface runoff (zones that are not green areas, built areas).
		2	Not urbanized area with rural use.
		3	Periurban area with low urbanization or green areas within the urban perimeter, and with linear structures that facilitate the concentration of surface water.
Risk	Calculated according to the proximity of the erosions of built areas, based on the analysis of orbital image compositions.	1	Area without residences or public infrastructures over 300 from the surroundings of erosion.
		2	Area with residences or public infrastructures between 300 and 100 metres from erosion.
		3	Area with residences and public infrastructures less than 100 metres

“Environmental risk” was quantified by summing up the scores attributed to the parameters (Erosion area size + Erosive Process Activity + Zoning + Risk).

3.5.2. Marketing

Marketing potential was assessed based on the integration of data from the previous steps, aiming at obtaining indications for future use, as well as identifying trends in relation to land use and occupation in the municipality of Bauru.

In the “attractiveness and marketing class”, the score used for final classification considered the infrastructure, expected restauration costs, connection to drainage and ease of developing new enterprises. The score regarding the possibilities of future, commercial, residential and industrial uses was not considered because each area of the city has specific restrictions for use, as indicated in the Municipal Master Plan for each neighbourhood in the municipality; in this way, only the sum of the other parameters was considered, they being: expected regeneration costs, ease of developing new enterprises, drainage, and infrastructure.

4.5.3. Classification of Priority Erosions

4.5.3.1. Local potential for business development – Class 1

Regarding value per square metre, approximately 85% of erosions occurred in areas with costs between $6 and 60 dollars. At least 50% of erosions are in areas with a population density of up to 500 people per hectare. Fifty-four percent are in areas of urban expansion with still open space. Approximately 50% of the areas are in regions very close to educational institutions, and 59% are in regions with a complete sanitation structure. 51% have good transportation connections (Figure 23). The only parameter that did not have a good correlation with erosions was related to health structures, and the classification displayed a good distribution between the established score for this parameter (Table 21). The overall classification of this criterion indicated that the areas with the highest are in urban expansion zones or in urban open space (Figure 24).

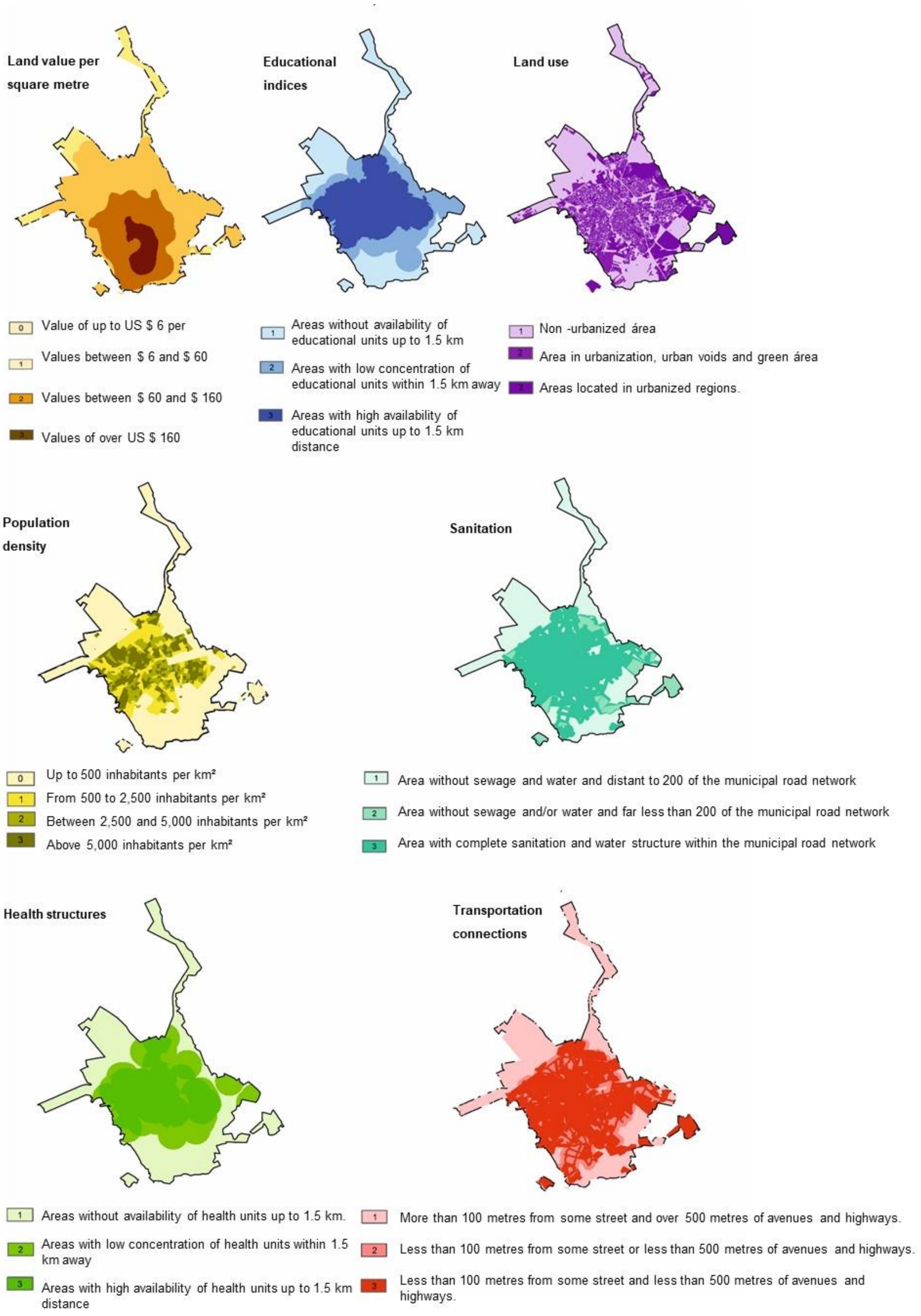


Figure 23. *Maps produced for analysis of the proposed parameters and scores in the work methodology for "Local potential for business development" classification.*

Table 21. *Relationship between identified erosions and parameters established in the methodology for "Local potential for business development" analysis.*

Parameter	Score	Number of erosions	Percentage
Square Metro Value	0	0	0.0%
	1	162	85.7%
	2	31	16.4%
	3	6	3.2%
Population density	0	96	50.8%
	1	60	31.7%
	2	24	12.7%
	3	9	4.8%
Educational indices	1	37	19.6%
	2	57	30.2%
	3	95	50.3%
Sanitation	1	67	35.4%
	2	2	1.1%
	3	112	59.3%
Land use	1	103	54.5%
	2	21	11.1%
	3	65	34.4%
Transportation connections	1	66	34.9%
	2	25	13.2%
	3	98	51.9%
Health structure	1	61	32.3%
	2	56	29.6%
	3	72	38.1%

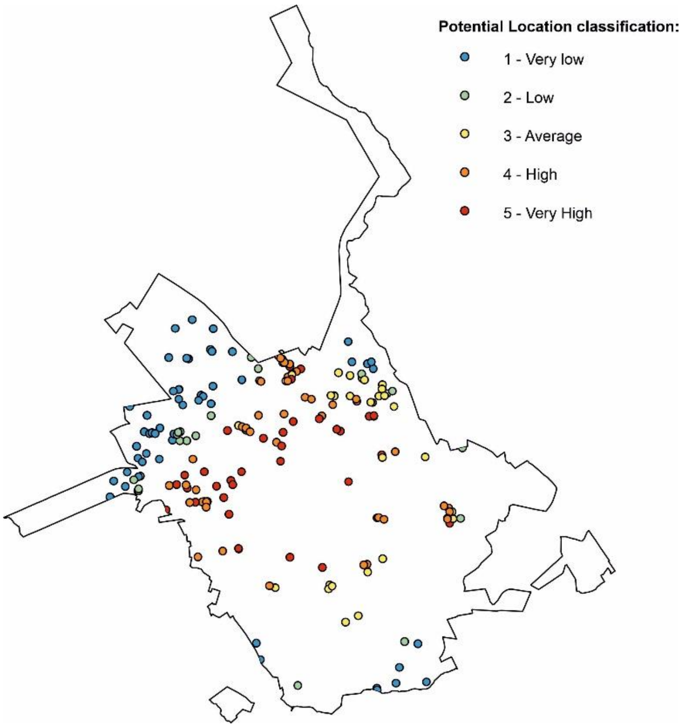


Figure 24. *Map indicating the ranking of erosions in relation to the "Local potential for business development".*

3.5.3.2. Attractiveness and marketing of the area affected by ravines or gullies – Class 2

Analysis of attractiveness and marketing of the area affected by the ravines or gullies (Figure 25). Some parameters indicated good correlation with areas affected by linear erosion.

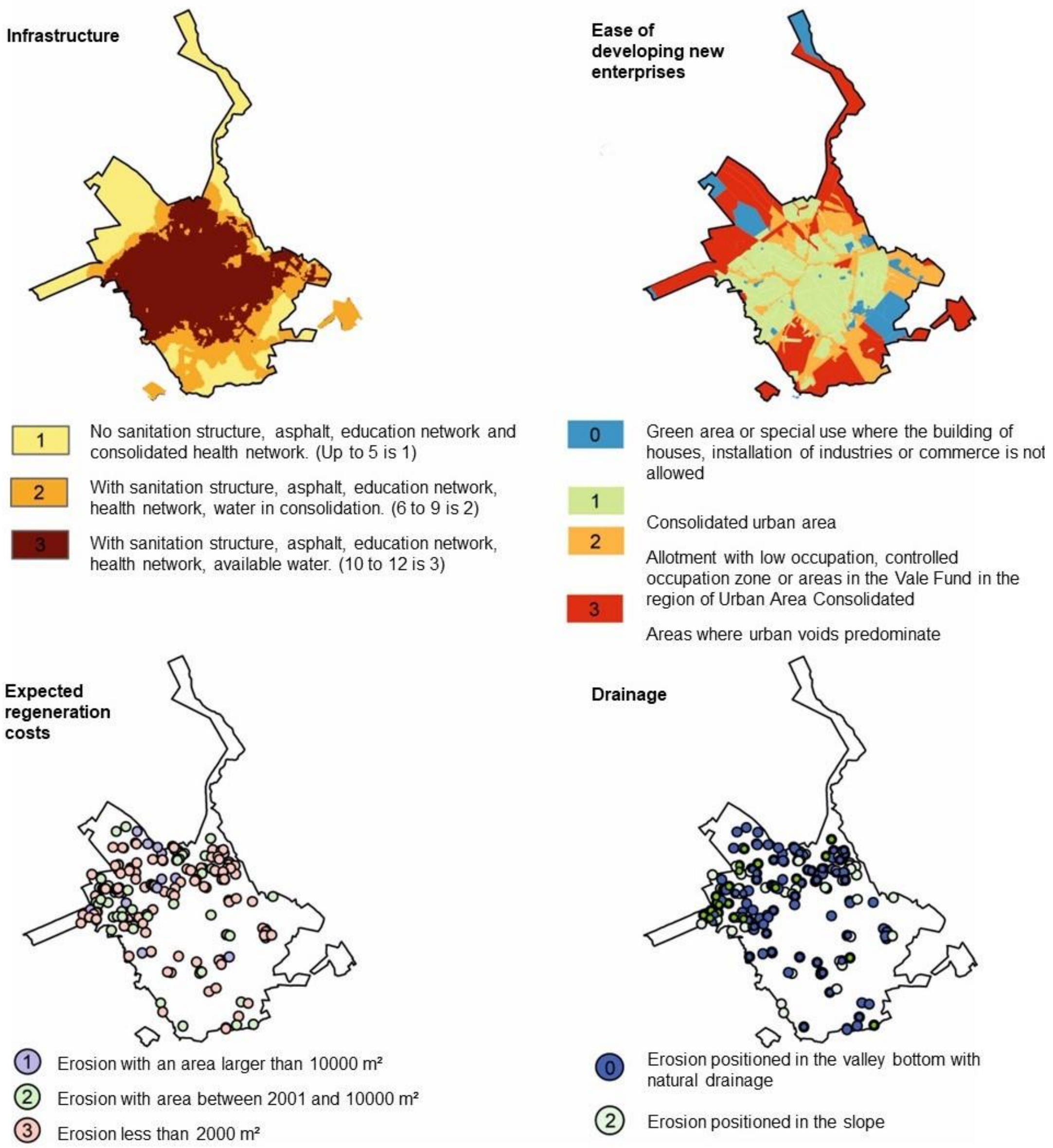


Figure 25. Maps produced for analysis of the proposed parameters and scores in the work methodology for classification of attractiveness and marketing.

Most erosions, 52%, are in areas with good municipal urban structure. Approximately 65% of erosions affect an area less than 2000 m², and most erosions are in slope areas without contact with natural drainage. The ease of developing new ventures has not indicated any correlation.

Among the possible uses for the areas (Table 22), most of them, 73%, can be used for different residential uses. Use for small business or industrial activities compatible with residential use is indicated in 41% and 60%, respectively. As three distinct analyses of use were applied, residential, commercial and industrial, three different classifications were also generated for this class (Figure 26). The result indicates the three different classifications for the "attractiveness and marketing potential" class, according to the existing municipal master plan restrictions for residential, commercial or industrial use (Figure 27).

Table 22. *Relationship between identified erosions and parameters established in the methodology for attractiveness and marketing analysis.*

Parameters	Score	Number	Percentage
Infrastructure	1	46	24.3%
	2	43	22.8%
	3	100	52.9%
Expected regeneration costs	1	12	6.3%
	2	53	28%
	3	124	65.6%
Ease of developing new enterprises	0	13	6.9%
	1	39	20.6%
	2	71	37.6%
	3	66	34.9%
Drainage	0	105	55.6%
	2	84	44.4%
Possibilities of future uses for residence	0	49	25.9%
	1	1	0.5%
	2	0	0%
	3	139	73.5%
Possibilities of future uses for trade	0	14	7.4%
	1	78	41.3%
	2	57	30.2%
	3	40	21.2%
Possibilities of future uses for industry	0	14	7.4%
	1	115	60.8%
	2	25	13.2%
	3	29	15.3%
	4	6	3.2%

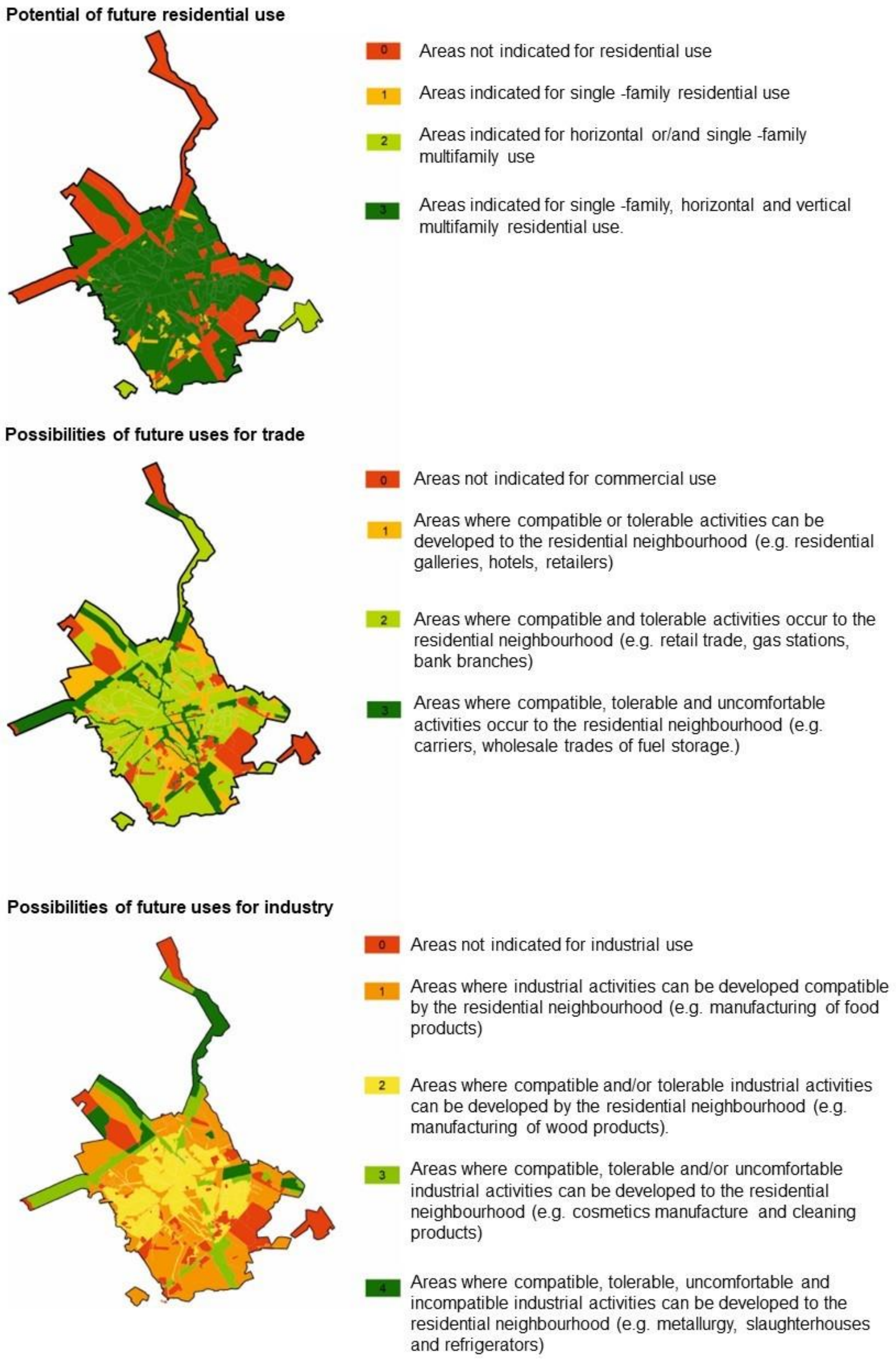


Figure 26. *Map with the different possible uses, as indicated in the Municipal Master Plan for each region of the city, considering the possibilities of residential, commercial and industrial use.*

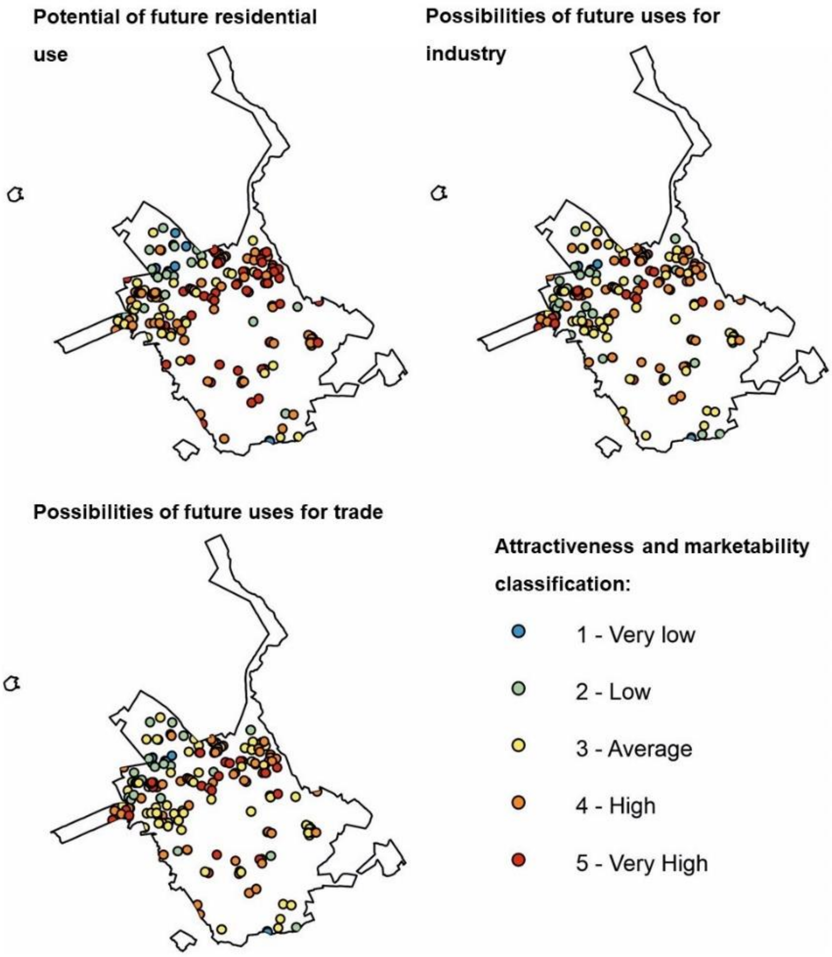


Figure 27. *Map indicating the classification of erosions regarding attractiveness and marketing, considering the possibilities of residential, commercial and industrial use.*

3.5.3.3. Environmental risks - Class 3

Environmental risk analyses considered the size of the area of erosion; whether erosion was active or developing, urban zoning in relation to urbanized areas, areas with urban voids and nonurbanized areas and green areas, and in risk analysis, proximity to urban structures (Figure 28) was considered.

Most erosions, 65%, have areas less than 2000 m². The analysis indicates a correlation with erosion activity, and 73% of erosions are classified as stable. In the zoning class, there was no strong correlation with any of the classes (Table 23). All erosions analysed are at least 300 metres from some public or private infrastructure. Based on the criteria analysed, erosions were classified in relation to environmental risks (Figure 29).

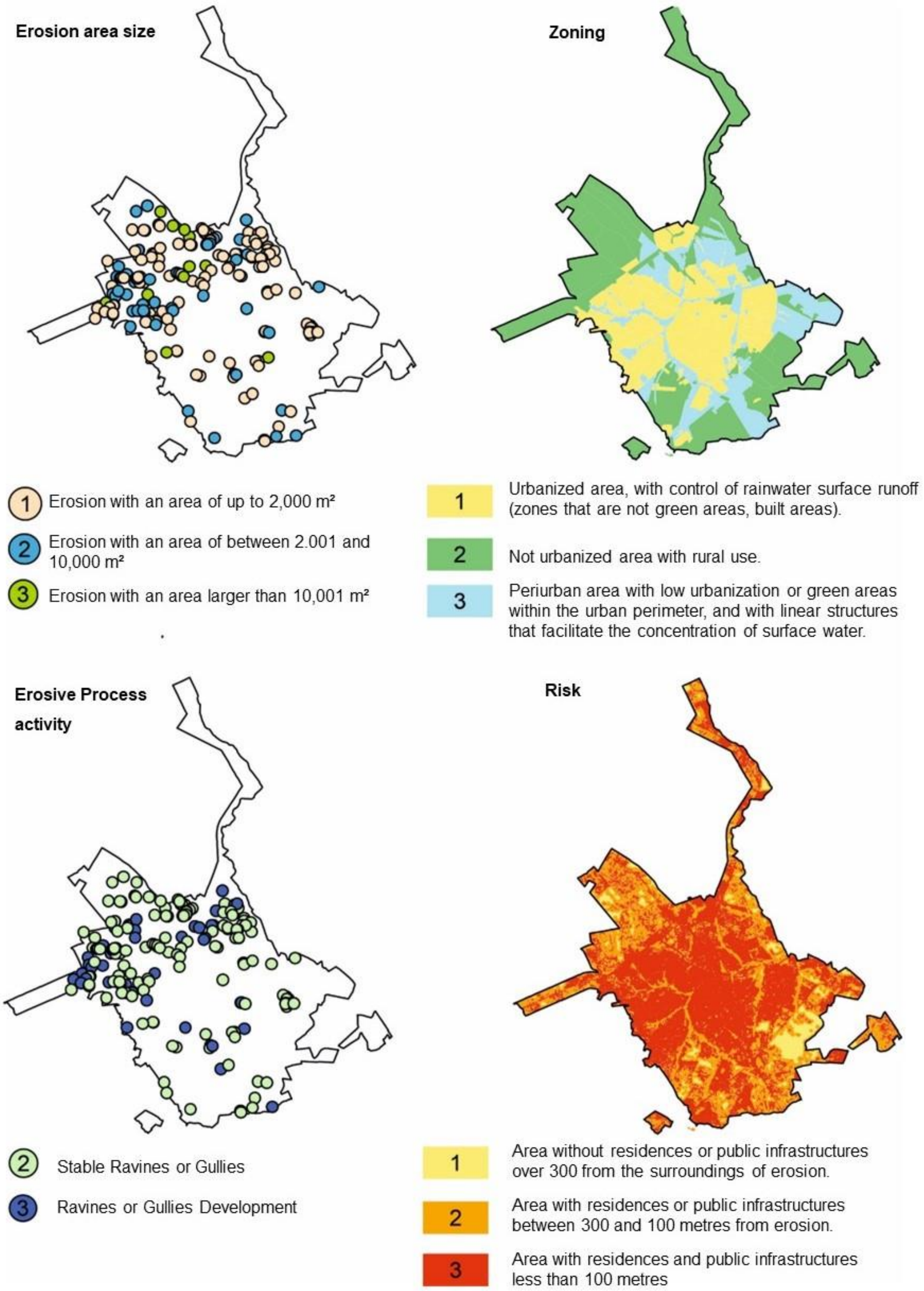


Figure 28. *Maps produced for analysis of the proposed parameters and scores in the work methodology for environmental risk classification.*

***Table 23**. Relationship between identified erosions and parameters established in the methodology for environmental risk analysis.*

Parameters	Score	Number	Percentage
Erosion area size	1	124	65.6%
	2	53	28%
	3	12	6.3%
Erosive Process activity	2	139	73.5%
	3	50	26.5%
Zoning	1	39	20.6%
	2	78	41.3%
	3	72	38.1%
Risk: Proximity with urban structures	1	0	0%
	2	95	50.3%
	3	94	49.7%

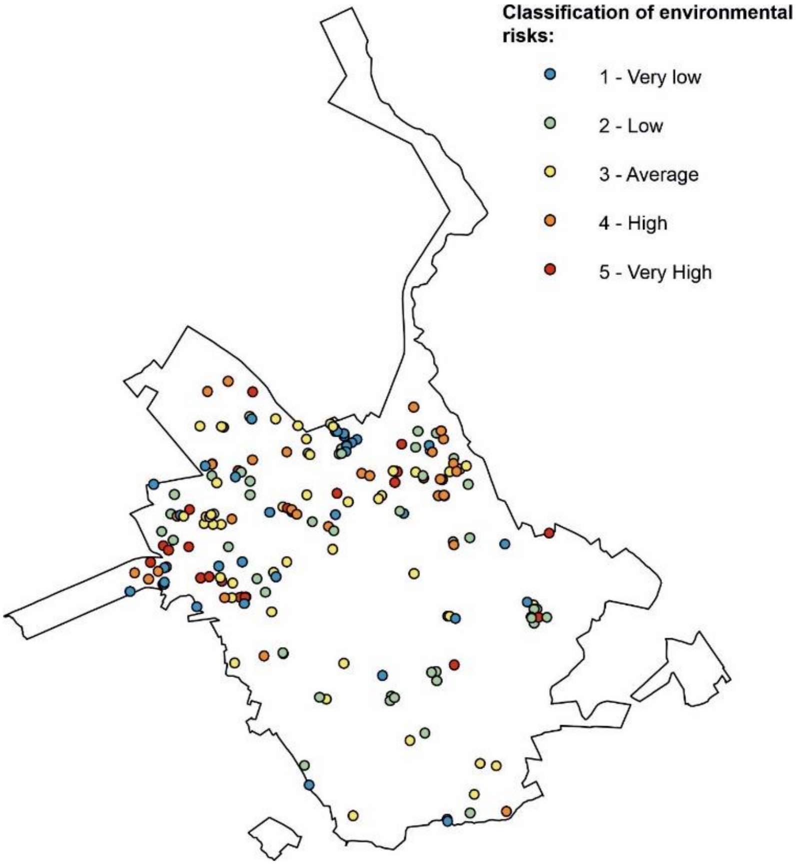


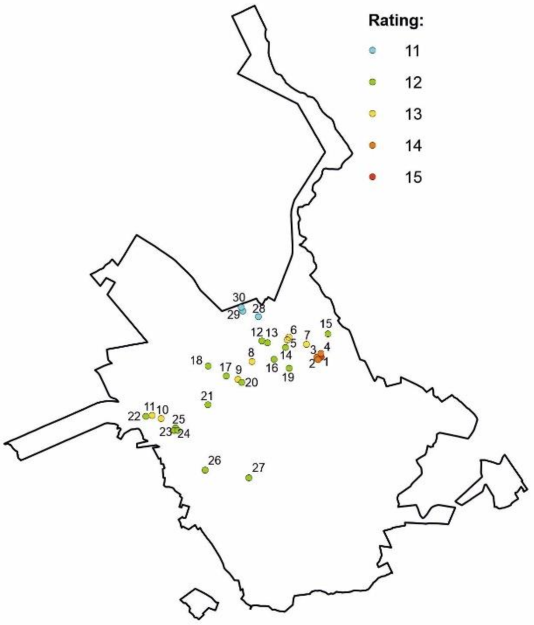
***Figure 29.** Map indicating the classification of gullies in relation to environmental risks.*

4.5.4. Analysis of priority areas

The 30 best classified erosions when adding the scores of the 3 classes analysed are concentrated mostly in the area of urban expansion, northwest of the city (Figure 30 A). The 7 erosions with the highest potential are concentrated in the Quinta da Bela Olinda region. The data indicate that this is the area with the highest development potential today and has erosion with the highest risk of activities.

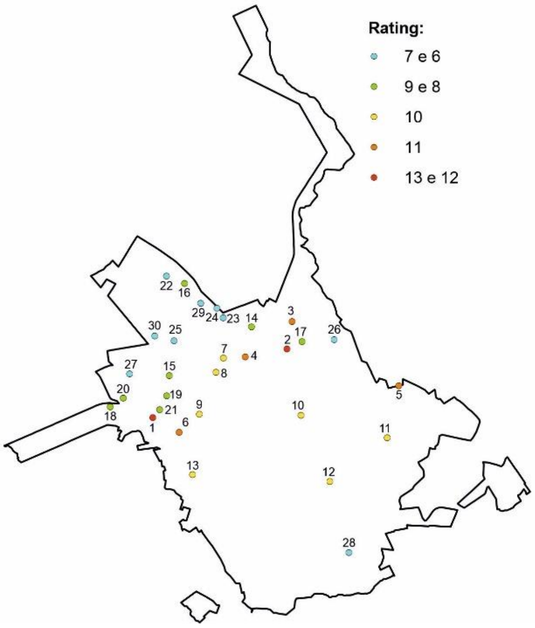
When considering the 30 best classified erosions with an area greater than 5000 m² (Figure 30 B), although there is still a larger concentration of erosions in the northwest sector of the city, well-classified erosions also occur in other sectors, indicating a greater dispersion of erosive processes.

A **Classification of the 30 priority erosions**



Number	Area (m²)	Class 1	Class 2	Class 3	Ranking
1	114	5	5	5	15
2	177	5	5	4	14
3	1354	5	5	4	14
4	236	5	5	4	14
5	45	3	5	5	13
6	104	3	5	5	13
7	2906	4	4	5	13
8	289	5	5	3	13
9	276	4	5	4	13
10	808	5	3	5	13
11	5858	5	3	5	13
12	199	4	4	4	12
13	124	4	4	4	12
14	5563	4	3	5	12
15	901	3	5	4	12
16	891	5	4	3	12
17	1898	5	5	2	12
18	2271	4	3	5	12
19	534	5	5	2	12
20	839	5	5	2	12
21	1626	5	4	3	12
22	2701	4	3	5	12
23	392	4	3	5	12
24	337	4	3	5	12
25	153	4	3	5	12
26	240	5	5	2	12
27	481	5	4	3	12
28	1685	5	5	1	11
29	425	4	4	3	11
30	398	4	4	3	11

B **Classification of the 30 priority erosions greater than 5000 m²**



Number	Area (m²)	Class 1	Class 2	Class 3	Ranking
1	5858	5	3	5	13
2	5563	4	3	5	12
3	9774	3	3	5	11
4	11949	4	2	5	11
5	6908	2	4	5	11
6	40070	4	2	5	11
7	50666	4	3	3	10
8	21972	4	2	4	10
9	5337	5	2	3	10
10	7327	5	2	3	10
11	9721	4	3	3	10
12	15284	3	2	5	10
13	42385	4	2	4	10
14	5511	5	3	1	9
15	6275	2	3	4	9
16	11684	1	2	5	8
17	6955	3	2	3	8
18	9334	1	2	5	8
19	19087	4	2	2	8
20	12119	1	2	5	8
21	5650	5	2	1	8
22	5537	1	2	4	7
23	58596	2	2	3	7
24	13349	2	2	3	7
25	8627	1	1	5	7
26	7175	2	2	3	7
27	5853	1	2	4	7
28	7341	2	2	3	7
29	12162	1	2	3	6
30	6099	1	1	4	6

Figure 30. *Considering the three classes considered: local potential for business development (Class 1); attractiveness and marketing potential (Class 2); and environmental risks (Class 3), the figure shows the classification of priority ravines and gullies: a) map with the 30 best classified erosions; B) map with the 30 erosions larger than 5000 m² better classified.*

4.5.5. Discussion about priority areas

The inventory indicated an increase in the number of erosions between 2004 and 2020 from 175 to 189. The area directly affected by erosion channels decreased from 64.1 hectares to 62.5 hectares. The contrast between the increased number of erosions and the reduced area is the result of the remediation of large channels among the 37 recovered erosions; most small erosions (51 new channels) emerged between 2004 and 2020, indicating that ravines and gullies will increase in number, but these erosions still have a smaller size. Although the reduction in the affected area is good news, the existence of a greater number of erosions may indicate a growth trend of these erosions in the medium term.

Although the area directly affected by the erosion channels is 62.5 hectares, the surrounding area indirectly affected can easily be 10 times larger, as the ravines and gullies make the use of the surrounding area unfeasible. This demonstrates that erosions represent a problem with very significant dimensions. Reintroducing these spaces for urban use is a necessity in the management of the city. Although they are a problem, the existence of large urban areas without occupation is also an opportunity, and the size of brownfields in hectares was indicated by Osman et al. (2015) as a positive parameter for areas to be recovered.

The recovery of areas affected by erosion also prevents new damage in the vicinity. The inventory indicated that the areas of urban expansion have the largest number of erosions, while in consolidated urban areas, new erosions in most cases are related to inadequate drainage structures.

Regarding the class “local potential for business development”, among the parameters, the strongest correlate correlation was in relation to costs per square metre between \$6 and \$60, which was one of the lowest scores in the analysis. This indicates a relationship between the existence of erosion and the low value of the property. However, this correlation can also indicate an opportunity. Low land prices increase attractiveness for potential investors (Turecková et al. 2018). However, the data also indicated that most areas affected by erosion are in places close to educational institutions and with public sanitation and good transportation calls. Thus, the recovery of areas affected by ravines and gullies can be a good opportunity considering the existing public infrastructures in the surroundings. In the long run, the trend is that the areas affected by erosion that are not considered today for new enterprises become attractive due to their location in the city. Local potential analyses developed in this work can accelerate this process due to the creation of indicators that demonstrate the competitive differences of each area.

The class “attractiveness and marketing” showed that most erosions are positioned in places with good urban infrastructure and have a scar with an area of less than 2000 m². According to Hudec et al. (2005), small gullies have not only lower costs for regeneration but also less technical complexity than large erosions.

Regarding the ease of development of new enterprises, a strong correlation with any proposed class was not indicated. However, as already addressed by Osman et al. (2015), large urban voids may provide excellent opportunities for large enterprises, which helps to cover eventual remediation costs.

The analysis of attractiveness and marketing allows us to relate erosions to the possibilities provided for in the city's master plan. This is interesting to identify areas most suitable for specific use according to municipal standards. Residential use was the most suitable in 73% of cases, but small industries and trades were also possible in 60% and 41% of areas, respectively. If enterprises seek the construction of large industries and trades, the map produced also allows an easy view of the areas possible to develop this activity.

Low potential areas for these three uses (residential, industries and trades) can be used as green space or left as brownfield, which does not involve the construction of infrastructure (BARDOS et al. 2016). Alternative uses may be connected to geotourism and education programs (ZGŁOBICKI et al. 2015b). Municipal public policies and tax incentives can assist in more sustainable land use, allowing the best option to be taken for the urban community (TURECKOVÁ et al. 2018).

Risk analysis has indicated that all existing erosions in the area are at least 300 metres from some public or private infrastructure. This indicates the need for monitoring all erosions, as in some cases, these erosions may have a rapid evolution, and if mediation measures are not performed, they can destroy infrastructures and even cause deaths. Most erosions are less than 2000 m² and classified as stable, so the reactivation of these channels or the rapid growth of smaller channels may occur when soil use and occupation change or extreme weather events occur.

The three priority classes can be analysed separately according to the user's interest; for example, if the interest is to find areas with good local potential, only class 1 should be considered, but if the goal is to analyse or monitor the evolution of the erosion risk, class 3 will indicate priority erosions that may cause significant economic or environmental damage.

The final priority analysis indicated that the area of Quinta da Bela Olinda has better classified erosions, considering the sum of the three priority classes. This reinforces the analysis performed step valuation, who estimated that approximately 80.7 hectares in that region are affected due to the existence of ravines and gullies. The environmental and economic impacts calculated by the authors demonstrate that losses exceed $76.4 Million over the last few decades. The area was planned for residential use, but the development of ravines and gullies over the last three decades made it impossible to use the site. Reintegrating this area into the urban environment represents a good opportunity for municipal entrepreneurs and managers, but this requires creating marketing strategies to convince local actors. The creation of databases that brings together information on the techniques used to regenerate the areas, existing costs and monitoring measures applied may represent a risk reduction factor and improve agility in decision-making and application of resources more assertively.

Although the data collected in this study provide important information on the areas with the highest potential, it is necessary to consult the population and local managers to build consensus and establish priorities for use for the affected areas. This will also depend on land ownership (public vs. private land).

To convince stakeholders, dialogue strategies must be developed. Rizzo et al. (2015) identified five groups interested in brownfield regeneration: site owners, authorities, neighbours and others interested in the problems related to the area, service providers, and scientific community. These same authors propose a participatory methodology consisting of five phases, which involves (i) planning and preparatory work, (ii) mapping of stakeholders, (iii) development of activities such as workshops and lectures to foster engagement, (iv) application of a devolutionary questionnaire and (V) feedback for each of the stakeholders involved.

The establishment of a governance strategy through policies is another factor that can help in the regeneration of Brownfields, as the time required for complete implementation of a municipal or even project strategy may be longer than the period of managers' electoral mandates (Klusáček et al. 2022).

The classification presented here provides an important indicator for erosion brownfield management, just as it is already done with other types of brownfield portfolios. To identify the variables that are most relevant for area recovery. The construction of databases assisting the analysis of territorial evolution can be an important metric to make decision-making increasingly assertive.

Application of this method to other places is possible provided it is adjusted to local data. The development of decision support systems (DSS) for erosion management in urban areas can help solve the complexity involved in the areas, as proposed by Stezar et al. (2013) for contaminated areas. Tools also help identify and manage the specific opportunities and risks of each remediation project (HUYSEGOMS and CAPPYNS 2017).

5. Conclusions

The data obtained in this thesis facilitated the systematization of a method for evaluating the economic and environmental costs of ravines and gullies, considering the short-, medium- and long-term impacts. This information is important for several countries around the world in which ravines and gullies are a problem that affects territorial and city management. Understanding the cost of the impacts caused is a step towards making society aware of the importance of reintroducing areas affected by erosion into the economic and social scenario.

Demonstrating the long-term impacts and how damaging an area can be, especially in urban areas, is a way to carry out studies and use appropriate techniques for the control and remediation of affected areas, ravines and gullies.

In Brazil, analysis of official Civil Defense data indicated a correlation between the disasters recorded in recent decades and the country's agricultural frontier in areas of the Amazon and Cerrado biomes. The official impacts account only for short-term damage, and in the 24 cases analysed, they totalled 54 million. On the other hand, a trend of underreporting was identified in rural areas and in small and poorer municipalities. In the next stage of the project, it became clear that between 2004 and 2020, dozens of erosions caused impacts in Bauru, and even so, no records were made in the civil defence system, which indicates that underreporting could be even greater.

In the municipality of Bauru, in 2020, erosion channels alone represented an area greater than 62 hectares, which represents the equivalent of more than 75 football fields. However, in many cases, ravines and gullies have also made large surrounding areas unfeasible.

The valuation of three areas carried out in the municipality of Bauru indicated impacts of more than US$ 173 million. In addition to damage to infrastructure and housing and impacts on ecosystem services, analyses show that ravines and gullies generate losses in municipal tax collection and economic losses due to the abandonment of urban areas. The use of GDP per square metre to analyse economic losses is a simplified way of valuing the impacts on the urban environment that can help indicate the impacts caused by erosion in this area.

Urban ravines and gullies can be considered a form of brownfield. The adaptation of the Timbre methodology for classifying ravines and gullies that should be a priority for remediation allows for a more assertive allocation of resources, which are often limited in developing countries. The analysis of the 3 classes used in the prioritization stage pointed to the Quinta da Bela Olinda region, where the 7 priority erosions for recovery in the city of Bauru are located.

In this way, this thesis helped both to identify the cost of the impacts caused by ravines and gullies and to identify which erosion types should be prioritized for remediation. These two responses are fundamental for building strategies for soil management, erosion prevention and control. The reintroduction of areas affected by ravines and gullies can be a necessary and important measure for achieving sustainability in cities and reducing the risk of natural disasters.

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APPENDIX A - Accepted and submitted manuscripts.

A.1 Ravines and gullies, a review about impact valuation

A.2 The record and trends of natural disasters caused by gullies in Brazil

A.3 Economic impacts of an urban gully are driven by land degradation

A.4 Adaptation of the Timbre methodology for gully erosion analysis in urban areas.

APPENDIX A.1. MANUSCRIPT: Ravines and gullies, a review about impact valuation

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Abstract

Gullies and ravines affect human lives and the environment in many countries worldwide, however, few studies have assessed the impacts of the damage caused by these large linear erosions and clarified their influencing parameters. This work systematizes available information about the variables relevant to analyze the impacts of ravines and gullies on socioeconomic conditions and ecosystem services. Based on keyword searches performed in the Scopus, Web of Science and Dimensions databases, more than 120 articles from 27 countries were identified that addressed and valuated these different types of impacts. Although many studies discuss the impacts of ravines and gullies, few studies have performed valuations of these impacts. We compiled the impacts in urban and rural areas, considering the changes caused by ravines and gullies throughout a hydrographic basin. The results allowed for the elaboration of a theoretical model of the possible impacts of gullies and ravines and how they can be valued. The results demonstrate that the most significant impacts, according to the literature, are in South America, Africa, China and India, which are related to disordered land occupation. In some cases, the lack of capacity to respond to environmental and social problems aggravates the scenario and leads to significant losses. Implementing the evaluation is challenging due to the high number of different forms of possible impacts, in the short, medium and long term, related to environmental, economic and social changes.

Key words: evaluation, impact analysis, linear erosion, ecosystem services.

1. Introduction

Gullies develop via a combination of extreme rainfall events and socioeconomic changes, such as the conversion of forests to cultivated areas, which has been described for the prehistory and the Roman period in Belgium, Poland and Germany by Poesen (2011) and Dagar (2018). In North Carolina, United States, Spell and Jonson (2019) related the formation of ravines to the initial deforestation and agriculture activities carried out by settlers in the 18th century. Bacellar *et al.* (2005) list erosions in the state of Minas Gerais, Brazil, as a consequence of inadequate land use practices in the late 17th century, such as the construction of boundary ditches.

Several authors carried out reviews addressing different aspects related to gullies and ravines: Valentin *et al.* (2005) addressed erosion impacts, causes and control; Castillo and Gómez (2016) assessed the evolution of erosion; Vanmaercke *et al.* (2016) studied the mapping of temporal and spatial evolution; Poesen (2017) identified that there are still gaps in studies on gullies related to understanding the spatial and temporal patterns of soil erosion rates and landscape evolution and to the development of innovative techniques and strategies to prevent or reduce soil erosion; Dagar (2018) evaluated the history and trends of gullies and ravines in recent studies, particularly regarding the formation process and methods of recovery and containment of linear erosion; Romero-Díaz *et al.* (2019) carried out an analysis on methodologies for the rehabilitation of affected areas; and Dube *et al.* (2020) carried out an analysis on the evolution and morphology of erosion in different climates, among others.

Only a few studies, including those by Yitbarek *et al.* (2012) and Ayele *et al.* (2015), have focused on the valuation of the impacts of linear erosion. Therefore, there is still no widely accepted method in the literature for assessing damage caused by ravine and gully development. Economic losses and impacts on ecosystem services are mentioned in several works in the literature but mostly without an impact assessment (Balzerek *et al.* 2003; Argüello *et al.* 2006; Abdo *et al.* 2013; Rowntree 2014; Somasundaram *et al.* 2018; Kouidri 2018; Paredes *et al.* 2020). Environmental and socioeconomic impacts are easily observed in many places in the world, such as the city of Kinshasa and the Democratic Republic of Congo (Figure 1). Accounting for the impacts of ravines and gullies is important to justify the use of financial resources in the prevention and recovery of areas affected by erosion.

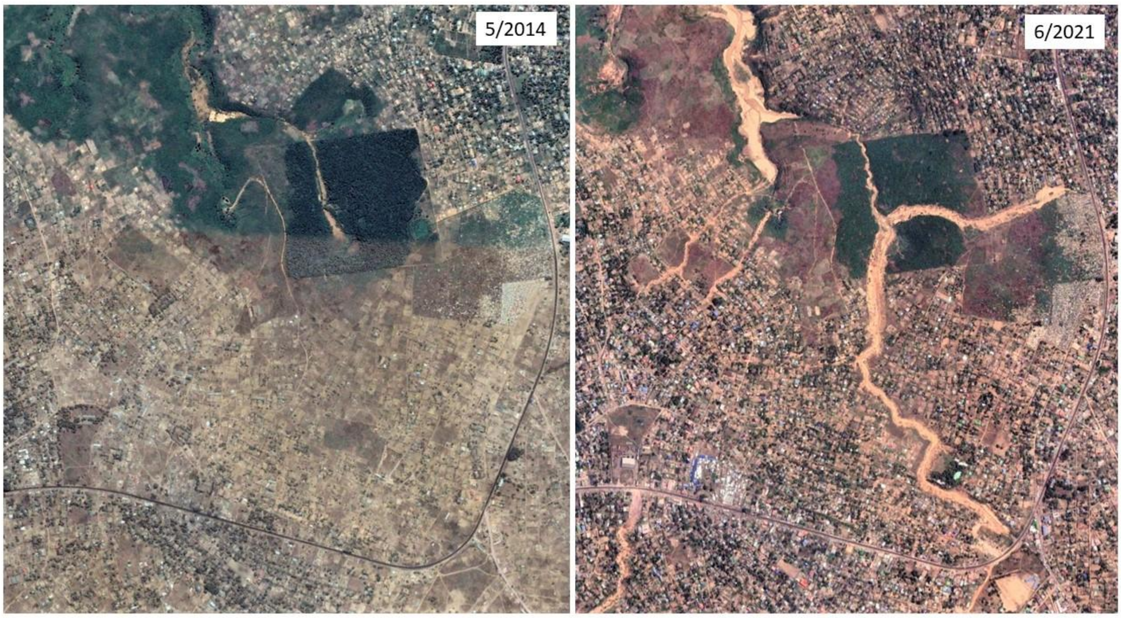


Figure 1: Comparison of two images of the same area, the first from 2014, where the erosive process development of the ravines is clearly visible between 2014 and 2021, in an area with high population density in Kinshasa, the Republic Democratic Republic of Congo. Images extracted from Google Earth (Lat. 4°30'6.50"S - Log. 15°13'3.67"L).

Among the factors that influence gully erosion/ gullied area recovery and control measures are a) the characteristics and dimensions of erosion at the site; b) geomorphological conditions; c) land use characteristics; d) the availability of alternative areas; d) access to water; e) distance from residences; f) history of erosion at the site; and g) cost of recovery with works (Pani 2016). Romero-Díaz et al. (2019) cite among the consequences of erosion control an increase in the production of food, organic matter and wood, an increase in the cultivable area and water retention, and an improvement in water quality.

To contribute to a better understanding of the impacts of linear erosion, this article presents a systematic bibliographic review using a state-of-the-art evaluation of the socioeconomic impacts and ecosystem services caused by erosion in ravines and gullies. In addition, a discussion is carried out regarding the conditions that aggravate these impacts and the recovery processes of areas affected by erosion, considering the spatial dimensions of the hydrographic basin and the temporal evolution of erosion. An overview on the current methodologies/available technologies to measure/quantify erosion over time is given. A special focus on erosion processes in gullies and ravines in Brazil supports the development of an evaluation method for an area in the city of Bauru that has a long history of erosion.

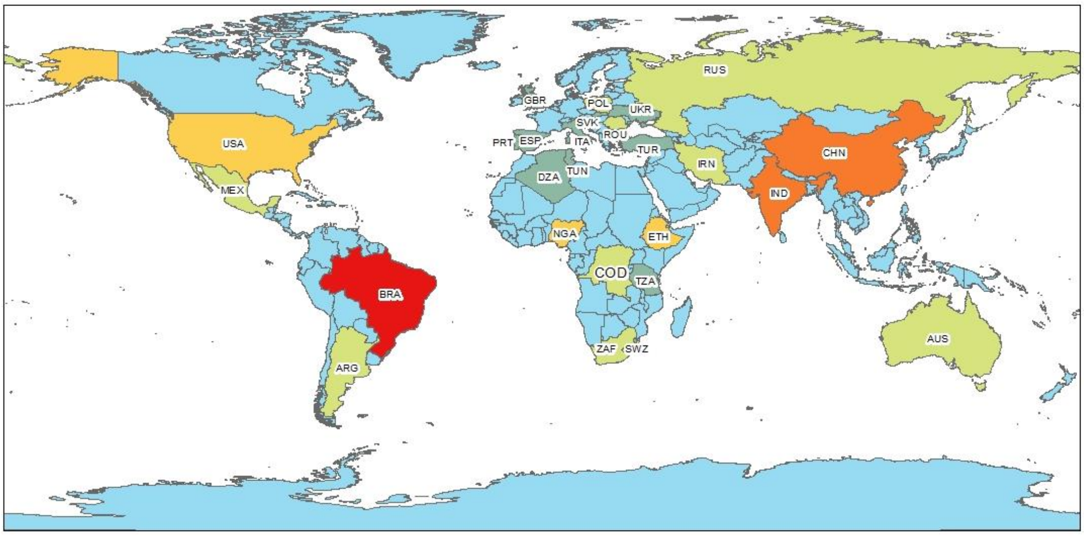
2. Bibliographic Methods

The bibliographic search was carried out in the Web of Science, Dimensions and Scopus databases. Several combinations of the following keywords were used: ravines, gully, valuation, natural hazards, invest, soil loss, urban, city, disaster, ecosystem services and linear erosion. After reading abstracts, 124 works from 27 countries were analyzed in full (Figure 2). The criterion for selecting the articles was the existence of results that help to understand the temporal evolution and impacts caused by ravines and gullies and the recovery measures implemented. In addition, the articles published related to Brazil are overrepresented in relation to other countries because the chosen sample is related to research on the valuation of linear erosions in Brazil (additional keyword "Brazil").

This search had limitations because the searches were performed with only English keywords. Gray literature, such as reports and technical studies or articles that were not indexed in the three cited databases, are underrepresented in the analysis. However, when some relevant information from any of these bibliographic sources was identified in the references of some work, the reading and analysis of the contents were performed.

Ecosystem services and natural capital are fundamental for supporting life and essential for human beings (Costanza et al. 1997). They must be accounted for as part of the overall economic value, along with other commercial values. Ecosystem services cited include gas regulation, climate regulation, disturbance regulation, water regulation, water supply, erosion control and sediment retention, soil formation, nutrient cycling, waste treatment, pollination, biological control, refugia, food production, raw materials, genetic resources, recreation and cultural (Costanza et al. 1997).

From the analyzed bibliography, the anthropic and biophysical factors that influence the development of ravines and gullies, methods of prevention and analysis of temporal evolution, methodologies for the recovery of areas affected by linear erosion and the socioeconomic and ecosystem services impacts are discussed. When data regarding the costs of impacts or other recovery measures were presented in currencies other than US dollars, they were converted to US dollars at the rate for 04/26/2021.



Country	Abbreviation	Country	Abbreviation	Country	Abbreviation
Algeria	DZA	Italy	ITA	Spain	ESP
Argentina	ARG	Mexico	MEX	Swaziland	SWZ
Australia	AUS	Nigeria	NGA	Tanzania	TZA
Brazil	BRA	Poland	POL	Tunisia	TUN
China	CHN	Portugal	PRT	Turkey	TUR
D. R. Congo	COD	Romania	ROU	Ukraine	UKR
Ethiopia	ETH	Russia	RUS	United Kingdom	GBR
India	IND	Slovakia	SVK	United States	USA
Iran	IRN	South Africa	ZAF		

Figure 2. Map with the distribution of publications analyzed by country.

3. State of the art on studies of ravines and gullies

3.1. Factors that influence the intensity of impacts

Erosion occurs due to changes in land use and occupation caused by anthropogenic interventions, followed by rainfall events.

Among the anthropogenic factors that contribute to the development of erosion are vegetation removal, overgrazing, deforestation, forest burning, infrastructure construction such as roads, arable land obstacles that promote the accumulation of surface runoff, hydrological changes in rural and urban areas, trails used by animals or humans, retention basin overflows, mining activities or other interventions that concentrate surface flow water (Saksa and Minár 2012; Valentin *et al.* 2005; Dagar 2018; Wouters and Wolff 2010).

When analyzing the development of ravines in Kinshasa (Congo), Imwangana *et al.* (2015) observed that between the initial construction of buildings and streets and the appearance of the first ravines, there was a time span of 5 to 10 years, suggesting that a critical density of houses and roads in the area was needed for the erosion process to develop.

In urban centers, according to Kayembe and Wolff (2015), the impact of erosion tends to be greater in neighborhoods with low-income populations. According to the authors, among the factors that contribute to erosion are the type of roads and houses constructed without appropriate drainage system and surface runoff planning and the lack of maintenance of the erosion control system.

The development of linear erosions is related to the concentration of rainwater on the surface; thus, the greater the intensity of rainfall is, the greater the possibility of developing gullies and ravines. According to Wischmeier (1959), erosivity by water is calculated based on kinetic energy and rain intensity (mm per hour)

(Wischmeier 1959). Soil erodibility is calculated by the ratio between soil losses and rainfall erosivity (Wischmeier and Smith 1978). That is, erosivity is related to the intensity of rainfall that triggers erosion, and erodibility is related to the susceptibility of the soil to erosion.

The percentages of soil erosion and water erosivity demonstrate a correlation between erosive dynamics and rainfall regimes (Busnelli *et al.* 2006). There is a relationship between the deposition of sediments in the hydrographic basin and the rate of rain intensity, that is, the amount of kinetic energy and runoff, and both factors contribute to greater erosion via rain (Onyelowe *et al.* 2018). Prolonged drought periods followed by short rainy periods favor runoff and erosion (Arabameri *et al.* 2019).

Based on the calculation of the kinetic energy of rain, Klik *et al.* (2016) found that high-intensity storms combined with fragile ground cover in steep slope regions created perfect conditions for laminar erosion and gully formation in the Ethiopian highlands.

Argüello *et al.* (2006) described the occurrence of extreme hydrometeorological events as the main cause for the development of erosions in Corralito, Argentina, in 1978/79, when the precipitation of just one month almost reached the precipitation of the driest year (1971/72). In an exceptionally humid hydrological year (1978/79), rainfall accumulated to 1348 mm, much higher than the average in the region, and according to analyses carried out by the authors, the 230 mm precipitation observed in September 1978 would have a return period of 500 years and the 180 mm from February 1979 would have a recurrence of 200 years.

In Seirós, Portugal, an extreme rainfall event, with precipitation of close to 160 mm in the head of the basin and precipitation of 80 mm and 120 mm at the site on the 14th and 15th in December 2015, caused the development of erosion with a 49 m long channel, 0.70 m wide and 0.75 m deep (Martins *et al.* 2019).

Soil saturation due to recurrent rains and the consequent increase in runoff is an important factor in erosion development, as it can lead to significant environmental and socioeconomic impacts. One case in Comodoro Rivadavia documented by Paredes et al. (2020), which considered decade- and century-long climatic cycles, demonstrated the destructive potential of extreme rain events associated with changes in the physical environment for which appropriate planning was not done. The authors noted that between March 29 and April 8, 2017, precipitation of 399.4 mm and 232 mm occurred only on March 30. This event modified the landscape and created several ravines and gullies, the largest of which had a V-shaped cross section, exceeding 15 m in depth and 870 m in length (Paredes *et al*. 2020). According to the same authors, area photographs from the 1970s revealed that ditches in the area were filled during the construction of the city, modifying old drainage routes. A slope of 20° and the depth of the resistant substrate at its foot were also factors that influenced the development of erosion.

Rowntree (2014) reported the development of erosions related to extreme rainfall events of 90 mm in September 1891 in Wellwood and 81 mm in September 15 and 16 in Cranemere, South Africa, followed by other high intensity events in 1900, 1902 and 1903.

Ravines and gullies occur in all climates, except for locations close to the poles with permanent ice (Castillo and Gómez 2016). Dube *et al.* (2020) analyzed length and depth in ravines under different climatic conditions. The length tends to increase in a temperate climate when compared to the existing features in subtropical and/or tropical climates, which have similar sizes. On the other hand, gullies tend to be narrower in temperate climates than in subtropical climates. The shallowest gullies have been found in tropical climates.

Vanmaercke *et al.* (2016) carried out a literature review related to the progression rates of 933 ravines in more than 70 study areas and assumed that the main variables influencing erosion headcut advances are the upstream drainage area and the normal rainy day (average rainfall depth on a rainy day). The authors found a relationship between the rate of linear erosion and the affected volumetric area ($r^2 = 0.83$). In the studies analyzed, the retreat rate varied between 0.01 and 135 m y^{-1} (median: 0.89 m y^{-1}), and the affected area varied between 0.01 and 3628 m2y^{-1} (median: 3.12 m y^{-1}). The width varied between 0.4 and 104 m (mean: 9 m, median: 3.2 m), and the depth varied between 0.2 and 35 m (mean: 2.1 m, median: 1.3 m). The normal rainy day and the upstream drainage area were the main factors that influenced the rate of erosion growth.

In Brazilian classifications, an aquifer connection differentiates ravines, which are linear features with a depth of more than 50 centimeters, generally V-shaped and rarely branched; gullies, the next stage in the evolution of erosion, are created when an aquifer intersects a ravine, usually have a U-shape, and, as erosion evolves, tend to branch out into several channels (Salomão 1994). In tropical regions, due to the high volume of annual rainfall, the connection between linear erosion and the aquifer becomes clearer; when intercepted, the lateral evolution of erosion is favored, which explains why in these climatic conditions, erosions tend to be shallower than in colder climates with less annual rainfall.

For Real *et al.* (2020), fault and/or shear zones favor the development of soil erosion. Da Silva et al. (2003) related the development of ravines and gullies in Paty do Alferes, Rio de Janeiro, Brazil, to the low resistance to weathering and high permeability of the mineralogical and textural characteristics of the rocks. For the authors, the presence of structural lineaments favors the development of erosion. Likewise, Akgün and Türk (2011) noted that in Turkey, most gullies occurred in areas with a high density of lineaments; thus, the distribution of lineaments and lithological variations can affect the location of erosive processes. In addition, the type of rocks and susceptibility to weathering influence the formation of the soil.

Geology can also be related to uplift in tectonically active regions such as the Loess Plateau in China, with a rise in elevation of 150-200 meters during the Quaternary, which increased the kinetic energy of the area and thus favored erosion (Hui and Mingan 2000).

Vegetation also influences the development of erosion; when present, it protects the soil from the impact of rain, helps to maintain the soil structure, reduces the speed of surface runoff and favors the infiltration of water into the soil due to root channels (Dagar 1986, 2018). Therefore, in arid and semiarid regions, the low presence of vegetation favors the formation of ravines.

Dasgupta *et al.* (2013) considered vegetation cover to be the most important factor for the protection of soil fertility. The removal of vegetation can favor the loss of nutrients. Selkimäki and González-Olabarria (2017) reported that forest domains reduce the probability of erosion development. However, forest fires, especially in regions with trails, tend to increase water connectivity and favor erosion (Martínez-Murillo and López-Vicente 2018). According to the authors, after vegetation has recovered, water connectivity also returns to its initial state.

Vegetation plays a very important role in the recovery of areas affected by erosion. For Gardziel *et al.* (1998), biological construction, through the introduction of different types of plants in an affected area, is an alternative to reduce the evolution of erosion. Vegetation is important to both prevent erosion and recover areas affected by erosion. Vegetation cover reduces the velocity and volume of surface runoff, favors the infiltration of water into the soil and helps retain nutrients and sediments.

Topographic or physiographic characteristics influence the development of ravines and gullies, according to Valentin *et al.* (2005), Dagar (2018), Gayen *et al.* (2019), and Dube *et al.* (2020). For example, the size, shape and drainage density of the catchment and the curvature, length and gradient of the slopes control the flow speed and erosive forces. Vanmaercke *et al.* (2016) reported a relationship between the size of the upstream area that drains into the gully headcut, the amount of runoff, and the rate of erosion. For Valentin *et al.* (2005), the impacts of soil erosion must be analyzed at the basin scale. If, on the one hand, the larger the size of the watershed area is, the greater the potential for rainwater concentration during extreme events, then the shape of the slope determines how the runoff will occur; for example, in concave slopes, the concentration is greater, and the slope helps to determine the erosion potential of runoff.

Soil properties such as texture, moisture, bulk density, water retention, and inflation capacity also influence the development of erosion and influence the formation of ravines and gullies (Stocking 1972, Morgan 1984, Dagar 2018). For Real *et al.* (2020), the boundary between different soil types may favor the development of gullies due to changes in soil properties.

Although the infiltration rate increases from clayey to sandy soil, the resistance to erosion decreases; thus, erosion in sandy soils is higher (Hillel 1982; Dagar 2018). The type of soil can favor the development of linear erosions. For example, lateritic soils are highly weathered and leached and are fragile due to characteristics related to aridity, loss of nutrients, chemical deficiency, crust formation, water erosion and poor water retention capacity, thus favoring the development of erosive processes (Jha 2008; Jha and Kapat 2009). According to Hudec *et al.* (2005), ravines advance faster when the erosion reaches the lateritic horizon, with lateral advance widening the transversal size of the erosion.

Several studies done in different locations throughout the world report different types of soils in regions prone to the development of ravines and gullies. In Seirós, northern Portugal, erosion features reported by Martins *et al.* (2019) showed depths limited to the thickness of the colluvium. Nosko et al. (2019) reported that accelerated runoff causes more gullies. Sandy materials are more permeable but have little cohesion (Lucía *et al.* 2011; Vanmaercke *et al.* 2016).

Several studies have related erosion to soil characteristics in Brazil. For Guerra *et al.* (2018), erosion is more intense in friable and unconsolidated soils. De Lima and Guerra (2019) described soil degradation and the development of erosive processes in latosols and clayey soil following the implementation of the Dourados National Agricultural Colony in the 1950s. Souza *et al.* (2017), in an analysis carried out along the Malha Paulista railway line, identified the predominance of gullies in latosols, which are deeper soils with high maturation that facilitate erosion, but the authors also identified the development of erosions in Argisols, Nitosols and Neossols. In the hydrographic basin of Maracujá, Minas Gerais, gullies were found in areas of thicker saprolites and in places with natural concentrations of surface or groundwater (Bacellar *et al.*, 2005). Wantzen *et al.* (2006) noted the proximity to footpaths and springs in gullies located in the plateau region in the cerrado biome. For the authors, porous and slightly cohesive soils favor the development of ravines. Erosion in sandy soils was found in the Ibicuí basin (Corbonnois et al. 2011). For Rotta and Zuquette (2014), erosion in Casa Branca occurred in response to reworked, unconsolidated, thick and porous sandy soils.

Table 1 shows how each of the factors described above can aggravate the impacts caused by linear erosion based on the information described in the previous paragraphs.

Soil characteristics such as permeability and porosity influence water infiltration. Although porous and permeable rocks and soils favor infiltration, once saturated, surface runoff triggers linear erosion. If the ravine created intercepts the groundwater table, internal erosion by piping starts in addition to tail erosion by runoff.

Table 1: List of factors that influence the development of ravines and gullies.

Factor	Description	Influence
Climate	Prolonged droughts followed by heavy rains	Weakens soil structures and facilitates erosion.
	Erosion morphology	Length: Longer if compared to features existing in temperate climate to subtropical and/or tropical; b) Width: Narrower than subtropical, the connection with water table in tropical climates favors lateral evolution; c) Depth: Shallower in tropical climates due to connection and stabilization with the water table; greater in temperate climates than in tropical climates.
	Weathering	The hotter and rainier, the greater the weathering blanket
Rain	Accumulated volume of rain over several days	Saturates the soil
	Extreme rain events in a day	Favor surface runoff
Geomorphology	Slope	The larger, the greater the kinetic energy of the flow
	Drainage basin size	The greater, the greater the flow possible during extreme events
	Strand shape	Can favor accumulated flow
Geology	Rock type	Influences the formation of the soil; in some cases the rock has low cohesion, behaving similar to the soil.
	Aquifers	The characteristics of the rocks influence the characteristics of the local aquifer. The relationship between the local aquifer and erosion is important in tropical regions.
	Uplift of old surfaces	Changes kinetic energy and favors the development of gully systems with a regional dimension.
Soil	Cohesion	Clayey soils are more cohesive, sandy soils less cohesive
	Permeability	Greater infiltration in sandy soils
	Erodibility	Tends to be higher on sandy and loose soils
	Depth	The deeper the soil or loose sediment package, the greater the risk of formation of large linear erosions.
Vegetation	Sediment retention and soil preservation	In semiarid climates, little vegetation favors erosion and hinders recovery; in tropical climates, the frequency of rain favors the insertion of vegetation in the affected area
Anthropogenic changes	Linear structures (trails, roads...)	Favor the surface flow water concentration
	Soil compaction or area waterproofing	Reduces infiltration and favors surface runoff
	Removal of vegetation or burning	Exposes the soil
	Changes in natural runoff	Redirect water flow
	Precarious social conditions	Limit the ability to respond to erosions

The cases of extreme events in places of low cohesive soils in Africa, Argentina, Portugal, among others, indicate that the combination of land use on vulnerable soils and/or friable rocks and large areas of drainage and extreme rainfall events have the potential to form gullies and ravines hundreds of meters long and tens of meters wide and deep in a few days.

In other regions, due to climatic conditions that hinder consolidated vegetation cover, e.g., semiarid regions, significant impacts from ravines and gullies must be expected. In some specific cases, such as the Loess Plateau, the recent uplifting of old surfaces may be important to the existing impacts of erosion on the site.

Although linear erosion occurs in many soil types (clayey, sandy, or loosely cohesive soils), oxisols, colluvium, sandy soils and friable soils, or thick soils of tens of meters, are developed in regions where the climate favors the development of a thick intemperate blanket (Guerra et al. 2018; Dagar 2018; De Lima and Guerra 2019; Martins et al. 2019). The faster the linear erosions form and/or evolve, the more complex the erosion control process is due to the need for quick response and the difficulty in carrying out sediment retention.

3.2. The evolution of erosion

Linear erosions, although they can have moments of rapid evolution due to storms, when not stabilized, have variable annual growth. Understanding how gullies and ravines evolve is important to analyze the impact of these processes in the medium and long term.

The quantification of the erosion rate is performed by several methods, such as the dendrochronological method, which uses the roots exposed in ravine areas to estimate the erosion rate (Vandekerckhove *et al.* 2001); orbital image analysis (Busnelli *et al.* 2006); use of isotopic tracers of elements such as carbon and nitrogen to analyze the fingerprint of sediments (Valentin *et al.* 2005); topographic field surveys (El Khalili *et al.* 2013); and use of images of drones and unmanned aerial vehicles (Martínez *et al.* 2018; Julian and Nunes 2020).

However, according to the review carried out by Poesen *et al.* (2011), there are still no reliable and validated models that allow foreseeing all factors related to the evolution of ravines and gullies, such as infiltration, time scales, sediment production, and evolution of the landscape. Guerra et al. (2017) considered that there is a need to monitor soil erosion using experimental stations, but although these data are important for understanding erosion, even when monitoring is carried out for decades, they generally will not record extreme events such as high magnitude precipitation.

Calculating the future evolution of linear erosion is a topic that still requires attention via scientific research, but the current state-of-the-art research on the evolution of erosion allows us to establish some assumptions about the development of this process, which can be used to analyze the valuation of its impact. The first assumption is that it is possible to identify the past evolution of erosion through the analysis of satellite images and aerial photos, in which the erosion scar dimensions can be identified. The data on the evolution of erosion allow us to create scenarios about the possible impacted area in the coming years or decades. The rate of erosion tends to be regressive, that is, to grow at an ever-slower pace, but the natural growth of erosion tends to impact a growing area for decades or centuries. Some of the methods described are best applied on a regional scale, while others are best applied on a local scale (Table 2).

Table 2: Main methods used to analyze erosion evolution and the recommended work scale for each method.

Method	Scale
Satellite image analysis	Regional or local

Aerial photo and image analysis using drones, unmanned aerial vehicle (UAV) or Digital Terrain Model (DTM) analysis (LiDAR data)	Regional or local
Terrestrial laser scanner (TLS)	Local
Chronological analysis (e.g. isotopes, dendrochronology)	Local
Isotopic Tracers and Sediment Analysis	Local or Regional
Topography	Local

3.3. Recovery and containment

Among the measures that can slow erosion, remediate affected areas, and slow the development of ravines and gullies are dams, drainage energy dissipators, spillways, accumulation basins, protection dikes, artificial channels and water capture structures, watercourse and lake desilting, earthworks, pasture area revegetation, gabions with vegetation, grass planting, biodegradable mats, conservation practices in agriculture such as no-tillage, fire control, crop rotation, soil fertilization, permanent protection strips, furrow terracing, level spreaders, and infiltration piers, among others (Rotta and Zuquette 2014; Dagar and Singh 2018).

Rotta and Zuquette (2014) divided recovery measures into five categories: ecological, agricultural, mechanical, structural macrodrainage and structural microdrainage. Romero-Díaz et al. (2019) classified gully control measures as (i) structural, (ii) vegetative and (iii) structural/vegetative. The gully headcut area and the head of the erosive process are important places to stop erosion; vegetative measures within the channel and containment of impacts in the basin, such as sediment retention dams in the river channel, are valuable practices (Frankl *et al.* 2021).

Dagar (2018) considers the following steps to be important for the control of ravines and gullies: a) improvement of the hydrographic basin by reducing the peak flow rate; b) stabilization of the head of the ravines; c) development of structural measures and revegetation; d) reduction of the slope of the sidewalls; and c) treatment of the area affected by erosion.

In a review carried out by Bartley (2020), the author divided the recovery measures into three categories according to location: a) treat the watershed above the erosion, aiming to reduce runoff discharge; b) carry out measurements within the channel, with the objective of interrupting the expansion of the ravine; and c) a combination of both approaches. According to the review carried out by the author, after stabilizing erosion, there is a reduction in sediment production between 12% and 94%. Remediation in only the area upstream of erosion has an average response value of approximately 28 years; when the treatment is carried out only in the area directly affected by erosion, the response occurs in approximately 25 years, and when several methodologies are integrated, the average recovery value of the area drops to approximately 19 years (Bartley 2020).

The data demonstrate that containment and recovery measures can be implemented considering the biophysical and social conditions of the region. The greater the erosion, the more complex the containment and recovery of the area. To contain erosion, actions in the hydrographic basin and in the canal are necessary, but measures can also be taken downstream, such as dam construction, to reduce the impacts related to the released sediments. Vegetation has the most impact and the best results in the long run, but structural measures also have an important effect on containing erosion. The need to maintain the installed structures must also be accounted for in any analyses.

All measures adopted have costs, whether in relation to the implementation itself, shutdown of activities, labor costs, and maintenance costs, among others. Some works have analyzed the costs that exist in the recovery of ravines and gullies. The cost of actions to recover areas affected by erosion depends on the biophysical characteristics of the site and the technique applied (De Brito Galvão *et al.* 2011; Romero-Díaz *et al.* 2019).

Balzerek *et al.* (2003) reported that unsuccessful erosion control measures cause more damage, and to carry out appropriate measures, it is necessary to plan, coordinate and organize their implementation. According to Rotta and Zuquette (2014), in some cases, problems are related to the adoption of inadequate recovery measures, which are chosen due to popularity or ease and do not always result in the best recovery of the area, or in some cases, the measures are poorly executed or scaled. Guerra et al. (2017) stated that the integrated management of watersheds for soil conservation and the use of bioengineering can offer alternatives for erosion control.

Containment and analysis of erosion impacts cannot be carried out in a generic way, and the actions taken need to be implemented and monitored by qualified professionals, aiming to apply resources and measures that are truly effective. In this way, an understanding about the dimensions of the impacts of linear erosion by civil society and managers becomes even more necessary. The recovery of affected areas demands time, financial resources and qualified work.

Among the existing problems for the containment of ravines and gullies is the cost of recovery actions. Valentin *et al.* (2005) have discussed the difficulty for farmers in adopting techniques for the prevention and recovery of ravines due to the small short-term return, but in the long term, the returns are more significant. Dagar and Singh (2018) reported that gully recovery techniques are rarely adopted by farmers due to deficiencies in extension services, policy implementation and return on investments.

For Romero-Díaz *et al.* (2019), increased productivity is the best argument to convince farmers to develop soil and water conservation measures, and the possibility of increasing the productivity of the area, in addition to reducing soil loss, reducing flooding and increasing soil moisture and vegetation cover, can be noted as some ecological benefits.

The development of a valuation methodology that allows the identification of the dimensions of the impacts of ravines and gullies can contribute to the construction of policies or lines of financing that help to make it possible to contain erosion.

Thus, this work classifies the recovery and containment measures into four different types: a) structural, b) watershed management, c) vegetative and d) educational or/and qualification (Table 3). Both measures can be implemented to contain the same erosion.

Table 3: Classification of recovery and control measures for areas affected by ravines and gullies.

Type	Description
Structural	Engineering works built in the hydrographic basin, either upstream, downstream or at the erosion site
Basin management	Adoption of good practices within the watershed to reduce surface runoff and increase soil seepage
Vegetative	Introduction of vegetation in the watershed area and at the site of erosion
Educational and Qualifying	Development of actions to guide the population of the affected area or train people on how to manage areas affected by erosion

4. Results and discussions

4.1. Economic impacts

Among the economic impacts of ravines and gullies are reduced agricultural productivity due to a loss of planting areas and change in soil characteristics; a loss of crops and available land; increases in agricultural costs; increases in agricultural activities workloads due to limitations or difficulties imposed by erosion and the cost of production agriculture and livestock in rural areas; the siltation of reservoirs and their consequential loss of functionality; increases in flooding risks and the subsequent damage to infrastructures situated in areas located near rivers; damage to infrastructure and increases in costs of drains or channel maintenance; and the rapid drainage of aquifers, which lowers the water table and subsequently dries up wells (Balzerek *et al.* 2003; Valentin *et al.* 2005; Romero-Díaz *et al.* 2019).

In rural areas, several authors have described impacts related to the occurrence of ravines and gullies. Zgłobicki *et al.* (2015a) analyzed the impacts of ravines in eastern Poland. For the authors in some districts where gullies covered more than 2% of the area, where there is a high density of ravines, special management must be carried out to reduce negative economic impacts. According to the authors, the landscape forms developed by ravines are unfavorable to modern agriculture and can become an obstacle to the development of efficient agriculture or to the consolidation of agricultural land.

According to Daba (2003), gullies are expanding in areas of agricultural land in Ethiopia at an accelerated rate. They are considered to be the main cause of silting of lakes (such as Lake Alemaya) and other sources of drinking water and irrigation; in addition, they increase the risk of flooding.

Gullies and ravines reduce the cultivated area, reduce production, hamper the movement of people and livestock, and have other environmental impacts (Belayneh *et al.* 2020). Ravine fields cause a permanent loss of agricultural land if recovery measures are not carried out based on government funding (Olson and Morton 2012).

Abdo *et al.* (2013) noted that, in Australia, progressive erosion made it impossible to continue farming in areas previously used for agriculture; however, these areas could still be used for fishing, ecotourism and other economic activities. The first step in restoration is to interrupt the evolution of the erosion process and recover the area through engineering works, restrict livestock use, and recover the natural vegetation.

Morokong and Blignaut (2019) analyzed the costs and benefits of reducing soil erosion in the municipality of Mutale, South Africa. The authors identified that an area of 1470 hectares (ha) was affected by soil erosion; in some places, the observed impact was related to the loss of pasture productivity, siltation of rivers and loss of water bodies, as well as the consequent increase in the cost of water, loss in land production capacity, destruction of residential areas and interruption of roads. If considering the opportunity cost lost by unrestored land, the value is estimated at US$10 per hectare and US$56 per hectare for crops. To control erosion, US$ 0.5 million was spent using rock structures for the period 2010-2016, and with this investment, a benefit between US$ 140 thousand and US$ 200 thousand was generated, in other words, a cost–benefit between 0.29 and 0.41.

Pani (2017) determined that of 766 villages in India, 343 are affected by ravines, among which the main effects are the loss of agricultural land, reductions in production, changes in villages, and impacts on infrastructure and subsistence economic activities. Ravines affect access to land and can contribute to changes in the drainage pattern, in addition to affecting the supply of public goods and basic human development structures such as access to health and education.

According to Pani (2016), in the Chambal Valley, India, ravines affected 26.5% of the total agricultural land, but the percentage varied by village. According to the author, 71 families reported the loss of land due to the development of ravines; of this total, 11% were unable to recover the land, 76% partially recovered it and 13% moved to new land.

Busnelli *et al.* (2006) described the silting of an artificial lake in La Angostura, Argentina, where there was a reduction in the depth and loss of surface area of the reservoir, from 23% between 1977 and 2000. They demonstrated the impact of erosion on the useful life of reservoirs.

In urban areas worldwide, the impacts of ravines and gullies are felt. Balzerek *et al.* (2003) noted the destruction of houses, streets and bridges in the State of Gombe, Nigeria. Hudec *et al.* (2005) mentioned that in Nigeria, according to official data, between 1981 and 1994, erosion and other forms of soil degradation caused the country to lose 3.7 million hectares of forests and agricultural land. The authors noted an expenditure of approximately US $ 7.7 million in the state of Imo, with the objective of reducing gullies in the southeast of the country.

The city of Kinshasa (Congo) has the best documented processes of erosion in the literature. Accumulated erosion in the last 50 years in this municipality totaled 308 linear features totaling 94.7 km, that is, an average advance of 2 km annually. The 10 largest gullies had an average width of 57 m and an average depth of 20 m; however, when considering the general average of all gullies, the numbers dropped to 17 m and 6 m, respectively (Imwangana *et al.* 2015). The annual economic impact caused by the destruction of a home is US $ 1.5 million per year, in addition to other expenses such as US $ 10 million for the reconstruction of the Drève de Selembao in 2004 and US $ 7.8 million in 2006 for the recovery of areas affected by gullies in the Mataba district (Imwangana *et al.* 2015). Another author who described erosion processes in Kinshasa was Ozer (2014), who, through the observation of images, identified the destruction of more than 60 houses due to the development of a ravine between 2006 and 2011.

Erosions in some cases evolve suddenly due to large storms and occupational use that has not been properly planned, as in the case of Comodoro Rivadavia in Argentina in 2017. After heavy rains, a large number of V-shaped gullies were generated with lengths of up to 870 m and depths of up to 15 m; the event transported over 400,000 m3 of fine to very fine sand and damaged or destroyed more than 400 houses, in addition to urban and industrial infrastructure (Paredes *et al.* 2020).

The increase in the cost of maintaining roads and transport routes, or costs with the paralysis of roads, is also another type of existing economic impact of ravines and gullies. Souza *et al.* (2017) stated that their possible impacts on the Malha Paulista railroad in Brazil included the halting of cargo and passenger transportation, the occurrence of accidents involving employees and passengers or even the spillage of flammable cargo, which contaminate soil and water resources. In Algeria, Kouidri (2018) described the impacts of ravines formed after civil works on roads, which included erosion in the fields and the consequent abandonment of production in the area, an increase in the cost of maintaining roads and railways, and impacts on bridges, dikes and water pipes.

The use of gullies and ravines areas after the development process is only possible once the area has recovered. In countries such as Poland, there are geotourism initiatives inside old ravines, but even after stabilization, intensive use can reactivate erosive processes (Zgłobicki *et al.* 2015b).

Despite being cited in several studies, the socioeconomic impacts of Gullies and ravines are not usually detailed. Perhaps this lack of detail influences the focus of the works on typology, spatial evolution of erosion, efficiency of containment processes, among others. However, including a brief description of their impacts, mainly financial ones, can be an important step to demonstrate the losses caused by ravines and gullies and, in this way, demonstrate to society why it is so important to take measures to prevent and contain linear erosions.

Socioeconomic impacts occur in three different areas of the hydrographic basin (Table 4). The first of these is damage caused to the place where erosion occurs, which can mean from a permanent loss of an area that previously could be used for economic activities or a partial or temporary loss, depending on the recovery measures that are established. Among the damages caused are also economic losses in productivity, the destruction of infrastructures and homes, losses of production or animals, the loss of water sources and drying of wells, an increase in production costs and reduction in productivity, and an expansion of the risk of flooding, among others. The second is the downstream impact on the basin, such as an increase in the cost of water treatment and silting up of reservoirs, among others. Finally, upstream impacts may include, for example, the drying of wells or the loss of access routes (Figure 3).

Table 4: Main economic impacts identified in the literature, classified as follows: impact (0) does not occur; (1) may occur but is not common; (2) occurs but is not predominant; and (3) is predominant.

Impact	Land-use type		Location in the basin		
	Rural	Urban	Upstream	Erosion area	Downstream
Reduced agriculture and livestock productivity	3	2	3	3	1
Increased workload in productive activities in the affected areas	3	2	2	3	1
Silting of reservoirs	3	3	0	0	3
Increased risk and impacts of floods	2	3	0	0	3
Damage to infrastructure and homes	2	3	0	3	1
Increase in the cost of maintaining drains and channels	1	3	0	3	2
Increase in the cost of road maintenance	3	3	1	3	2
Loss of access to water	1	2	2	0	0
Loss of areas with economic and social use	3	3	1	3	1
Changes in the use of the area	3	3	1	3	1
Change in access to areas	2	2	1	3	1
Abandonment of farmland	2	1	1	3	1
Home abandonment	2	3	1	3	1
Loss of access to land	2	2	1	3	1
Use of reclaimed areas for geotourism	1	1	0	1	0
Development of new economic activities in reclaimed areas	2	2	1	1	1
Expansion of agricultural land in areas of silted dams	2	0	0	0	1
Loss with land tax collection	1	3	1	3	1

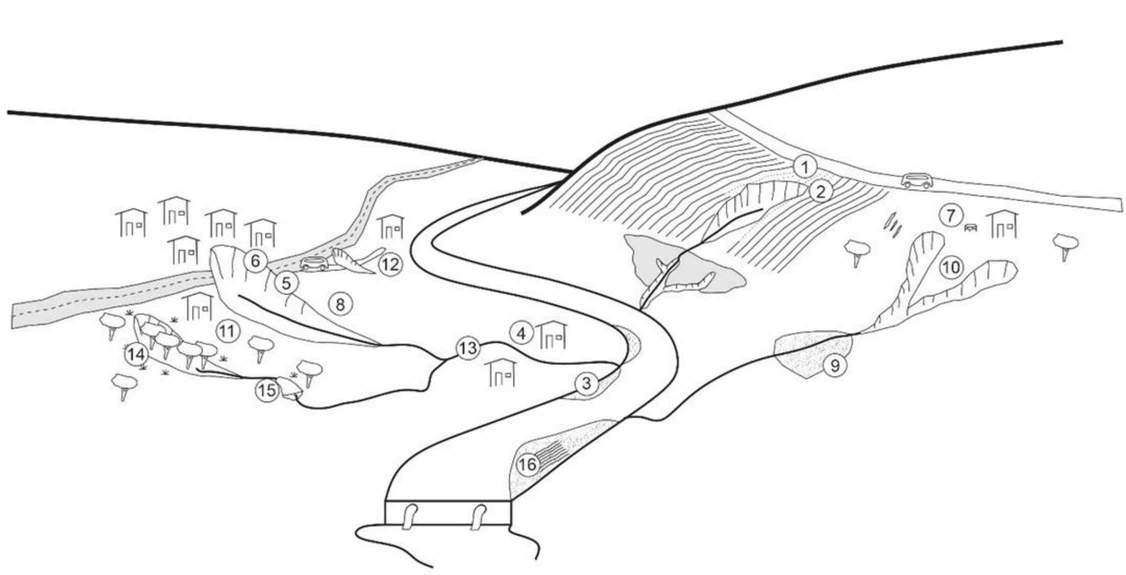


Figure 3. Schematic spatial distribution of the socioeconomic impacts of ravines and gullies in the hydrographic basin. 1 – reduced productivity; 2 – increased workload; 3 – silting of reservoirs; 4 - increased risk and impacts of floods; 5 – damage to infrastructure and homes; 6 – increase in the cost of road maintenance; 7 – loss of access to water; 8 – loss of areas with economic and social use; 9 - changes in the use of the area; 10 – abandonment of farmland; 11 – home abandonment; 12 – loss of access to land; 13 – increase in the cost of maintaining drains and channels; 14 – use of reclaimed areas for geotourism; 15 – development of new economic activities in reclaimed areas (e.g., fishing); 16 – expansion of agricultural land in areas of sited dams.

4.2. Impacts on ecosystem services

In the literature, impacts on ecosystem services are mentioned, such as loss of nutrients from surface layers, reduction in soil productivity, drainage of aquifers, changes in river drainage patterns, loss of soil, loss of moisture and soil cover, increases in surface runoff, increases in adverse events, reductions in aquifer recharge, reductions in carbon sequestration capacity and soil organic matter, changes in the biodiversity of plants and animals, reductions in soil moisture and vegetation cover, increases in floods, contamination of soils and surface and groundwater, wetland dryness, changes in sediment load and impacts on life in rivers, lakes and seas (Balzerek *et al.* 2003; Abdo *et al.* 2013; Rowntree 2014; Rust and Star 2018; Somasundaram *et al.* 2018; Romero-Díaz *et al.* 2019; Paredes *et al.* 2020).

The effects of ravines and gullies impact several fundamental ecosystem services, for example, a) provisioning services: production of food, fibers, fuel and water; b) regulation: climate, natural risks, soil erosion, water cycle and biodiversity and health; and c) support: protection of genetic reservoirs, nutrient cycling and soil formation (Romero-Díaz *et al.* 2019).

In cases such as in the Peak District (United Kingdom), peat erosion can release lead-contaminated sediment (Rothwell *et al.* 2010). According to Shuttleworth *et al.* (2015), truffles are an important carbon stock but can also assimilate heavy metals; thus, truffle erosion in the UK contributes to carbon and pollutant storage. If these systems are affected by erosion, their functions will be modified.

According to Valentin *et al.* (2005), gullies tend to increase drainage and increase the speed of the aridification process in semiarid areas. Morokong and Blignaut (2019) noted among the impacts caused by ravines the compromise of ecosystem water services, in addition to the reduction of carbon sequestration.

Somasundaram *et al.* (2018) considered ravines to be an extreme form of soil degradation and mentioned that in India, this kind of erosion process occupies an area of approximately 10.37 million hectares. For the authors, these areas, if restored, could contribute to carbon sequestration through the adoption of restoration practices such as leveling land, planting perennial trees and sowing legume strips, all of which aim to improve soil quality.

Didoné *et al.* (2014) indicated that erosion problems include changes in the amount of sediment in the water, the loss of fertility, loss of useful area, reduction of water storage in the soil, and remobilization of nutrients and pesticides to water courses, which can increase the cost of water treatment for society.

The impacts on ecosystem services also occur in three different positions in the hydrographic basin (Table 5). Where erosion has developed, loss of soil and removal of the most fertile horizons, loss of vegetation cover, changes in the landscape, reduction of soil biomass, reduction of carbon sequestration, drying of wetlands and reduction of biodiversity have occurred. Downstream from erosion, contamination of watercourses, silting and changes in river drainage patterns can occur, increasing the sediment load, which can impact biodiversity in rivers and coastal regions. Upstream, aquifer drainage can occur (Figure 4).

Table 5: Main ecosystem impacts, where they occur in the hydrographic basin and to what extent they occur. Impact (0) does not occur; (1) may occur but is not common; (2) occurs but is not predominant; (3) is predominant.

	Location in the basin			Extent of impact		
Impact	Upstream	Erosion area	Downstream	Permanent loss	Partial when area is reclaimed	Benefits after recovery
Loss of soil nutrients	1	3	1	x		
Aquifer drawdown	3	3	0	x		
Changes in the drainage pattern	0	3	2	x		
Increased runoff	0	3	3		X	
Soil erosion	1	3	1	x		
Reduction of organic material in the soil	1	3	1		X	
Impact on fauna and flora biodiversity	1	3	2	x		
Reduction of vegetation cover	1	3	1			x
Reduction of soil moisture	1	3	1		X	
Dryness of wet areas	0	2	2	x		
Increased sedimentary load	0	1	3			x
Impact on the life of lakes, rivers and seas	0	1	3		X	
Water contamination	0	2	2		X	

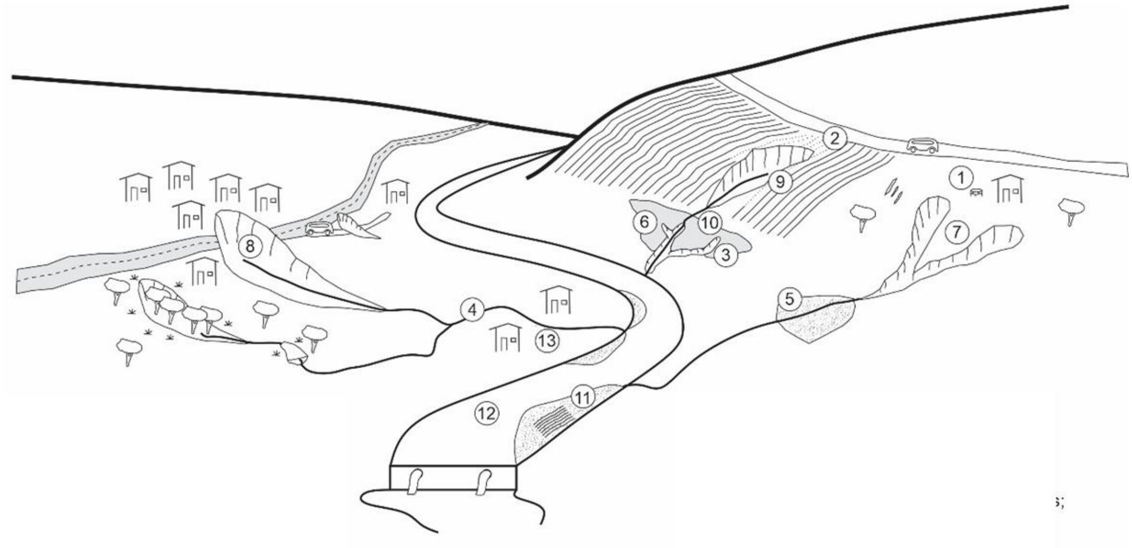


Figure 4. Schematic spatial distribution of impacts caused by linear erosion on ecosystem services in the watershed. 1 – aquifer drawdown; 2 – loss of soil nutrients; 3 - changes in the drainage pattern; 4 – increased runoff; 5 – reduction of organic material in the soil; 6 – impact on biodiversity fauna and flora; 7 – Reduction of vegetation cover; 8 – soil erosion; 9 – reduction of soil moisture; 10 - drying of wet areas; 11 – increases in sedimentary load; 12 – impact on the life of lakes, rivers and seas; 13 – contamination of water.

4.3. Impact valuation

Few studies have evaluated the impacts caused by ravines and gullies; those that have include Yitbarek *et al.* (2012), Ayele *et al.* (2015) and Rust and Star (2018).

Yitbarek *et al.* (2012) developed a technique for valuing the financial impacts caused by ravines related mainly to soil components. The authors analyzed the cost of 4 erosion events in Ethiopia by analyzing yield loss, the cost–benefit of soil rehabilitation, rehabilitation and personnel costs and the monetization of soil nutrients, based on the price of fertilizers. For the rehabilitation of ravines, structural measures were used, such as loose stones, gabion boxes and other structures of control dams, to reduce the speed of the water and vegetative measures, with the instruction of trees and grasses in the affected area. The soil loss estimate was performed according to dimensions such as mouth width, depth, width of the erosion bed, and length of the ravine. The cost of erosion was obtained based on the loss of income in the area, adjusted by the interest rate of the Central Bank of Ethiopia. Rehabilitation expenses considered from the initial surveys to the final maintenance costs, that is, all expenses with labor, materials, training, equipment in the stages of rehabilitation or maintenance. The cost of nutrient loss considered the conversion of the percentage of lost values of nitrogen (N), phosphorus (P) and potassium (K) and the level of organic carbon (OC) and the replacement cost based on the values of the fertilizers. To calculate the loss of productivity in the area, the period of time since the ravine was formed and the reduction in the cultivated area due to erosion were considered. Werken Gashajagrie, Werken Adura, Eshim Wofena and Tsegur Eyesus, the areas directly affected by each of the ravines in hectares were 2.60, 1.87, 1.51 and 0.95, respectively. For the four erosion events, the damage caused was US$ 4,896, the rehabilitation cost was US$ 24,480 and the replacement of nutrients was US$ 28,320. According to the calculation developed by the authors, the cost of rehabilitation tends to be greater than the future gains from recovery, which makes it difficult for poor farmers to implement these actions.

For Yitbarek *et al.* (2012), if the study had accounted for the monetary value of wood production, grass fodder, carbon sequestration and sedimentation in bodies of water, the benefits of recovery would probably outweigh the costs.

Other authors, such as Ayele *et al.* (2015), also accounted for the cost of erosion in Ethiopia's highlands by counting the loss of soil nutrients (N and P) and the cost of missed opportunities; the value of the daily wage was used to account for the loss of opportunities related to increased travel time due to road interruptions and the value of animal deaths and tree replacements. In the hydrographic basin studied, the cost over two years was US$18,000, which corresponds to US$22 per ha per year, or a value of US$17 per person per year, which represents 19% of the per capita income. According to the authors, although the estimated costs are high compared to family income, they may still be underestimated because the nutrient replacement cost may not reflect the total replacement value. In addition, the estimated values did not consider costs such as the silting of reservoirs, reduction in hydroelectric power generation, impacts on irrigation, and the reduction of water quality, among other types of ecosystem services.

Due to the increase in sediment load in Fitzroy, Australia, and the subsequent changes in the Great Barrier Reef, Rust and Star (2018) carried out a study to analyze the cost of remediation of six gullies, considering measures to decrease stocking rates in pasture, increase revegetation and increase infrastructure construction to contain erosion and earthworks. The calculation of the cost of remediation was carried out by the authors considering the cost of construction, the cost of annual maintenance and the opportunity cost requested, considering a period of 10 years and a discount of 7% per year, in addition to the exclusion of cattle from the site for a period of 18 months. Among the six properties analyzed, the value to prevent erosion of one cubic meter of soil ranged between US$ 78.43 and US$ 604.96 m^3 per year, and the general average was US$ 127.42 per m^3 per year of sediment.

Rust and Star (2018) considered that the study presented a view on the complexity related to the cost of gully remediation measures, as the specific characteristics of each erosion event impact the final cost of recovery. Hence, the construction of policies becomes more difficult.

The works analyzed above in this topic were all carried out in rural regions. The case of changes caused by the increase in sediment load on Australia's reefs is a clear example of impacts outside the area directly affected by erosion. To analyze the socioeconomic impacts and ecosystem services impacts, the three different areas of the hydrographic basin must be considered.

The greater the erosion and/or the longer it takes for measures to contain erosion, the greater the impacts. The estimates proposed by Bartley (2020) of the reduction in sediment load downstream of erosion in a period between 19 and 28 years after the adoption of recovery measures indicate that linear erosion is a problem that requires planning and analysis that consider the results in the medium and long term. The review carried out by Romero-Díaz et al. (2019) indicated that after adopting recovery measures, the positive results increase over the following years.

Considering the economic and environmental impacts described in the previous items, there are complex cases in cities such as the city of Kinshasa in Congo, where in the literature, there is a report of destruction of dozens of houses due to the evolution of only one erosion area (Ozer 2014; Imwangana *et al.* 2015), demonstrating that in urban areas, the costs can be higher. The case of the Comodoro Rivera in Argentina is another example of significant damage in urban areas (Paredes *et al.* 2020). The waterproofing of areas, which changes the natural dynamics of rainwater runoff, the construction of linear structures and the exposure of the soil can favor the rapid development of large erosions. However, none of the analyzed studies assessed socioeconomic impacts or ecosystem services in urban areas.

An analysis of the impacts of erosion must consider the temporal and spatial dimensions of the damage caused, including the direct economic losses at the erosion site, downstream and upstream; the value of the containment or recovery measures; the partial or permanent losses of the productive area, according to the period in which the erosion developed; and the cost of maintaining any containment measures, in addition to accounting for impacts on ecosystem services along the hydrographic basin (Table 6).

Table 6: Impacts and measures for the recovery and containment of the affected area and variables and units that can be used to calculate the total cost.

Socioeconomic impacts	**How to calculate**	**Variable**
Reduced productivity in the affected area	Comparison between previous productivity and the productivity of the area after having been affected	Accumulated losses with time
Increased workload with measures related to erosion	Cost of working hour	Accumulated losses with time
Well drying	Unit cost	Accumulated losses with time
Loss of access to areas	Travel cost and resulting losses	Sum of cost plus per year
Destruction or damage to infrastructure and homes	Infrastructure cost	Accumulated losses over time. For example, monthly rental cost
Loss of area for social and economic use	Area cost	Area productivity
Increased production cost	Added cost	Sum of cost plus per year
Reduced access to water	Cost of measures to re-establish access to water	Maintenance costs or other monthly or annual costs
Increased time spent on moving people, animals and machinery	Work hour cost	Sum of cost plus per year
Loss of crops and animals	Cost of annual crop loss	Sum of cost plus per year
Increased cost of maintenance of transport routes;	Cost of recovery measures	Sum of cost plus per year
Abandonment of urban or rural properties;	Cost of properties and improvements	Accumulated losses with time
Loss of access to water;	Cost of measures to re-establish access to water	Maintenance costs or other monthly or annual costs
Dam silting and loss of functionality;	Cost of measures to reduce the impacts of silting or dam cost	Accumulated losses with time
Increased cost of water treatment;	Difference between the cost of treatment before and after erosion	Sum of cost plus per year

Increased risk and impacts of floods	Difference between costs related to previous and subsequent floods	Accumulated losses with time
Changes in the use of the area	Value per m² prior minus the value per m² after recovery	Difference in values and time estimation
Loss of land tax collection	Calculated by considering the average of the amounts charged for land taxes in the region.	The loss calculation needs to consider the value of the annual fee and the number of years that the area has been affected
Impacts on ecosystem services	**How to calculate**	**Variable**
Lowered aquifer water table	Reduced aquifer volume in cubic meters.	Cost of aquifer recovery (when possible)
Nutrient loss	Amount of nutrients. Replacement cost.	Accumulated losses with time
Soil loss	Volume in cubic meters or tons.	Replacement cost of accumulated losses over time
Wetlands dryness	Environmental changes	Valuation of ecosystem services or analysis with a willing-to-pay method
Reduced carbon sequestration capacity	Amount of nutrients.	Replacement cost of accumulated losses over time
Plant and animal biodiversity impacts	Loss of biodiversity	Valuation of ecosystem services or analysis with a willing-to-pay method
Increased sediment input and water turbidity	Difference in water quality	Valuation of ecosystem services or analysis with a willing-to-pay method
River siltation	Sediment volume	Cost of recovery measures, cost of impact
Drainage pattern changes	Environmental changes	Valuation of ecosystem services or analysis with a willing-to-pay method
Organic soil material reduction	Environmental changes	Valuation of ecosystem services or analysis with a willing-to-pay method
Increased runoff	Damage caused by the new flow dynamics	Accumulated losses with time
Vegetation cover reduction	Environmental changes	Valuation of ecosystem services or analysis with a willing-to-pay method
Water contamination	Changes in water quality	Cost of recovery measures, cost of impact
Cost of recovery or containment measures	**how to calculate**	**Variable**
Measures to control surface runoff and increase soil water retention,	Cost of measurements	Monitoring and maintenance cost
Revegetation,	Cost of measurements	Monitoring and maintenance cost
Construction of energy sinks and water storage basins	Cost of measurements	Monitoring and maintenance cost

Construction of structural measures;	Cost of measurements	Monitoring and maintenance cost
Development of revegetative measures;	Cost of measurements	Monitoring and maintenance cost
Erosion grounding;	Cost of measurements	total cost
Terracing and planing areas;	Cost of measurements	Monitoring and maintenance cost
Maintenance of built structures;	Cost of measurements	Monitoring and maintenance cost
Replenishment of nutrients in the soil	Cost of measurements	follow-up cost
Construction of sediment retention dams;	Cost of measurements	Monitoring and maintenance cost
Desilting of water courses.	Cost of measurements	follow-up cost
Cost of other recovery or containment measures adopted	Cost of measurements	Monitoring and maintenance cost
Qualification actions for public agents and farmers	Cost of shares	Sum of cost plus per year
Education actions in affected communities	Cost of shares	Sum of cost plus per year

Three possible future evolution scenarios may be considered: a) total recovery, that is, where through recovery measures, the affected area can recover all environmental, social and economic functions; b) stabilization, in this case, the recovery measures stabilize the erosion; however, some of the socioeconomic or environmental functions are not recovered or are partially recovered; and c) natural evolution, where no recovery measures are taken, and in this way, erosion continues to grow until is stabilizes naturally.

The calculation of the impact of erosion depends on the variables measured in the affected area. In all cases, the damage caused and/or recovery measures will be carried out in different locations in the watershed area. Some variables will always be linked to the time the impact, damage or cost persisted, such as, for example, the stoppage of economic activities, loss of cultivated areas, and cost of annual maintenance. Other variables, however, generate direct damage that may persist until the item is replaced or rebuilt, such as animal death and infrastructure destruction. Additional variables are linked to local socioeconomic changes, such as increased workloads due to erosion containment and route changes to address road interdiction. Ecosystem services can be monetized by analyses such as replacement cost, as performed by Yitbarek *et al.* (2012), or by other methodologies that allow stipulating the value related to each variable already used for monetization of impacts such as the Contingent Valuation Method (CVM), Willingness to Pay (WTP) and Net Present Value (NPV) (Getzner *et al.* 2017, Maghsood *et al.* 2019, Moos *et al.* 2019), which have been used by the authors to value forests, manage floods under climate change and reduce risks based on the ecosystem provided by the forest. The final calculation of the impacts of erosion will be the result of the sum of the total variables and expenditures made at the site considering the time, the recovery measures, the impacts on ecosystem services and socioeconomic impacts.

5. Conclusions

The analysis and valuation of the impacts of ravines and gullies is an important step in quantifying their actual social, economic and environmental dimensions. This review summarizes and evaluates the different dimensions of their impacts and the costs and achievements of their associated recovery measures. The impact assessment should consider the spatial and temporal dimensions of the impacts, such as damage caused, recovery time and the cost of the measures taken downstream, at the erosion site and upstream.

With worldwide demographic growth, a growing demand for food, and a greater concern about human impacts on the environment, the control of linear erosion and the recovery of affected areas has become a fundamental measure to optimize the use of natural resources.

The recovery of affected areas means introducing, or reintroducing, valuable portions of land into the economic and social scenario and making it possible to maximize the available ecosystem resources. Erosion recovery and control play an important role in preventing environmental, social and economic damage, especially in cities where there is a large population concentration. In rural areas, impacts can make economic activity on properties unfeasible.

The recovery of affected areas and the containment of evolving ravines and gullies should be considered in addition to the individual benefits to the landowner, as the impacts affect the entire watershed and can modify the way the site can be used for decades or centuries.

An analysis of erosion evolution and impacts must consider the appropriate scales and limitations of each method. The list of impacts listed in this work and the different forms of analysis for each variable allow valuations to be carried out anywhere on the planet. However, for the analysis to be accurate, it is necessary to identify which variables are applicable in the area under study and what information is available to support the valuation process.

The lack of basic sanitation infrastructures in cities, the use of inadequate agricultural techniques, the lack of response capacity, the delay in the response to control small erosions, and the existence of roads, especially unpaved, unplanned and incorrectly executed engineering ones, contribute to the rapid evolution of erosions in developing countries.

The best measure for areas susceptible to the formation of gullies and ravines is the correct planning of territorial occupation and the rapid recovery of any small erosion that appears. However, for other areas where erosion has become a problem in recent decades, understanding the environmental and economic impacts is important to know how to prioritize the application of financial resources in the recovery and containment of linear erosion.

Declaration

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Author Contributions

Kuhn CES and Reis FAGV contributed to the study conception and design. Material preparation, data collection and analysis were performed by Kuhn CES. The first draft of the manuscript was written by Kuhn CES and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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APPENDIX A.2. MANUSCRIPT: The record and trends of natural disasters caused by gullies in Brazil

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ABSTRACT

Ravines and gullies are advanced stages of linear erosion that occur in many countries, causing economic, social, and environmental impacts. This research aims at analyzing the official record of disasters caused by ravines and gullies in Brazil, with a focus on analyzing the economic impacts. The Brazilian Civil Defense Integrated Information System (S2ID) database was applied in the analysis, combined with a bibliographic review made in the Scopus database. The results obtained from the civil defense database show a growing trend in the number of disasters related to ravines and gullies in the last decade (2011-2020), with 76 cases recorded between January 2013 and May 2019. From these 76 cases, 24 of them were further analyzed to provide information about the socioeconomic impacts. In total, an estimated loss of US$54 million was recorded in the considered period. The greatest economic impacts were related to damage to public infrastructure, such as sanitary and sewage water system, buildings and, especially, residential areas in urban perimeters. The spatial distribution of disasters related to linear erosion in Brazil suggests a connection between the development of ravines and gullies and the agricultural frontier of the country, especially in the North and Midwest regions, including the biomes of Cerrado (Brazilian Savanna) and Amazon Rainforest, where the greatest changes in land use occurred between the end of the 20th and the beginning of the 21st century. Although the S2ID is an important data base for analyzing the impacts caused by ravines and gullies, the results suggest that the system's records do not account for medium and long-term impacts.

Key words: erosion; valuation, civil defense, amazon, Brazilian savanna.

1. INTRODUCTION

Soil erosion represents a great hazard to agricultural and residential areas, causing relevant socioeconomic and environmental impacts, especially in the Global South (Dagar 2018; Kuhn et al 2023). Ravines and gullies are the most recurrent types of soil erosion and are characterized by steep incisions in soils, forming unstable channels that range from a few to many meters in depth and up to hundreds of meters in extension during its final stages, when erosion naturally stabilizes establishing the new balance profile (Dagar 2018; Kuhn et al 2023).

The development of ravines and gullies is generally the result of several different factors, which may include heavy rainfall, topography (e.g., slope, critical drainage area, shape of the catchment), geology and the geotechnical conditions of the soil (e.g., porosity and permeability, compaction, slope instability, hydrological condition) (Akgün and Türk 2011; Castillo and Gómez 2016; Amorim 2017; Dagar 2018; Pereira Filho et al 2018; Kuhn et al 2023). Anthropogenic activities constitute another important element in ravine and gully development, especially related to deforestation, forest fires, overgrazing, mining, intensified agriculture, and urbanization, which all can cause enhanced runoff (Busnelli et al. 2006; Akgün and Türk 2011; Ozer 2014; Castillo and Gómez 2016; Amorim 2017; Dagar 2018; Golosov et al. 2018; Guerra et al. 2018; Xu et al. 2019; Kuhn and Reis 2021).

Ravines and gullies are mainly a result of poor territorial planning, and lack of governance (Ozer 2014). Territorial space is an increasingly scarce resource, so the implications related to land degradation are serious (Pani 2016). Ravines and gullies can damage agricultural land, infrastructure, and urban areas, also leading to increased injustice and finally social segregation (Kayembe and Wolff 2015; Arabameri et al. 2019). Moreover, ravines and gullies are one of the most efficient processes in sediment mobilization (Gayen et al. 2019), contributing to the silting up of rivers and dams if the sediment load is higher than the transport capacity of watercourses.

According to the Brazilian federal classification, the negative impacts of ravines and gullies are considered as a type of natural disaster (Brasil 2012a) and the economic impacts caused by ravines and gullies are recorded worldwide (Kuhn et al 2023). The destruction of houses, bridges, and other types of infrastructure, as well as fatalities, are some of the results of linear erosion in countries such as Nigeria (Balzerek et al. 2003) and the Democratic Republic of Congo (Ozer 2014; Imwangana et al. 2015). In Australia, Abdo et al. (2013) describe the loss of agricultural areas due to erosion caused by ravines, similarly to what is observed in in India (Pani 2017), for instance. In Algeria and India, erosion is reported to severely impact these countries’ infrastructure, damaging, and destroying roads, dikes, bridges, water lines, increasing the costs for road and railway maintenance (Pani 2017; Kouidri 2018).

In Brazil, gullies and ravines are a historical problem in several regions, especially in those that experienced different colonization cycles (Bezerra et al. 2009). During the gold cycle in the Minas Gerais state, starting at the end of the 17th century, rural roads linked to gold mining contributed to the development of gullies and ravines due to the concentrated surface runoff of rainwater (Ferreira et al. 2011). On the western plateau of the São Paulo state, coffee farmers occupation in the 1920s, known as the coffee cycle, is also closely linked to the development of ravines and gullies caused by deforestation and intensified agriculture (Bezerra et al. 2009). More recent occupational territory cycles encouraged by the Federal Government in the 1950s, especially in the central and northern areas of the country, are connected to the increasing challenges related to ravines and gullies (De Lima and Guerra 2019).

The increase in the frequency of heavy rain events, consequences of climate change, will likely contribute to worsening erosion, with more intense droughts that can weaken soil structure and favor instabilities (Valentin et al. 2005; Cabral et al 2022). Projections of climate change in Brazil indicate an increase in temperatures across all regions and more frequent intense rain events in the South and Southeast, as well as more droughts in the Amazon and in the Northeastern region (Marengo et al. 2021; Pereira Filho et al 2018; Lopez et al 2023).

Knowledge of the economic impacts of ravines and gullies is an important prerequisite to develop actions and public policies aiming at land degradation mitigation. Although this is a problem affecting many regions in Brazil, few studies have been carried out quantifying the impacts caused by ravines and gullies (De Brito Galvão et al. 2011; Rotta and Zuquette 2014; Souza et al. 2017; Guerra et al. al. 2018) and no previous study exists on a national level. Thus, this study aims at providing an overview of the official record of natural disasters caused by ravines and gullies, in Brazil, with a focus on analyzing economic impacts, by evaluating the S2ID database and complementing it with other databases and a literature review. Based on these results, recommendations are drafted on how to improve the long-term record of ravines and gullies in Brazil, which is fundamental for the prevention and mitigation of future disasters.

2. METHODS

The study was conducted in three stages: (1) collection and analysis of civil defense data available in the S2ID system, (2) bibliographic search in the Scopus database, and (3) data integration and discussion based on the scope of the research.

Even though records of natural disasters caused by ravines and gullies in Brazil are available since 2003, we analyzed in greater detail the information between January 2013 (implementation of the S2ID, available in: https://s2id.mi.gov.br/) and May 2019 (date on which data acquisition was performed). This time interval was chosen due to a more systematic record of disasters in the S2ID database, covering two levels of detail (Figure 1):

a) Occurrence record: location (city and state and basic information), date, type of disaster and estimated number of people affected.

b) Complete record: general information on impacts, damages and actions taken.

The latter (b) can be extracted in documents attached to the S2ID, namely the Municipal Declaration of Emergency Action (DMATE) and the Disaster Information Form (FIDE). In FIDE, in addition to basic information, data related to municipal finances are recorded, as well as description of the affected area, causes and effects of the disaster, human, material or environmental damage, and public and private economic losses. The DMATE includes the history of the disaster, information about the municipal disaster management, mobilization, and use of material and financial resources. This information is usually accompanied by technical and photographic reports on the affected area. Usually, the occurrence record occurs when the disaster is restricted to a single municipality, while the complete record occurs when the magnitude of a disaster is higher, when there is a need for resources from institutions at a state or federal level.

For all events identified, additional data from the National Department for Civil Defense and Protection (SEDEC) was requested, mainly the economic impacts caused, using the Citizen Information Service (SIC, available at: https://www.gov.br/economia/pt-br/acesso-a-informacao/servico-informacao-cidadao-sic). Financial losses reported in Brazilian currency (Reais – BRL) were converted into United States Dollars (exchange rate: R$ 3.20 U$ 1 representing an average between R$ 2 and R$ 3.9 over the period between January 2013 and May 2019).

The bibliometric analysis was performed considering the results acquired in the Scopus database. Scopus provided the largest diversity of publications on the subject, according to our analysis. The following keywords were chosen: "ravines or gully" and “Brazil”, limited to the subarea "earth" or "environment". The survey was conducted in English. Research in Portuguese were considered in those cases that had an abstract in English. Documents not indexed in the Scopus database, such as theses and dissertations, technical reports, or non-indexed articles were not considered. Single events such as in Bauru in 1993 (Almeida Filho 2000; Salomão 1994) and other historical cases outside the time period were not considered due to the lack of precise records.

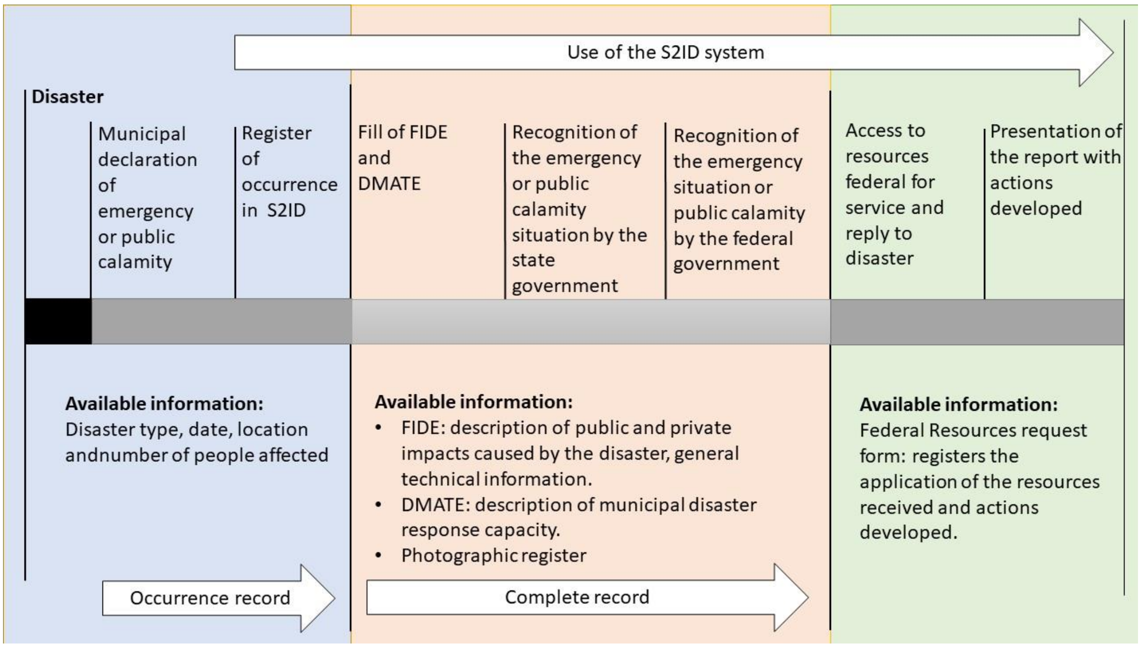
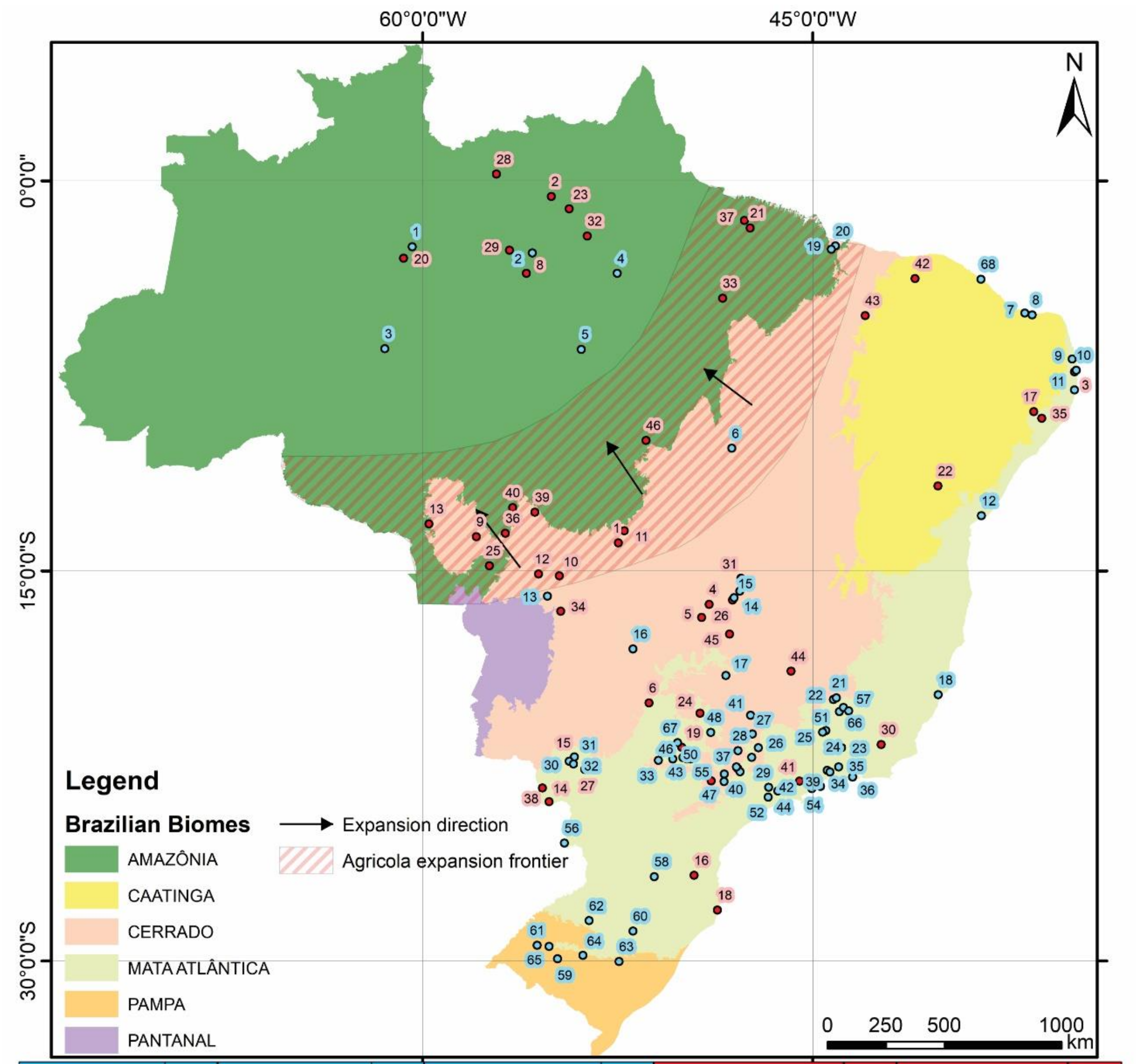


Figure 1: Timeline of the disaster record in the S2ID system, and the type of information available at each stage.

3. RESULTS AND DISCUSSION

3.1 Data overview

The data extracted from the S2ID system and the information available in the Scopus database allowed the identification of municipalities with records of impacts related to ravines and gullies (Figure 2). The S2ID database indicated the occurrence of ravines and gullies in 46 municipalities, while the bibliographic analysis indicated their occurrence in 68 municipalities, with a single municipality (Deodápolis) appearing in both analyses (Table 1). Therefore, 113 municipalities have recorded significant impacts related to ravines and gullies.



County	Code	County	Code	County	Code	County	Code	County	Code
Manaus	1	Conceição Da Barra	24	Pardinho	47	Água Boa	1	Nova Granada	24
Santarém	2	Nazareno	25	Pindorama	48	Alenquer	2	Nova Olímpia	25
Manicoré	3	Casa Branca	26	Piracicaba	49	Alhandra	3	Novo Gama	26
Brasil Novo	4	Cajuru	27	Bacia Rio do Peixe	50	Anápolis	4	Novo Horizonte do Sul	27
Altamira	5	São Carlos	28	Bacia do Rio Maracujá	51	Aparecida de Goiânia	5	Oriximiná	28
Palmas	6	Leme	29	São Paulo	52	Aparecida do Taboado	6	Parintins	29
Porto Do Mangue	7	Fátima Do Sul	30	São Pedro	53	Avaré	7	Pirapetinga	30
Macau	8	Deodápolis	31	Ubatuba	54	Aveiro	8	Planaltina	31
Rio Tinto	9	Glória de Dourados	32	Vera Cruz	55	Campo Novo do Parecis	9	Prainha	32
Conde	10	Rancharia	33	Foz Do Iguaçu	56	Campo Verde	10	Rondon do Pará	33
Recife	11	Paraty	34	Ouro Preto	57	Canarana	11	Rondonópolis	34
Salvador	12	Pinheiral	35	Caçador	58	Chapada dos Guimarães	12	Santana do Mundaú	35
Jaciara	13	Rio De Janeiro	36	Cacequi	59	Comodoro	13	São José do Rio Claro	36
Brasilia	14	Aguas de São Pedro	37	Guaporé	60	Coronel Sapucaia	14	São Miguel do Guamá	37
Gama	15	Arapei	38	Manoel Viana	61	Deodápolis	15	Sete Quedas	38
Bacia de Queixada	16	Bananal	39	Pejuçara	62	Doutor Pedrinho	16	Sorriso	39
Uberlândia	17	Botucatu	40	Rio Pardo	63	Garanhuns	17	Tapurah	40
Aracruz	18	Franca	41	Santa Maria	64	Garopaba	18	Taubaté	41
São Luis	19	Franco Da Rocha	42	São Francisco De Assis	65	Getulina	19	Tianguá	42
Paço do Lumiar	20	Garça	43	Itabirito	66	Iranduba	20	Timon	43
Contagem	21	Itaquaquecetuba	44	Alegre	67	Irituia	21	Tiros	44
Betim	22	Jacareí	45	Fortaleza	68	Mairi	22	Urutaí	45
Lima duarte	23	Marilia	46			Monte Alegre	23	Vila Rica	46

Figure 2. Distribution of the municipalities and regions; in red, municipalities where cases have been reported by the civil defense database and in blue the location of the studies analyzed in the literature review (Scopus); biomes (IBGE 2019) are indicated in colors and the arrows indicate the frontier of agricultural expansion in Brazil.

Table 1: limitations and contributions of each source of information used in this study.

Source of information		**Limitations**	**Contributions**
S2ID data base	Occurrence record	- Presents little information about the disaster.	- Allows identifying places where there are relevant cases of ravines and gullies.
	Complete registration	- Information about impacts was no longer updated after completion or state or federal recognition. - information on medium and long-term impacts is not recorded.	- Allows identifying places where there are relevant cases of ravines and identifying the impacts caused up to the date of filling out the forms. - Photographic record. - In general, records are accompanied by technical analyses, carried out by engineers or geologists.
Literature review		- Absence of studies that have previously evaluated impacts.	- Allows identifying places where there are relevant cases of ravines and gullies. - Analyzes typology case studies, containing techniques and other important information to discuss the data obtained in the S2ID. - Provides an overview of the impact of ravines and gullies in Brazil.

3.1.1. S2ID database

A total of 76 cases were registered in the 46 municipalities in the S2ID database. Of this total, 52 contain only “occurrence records”, in which solely the typology of the process is classified and an estimate of the number of people affected is presented. For the other 24 cases, full information was available, which documents describing the impacts caused by the disaster and the inclusion of documents such as the DMATE and FIDE. None of the documents had information about the measures taken after the federal recognition of the disaster.

A total of 296,324 people were affected between 2013 and 2019 and 75% of the recorded events (57) are concentrated in five states: Mato Grosso - MT (19 cases); Pará - PA (16 cases); Goiás - GO (11 cases), Mato Grosso do Sul - MS (9 cases) and Amazonas - AM (7 cases). From 2010 to 2019, a growing trend in the number of annual records of natural disasters caused by ravines and gullies was observed, peaking in the last year with a complete dataset (2018) (Figure 3).

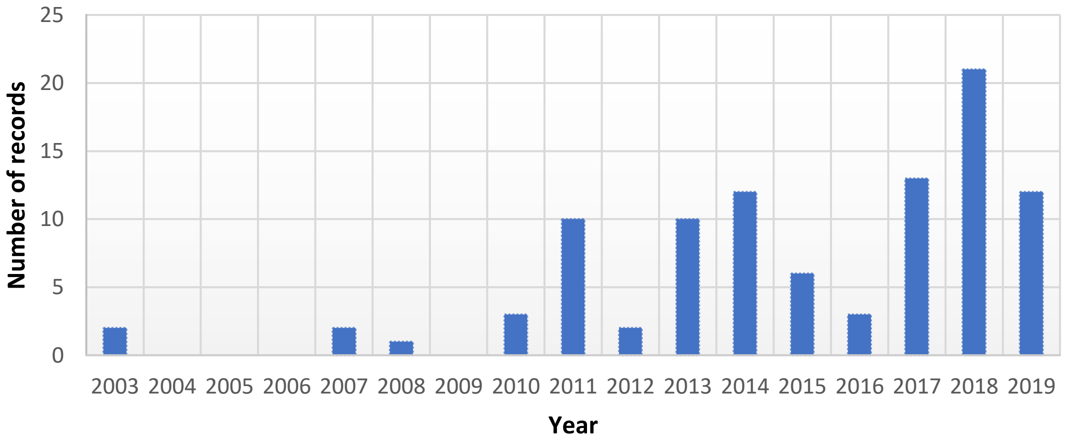


Figure 3. Number of disasters caused by ravines and gullies per year, based on civil defense data obtained in May 2019.

The municipalities with the highest number of records were Oriximiná (PA) with 7, Novo Gama (GO) with 5, Iranduba (AM) with 4, and Canarana (MT), Comororo (MT) and Coronel Sapucaia (MS) with 3 events each. The municipalities with disasters induced by ravines and gullies are among the 50% most populous and/or among the 50% with the best proportion of Gross Domestic Product (GDP) per capita in the country, according to official information from the Brazilian Institute of Geography and Statistics (IBGE, 2020)

3.1.2. Literature review

The Literature review considered 63 publications, which recorded the occurrence of ravines and gullies in 68 municipalities. Published studies are concentrated in the states of São Paulo (SP), Minas Gerais (MG), and Rio Grande do Sul (RS). The municipality of São Pedro was the most studied area 6 publications, followed by São Luis (4), Nazareno (3) and Marília (3). Among the articles available in the literature, none focused on assessing the economic impacts caused by ravines and gullies in Brazil. Other relevant information presented in the articles analyzed was used in the discussion of the work.

3.2 Records of damages in the S2iD database

According to the information available in the Disaster Information Form (FIDE) (Table 2), 20 of 24 cases affected urban areas, one of them a rural site and three of them affected both (Figure 4 and 5). Economic impacts were characterized by: 1) material damage causing a total cost of US$26 million covering public infrastructure, residences, public health facilities, public facilities providing other governmental services, and public infrastructure; 2) economic losses in the public and private sector of approximately US$ 17.9 mi, including damage in the sanitary and rainwater system, drinking water supply, medical care, public health and emergency medical care; 3) public losses of U$ 4.73 mi in local and regional transport systems, public security, disinfestation and disinfection of insects, pest and vector control, schools, electricity generation and distribution; 4) private losses of US$ 3.45 mi in the service sector, livestock and industry; and, finally, 5) costs of ongoing actions of US$ 2.55 mi to be covered by the municipal annual budget and municipal extra-budget sources (Table 3). Ravines and gullies in most cases initiated due to atypical rainfall, lack of drainage infrastructure or insufficient urban planning.

Table 2: Analyzed events in relation to the biomes they are inserted in.

County	State	Year	Biome
Anápolis	GO	2013	Cerrado
Aparecida de Goiânia	GO	2013	Cerrado
Irituia	PA	2013	Amazon
Novo Gama	GO	2013	Cerrado
Comodoro	MT	2014	Amazon
Novo Gama	GO	2014	Cerrado
Novo Gama	GO	2014	Cerrado
Novo Gama	GO	2014	Cerrado
Tiros	MG	2014	Cerrado
Garanhuns	PE	2015	Caatinga / Atlantic Forest
Novo Gama	GO	2015	Cerrado
Aparecida de Goiânia	GO	2017	Cerrado
Avaré	SP	2017	Cerrado / Atlantic Forest
Pirapetinga	MG	2017	Atlantic Forest
Pirapetinga	MG	2017	Atlantic Forest
Rondonópolis	MT	2017	Cerrado

Timon	MA	2017	Cerrado
Deodápolis	MS	2018	Atlantic Forest
Parintins	AM	2018	Amazon
Rondon do Pará	PA	2018	Amazon
Santana do Mundaú	AL	2018	Atlantic Forest
Urutaí	GO	2018	Cerrado
Getulina	SP	2019	Atlantic Forest
Timon	MA	2019	Cerrado

Figure 4. Examples of gullies and ravines in Brazil. A and B: Gully located at Rua 14-E, municipality of Aparecida de Goiânia, state of Goiás (Cardoso 2013); C: Unstable areas with imminent risk of landslide. Santana do Mundaú, state of Alagoas (Da Silva 2018); D: Ravine under development, 3 meters from residences, municipality of Timon, state of Maranhão (De Oliveira Filho and Dos Santos 2014) (Source: S2ID system reports).

Table 3: Costs caused by ravines and gullies according to the records described in FIDE between January 2013 and May 2019.

Sectors affected	**Estimated value in millions of US$**
Material damage	
Public infrastructure	18.1
Housing units	6.53
Public health facilities	0.88
Public facilities providing other services	0.36
Public facilities for community use	0.11
Public teaching facilities	0.04
Public and private infrastructure	
Sanitary sewage and rainwater system	16.48

Urban cleaning and waste collection and disposal system	0.82
Drinking water supply	0.41
Medical care, public health and emergency medical care	0.25
Public services	
Local and regional transport	3.68
Public security	0.35
Disinfestation and disinfection of insects, pest and vector control	0.34
Teaching	0.31
Electricity generation and distribution	0.06
Private business	
Service sector	2.02
Livestock	0.96
Industry	0.47
Emergency services	
Municipal anual budget	1.00
Municipal extra-budget	0.91
Other sources (federal or state)	0.65
Total	54.73

Figure 5. Examples of gullies and ravines in Brazil. A and B: Rural roads affected by erosion in Tiros, Minas Gerais state (Longe 2014); C and D: residence close to erosion and the Cascalheira stream where water is collected for public supply, municipality of Comodoro, state of Mato Grosso (dos Santos 2014) (Source: S2ID system reports).

The municipality of Novo Gama (GO), with five records, was the municipality with the most affected people (Figure 6). The cases with the greatest material damage were Anápolis (GO) (U$ 6.4 mi); Aparecida de Goiânia (GO) (U$ 5.46 mi) and Novo Gama (GO) (U$ 3 mi). The greatest public and private economic losses were recorded in Aparecida de Goiânia (GO) in 2013 (U$ 5.81 mi) and 2017 (U$ 5.46 mi), followed by Timon - MA in 2019 (U$ 2.37 mi). The largest private economic losses were recorded in Comodoro - MT, related to the livestock sector in 2014 (U$ 0.95 mi) and in the municipality of Novo Gama (GO), in the service sector both in 2013 (U$ 0.87 mi) and 2014 (U$ 0.87 mi).

Although the data available by the S2ID database includes different types of impacts, the total sum US$ 54 million (Table 3), is interpreted as an underestimation. The records do not adequately consider post-impact costs, such as declining economic activities, expenses for land recuperation, changes in the type of economic activity, etc. Another existing shortcoming is that the impacts on the ecosystem are not considered. Environmental impacts are mentioned in FIDE as a percentage of contamination or pollution of water, air, and soil, in addition to water reduction or depletion. The reports do not present information on the dimension of environmental impacts in the watershed or even the volume of eroded sediments. Magnitude estimation and a more detailed description of the dimension of the event are important indicators, identifying areas impacted by silting and production losses, thus contributing to the improvement of the economic and environmental impacts records.

The Municipal Declaration of Emergency Action presents information on how the municipality organizes itself in relation to the national policy for civil protection and defense, describing the municipal capacity to deal with adverse events. Out of the 24 cases analyzed, 16 of them occur annually, with only 6 being "first time" records.

Figure 6. Destruction of public structures and residences in the municipality of Novo Gama, state of Goiás (Pimenta 2015). (Source: S2ID system reports).

The magnitude of many events exceeded the capacity of the municipal management to deal with the disaster in most cases (21 of 24) and the losses affected the response capacity of the municipal government in 22 cases. In 13 cases, public and private economic losses were separated, and in 20 cases, economic losses caused by ravines and gullies were mentioned. Most municipalities have municipal committees, or a corresponding body structured to monitor disaster situations, in addition to having the support of state agencies and institutions. In 22 of the 24 cases, municipal maps of geological hazard areas already existed.

In most cases, however, there is no provision for programs and projects for actions aimed at tackling the problem in the Multiannual Plan (PPA), which is the document that guides the application of public resources over a four-year period, or in the Budget Guidelines Law (LOA), which approves the city's annual budget. When a disaster occurs, it is necessary to approve extraordinary resources, either from the municipal budget itself or from the National Fund for Public Disasters, Protection and Civil Defense (PNPDEC), which grants resources to municipalities that have an emergency recognized by the federal government, so that they carry out prevention, mitigation, preparation, response, and recovery measures (Brasil 2010, 2012b).

In Brazil, despite recent advances in the mapping of risk areas in the municipalities of the country by the Geological Service of Brazil, which produced Geological Risk Sectorization maps in 1607 of the 5568 municipalities (CPRM 2021), the incorporation of prevention and mitigation measures has not yet occurred in most of the municipalities analyzed. Complete records of the disasters in the S2ID system can contribute to the analysis of impacts, which is important to convince public managers to develop preventive measures, as well programs that consider the planning and recuperation of areas affected by ravines and gullies. The integration between the technical analysis that is consolidated through maps of risk areas and the evaluation of damage caused by natural disasters can complement each other, demonstrating the potential losses if a disaster occurs and that preventive measure can lessen the socioeconomic impacts.

3.3 Integration of the S2iD database and the results of the literature review: an analysis of the economic impacts of ravines and gullies in Brazil

The cases reported in the S2ID system are mainly related to the urban perimeter. Urbanization results in changes in runoff behavior, due to impermeable surfaces (paving and buildings), and an inadequate urban planning can favor the development of ravines and gullies (De Albuquerque et al. 2020). Only 4 of the 24 the impacts recorded in rural areas amount to U$ 0,96 mi damage and are mainly related to livestock in a single event in the state Mato Grosso (Table 2). De Brito Galvão et al. (2011) mention that in the last decades there has been an increase in the number of studies that pursue to understand the impacts of ravines and gullies on agriculture, land conservation and water dams.

Brazilian studies address the impact of ravines and gullies, but in general, they do not measure economic losses, focusing more on the characterization of the process and the qualification of socio-environmental impacts. The few studies that focus on the economic losses are discussed in the following. Guerra et al. (2018) cited that severe erosion poses risk to people in the state of Maranhão. The economic losses reported in Rotta and Zuquette (2014) are related to unsuccessful land recuperation measures in cities such as São Pedro, Franca, São Carlos, Casa Branca and Cajuru, all of them in São Paulo state. The impacts caused by the development of ravines and gullies in railways are mainly interruptions in cargo and passenger transport (Souza et al. 2017). Few studies address socioeconomic losses on the country's agricultural frontier and are in Mato Grosso and in the northern region, where the highest numbers of disasters caused by ravines and gullies are recorded. Although they are mostly described for urban areas, they are not limited to these but can also occur on agricultural land.

S2ID presents raw data with important information about disasters and the impacts caused throughout the national territory. This database can be an important source of information to indicate potential areas for scientific research, which can study and understand the most significant disasters, seeking to strengthen the protection and civil defense policy in Brazil. In addition, transforming database information into scientific publications is a way of validating existing information.

To reduce underreporting and expand information on existing disasters in the country, the federal government and the civil defense could establish the obligation that public concessionaires, be they highways, gas pipelines, sanitation infrastructure, transmission lines etc..., must report cases of ravines and gullies in the S2ID. This type of action would allow recording small-scale impacts. Another gain that could be achieved with this measure is the identification of areas where problems with ravines and gullies are recurrent, which is essential for public institutions to be able to identify the environmental sensitivity of areas with low population density, such as the agricultural frontier of Brazil.

In some cases, as in the cities of Novo Gama (GO) in 2014 and Pirapetinga (MG) in 2017, the existence of two or more different processes in the same year, may indicate duplication of registration, or register damage caused due to the evolution of the same erosion at different times. To improve the analysis on the recording of natural disasters, it is necessary to add information describing the evolution processes that caused the disaster. In addition, it is necessary that a new event can be linked to the previous one, creating a documentary timeline of the impacts and actions carried out.

The fact that disaster records only exist in municipalities with Gross Domestic Product (GDP) per capita among the 50% largest in the country, and/or in municipalities among the 50% most populous, suggests that smaller and poorer municipalities can experience difficulties carrying out disaster cataloguing. The increase in the number of recorded events after 2012 may represent a growth trend or an improvement in reporting due to changes in the civil defense system and the structuring of public policies related to the disaster database in the country (Kuhn et al. 2022).

The significant number of disasters in the states of Mato Grosso, Mato Grosso do Sul, Pará, Amazonas and Goiás suggests a relationship between the expansion of the agricultural frontier in Brazil and accelerated erosion processes due to changed land use. The formation of ravines and gullies are directly connected to the release of high sedimentary loads, which may contribute to the silting of rivers and changes in water dynamics. The data related to deforestation in Brazil demonstrate that in the Amazon biome between 1988 and 2020 most accumulated deforestation was with 157 667 km² in the state of Pará and with 147 926 km² in the state of Mato Grosso, corresponding to more than 66% of the biome's total deforestation (INPE 2021). In the Cerrado Biome, between 2001 and 2020, 4 878 192 km² were deforested in Mato Grosso, followed by Goiás with 4 586 154 km² (INPE 2021). These changes occurred mainly due to the growth of agricultural and livestock activities.

The S2ID data showed that in 22 of the 24 cases analyzed, the municipalities had maps of risk areas in the municipalities. Although the ravines and gullies are considered a common process in 16 of the

24 cases analyzed. In most municipalities, there are no permanent programs or resources foreseen in government budget instruments for erosion prevention or control. This indicates that although the risk areas are known, most municipalities have not developed measures to prevent and contain ravines and gullies.

In rural areas, the production of erosion susceptibility maps has been simplified due to technological development, especially GIS software. Remote sensing methods combined with artificial intelligence were used in the Brazilian Cerrado (Minas Gerais), for automatic classification of optical images to identify ravines and gullies with high precision (Vrieling et al. 2007). Image analysis through remote sensing thus is an important tool to quantify the size, volume, downstream silted areas and affected infrastructure. Furthermore, the use of drones can provide more quantitative information related to estimates of economic and environmental impacts.

The existing data in the bibliography review indicates that in several places in the world the control of ravines and gullies is part of a regional strategy, with costs that in general exceed the municipal capacity to deal with this process of the physical environment alone. Therefore, the help of regional and national governments is needed for better management and financial support.

In addition to accounting the direct impacts of ravines and gullies, it is necessary to expand the studies to consider the cost of land recuperation and the losses related to halting the economic activity. Romero-Díaz et al. (2019) analyzed 26 documented cost actions to control ravines and gullies and indicate that costs could vary by a factor of 100, e.g., between US $ 100 and US $ 10,000 per hectare. While the annual maintenance costs for 50% of cases are less than US $ 100 per hectare, for the other 50% it can be as high as US $ 1000 per ha. According to De Brito Galvão et al. (2011) traditional methods of movement of large volumes of soil and measures of revegetation works, while drainage infrastructure is more expensive. While bioengineering methods tested by the author such gully revetment with blankets and re-vegetation works and partial grading of the gully and cheaper drainage system works. These large inconsistencies in costs reported demonstrates the need to carry out further research and studies in search of cost-efficient solutions to contain ravines and gullies in diverse climate and geological-geotechnical settings.

4. CONCLUSION

Our analysis suggests a growing trend in the number of disasters related to ravines and gullies in Brazil. The data suggest a correlation between the higher concentration of cases of disasters caused by ravines and gullies, and the growth of cities and changes in land use, especially in the Biomes Cerrado and Amazonia, where significant deforestation has been recorded in recent decades, according to INPE (2021).

The cases analyzed show that costs of erosion impacts are probably underestimated, because the long-term effects are not accounted for in the methodology used by the civil defense authority. Ravines and gullies gradually evolve over time scales of many decades, and this must be considered in the S2ID record. The relatively small number of publications on ravines and gullies in the states of the Midwest and Northern regions of Brazil, combined with the high number of disasters recorded in these two regions, indicates a major gap between research interest in universities and current development trends ravines and gullies. The S2ID data are registered by the civil defense, in general, municipal, therefore, all municipalities in Brazil, if they have active civil defense, can carry out the registration. On the other hand, academic articles are prepared by research groups, which are generally linked to universities. The main Brazilian universities are in the south and southeast regions, the proximity to the research areas, may have been one of the factors that favored the concentration of case studies in these regions.

The impacts caused by erosion were recurrent in several municipalities, with a better report in those with higher GDP and/or with higher population. Underreporting is common especially in small municipalities and in rural areas. Thus, the poorest and least populated municipalities are affected most and financial and technical support from the state and federal government is required, and long-term territorial planning must be improved.

Land use guidelines for territorial management and erosion susceptibility maps may help to prevent ravines and gullies Municipal preventive action programs are needed to control erosion in early stages and to reduce resources for mitigation and control of gullies and ravines.

Although the economic loss associated with disasters related to gullies and ravines is probably underestimated in Brazil because available civil defense and the disaster databases lack information on long-term effects. The analysis carried out in our study allows us to suggest improvements in record keeping and in economical assessment of the impacts caused by ravines and gullies in Brazil, as summarized in Table 4. The measures suggested mainly target on strategies to reduce the underreporting of events, how to expand information of the damage and the measures that could be adopted in land recuperation of affected areas (Table 4).

Table 4: Summary of the challenges identified and suggestions that could be taken to improve the record of the impacts caused by ravines and gullies.

Responsible	**Challenge**	**How to improve**
Civil defense and university	Events studied at universities and disasters recorded in S2ID in recent decades are concentrated in different regions	Encourage the use of the S2ID database for research development in the universities.
	Uncertainties about the quantification of impacts	Establish methodological paths for recording and analyzing impacts, through the use of remote sensing.
Civil defense and engineering and agribusiness companies	Underreporting in rural areas	Motivate concessionaires of highways, railways, transmission lines, sanitation, among others to register ravines and gullies if they are affected.
Civil defense and federal, state and municipal public management.	Disaster hot spots in the agricultural frontier region of the Cerrado and Amazon biom	Develop erosion susceptibility maps in agricultural frontier areas. Development of information campaigns on the impacts and damage caused by erosion.
Civil Defense and municipal public management	Little use of risk maps and susceptibility maps	Conduct campaigns on the cost of disasters for the municipality.
	Deficient planning of land use.	Carry out the planning considering the susceptibility to erosion and develop risk maps. Guide public and private officials on conditions favoring erosion.
	Lack of resources in ongoing programs to combat erosion.	Train city hall employees on procedures for obtaining state and federal resources for the prevention and mitigation of natural disasters.
Civil Defense and S2ID System	High costs of containment infrastructure	Include cost information in S2ID for containment and maintenance of infrastructures for control and restoration of areas affected by erosion.
	Insufficient environmental impact records	Establish mandatory description of environmental impactsof erosion such as area and volume of eroded soil, silted area, loss of ecosystem services, etc...

	Lack of medium and long-term records of impacts caused by ravines and gullies in S2ID	In the case of disasters of gradual development, as is the case of ravines and gullies, establish the need to update data on the impacts and dimensions of erosion annually.
	Too many records without filling FIDE and DMATE	Establish the obligation to fill in the FIDE and DMATE even for cases of occurrence registration.

Declaration

The authors inform that they have no conflicts of interest.

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Author Contributions

Kuhn CES and Reis FAGV contributed to the study conception and design. Material preparation, data collection and analysis were performed by Kuhn CES. The first draft of the manuscript was written by Kuhn CES and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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APPENDIX A.3. MANUSCRIPT: Economic impacts of an urban gully are driven by land degradation

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Abstract

This study carries out the first evaluation of the impacts of ravines and gullies in urban areas in Brazil considering environmental damage, such as costs related to land restoration and erosion control, infrastructure destruction, economic losses and income losses related to property and urban land taxes. In this study, the city of Bauru, Brazil, has been selected as study site, where three areas were chosen due to the large impact that ravines and gullies have caused over the past two decades. Our analysis indicates that the total damage exceeds US$ 173 million and is mainly related to land degradation. The cost of replacing the eroded soil in these three areas is estimated at approximately US$ 13.3 million. Furthermore, according to our analysis, urban areas affected by ravines and gullies represent problems similar to brownfields. The assessment of the impacts and challenges associated with urban ravines and gullies can help promote accountability by those responsible for their initiation and may contribute to decreasing the development of new eroded areas.

Keywords: valuation, brownfields, city management, impacts

1. Introduction

Ravines and gullies are advanced forms of soil erosion, whose evolution can be divided into three stages: 1) surface water runoff concentration or groundwater contribution through liquefaction; 2) V-shaped linear channel development; and 3) stabilization of the downcut after reaching the water table, development of the channel and U-shape resulting from the joint action of surface and underground runoff leading to a morphological and hydropedological imbalance, which can branch out into several channels (Carvalho Junior et al. 2010, Abdo et al. 2013).

Human influence is usually the main trigger, while factors such as soil type, relief and hydrogeological properties determine the susceptibility to erosion and the consequent magnitude and speed of the process (Castillo and Gómez 2016). The development of gullies and ravines following agricultural land use change is well documented in many tropical developing countries (Mirghaed et al. 2018). However, a literature review indicated that only 3.1% of the studies address ravines in urban areas, while 13.2% address ravines in forest areas and just over 40% address ravines in pasture and plantation areas (Castillo and Gómez 2016).

Although scarcely studied, ravines and gullies impact cities worldwide. Balzerek et al. (2003) report the destruction of residences, streets and bridges in Nigeria. Hundreds of ravines in Kinshasa, Democratic Republic of the Congo, caused the destruction of housing and urban infrastructure (Ozer 2014, Imwangana et al. 2015, Landu et al. 2023, Mawe et al. 2024). In Tanzania, in the city of Babati, Strömquist (1992) reported the destruction of urban infrastructure by gullies. In Argentina, in the city Comodoro, more than 400 houses were destroyed or damaged, in addition to various urban infrastructures, as a result of ravines or gullies (Paredes et al. 2020).

Although the risk of disasters in cities cannot be totally eliminated, it can be reduced (Lall and Deichmann 2012). Market price analyses, which allow the estimation of the economic cost of impacts, can contribute to creating incentives or mechanisms for transferring the risk of losses, combined with economic policy and urban management, make it possible to develop an assertive response (Logar and Van Den Bergh 2013).

The low number of fatalities related to ravine and gully normally does not make international headlines (Balzerek et al. 2003). Likewise, studies estimating the cost of ravines and gullies are rare. However, Yitbarek et al. (2012) performed a cost–benefit analysis of ravine and gully rehabilitation on farmland in Ethiopia. In the same country, Ayele et al. (2015) quantified the cost of erosion, considering topsoil nutrient losses, time costs due to disrupted travel networks, and the value of lost animals and trees. Additionally, in the Fitzroy region of Australia, Rust and Star (2018) discussed strategies to reduce the amount of sediment export from ravines and gullies, considering the costs of the measures applied.

In Brazil, the impacts of ravines and gullies in urban areas have been studied by several authors. Guerra et al. (2018) analysed a case of ravines in the city of São Luís in the state of Maranhão. Rotta and Zuquette (2014) developed methodologies to study erosion based on the municipalities of São Pedro, Franca, São Carlos and Casa Branca in the state of São Paulo and in the municipality of Fortaleza in the state of Ceará. Gullies have caused economic impacts in dozens of municipalities, especially in the Cerrado (Brazilian Savanna) and Amazon Rainforest biomes, related to changes in land use (Kuhn et al. 2023). One of the Brazilian cities with the highest number of cases of erosion is Bauru, in the state of São Paulo, where Almeida Filho (2000) described more than 25 gullies or ravines in the late 1990s, which represented a loss of almost 2 million m³ of sediment. However, in none of these cases, an assessment of the impacts was carried out, leaving open the question: What are the economic impacts caused by a ravine or gully?

Considering the replacement price of different items, this work aims to estimate the economic impacts of ravines and gullies in the municipality of Bauru, Brazil. For this purpose, Google Earth timelapse, as well as previous studies conducted in the municipality and field campaigns conducted herein, were applied to reconstruct the history of the three regions analysed in this study.

1.1. Study area

Founded in 1896, the emergence of the city of Bauru (Figure 1) was due to the establishment of coffee plantation areas in the second half of the 19th century. The construction of the railroad in the early 20th century gave the city a privileged position related to logistics (Alves 2009), which boosted population growth. The appearance of ravines and gullies worsened in the second half of the 20th century with the creation of subdivisions without considering geotechnical criteria (Da Silva and Barbieri 2004, Ide et al. 2009). The sandy lateritic soils, which are slightly cohesive and permeable with depths of more than 13 m, in a region where wide hills predominate and which annually experiences tropical rains that exceed 100 mm daily, combined with land occupation without proper planning, created a scenario that favoured the development of ravines and gullies that can exceed 1500 m in length (Salomão 1994, Almeida Filho 2000, Da Silva et al. 2004, Rocha and Giacheti 2018). Ravines and gullies cause several impacts in the municipality, including loss of land and property values and silting of rivers and consequent flooding (Santos 2008).

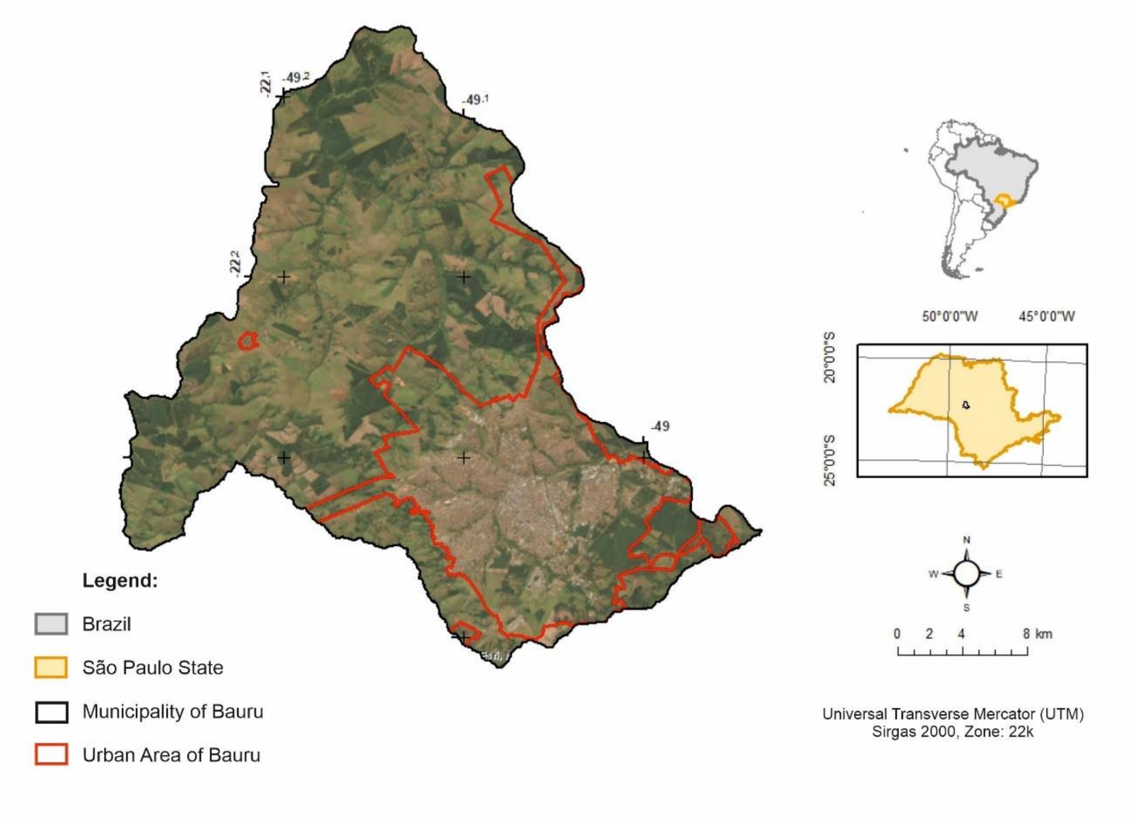

Figure 1. Location map of the municipality of Bauru.

2. Materials and Methods

The work was carried out in two main stages: a) analysis of the evolution and impacts of ravines and gullies and b) assessment of impacts (Figure 2).

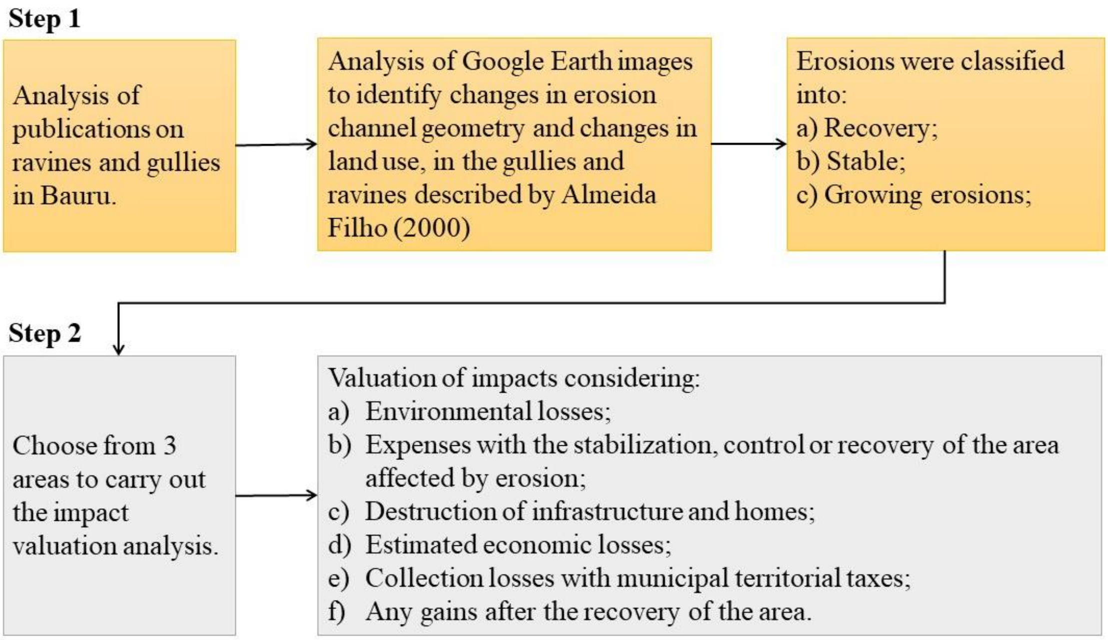

Figure 2. Summary of the methodological approach adopted in this study.

2.1 Analysis of the evolutions and impacts of ravines and gullies

Theses, dissertations, scientific, peer-reviewed articles, technical reports and other publications were used in the identification of erosional events and estimation of their impacts in Bauru. The work by Almeida Filho (2000) was considered the most complete and was used as a basis for obtaining descriptions of ravines and gullies. Then, Google Earth images taken between 2004 and 2021 were analysed to a) identify changes in the geometry of the channel, b) remeasure the basin for containment or restoration of the area, c) monitor the change in land use and land cover and d) determine the environmental impacts to the region. In addition to the information obtained from the analysis of the images, two field studies were carried out, in December 2020 and in March 2022 to analyse the areas.

The ravines and gullies analysed were classified as follows: a) recovered: the erosion scar area was restored through recovery measures and the social and economic use was resumed; b) stable: erosion was stabilized due to measures aimed at recovering the area, but without fully restoring the use of the area; c) in development: ongoing, gradual increase in the size of the eroded area over time.

The watershed limits of the areas chosen for the case studies were extracted using tools available in ArcGis, using Shuttle Radar Topography Mission (SRTM) images available on the Topodata portal of the National Institute for Space Research of Brazil (INPE).

2.2 Impact valuation

To identify the impacts of urban ravines and gullies, the classification proposed by Kuhn et al. (2023) was employed. Impacts were classified into a) environmental, considering the cost of replacing soil, nutrients, carbon and pasture; b) costs for recovery and mitigation of erosion in the watershed area; c) destruction of infrastructure, impacts on streets, storm sewers, dams, residences, among others; d) estimated economic losses, which were calculated considering the surface area directly affected by the channels in ravines and gullies, the annual loss of gross domestic product (GDP) per square metre in the affected area in allotments; e) loss of collection of the Property and Urban Land Tax (IPTU); and f) positive impacts after the recovery of areas affected by ravines and gullies.

The analysis time of the estimated economic impacts and tax collection losses was limited to between 2000 and 2021 based on the information sources described in Section 2.1. The cost of the environmental impacts, public infrastructure destruction, and erosion containment and recovery associated with urban gullies and ravines were estimated by considering identified infrastructure close to erosions and descriptions of the channels affected by erosions, that is, all impacts that could be identified from the onset of erosion to the date of the current analysis.

The valuation of the impacts was carried out considering the replacement cost, which is the amount currently paid for the affected items and products (Lillo et al. 2014). The values obtained allow identifying the magnitude of the impacts.

Because current replacement cost values and impact dimensioning were used, inflationary updates were not performed, as it is understood that these values are already considered in the current cost. To convert the value from Brazilian real to U.S. dollar, the reference value of 5.30 reais to 1 U.S. dollar (as of November 14, 2022) was used.

2.2.1. Environmental impacts

For soil-related environmental costs, such as loss of vegetation, information from the Anuário da Pecuária Brasileira [Brazilian Livestock Yearbook] (Anualpec 2022) was used. The previous standard vegetation was considered pasture and semi-intensive. According to the yearbook, pasture is worth US$ 756.68/ha.

The loss of nutrients—nitrogen (N), phosphorus (P) and potassium (K)—and of organic carbon (OC) in the soil caused by ravines and gullies were monetized considering the replacement cost, as previously done by Yitbarek et al. (2012). For the analysis of replacement of soil nutrients (NPK), data from Radam Brasil (Brasil 2018) were considered for up to 1 m of soil depth, according to analyses carried out on the Pederneiras-Bauru Road. A reference value of 1.4 t/m³ of soil was adopted. The total value of nutrient loss per square metre (Table 1) was calculated according to the market price of the fertilizer sector statistical yearbook (Anda 2022) for 2021.

For the analysis of the carbon stock, data from Sobral et al. (2014), who reported that the carbon stock in the region ranges from 49.2 to 221.0 Mg ha^{-1}, with 96.5 Mg ha^{-1} of C being stored in undisturbed vegetation types; thus 9.65 kg/m² was adopted as a reference value for the region. According to the Power BI platform (2022), the average price paid for carbon stocks is $32.37 per ton (22/10/2022). Thus, the value of 9.65 kg/m² proposed by Sobral et al. (2014) represents a corresponding stock of $0.31 of carbon per square metre.

Table 1. Amount of nutrients per square metre and replacement cost.

Nutrient	Amount to be replaced, in kg/m³, in the soil up to 1 m deep	Concentration used for replacement	Required quantity of product	Cost per kg of product used for replacement (US$)	Cost of nutrient loss per kg/m³ (US$)
P_2O_5 fertilizer	0.22 kg/m^3	20%	1.2 kg/m³	0.35	0.42
Potassium chloride	0.26 kg/m^3	53%	0.501 kg/m³	0.59	0.30
Nitrogen (Urea)	0.32 kg/m^3	45%	0.711 kg/m³	0.63	0.45
Total					1.16

Source: Fertilizer sector statistical yearbook (Anda 2022).

2.2.2. Erosion recovery and containment and public infrastructure destruction

To estimate the costs of containment works and recovery of the affected areas and destruction of homes and infrastructure, the National Research System of Civil Construction Costs and Indices (SINAPI), the System of Reference Costs of Works (SICRO) and Civil Construction Union (Sinduscon) were used for cost analysis of engineering works in Brazil (Sinapi 2021, Sicro 2021, Sinduscon 2021) according to the compositions elaborated in Table 2:

2.2.3. Estimated economic impacts

To estimate the economic losses caused by the impacts of urban ravines and gullies, an analysis of the GDP per square metre was also carried out, according to official information available from the Brazilian Institute of Geography and Statistics (IBGE 2019, 2022). The value of the municipal GDP is US$ 2,891,432,319, divided by an area of 667,684,000 m², which represents a GDP/m² of US$ 4.33 per year. Estimates of economic impacts were carried out considering a time interval of 20 years between 2000 and 2020.

The loss of useful area of urban space was calculated by the average of the existing values in Municipal Law No. 7,510/2,021 (Bauru 2021), which corresponds to US$ 72.88/m². The costs of the affected area were calculated based on the market price available on online sales sites. The following average values were used: a) US$ 72.57 per square metre for unused lots on paved streets; b) US$ 36.28 per square metre for unused lots on unpaved streets.

2.2.4. Urban Property and Land Tax (IPTU)

Municipal losses or gains from tax collection were calculated using the information available in Municipal Law No. 7,510/2,021. The calculation considered the following equation as the Urban Land Tax (IPTU) value: 1% of the value resulting from the multiplication of the average land value per square metre (US$ 72.88) by the size of the affected area and the number of years that erosion has affected the site (Bauru

2021, 2022). Estimates related to gains or losses in IPTU collection performed considering a maximum time interval of 20 years. The calculation was carried out considering the lots indicated in the Google Earth images or estimates made based on the existing streets in the area; that is, areas used for streets, sidewalks, green areas and other infrastructure were not considered.

Table 2. Compositions used to calculate impacts, according to data from SINAPI (2021), SICRO (2021) and SINDUSCON (2021).

Composition	Item	Form of valuation	Unit	Unit value (US$)
1	Excavation of an area for the construction of a contour line or a containment basin or dam or weir	Cost of machinery for excavation 1 m³/m². Reference codes in SINAPI (2021) used for valuation 100973, 100574 and 96386.	m³/m²	4.02
2	Replacement of eroded soil	Value for removal, transport and reallocation of soil on site, considering an estimated transport distance of 10 km. Reference codes in SINAPI (2021) used for valuation 100973, 100574 and 96386. 10x95877 and 00006079 (I)	m³	19.81
3	Destruction or unfeasibility of a paved street with an urban structure	It is estimated that the cost of a kilometre of highway today is in the range of 1.5 to 2.5 million, including the support structures. Estimated value according to average construction cost.	m	377.36
4	Destruction or unfeasibility of paved, unpaved, or unstructured street	Cost of machinery for opening the street. Estimated value according to average construction cost.	m	188.68
5	Destruction of rainwater pipes	Construction cost. Reference codes in SINAPI and SICRO used for valuation 102279, 0804037 (SICRO) and 93367.	m	149.26
6	Hydraulic ladder construction	Construction cost. Reference codes in SINAPI used for valuation 100973, 100574, 96386 and 91070	m	28.92
7	Implementation of a drainage system in streets parallel to the gully with corrugated steel pipes, with one of the lines being 0.80 m or 1.20 m, with a collection system through manholes	Excavation, sand cradle, installation, backfill and drainage pipe compaction. Reference codes in SINAPI used for valuation 102279, 804029, 93367.	m	122.64
8	Mixed underground drain built with hollow tube and upstream. Approximately 600 m of plumbing. The plumbing system is 5 m away. Erosion has been buried in these pathways.	Excavation, sand cradle, installation, backfill and drainage pipe compaction. Reference codes in SINAPI used for valuation 102280, 804037, 93372.	m	157.61
9	Popular housing	Cost per square metre of popular housing according to the SIDUSCON table is R$ 1278.90 m². For calculation purposes, an average area of 50 m² for houses was considered.	house	12,065.09

Source: National System for Surveying Civil Construction Costs and Indices (SINAPI 2021) System of Reference Costs for Works (SICRO 2021) and Civil Construction Union (SINDUSCON 2021).

2.2.5. Data presentation

The data obtained in the analysis are presented in spreadsheets, considering the values obtained in the impact analysis considering the number of units and the total value of the impact. For impacts that are continuous, such as Urban Property and Land Tax (IPTU) and estimated economic impacts, the value over 20 years was considered.

3. Results and discussion

3.1. History of erosion processes in Bauru

Several studies, such as Salomão (1994), Almeida Filho (2000), Da Silva and Barbieri (2004); Corghi (2008), Santos (2008), Ide et al. (2009) and Thomazini and da Cunha (2012) have been carried out to understand the evolution of erosion in the municipality of Bauru.

Salomão (1994) carried out an analysis of aerial photographs from 1972 and identified a total of 516 ravines and 409 gullies in the region, most of which formed in drainage headwaters after deforestation due to changes in hydrological conditions related to increased surface runoff. Some were also formed due to the impacts of deepening and widening of river channels.

The most impressive case recorded in the municipality occurred between November 1992 and April 1993. The month of February 1993 was atypical, with the monthly rainfall exceeding 450 mm, approximately 250 mm above the usual amount. The gully formed was 800 m long, with an average width of 26 m, a maximum width over 50 m and a depth ranging from 15.5 to 28 m, removing a volume of approximately 360,000 m³ of sediment (Almeida Filho 2000). According to Santos (2008), there was one death related to the development of the gully.

Almeida Filho (2000) described in detail the 25 areas affected by ravines and gullies in the late 1990s (Table 3). The survey of erosion evolution in the municipality of Bauru between 2004 and 2021 identified 7 features in the recovered class, 7 in the stable class and 11 in the in-development class. In some regions, such as Quinta da Bela Olinda, although the main gully has not shown reactivations in the last 20 years, new large-scale erosion has appeared, increasing the impact on the basin.

In the municipality of Bauru, ravines and gullies caused the following impacts: silting of watercourses and reservoirs (Figure 3 A); destruction or clogging of the storm sewer network (Figure 3 B); soil loss, destruction and breakdowns in the water and sewer system; expansion of floods; dispersion of pollutants; isolation of housing or neighbourhoods; social and economic damage caused by flooding; increase in the cost of maintaining streets, canals and sewers; environmental changes caused by siltation (Figure 3 C and D); depreciation of real estate value; discouragement of new investments; decrease in water potential; loss of agricultural areas; increased cost of production and increased cost of water treatment (Almeida Filho 2000, Da Silva and Barbieri 2004, Thomazini and Da Cunha 2012). Another type of impact cited is decreased urban mobility (Cunha 2020). For Santos (2008), among the problems triggered by erosion is the fragmentation of the city and the creation of urban voids.

Bauru is located in the Western Plateau of São Paulo, located within the Tiete watershed. The Bauru and Ribeirão do Campo Novo River subbasins are composed of wide hills. The Ribeirão da Água Parada area is composed of 85% wide hills and 15% medium hills. In the Batalha River subbasin, 66% of the area are wide hills, 9% are medium hills, 8% are elongated hills and spires and 7% are slopes furrowed by subparallel valleys (Almeida Filho 2000). According to Salomão (1994), the local relief favours the concentration of rainwater.

In addition to the relief in Bauru being composed of wide hills, and the thick, loose and sandy soils favour soil erosion. According to Salomão (1994), the changes in water conductivity and porosity between different soil horizons and between different soil types, added to ruptures in the topography, favour the development of the piping phenomenon. This occurs because in the higher positions of the slope, the more developed soil facilitates water infiltration, while in the lower positions, in addition to the natural tendency of the water table to be closer to the surface, the less developed soil contains more clay and the few, generally non-communicating macropores increase pressure and percolation forces (Salomão 1994).

Figure 3. A) Erosion process at the valley bottom, where the lowering of the channel upstream and the silting and drying of wetlands downstream occur; B) ravine at Quinta da Bela Olinda, developed due to problems in stormwater sewers; C) silted-up area in the region of Quinta da Bela Olinda; D) soil profile, indicating lowering of the channel and drying of wetlands.

Some erosions have affected large areas in the urban perimeter since the 1970s, as is the case for erosions located in the Jardim Grama region, which have been reactivated more than three times over the last 50 years, mainly related to years with atypical rainfall events or due to changes in land use in the watershed in areas close to the erosion process. Another problem is that the adopted structural measures are often inefficient or may lose efficiency due to the advancement of erosion or to the lack of periodic maintenance (Figure 4 A and B). The solutions adopted are, in general, palliative and do not resolve the causative factors, with inefficient measures that prioritize the channel of the formed feature, without considering the processes within the watershed as a whole.

Table 3. Current situation of erosions described by Almeida Filho (2000).

Erosions recovered between 2000 and 2021

Erosion name	Year	Classification	Length (m)	Average depth (m)	Average width (m)	Volume (m³)
Jardim América paulista	1995	Gully	600	13	30	234000
Jardim Ouro Verde	1999	Gully	200	3	4	2400
São Geraldo	1997	Gully	800	7	20	112000
Distrito Industrial	1993	Gully	500	4	18	36000
Conj. Habitacional 16	2000	Ravine	500	5	15	37500
Jardim das Orquídeas	1998	Gully	150	5	16	12000
Vila São Paulo	1995	Gully	400	6	30	72000

Erosions that showed significant changes between 2000 and 2021

Erosion name	Year	Classification	Length	Average depth	Average width	Volume
Vila Ipiranga	2000	Gully	450	4	25	45000
	2021	Gully	390	6	60	140400
Jardim Grama - Fepasa	2000	Gully	240	5	15	14400
Jardim Grama - IBC	1999	Gully	600	8	36	172800
Jardim Grama (Fepasa and IBC)	2021	Gully	1.271	6	29	221154
Cohab 16 – Eucaliptos	1995	Gully	200	5	15	15000
	2021	Gully	250	5	15	18750
Parque Bauru	1993	Gully	800	15	30	360000
	2000	Gully	150	4	20	12000
	2021	Gully	300	5	11	16500
Conj. Habitacional 2000	2000	Gully	150	6	40	22500
	2022	Gully	291	6	25	43650
Núcleo Popular	2000	Ravine	70	6	4	1680
	2021	Gully	500	5	15	37500
Cohab 16 - Fepasa	1995	Gully	120	6	10	7200

	2021	Gully	480	6	9	25920
Stable erosions between 2000 and 2021						
Erosion name	Year	Classification	Length	Average depth	Average width	Volume
Jardim da Grama – Tapeçaria Chic	2000-2021	Gully	120	5	15	9000
Santa Edwirges	1998-2021	Gully	230	6	25	34500
Jardim Vânia Maria	1995-2021	Gully	300	4	14	16800
Parque União	2000-2021	Gully	200	6	20	24000
CESP	1999-2021	Gully	1000	10	50	500000
Pousada da Esperança II	2000-2021	Gully	300	5	15	22500
Pousada da esperança I	2000-2021	Gully	200	5	15	15000
Otávio Rasi	2000-2021	Gully	570	6	10	34200
Horto Florestal-Codasp	2000-2021	Gully	300	6	10	18000
Clube do Recreio da Prefeitura	2000-2021	Ravine	150	5	30	22500
Conj. Habitacional I	2000-2021	Gully	150	5	20	15000
Jardim Guilherme	2000-2021	Gully	1000	10	25	250000
Quinta da Bela Olinda	1999-2021	Gully	500	5	16	40000

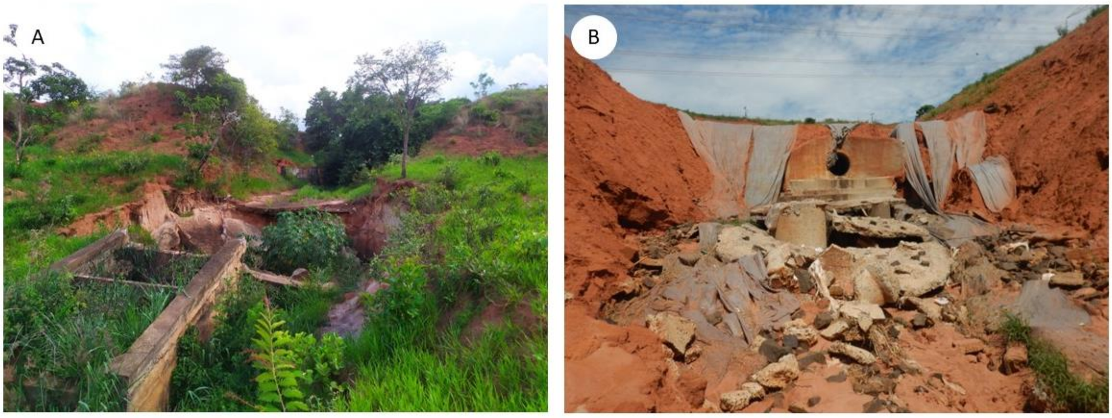

Figure 4. Erosion containment structures damaged by lack of maintenance or sizing errors: a) Jardim Grama; and b) Quinta da Bela Olinda.

Analyses of the evolution of land use and occupation between 2004 and 2021 also illustrate the dispute for urban space. The urban voids caused by ravines and gullies in development were the result of occupation by low-income communities in search of sites to build homes. Conversely, other areas, such as the erosion of Jardim América, were fully recovered, returning to the conventional social and economic use, because of its good location in the urban perimeter and appreciation of the area, which enabled the construction of a high-end condominium.

Although Brazilian law currently prohibits it, Almeida Filho (2000), Da Silva and Barbieri (2004), Corghi (2008) and Ide et al. (2009) cite the use of areas affected by erosion, such as ravine and gully channels for the disposal of urban waste and even hospital waste, as is the case of Vila Garcia, Pousada da Esperança II, Jardim Paulista, Jardim Colonial, Vila Jussara, Vila Santista, Cohab 16 and Quinta da Bela Olinda. In places such as Parque Bauru (Figure 5 A) and in the gully of Vila Ipiranga (Figure 5 B), garbage disposal, including of construction and organic waste, was observed during the field stage. These residues can contaminate the channel with leachate and pollute the environment through the release of gases, transforming these areas into areas of disease outbreaks and creating other types of problems related to soil and water contamination. According to Santos (2008), the use of technogenic materials, without performing technical analyses, aims at reducing costs for companies and may increase environmental impacts due to contamination of the soil and aquifers.

Some erosions have been fully or partially recovered. In the CESP gully, part of the area was recovered for the construction of an avenue. The erosion of the industrial district was recovered for the construction of industrial warehouses. In Jardim Ouro Verde, the erosion area was recovered for the construction of a soccer field. In Jardim América, the area was transformed into a high-end condominium.

In Núcleo Mary Dota, an allotment built over a buried gully, several houses have cracks, demonstrating the technical difficulty of recovering the affected areas (Santos 2008). The problems can be aggravated because in some cases, companies do not follow the technical suggestions for works in areas affected by ravines and gullies. In some cases, there are changes in the drainage regime and migration of watercourses (Santos 2008).

Figure 5. a) Use of the area affected by erosion for urban waste disposal (pruning, organic and construction waste); b) waste disposal in the gully channel in Vila Ipiranga.

The lack of an official technical record in areas affected by erosion made it difficult to build a detailed history of actions taken to analyse the related costs and technical solutions adopted.

3.2. Valuation of impacts

Three areas were selected to assess the economic and environmental impacts (Table 3). The areas were chosen for the following reasons: i) Quinta da Bela Olinda, an area where there are ravines and stable and developing pits; ii) Jardim América, as it represents a place where social and economic use has been fully recovered; iii) Parque Bauru, w one of the erosions that is partially recovered.

3.2.1. Quinta da Bela Olinda

The area of Quinta da Bela Olinda is located in the urban expansion zone. In this location, 5 linear erosions were identified (Table 4 and Figure 6), four of which (1, 2, 3 and 4) remained stable between 2004 and 2021, but in this period, ravine number 5 appeared due to problems in a rainwater pipeline. Despite attempts to stabilize the process, erosion has been growing at an accelerated rate (Figure 7 A and B). The largest gully in the area is stable, with vegetation in the channel and its surroundings and the development of a water source inside it (Figure 7 C). Other erosions, although stable, predominate the pasture, with few trees (Figure 7 D).

Despite several attempts to stabilize ravine 5 (Figure 6) by carrying out engineering works in the channel, including the implementation of barriers at contour lines, placement of rainwater drainage pipes and construction of gabion walls, erosion advanced in an accelerated manner after November 2017, causing a risk to homes and infrastructure located upstream. The works implemented thus far have proven to be palliative and ineffective in containing the advance of erosion.

Da Silva et al. (2004) note that the development of gullies made unfeasible a housing complex that already had a water distribution structure, sewage collection network, and asphalt and rainwater drainage system ready. According to the authors, part of this structure was destroyed. In the analysis of aerial images, it is possible to identify elements of the affected urban infrastructure, such as isolated and abandoned paved streets due to the development of erosion processes.

Table 4. Existing erosions in the Quinta da Bela Olinda area.

Erosion name	Year	Classification	Length (m)	Average depth (m)	Average width (m)	Volume (m³)
Quinta da Bela Olinda 1	1999-2021	Gully	500	5	16	40,000
Quinta da Bela Olinda 2	1999-2021	Ravine	80	4	8	2,560
Quinta da Bela Olinda 3	2004-2021	Ravine	66	5	15	4,950
Quinta da Bela Olinda 4	2004-2021	Ravine	60	5	10	3,000
Quinta da Bela Olinda 5	2021	Ravine	180	7	25	31,500

Table 5. Estimate of the impacts of erosion identified in the Quinta da Bela Olinda area.

Type	Impact description	Number of units	Unit	Unit cost (US$)	Amount (US$)	Value in 20 years (US$)
Environmental, per replacement cost	Loss of carbon stock in the area of 14405 m² (Erosion 1, 2, 3, 4 and 5)	14,730	kg	0.31	4566.30	4530.17
	Loss of nutrients in the soil (NPK) in the area of 14405 m² (Erosion 1, 2, 3, 4 and 5)	14,730	m³	1.16	17086.80	17086.80
	Erosion of 82010 m³ of sediments, including 40000 m³ (Erosion 1), 2560 m³ (Erosion 2), 4950 m³ (Erosion 3), 3000 m³ (Erosion 4) and 31500 m³ (Erosion 5)	82,010	m³	19.81	1624726.42	1624726.42
	Loss of pasture area in the area of 14405 m² (Erosion 1, 2, 3, 4 and 5)	14,730	m²	0.76	11144.77	11144.77
Erosion recovery and containment	Construction of an infiltration basin: area of 247 m² (Erosion 5), area of 800 m² (Erosion 1)	1,047	m²	4.02	4213.68	4213.68
	Construction of the contour line: 2260 m (Erosion 1), 200 m (Erosion 2) and 80 m (Erosion 5).	2,540	m	4.02	10222.30	10222.30
	Hydraulic ladder, shackles and sink (Erosion 5)	100	m²	28.92	2891.89	2891.89
Infrastructure destruction	Destruction/impairment of 1023 m of paved street with urban structure.	1,023	m	377.36	386037.74	386037.74
	Destruction/unfeasibility of 1614 m of unpaved, paved or unstructured street	1,614	m	188.68	304528.30	304528.30
	Destruction of 800 m of rainwater pipes (Erosion 5)	800	m	149.26	119409.81	119409.81
	Dam silting. The structure has 263 m, with a width of 80 m. Approximate value of the volume of soil used in the construction of the 105,200-m² dam. Considering that the dam has already lost 1/3 of the original water surface area, this proportion was applied in relation to the total value, considering the cost of 34716 m³ for calculation purposes.	34,716	m³	4.02	139715.52	139715.52
Estimated economic losses	Value of unused lots on the upstream paved street (13 × 20) – 103 lots	103	unity	18867.92	1943396.23	1943396.23
	Value of unused lots on the downstream paved street (13 × 20) – 51 lots	51	unity	18867.92	962264.15	962264.15
	Value of unused lots on unpaved streets (13 × 20) – 171 lots	171	unity	9433.96	1613207.55	1613207.55

	Annual GDP loss per square metre, in the area with affected social-economic use of 51 ha along the watershed (Erosion 1, 2, 3, 4 and 5)	807,000	PIB/ m²	4.15	3349811.32	66996226.42
	Surface directly affected by the scar caused by ravines and gullies, 14405 m². (Erosion 1, 2, 3, 4 and 5)	14,730	m²	72.88	1073511.28	1073511.28
Municipal tax collection losses	Annual loss of municipal tax collection (annual IPTU of land made unusable by erosion), 325 plots of 13 × 20 m	84,500	m²	0.73	61541.51	1230830.19
Total					11628275.57	76443943.21

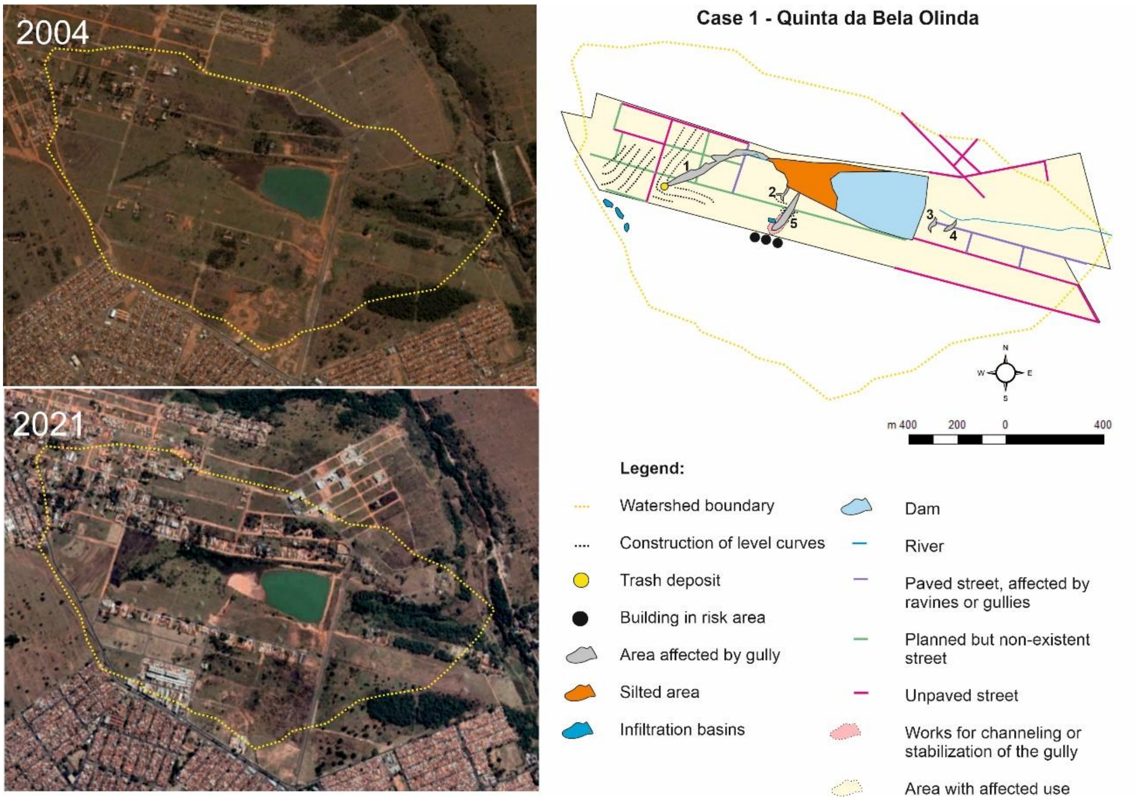

Figure 6. Quinta da Bela Olinda area and identified impacts.

Table 5 and Figure 6 show the impacts identified in the Quinta da Bela Olinda area, namely, soil erosion, loss of carbon stock, loss of pasture, loss of soil nutrients (NPK), destruction of storm drain pipelines, silting of the dam, destruction of streets, isolation of paved streets, unfeasibility of lot construction due to lack of access, unfeasibility of social and economic use of urban areas, loss of municipal tax collection, economic losses due to non-social use and economic impact of the areas surrounding the erosions. The following measures taken to control and stabilize erosion were identified: construction of contour lines, infiltration basins, hydraulic ladders, energy sinks and canalization of part of the erosion channel.

The impacts of erosion at Quinta da Bela Olinda are estimated at US$ 76.4 million, including US$ 17,300 in erosion recovery and containment, US$ 1.65 million in environmental impacts, US$ 72.5 million in estimated economic losses, US$ 1.23 million in lost municipal tax collection, and US$ 949,600 in infrastructure destruction.

Figure 7: a) top view of ravine 5, the implemented works already have some of their functionality damaged, b) top view of ravine 5, where it is possible to observe grooves demonstrating the concentration of surface runoff into the ravine channel; c) gully 1, which shows water flow in the channel and vegetation composed of trees in the surroundings; d) ravine 2, with pasture and small trees inside and around the channel, indicating stability of the feature.

3.2.2. Parque Bauru

Erosion in Parque Bauru developed mainly in February 1993 (Figure 8 A). To contain erosion in Parque Bauru, in February 1993, four works were carried out in the area: dams and infiltration basins upstream and works to divert and conduct rainwater downstream, in addition to the implementation of drainage systems in streets parallel and transverse to the gully. In October 1993, three more works were carried out: earth dikes with underground drainage with sewer networks (Figure 8 B), mixed underground drain and erosion embankment with slope abatement (Almeida Filho 2000). Due to the large volume of eroded soil, the gorge impacted the downstream drainage basin, causing the silting of the river and dams such as the one at Bauru Country Club (Figure 8 C and D).

Despite these emergency and subsequent works, in 2000, an accelerated erosion process from downstream to upstream was observed, compromising the works already carried out, with the destruction of 100 m of drainage pipes (Almeida Filho 2000).

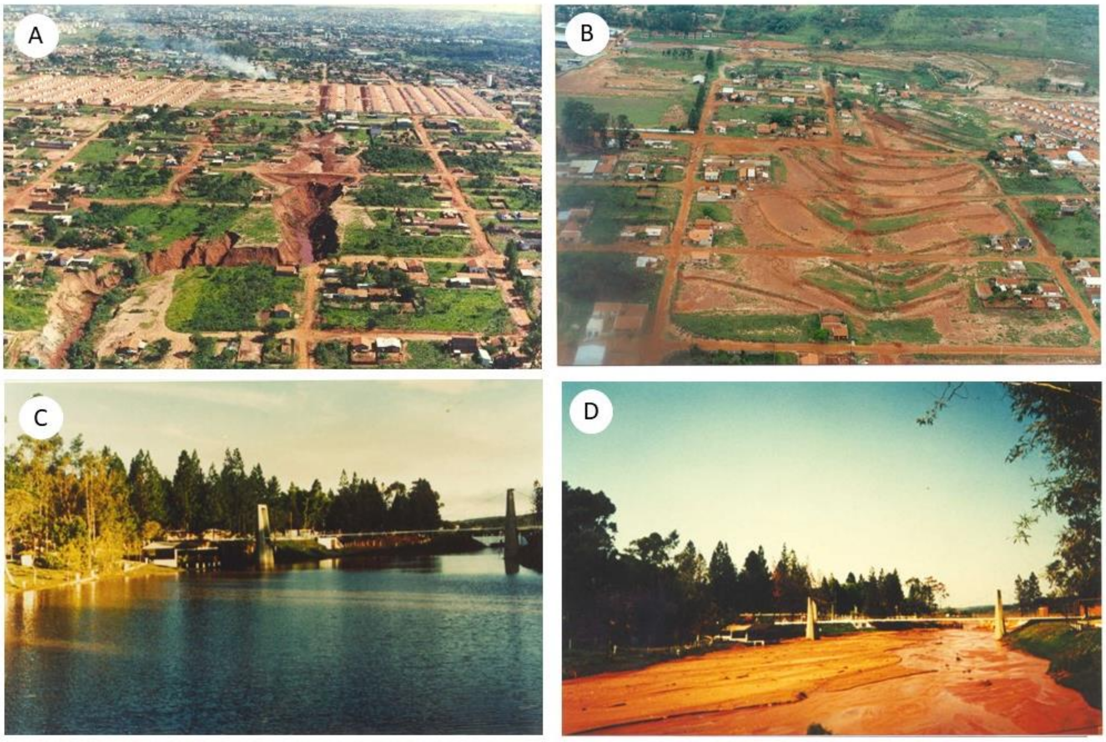

Figure 8. A) gully of Parque Bauru in 1993; B) emergency works to mitigate erosion; C) Bauru Country Club dam before the development of erosion; D) silting of the Bauru Country Club dam due to the development of erosion upstream in 1993 (Photos: Nariaqui Cavaguti).

In 2010, reports mention that erosion continued to cause problems. Because of this, in 2011, emergency works were carried out in Parque Bauru to recover the streets. To contain erosion on Maria de Lourdes Almeida Street, 65 trucks filled with dirt and debris were used. Other works, such as the construction of new sewers and paving, were carried out around the area affected by erosion in 1993. In 2016, a hole 3 m long and 4 m deep caused the partial collapse of a house. City Hall carried out new recovery works for sewers in the streets of Parque Bauru neighbourhood (Mello 2018).

Although it is not possible to identify all the impacts caused due to changes made in the area and the lack of adequate records, the erosion in Parque Bauru has caused recurrent problems in the area since its formation in 1993. The image analysis and field work allowed us to identify the following impacts (Figure 9): loss of soil, loss of nutrients (NPK) and carbon stock, silting of the dam of the former Bauru Country Club, destruction of houses and public structures, construction of erosion channels, making social use unfeasible, economic impact to the urban area, loss of pasture, loss of municipal tax collection, and economic losses due to the social and economic non-use of the areas surrounding the erosions (Table 6). The case of the gully in Parque Bauru demonstrates the partial recovery of an area affected by ravines and gullies, but part of the impacted area has continued to have no social use since 1993, in addition to causing damage to infrastructure and homes in the region.

Table 6. Estimate of the impacts of erosion identified in the Parque Bauru area.

Type	Impact description	Number of units	Unit	Unit cost (US$)	Amount (US$)	Value in 20 years (US$)
Environmental, per replacement cost	Sediment erosion volume at least 376000 m^3	360,000	m^3	19.81	7132075.47	7132075.47
	Loss of carbon stock in the area (Surface affected by erosion in 1993, 24,000 m^2)	24,000	m^2	0.31	7440.00	7381.13
	Loss of pasture area	24,000	m^2	0.76	18158.49	18158.49
	Soil nutrient loss (NPK) in the area (Area affected by erosion in 1993, 24,000 m^2)	24,000	m^2	1.16	27840.00	27840.00
Erosion recovery and containment	Construction of at least 3 infiltration basins on empty land, upstream, in the contribution basin, totalling an area of 275 m	275	m^3	4.02	1106.75	1106.75
	Construction of 1650 m of level curve	1,650	m^3	4.02	6640.47	6640.47
	Construction of rainwater channels, on Lucio Luciano Ave, with the aim of diverting and directing rainwater, which caused a lateral branch to the right; estimated area of 50 m.	50	m^3	4.02	201.23	201.23
	Implementation of a more complete drainage system on the two streets parallel to gully, with corrugated steel and concrete pipes, one of the lines measuring Ø = 0.80 m, and the other measuring Ø = 1.20 m, with a storm drain collection system on the parallel streets, grills on Lucio Luciano Ave. and dissipation system with rock blocks. 1300 m of estimated construction.	1,300	m	102.16	132803.58	132803.58
	Earth dike with underground drainage downstream of the second erosion curve. Approximately 200 m, 3 m deep and 6 m wide	3,600	m^3	4.02	14488.30	14488.30
	Earthmoving to land erosion in an area of 600 m by 30 × 5.	90,000	m^3	4.02	362207.55	362207.55
	Mixed underground drain, built with hollow pipe and upstream. Approximately 600 m of 2 × 2 piping. The plumbing system is 5 m away.	2,400	m^2	157.61	378253.58	378253.58

	Erosion embankment with slope abatement, movement of half of the eroded volume (188000 m^3).	188,000	m^3	4.02	756611.32	756611.32
Destruction of infrastructure	Destruction of 1 house	1	unit	12065.09	12065.09	12065.09
	Silting of the dam built by Bauru Country Club, 8670 m^2 of area, depth of 2 m.	17,340	m^3	4.02	69785.32	69785.32
Estimated economic losses	Surface affected by erosion in 2022, of 9700 m^2	9,700	m^2	72.88	706928.68	706928.68
	Possible use for directly and indirectly affected area. Use of 144 lots of 12 × 28	144	m^2	18867.92	2716981.13	54339622.64
	Annual loss of GDP per square metre, in the area with social-economic use. Area of 100200 m^2	100,200	m^2	4.15	415924.53	8318490.57
Municipal tax collection losses	Annual loss of municipal tax collection (annual IPTU of land made unusable by erosion), 144 plots of 12 × 28 m	48,384	m^2	0.73	35238.16	704763.17
Total					12794749.66	72989423.35

The impacts of the sinkhole in Parque Bauru are estimated at US$ 72.98 million, with US$ 1.65 million related to erosion recovery and containment, US$ 7.18 million to environmental impacts, $ 63.3 million to estimated economic losses, US$ 704,700 to lost municipal tax collection, and US$ 81,800 to infrastructure destruction. The damage caused by this erosion was not greater because the works carried out in 1993 allowed the control of erosion and the occupation of the area around and even under the old channel in the areas close to the head of the erosion.

The impacts caused by the erosion of Parque Bauru could be even greater, but the works carried out in 1993 allowed an area of 51,000 m^2 affected by erosion to be reinserted into the urban space in 1993; currently, this area houses more than 77 buildings (Figure 9).

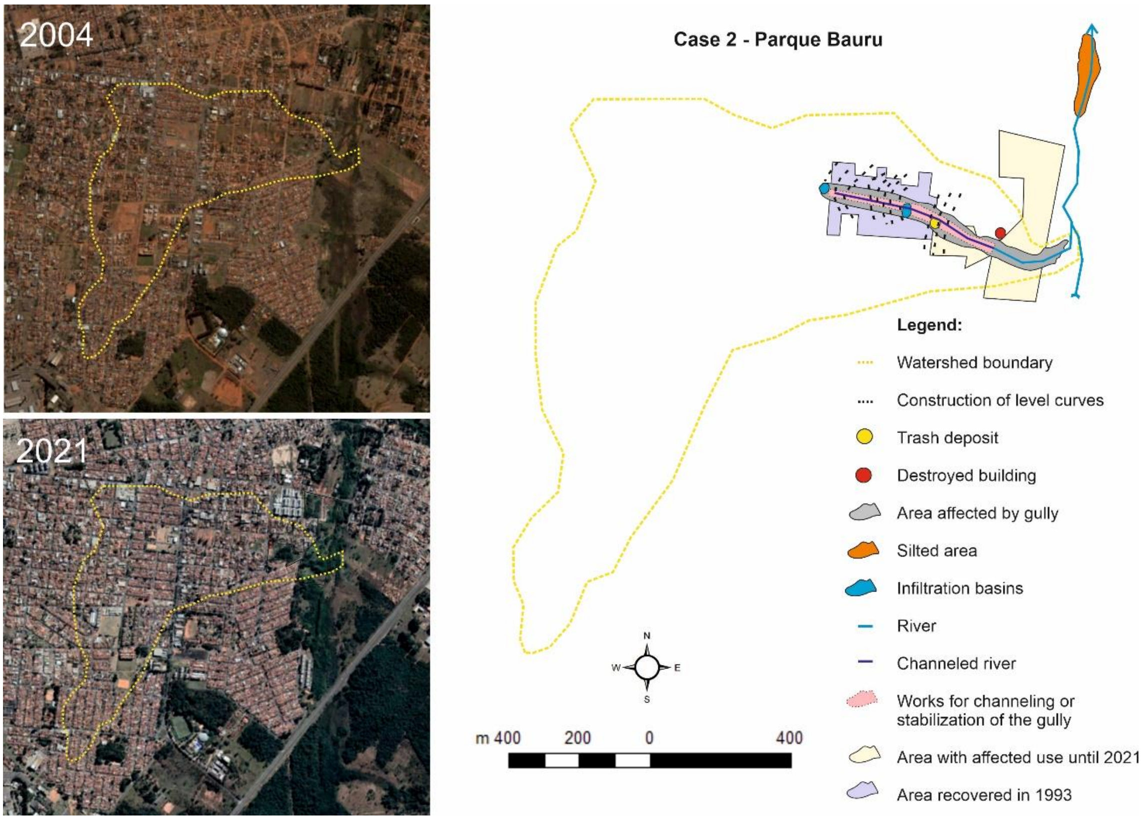

Figure 9. Parque Bauru area and identified impacts.

3.2.3. Jardim América

The Jardim América gully emerged between 1987 and 1988 and, since then, has been used for garbage disposal (Almeida Filho 2000). In 1993, City Hall implemented a drainage system inside the erosion with a network of sewers and a landfill with rubble. Erosion was completely recovered between 2004 and 2010, and a gated community with high-standard housing was constructed on the site. This case demonstrates that areas affected by ravines and gullies, if recovered with appropriate techniques, can be reinserted into the urban space, returning to social and economic use.

Among the impacts identified in the area until its recovery were soil erosion, loss of nutrients (NPK) and carbon stock, unfeasibility of social and economic use of the urban area, loss of municipal tax collection, economic losses due to the non-social and economic use of areas surrounding the erosion, and loss of pasture (Figure 10). In the areas, the containment and recovery measures identified were construction of contour lines, infiltration basins, drainage systems and sewer networks and landfill in the affected area (Table 7). After the recovery of the area, the value of a square metre of land increased to more than US$ 188, demonstrating a significant appreciation of the area. This change also increases the municipal tax collection.

The negative impacts of the Jardim América sinkhole are estimated at US$ 23.2 million, of which US$ 110,000 is related to erosion recovery and containment, US$ 4.67 million to environmental impacts, US$ 17.32 million to estimated economic losses, and US$ 1.16 million to lost municipal tax collection. In contrast, after the recovery and occupation of this area, the minimum estimated gains are US$ 19 million, with US$ 3 million from municipal tax collection after recovery of the area and US$ 16 million in estimated economic gains based on GDP per square metre.

Table 7. Estimate of the impacts of erosion identified in the Jardim América area.

Type	Impact description	Number of units	Unit	Unit cost (US$)	Amount (US$)	Value in 20 years (US$)
Environmental, per replacement cost	Sediment erosion volume of at least 234000 m^3	234,000	m^3	19.81	4635849.06	4635849.06
	Loss of carbon stock in the area	18,000	m^2	0.31	5580.00	5535.85
	Loss of nutrients in soils (NPK) in the area	18,000	m^2	1.16	20880.00	20880.00
	Loss of pasture area	18,000	m^2	0.76	13618.87	13618.87
Erosion recovery and containment	Construction of 3948 m of level curve	3,948	m^3	4.02	15888.84	15888.84
	Construction of an infiltration basin with an area of 1179 m^2	1,179	m^3	4.02	4744.92	4744.92
	In 1993, City Hall implemented a drainage system inside the erosion with a 600 m sewer network of 1 m pipe and a landfill with rubble	600	m	149.26	89557.36	89557.36
Estimated economic losses	Affected area of 18000 m^2	18,000	m^2	72.88	1311826.42	1311826.42
	Annual loss of GDP per square metre in the area with social-economic use. Area of 385700 m^2 between the 2000s and 2010s	385,700	m^2	4.15	1601018.87	16010188.68
Municipal tax collection losses	Annual loss of municipal tax collection (annual IPTU of land made unusable by erosion), approximately 380 plots of 12 × 35 m, considering the equivalent value of 1% of the average IPTU.	159,600	m^2	0.73	116236.98	1162369.81
Total negative impacts					7815201.30	23270459,79
Gains from municipal tax collection after recovery of the area	Gains from land tax collection (approximately 380 plots measuring 12 × 35 m), considering the equivalent value of 1% of the IPTU of the current land R$ of 1000 m^2.	159,600	m^2	1.89	301132.08	3011320.75
Estimated economic gains	Annual GDP gain per square metre after recovery of the area with social-economic use.	385,700	m^2	4.15	1601018.87	16010188.68
Total positive impacts after recovery					1902150.94	19021509.43

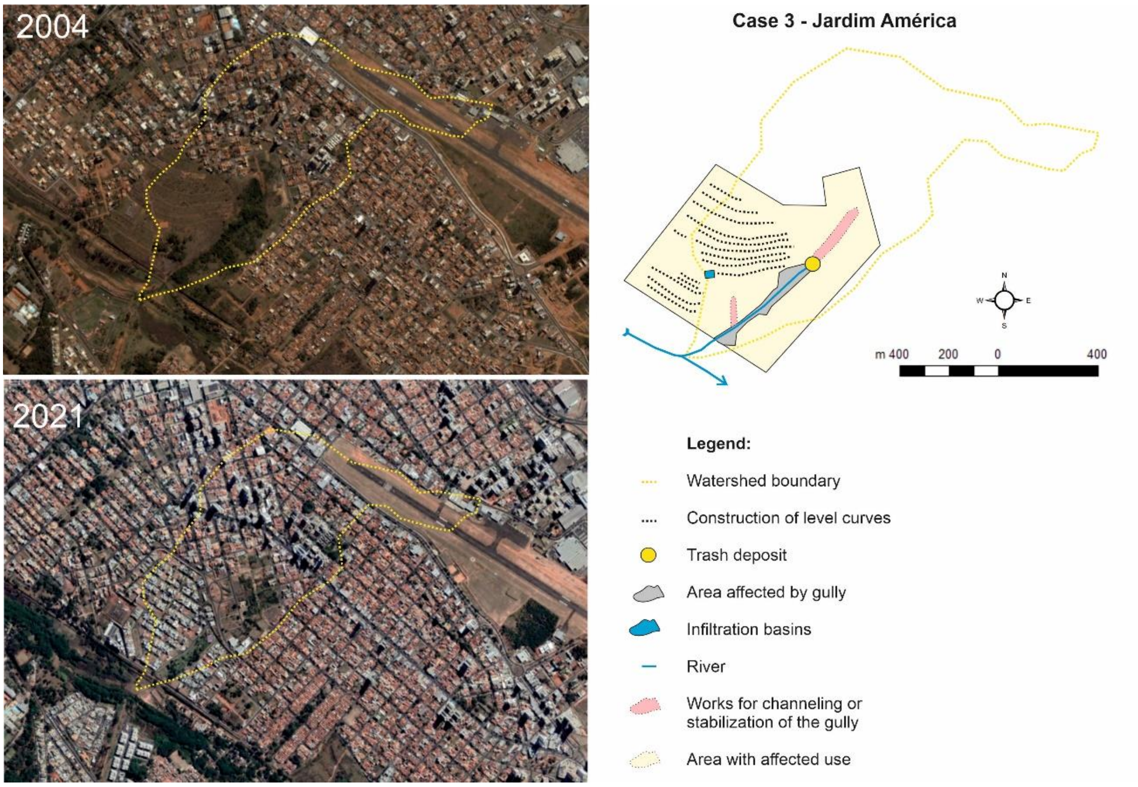

Figure 10. Jardim América area and identified impacts.

4. Discussion

The impacts of the three areas represent significant amounts spent by the government. Regarding costs with recovery and construction of containment structures, the highest estimated value was estimated for Parque Bauru, which exceeded US$ 1.65 million. With regard to environmental impacts, analysed by replacement cost, the highest value was estimated for soil replacement, which, due to the large volume of eroded material, can represent values of US$ 7.1 million in cases such as Parque Bauru if a complete replacement of the area affected by erosion were to be carried out with soil extracted from another location. Considering the three areas analysed, the cost of replacing the eroded soil is estimated at US$ 13.3 million.

The loss of soil nutrients, although having lower values, also exceeded US$ 27,800 in the case of Parque Bauru and US$ 17,000 in Quinta da Bela Olinda. These high values are the result of the large surface area affected by erosion channels.

The loss of carbon in the soil represented US$ 17,300 when adding the three areas analysed. According to Somasundaram et al. (2018), ravines are fragile ecosystems, and the recovery of carbon stocks is a slow and long-term process that requires continuous input of biomass into the soil. Thus, the recovery of these areas requires adequate conditions for a long period.

Quinta da Bela Olinda was the area where the value of infrastructure destruction was more relevant, as the damage exceeded US$ 949,000. The main cause for this value is the destruction of public infrastructure built for the development of the subdivision, such as paved streets, sidewalks and rainwater drainage systems.

The highest values found correspond to estimated economic impacts and losses municipal land tax collection.

Ravines and gullies in Bauru have created large urban voids. When calculated, the annual economic losses exceed values US$ 4.4 million in Quinta da Bela Olinda. This value is explained by the large unused area due to the development of erosion and the non-construction of the lots planned for the area, which was made unusable by erosion, despite the entire urban structure built. Likewise, the loss with municipal land tax collections between 2000 and 2010, considering the average IPTU value, exceeds US$ 113,000 per year in areas such as Jardim América. In this particular case, a comparative analysis of tax values can be performed for before and after recovery of the area affected by erosion. After 2010, a high-standard condominium was built on the site, where the value per square metre land exceeds US$ 188 dollars; thus, the IPTU value in the area, currently collected by the City Hall, is at least approximately US$ 300,000 a year. This change in value in the area after recovery is yet another strong argument for calculating losses in municipal taxes and the average value of GDP per square metre in analyses of impacts of erosion in urban areas.

If the impact from 2000 to 2021 is considered, Quinta da Bela Olinda had a municipal loss of US$ 76.4 million, Parque Bauru had a municipal loss of US$ 73.2 million, and Jardim América had a municipal loss of US$ 23.3 million up to the beginning of recovery, while after recovery the economic gains, including with municipal taxes, were at least US$ 15.8 million in Jardim América. Of this total, more than US$ 3.5 million was lost with IPTU collection in the three areas. In the Jardim América area, in the period between 2010 and 2021 alone, the gain in revenue after the recovery of the site exceeded US$ 3 million.

Among all the erosions described by Almeida Filho (2000), the recovery of areas affected by ravines and gullies occurred mainly for the development of public works, transport or leisure, or private undertakings related to subdivisions and condominiums. This is explained by the ease with which a large enterprise manages to dilute the cost of recovery among the gains provided by the reintroduction of social use to the area. The difference in recovery measures also results from the position of the erosion in the urban perimeter. In Jardim América, which is located in an upscale neighbourhood, the surroundings were occupied while leaving the feature area as a vegetated area with public squares and other spaces. In Parque Bauru, which is a popular neighbourhood, houses are being built on top of the channelled and buried feature, increasing the risk in this case.

The emergence of new ravines and gullies can increase the impact of these areas. This is the case for ravine 5 in Quinta da Bela Olinda, which, due to rapid growth, is getting closer every year to houses and other public infrastructure located upstream. The reactivation of erosion in periods of atypical rainfall or due to changes in land use is another factor that requires attention from City Hall and owners in areas affected by erosion or people who live in the surroundings.

Both the development of containment works and the recovery of areas affected by erosion need to be well documented to build a history of the measures taken in the area, so that it is possible to carry out cost analyses and more easily solve any future geotechnical problems.

Valuations carried out in rural areas by Yitbarek et al. (2012) and Ayele et al. (2015) calculated the values for variables similar to those analysed in this work, such as the cost of recovering the area, loss of nutrients, and cost of missing opportunities.

Yitbarek et al. (2012) quantified the costs of ravine erosion and the costs and benefits of rehabilitation in an area in Ethiopia. The authors used as a reference the cultivated area yield lost by farmers and calculations of rehabilitation costs, considering the cost of labour, materials and equipment at each level of rehabilitation or maintenance, in addition to the monetization of soil nutrients (NPK) and organic carbon (OC). The study indicated that ravine rehabilitation may be economically viable in some cases. The average cost of investment in gully rehabilitation per hectare was calculated at US$ 24,412. In the analyses carried out by the authors, the rehabilitation nutrient benefit generally exceeds the rehabilitation establishment cost by up to 25% more, as is the case for the Eshim Wofena gully, where the cost of erosion was estimated at approximately € 7,000, the rehabilitation nutrient benefit at € 57,100 and rehabilitation establishment cost at € 41,400.

Ayele et al. (2015) quantified the cost of erosion in Ethiopia in a watershed for two years and concluded that the cost of erosion was at least US$ 18,313, with US$ 7,848 related to loss of soil nutrients, US$ 7,204 to missed job opportunity cost, US$ 1,208 to animal losses, US$ 243 to eucalyptus wood losses, and US$ 1,810 to *Rhamnus prinoides* losses. According to the authors, the cost per ha per year was US$ 22, or US$ 17 per person per year, a figure that represents 19% of per capita income. The loss of nutrients in the soil and the cost of lost opportunities were the main impacts identified.

In rural areas, where the function of the land in general is related to agricultural production, the cost of ownership is much lower per square metre, and the ease of replacement of the area is greater. In urban areas, however, competition for land and the value per square metre are greater due to the proximity to numerous economic activities and public structures. The use of variables such as GDP per square metre was a simplified way of considering the economic complexity involved in urban space.

According to Lall and Deichmann (2012), the risk posed by ravines and gullies in cities should increase in the coming decades due to population growth and land scarcity. According to these authors, in cities such as Caracas, Venezuela or Rio de Janeiro, Brazil, poor families occupy land in risk areas to enter the urban labour market. In Bauru, the analysis of images taken between 2004 and 2020 demonstrates that areas affected by erosion are a frequent focus of irregular occupations for the creation of slums.

In cases of the use of engineering works for containment and control of ravines or gullies, long-term impact analyses need to account for the resources used to restore the functionality of infrastructure. In Bauru, at Quinta da Bela Olinda and other places such as Jardim Grama and Parque Bauru, several infrastructures such as hydraulic ladders have been partially or completely destroyed, suggesting that the works may have been poorly sized or that the solution was insufficient because it focused on the consequence, not the process. For Bartley (2020) and Frankl et al. (2021), the key to recovering areas affected by erosion is vegetation, as engineering works have a high failure rate. In this sense, Romero-Díaz et al. (2019) suggest that works built to stabilize ravines and gullies be checked annually after the season with the highest rainfall.

The use of urban waste to fill in gully areas can further aggravate the impacts of these processes. In areas of ravines and gullies, where garbage has been disposed of without any type of waterproofing, it is likely that in addition to the problem caused by erosion, there will also be problems with soil and groundwater contamination. The disposal of garbage in erosions also occurs in other cities of São Paulo. Rotta and Zuquette (2014) cite this practice in an erosion area in São Carlos. This suggests that urban ravines and gullies can also become contaminated areas and a source of contamination in the basin.

For Santos (2008), in addition to the problems in the area directly affected by erosion, ravines and gullies cause the devaluation of the land in the surroundings. According to the author, it is difficult to sell lots in closed subdivisions such as Chácara Odette and Jardim Tavano, and price dropped in areas close to the gully in Jardim Jussara.

Rotta and Zuquette (2014), when analysing areas affected by ravines and gullies in several cities in Brazil, presented examples of erosion that affected land development for decades. In São Pedro, gullies started in 1972 and were recovered with the construction of open channels after the advance of urbanization between 1995 and 2000. This allowed reinserting this area into the urban space with the construction of homes and public structures.

The problems and impacts caused by ravines and gullies in urban areas have many similarities with contaminated areas classified as brownfields. According to Cabernet (2006) brownfields are sites affected by previous use which are abandoned or underutilized due to real or perceived problems of contamination, occur mainly in urban areas, and require intervention so that the area can be used again for beneficial use. Ravines and gullies favour the creation of urban voids, where recovery measures aiming at the reinsertion of these areas into the urban space have a high cost. Contamination caused by garbage disposal in erosion channels brings the concept of brownfields even closer to the scenario created by large erosions in the urban perimeter.

Studies carried out for the recovery of brownfields demonstrate methodological paths that may be applied to the recovery and analysis of areas affected by ravines and gullies. The recovery of brownfield areas requires analysis of environmental, economic, social, time, uncertainty aspects and user friendliness of a sustainable site remediation (Huysegoms and Cappuyns 2017). Thus, the recovery of these areas involves risk assessment, land use planning and the selection of the best remediation methods and technologies (Hammond et al. 2021). Instruments, such as the Timbre Brownfield Prioritization Tool, that use multicriteria tools can help identify priority areas for remediation (Pizzol et al. 2016). If tools such as this are adapted, they can also be used for the analysis of ravines and gullies.

However, ravines and gullies are also a form of natural disaster. Thus, governmental and land planning aimed at reducing the risk of danger is essential. Gully erosion susceptibility maps are an important instrument in land planning and in the development of erosion control and mitigation measures (Arabameri et al. 2019). Monitoring the temporal evolution of erosion can be an important geoindicator (Busnelli et al. 2006), as urban development can affect hydrological connectivity, change natural flow routes (Gudino-Elizondo 2018), and promote erosion in areas with lower natural susceptibility.

The use of remote sensing can help in valuation analyses, as was the case with the use of Google Earth images in this study (Mahamba et al 2023). The analysis of spectral images allows the identification of land cover changes (Pani 2017). Automatic identification through the use of remote sensing is an alternative to area monitoring (Vrieling et al. 2007, Wang et al. 2023, Mawe et al. 2024). Municipalities with a high susceptibility to ravines and gullies can use this type of technology as an initial diagnostic tool. The early identification of areas with ravines and gullies at an early stage of development can facilitate a quick response to contain the process, thus avoiding greater environmental and economic damage.

Unmanned aerial vehicles (UAVs) and terrestrial laser scanners (TLSs) are other tools that can be used in the precision analysis of erosion (Julian and Nunes 2020). These methods can provide better results when monitoring the evolution of erosion processes, since two images from different dates are needed to carry out an impact analysis.

In places such as Erosion 1 at Quinta da Bela Olinda, where there is already a recovered erosion with dense vegetation and a watercourse in the interior, the development of a geotourism itinerary or educational itineraries aimed at explaining to students the processes that operate in the formation of ravines and gullies, as well as their economic and environmental impacts, can be an alternative use for these areas. Ravines are used for this purpose in other countries such as Poland (Zgłobicki et al. 2015).

Although natural conditions influence susceptibility and City Hall has an important role in land planning, the development of ravines and gullies is driven by human action. In this sense, the valuation process is also important in identifying those responsible for triggering accelerated erosion. The impacts of ravines and gullies can cause environmental, social and economic damage to several points of the watershed, including upstream, downstream and surrounding areas.

For other types of disasters, an increasing number of studies address their disasters and the value of remediation strategies. For example, Logar and Van Den Bergh (2013) examined the methods available to assess all types of drought costs, considering direct, indirect and nonmarket costs. Montaña et al. (2016) calculated the natural capital value of forests in Saldaña related to mitigating the risk of landslides. Additionally, Semenova et al. (2013) calculated the cost of wildfires in California. Valuing the impact of erosion is a way of following the same trend, whether to measure the impact for management purposes or for accountability purposes or to trigger any insurance that covers losses.

The method proposed in this study made it possible to carry out an analysis of the short- and long-term costs of urban erosion, considering important factors for understanding the problem, the cost of erosion recovery and containment, environmental impacts, estimated economic losses, loss of revenue from municipal taxes, and losses with infrastructure destruction, in addition to also demonstrating the positive impacts of remediation of these areas. Although the values of losses from erosion and gains due to the reinsertion of these areas can be calculated using the same variables, they need to be calculated separately. The different types of economic and environmental impacts can be identified following the proposal by Kuhn et al. (2023), while the loss of opportunity in the urban space can be determined considering the municipal GDP per square metre. The methodology used in this study can be replicated in other countries around the world, as long as local values are used to determine reference values for replacement or infrastructure costs.

The method proposed in this study allows the valuation of the impacts of ravines and gullies, considering the short-, medium- and long-term losses. The analysis of losses in urban areas, based on the calculation of GDP per square metre, is a simplified way to consider the impact of making areas unfeasible for use in cities, thus creating a way to account for the complexity of the urban environment. The results showed that the application of the replacement cost of items affected by ravines and gullies allows the valuation of items related to damage to infrastructure and ecosystem services performed by the soil. The method to be applied in other countries needs to use local reference values due to variations in the cost of products and services.

5. Conclusions

This study estimated the impacts of ravines and gullies in the medium and long term for the city of Bauru, Brazil. This estimation demonstrated that in the urban perimeter, the main impacts are related to the abandonment of the area and the creation of urban voids. Among the environmental impacts, the most significant is the mobilization of sediments. The data indicated that the recovery of areas affected by ravines and gullies is the best option in urban areas, although it can be a costly process for municipalities and governments. Gains from tax collection, risk reduction and economic gains are some of the main arguments for creating strategies aimed at reinserting these areas into the urban environment.

The valuation and remediation of areas affected by ravines and gullies can be facilitated by the creation of municipal databases of the actions and occurrences recorded in each erosion to allow reconstructing the history of costs and technical choices. For municipalities such as Bauru, the creation of a permanent erosion identification and infrastructure maintenance program can favour the early identification of ravines and gullies so that containment measures can be carried out quickly, avoiding the expansion of damage.

The use of GDP per square metre is a way of valuing impacts in the urban environment that simplifies the complexity of the city in an economic analysis of land use. The calculation of impacts, positive or negative, related to urban land taxes can be an important argument in convincing local municipal authorities.

Strategies for reinsertion of urban voids created by ravines and gullies need to be developed, similar to those that already exist for brownfields. Economic valuation and accountability analyses should also be carried out to identify the companies and individuals responsible for the development of ravines and gullies due to poor soil use. Similar other processes, such as forest fires, erosions can occur naturally, but when caused by human action, penalties must be imposed on those responsible and economic reparations must be made for the affected people.

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Author Contributions

Kuhn CES and Reis FAGV contributed to the study conception and design. Material preparation, data collection and analysis were performed by Kuhn CES, Reis FAGV, Peixoto ASP and Furegatti SA. The first draft of the manuscript was written by Kuhn CES and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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APPENDIX A.4. MANUSCRIPT: Adaptation of the TIMBRE methodology for brownfields gully erosion analysis in urban areas.

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Highlights

Gullies can be considered a form of brownfields

The TIMBRE methodology can be adapted for gully remediation

Remediating gullies are important to improve urban management

Brownfield analysis is needed to improve land use

Abstract

Soil erosion is a concern in many parts of the world, causing environmental and social impacts. Aiming at obtaining indicators of the recovery of brownfields created by gullies in urban areas, this study adapts the Tailored Improvement of Brownfield Regeneration in Europe (TIMBRE) for the analysis and classification of areas affected by gullies in the city of Bauru, Brazil. The TIMBRE methodology assists in the decision-making of priority areas for remediation and their reinsertion in urban spaces. The inventory of areas affected by gullies was compiled based on the analysis of two image sets (2004 and 2020) available on Google Earth. For the classification of brownfields, three classes were considered: Class 1 - local potential for business development, Class 2 - attractiveness and marketing, and Class 3 – environmental risks. These results demonstrate a correlation between gullies and urban expansion. The inventory identified 175 gullies in the municipality's urban perimeter in 2004, which affected an area of over 64 hectares. In 2020, the number of gullies increased to 189, but the affected area decreased to 62 hectares due to the recovery of some large gullies. The proposed methodology identified the area of Quinta da Bela Olinda as the one with the highest scores in all three classifications. Quinta da Bela Olinda is the location that has a local potential for business development, as it is the most attractive brownfield, as well as the area with the highest environmental risk. This area should, thus, be prioritized by public management for remediation. In conclusion, the proposed method of analysis can be transferred to other areas with adaptations in the criteria used and, therefore, may facilitate the management of urban areas affected by gullies in other places around the world.

Keywords: Greenfields, brownfields regeneration, Soil degradation, gully remediation.

Introduction

Gully erosion is a global concern of soil deterioration; it limits land use, affects infrastructure and, in cities, it creates urban voids/brownfields [1; 2; 3]. The impact of gullies on economic and ecosystem services are most commonly registered in Brazil, India, China, the Democratic Republic of Congo, Ethiopia and the United States, but damage also occurs in countries such as Algeria, Argentina, Australia, Iran, Italy, Mexico, Nigeria, Polonia, Portugal, Romania, Russia, Slovakia, South Africa, Spain, Swaziland, Tanzania, Tunisia, Turkey, Ukraine and the United Kingdom [4].

Although studies that address the development of gullies in rural areas are common [5, 6, 7], only 3.1% of published studies about gullies investigated gully erosion in urban areas [5]. Gullies are recorded in hundreds of cities in Brazil, in some cases causing significant damage to urban structures [8]. The issue of gullies in urban space was also the object of studies in Nigeria [9], in Kinshasa, and in the Democratic Republic of Congo [10], among other countries [2; 3; 5]. In addition to the impacts caused on urban structures, gullies affect significant areas, making the use of these urban spaces unfeasible. Areas affected by gullies can be restored, but if the necessary interventions are not enacted, they become urban voids [1; 11].

Although factors such as relief, climate, extreme rainfall events, geology, and soil type can influence susceptibility to the development of gullies, there is a consensus in the literature that human action or extreme events are important triggers for their development [3; 5; 12; 13]. Gully control results in various positive effects, such as on water flow regulation and biological diversity, and it reduces siltation and the risk of infrastructure damage [14].

In cities where there are hundreds of gullies, especially in developing countries, where financial resources are scarce [4; 9; 10; 11], creating criteria to know which erosions should be prioritized for remediation and reinsertion of the area into the urban environment becomes a necessary action. This study presents contributions to ranking erosion to assist in decision making, using as a basis methods developed for brownfield analysis.

Gullies in urban spaces create problems in territorial and environmental management comparable to brownfields [11]. Brownfields [15] are "places that have been affected by previous uses of the surrounding place or land; they are abandoned or underused areas that are mainly in totally or partially developed urban spaces, requiring intervention to bring them back to beneficial use and may have real or perceived contamination problems". The areas affected by gullies also had a previous use, and after the triggering event, the area is underused or abandoned, requiring intervention to remediate the area and, when possible, return it to beneficial use [4, 8, 11]. Brownfields are not necessarily contaminated areas, they can be considered areas with previous use, which have not been reintroduced for a new one [16, 17]. Thus, in cities heavily affected by gullies [8, 9, 10], this process can be considered as a form of brownfield.

Brownfield rehabilitation is a topic that has attracted the attention of researchers in recent decades in countries such as the United States, England, Canada, Germany, China, Italy, Czech Republic, Spain and Australia [18]. Decision support tools are potentially effective for brownfield evaluation and for the development of strategies for remediation or management of affected areas [19].

Recovery of brownfields preserves the environment. or the so-called Greenfields, which provide important ecosystem services [20]. However, brownfield recovery requires significant resource allocation in terms of time and cost, which often exceeds the cost of greenfield development [21].

The Brownfield Prioritization Tool "TIMBRE" is a decision-supporting methodology created for Brownfields analysis considering the economic, social and environmental dimensions [21; 22]. Brownfield analysis is performed in three steps [23]: 1) Inventory (mapping, problem identification and analysis), 2) Prioritization (assessment of redevelopment potential and environmental risks), and 3) Marketing (fundraising and investor search).

This work aims at applying a multiple criteria analysis based on the adaptation of the criteria of the Brownfield Prioritization Tool "TIMBRE",for the analysis of areas affected by gullies. The city of Bauru in Brazil is selected as our test-site, due to the impacts that gullies have on urban structures. We hypothesize that the TIMBRE methodology allows quick responses to gully management.

2. Method

The TIMBRE methodology proposes different levels of decision hierarchies to analyse brownfields [23], which we adapted for the analysis of gully-affected areas. In the adaptation proposed, three stages are used: a) Inventory - in which the gullies are classified according to their activity level; b) Prioritization - three classes are used, based on the sum of the scores of the proposed parameters described in section 2.2; c) Marketing - where the results are integrated to identify and discuss priority areas for recovery. The urban perimeter of the city of Bauru was chosen for the case study (Figure 1).

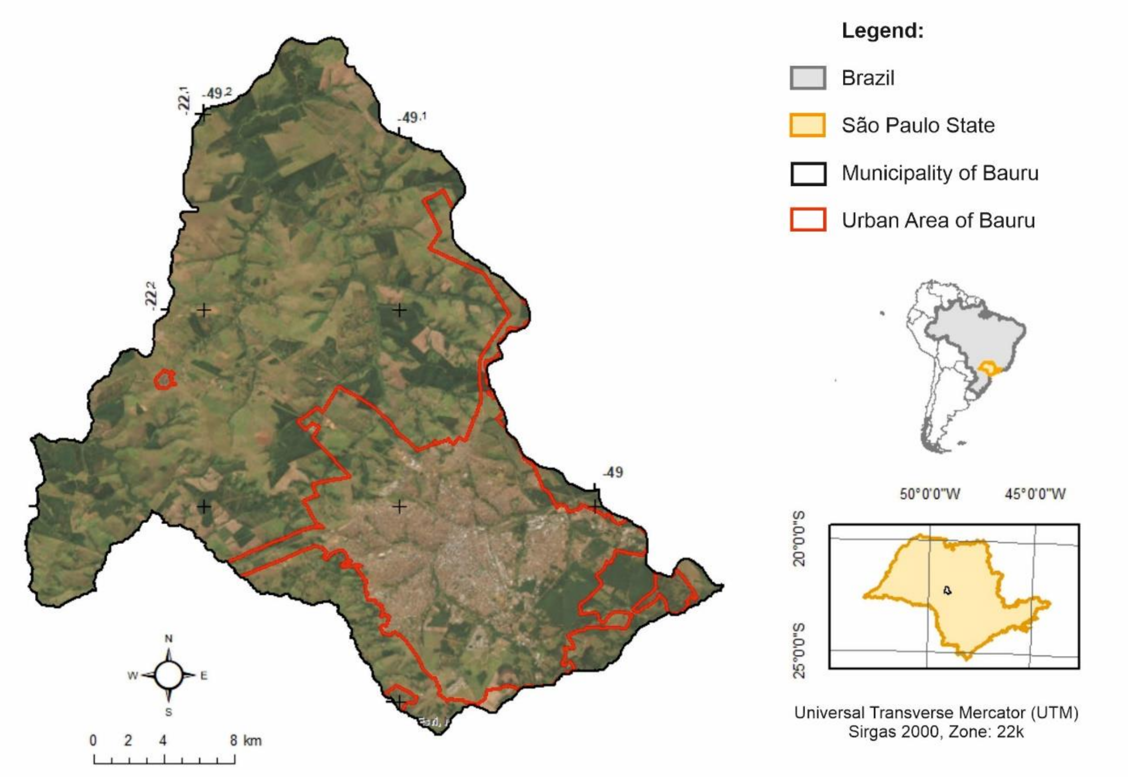


Figure 1: Location of the study area (red: urban perimeter of Bauru).

2.1. Inventory

The inventory step includes the mapping, identification and analysis of gullies. The identification of gully scars was performed using images from Google Earth from 2004 and 2020, extracting the location and size of the area affected on the two dates analysed. The use of aerial images for gullies analysis is a common method in many studies [24; 25; 26; 27]. Gullies were classified into three classes: a) "recovered areas", which represents areas that had their function in relation to land use recovered between 2004 and 2020 (e.g., they were filled with materials, aiming at the construction of houses, streets, urban parks, among others); b) "stable areas", representing where no further evolution of gullies in the considered period was visible, such as areas with consolidated vegetation (trees or grass) that do not show signs of sediment removal (e.g., silted areas); and c) "unstable", where gullies progressed visibly in satellite images (vegetation not consolidated and siltation occurred in channels or in downstream locations).

2.2. Prioritization

Prioritization was based on the analysis of land use and occupation according to Bauru's Master Plan [28]. Thematic maps were used to obtain information on urban infrastructure, population density, education and sanitation infrastructure, characteristics of soil use, transport structures, health services, development areas for new enterprises and proximity to watercourses. For development of the index of risks, gullies magnitude and activity, the results from the inventory stage were used. Land value was calculated based on the territorial taxes charged per square metre by the municipality [29]. The proximity of gullies to built areas was defined based on a map composition of spectral bands produced with the use of Landsat 8 orbital images extracted from the Portal of the National Institute for Space Research (INPE). The set of data used must be suitable for the municipal scale; i.e., to provide an analysis on the scale used by municipal managers to make decisions on urban planning.

The classification maps were created with arithmetic functions in geoprocessing software, so that the parameter scores could be established. The functions used were union, intersection and subtraction of polygons from the shapefiles of the Master Plan database provided by Bauru City Hall [29] or development of contour maps, created using the Inverse Distance Weighting interpolation method to establish the spatial variation of the value of the characteristic. The gullies were identified and georeferenced in a shapefile of points due to the adopted scale, which were classified by attributes, and later intersected with the areas of the municipality. The priority categories were defined as follows: 1) Class 1: "local potential for business development" comprising land value, population density, educational index, entrepreneurial activity, periphery and transportation connections (Table 1); 2) Class 2: "attractiveness and marketing potential" considering specific location, previous use, infrastructure, and expected regeneration costs (Table 2); and 3) Class 3: "environmental risks" accounting for gullies magnitude, activity (stable or dynamic) of the erosive process, location with respect to urban zonation and proximity to built areas (Table 3). The priority ranking was evaluated on a scale score from 0 to 4. Three Tables 1–3 summarize the methods of the prioritization.

Table 1 – Classification of "Local potential for business development"

Parameter	**Method for calculation**	**Score**	**Description**
Land value per square metre	land value per square metre provided by the municipality of Bauru	0	Properties located in rural or urban area with value of up to US $ 6 per square metre
		1	Properties located in urbanized or periurban regions, in neighbourhoods with low to medium standards and values between $ 6.1 and $ 60 per square metre
		2	Properties located in urbanized regions with values between $ 60.1 and $ 160 per square metre.
		3	Properties located in urbanized regions, in neighbourhoods with medium to high standards with values of over US $ 160.1 per square metre.
Population density	Heatmap on housing density	0	Up to 500 inhabitants per km²
		1	Between 501 to 2,500 inhabitants per km²
		2	Between 2,501 and 5,000 inhabitants per km²
		3	Above 5,001 inhabitants per km²
Educational indices	Distance to an educational unit (schools and university)	1	Areas without availability of educational units within a radius of up to 1.5 km
		2	Areas with one educational unit within a radius of 1.5 km

		3	Areas with two or more educational units up to 1.5 km distance
Sanitation	Distance from road with networks of water and sewage collection	1	Area without sewage and water and more than 200 meters away from the municipal road network
		2	Area without sewage and/or water and far less than 200 meters from the municipal road network
		3	Area with complete sanitation and water structure within the municipal road network
Land use	Use of the areas indicated in the Master Plan	1	Non-urbanized area
		2	Area in urbanization, urban voids and green area
		3	Areas located in urbanized regions.
Transportation connections	Distance from the main access roads	1	More than 100 metres from some street and over 500 metres from avenues and highways.
		2	Less than 100 metres from some street or less than 500 metres of avenues and highways.
		3	Less than 100 metres from some street and less than 500 metres from avenues and highways.
Health structures	Heatmap considering the distance from health facilities	1	Areas without availability of health units within a radius of up to 1.5 km.
		2	Areas with low concentration of health units within a radius of 1.5 km
		3	Areas with high availability of health units within a 1.5 km-distance

“Local potential for business development” was quantified by summing the scores attributed to each parameter (e.g., Land value per square metre + Population Density + Educational Indices + Sanitation + Land use + Transportation connections+ Health Structure).

Table 2 - Attractiveness and marketing potential

Parameter	**Method for calculation**	**Score**	**Description**
Infrastructure	Calculated according to the availability of paved roads, water and sewage network, distance from schools and health units	1	No sanitation structure, paved roads, education network and consolidated health network.
		2	With sanitation structure, paved roads, education network, health network, water in consolidation.
		3	With sanitation structure, paved roads, education network, health network, available water.
Potential of future residential use	Calculated as used in the Municipal Master Plan, considering the possibilities of use for homes.	0	Areas not indicated for residential use
		1	Areas indicated for single - family residential use
		2	Areas indicated for horizontal or/and single -family multifamily use

		3	Areas indicated for single - family, horizontal and vertical multifamily residential use.
Possibilities of future uses for trade	Calculated as used in the Municipal Master Plan, considering the possibilities of use for trade	0	Areas not indicated for trade use
		1	Areas where compatible or tolerable activities can be developed in residential areas (e.g. residential galleries, hotels, retailers)
		2	Areas where compatible and tolerable activities occur in residential areas (e.g. retail trade, gas stations, bank branches)
		3	Areas where compatible, tolerable and uncomfortable activities occur in residential areas (e.g. carriers, wholesale trades of fuel storage.)
Possibilities of future uses for industry	Calculated as used in the Municipal Master Plan, considering the possibilities of use for the industry.	0	Areas not indicated for industrial use
		1	Areas where industrial activities can be developed in accordance to residential areas (e.g. manufacturing of food products)
		2	Areas where compatible and/or tolerable industrial activities can be developed by the residential area (e.g. manufacturing of wood products).
		3	Areas where compatible, tolerable and/or uncomfortable industrial activities can be developed to the residential areas (e.g. cosmetics manufacture and cleaning products)
		4	Areas where compatible, tolerable, uncomfortable and incompatible industrial activities can be developed to the residential areas (e.g. metallurgy, slaughterhouses and refrigerators)
Expected regeneration costs	Calculated according to the size of the area of each scar of gully.	1	Gully with an area larger than 10000 m²
		2	Gully with area between 2001 and 10000 m²
		3	Gully less than 2000 m²
Ease of developing new enterprises	Calculated considering restrictions on use and the size of the surrounding areas. The larger the unused area the better the score, because the cost of giving recovery is more	0	Green area or special use where the building of houses, installation of industries or commerce is not allowed
		1	Consolidated urban area
		2	Allotment with low occupation, controlled

	easily diluted in areas that can be used by large enterprises.		occupation zone or areas in river valleys located in consolidated Urban Area
		3	Areas where urban voids predominate
Drainage	Consider whether Gully is in a natural drainage area. There are restrictions on Brazilian law for the development of enterprises in areas of drainage or source.	0	Gully positioned in the valley bottom with natural drainage
		2	Gully positioned in the slope

“Attractiveness and marketing potential” was quantified by summing up the scores attributed to parameter infrastructure, expected regeneration costs, ease of developing new ventures and drainage. The possibilities of future uses can be considered according to municipal planning (residence or commercial or induction).

Table 3 - Environmental risks

Parameter	**Method for calculation**	**Score**	**Description**
Gully area size	The higher the size of the gully the higher the risk	1	Gully with an area of up to 2,000 m²
		2	Gully with an area Gully area size of between 2.001 and 10,000 m²
		3	Gully with an area larger than 10,001 m²
Erosive Process activity	Score according to stability of the area of Gully.	2	Stable or Gullies
		3	Gullies unstable
Zoning	Calculated according to the proximity to urban infrastructure, being considered the highest grade for areas without structure and close to the urban perimeter.	1	Urbanized area, with control of rainwater surface runoff (zones that are not green areas, built areas).
		2	Not urbanized area with rural use.
		3	Periurban area with low urbanization or green areas within the urban perimeter, and with linear structures that facilitate the concentration of surface water.
Risk	Calculated according to the proximity of the gullies of built areas, based on the analysis of orbital image compositions.	1	Area without residences or public infrastructures over 301 from the surroundings of gully.
		2	Area with residences or public infrastructures between 300 and 101 metres from gully.
		3	Area with residences and public infrastructures less than 100 metres

“Environmental risk” was quantified by summing up the scores attributed to the parameters (gully area size + Erosive Process Activity + Zoning + Risk), considering the sum of all assigned values.

2.3. Marketing

Marketing potential was assessed based on the integration of data from the previous steps, aiming at obtaining indications for future use, as well as identifying trends in relation to land use and occupation in the municipality of Bauru.

In the “attractiveness and marketing class”, the score used for final classification considered the infrastructure, expected recovery (or restauration) costs, connection to drainage and ease of developing new enterprises. The score regarding the possibilities of future, commercial, residential and industrial uses was not considered because each area of the city has specific restrictions for use, as indicated in the Municipal Master Plan for each neighbourhood in the municipality; in this way, only the sum of the other parameters was considered, they being: expected regeneration costs, ease of developing new enterprises, drainage, and infrastructure.

3. Results

3.1. Inventory

The inventory of gullies demonstrated that in 2004 (Figure 2 A), 175 gullies existed in the urban area occupying an area of more than 64.1 hectares. In 2020 (Figure 2 B), the number of gullies had increased to 189, with an affected area of 62.5 hectares (Table 4).

Table 4: Number of gullies and affected area in 2004 and 2020. Stable areas, where no further evolution of gullies during the analysed time interval; and unstable where erosion progressed visibly in satellite images.

Classification		**Gullies number and percentages of total**		**Affected area m² percentages of total**	
Gullies in 2004	stable	145	82,9%	472425	73,6%
	unstable	30	17,1%	169043	26,4%
Total in 2004		175		641468	
Gullies in 2020	stable	139	73,5%	466400	74,5%
	unstable	50	26,5%	159527	25,5%
Total in 2020		189		625927	

Between 2004 and 2020, a total of 37 gullies were mitigated and reintroduced into urbanization with an area of 6.2 hectares (Table 5). Most recovered gullies were already stable with vegetation inside the gully channel. However, the area affected by the 13 active gullies that were recovered represented approximately 2/3 of the recovering area (Figure 3 A, B). Large areas affected by gullies were recovered during this period, generally for residential use or for the construction of urban infrastructure.

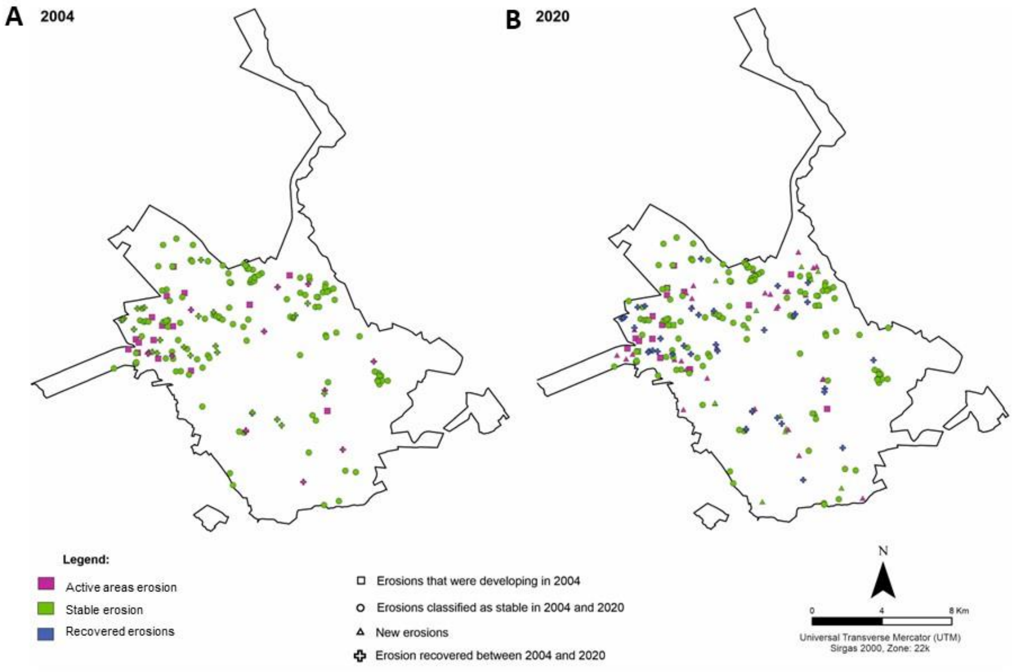


Figure 2: Gullies inventory in 2004 (A) and 2020 (B).

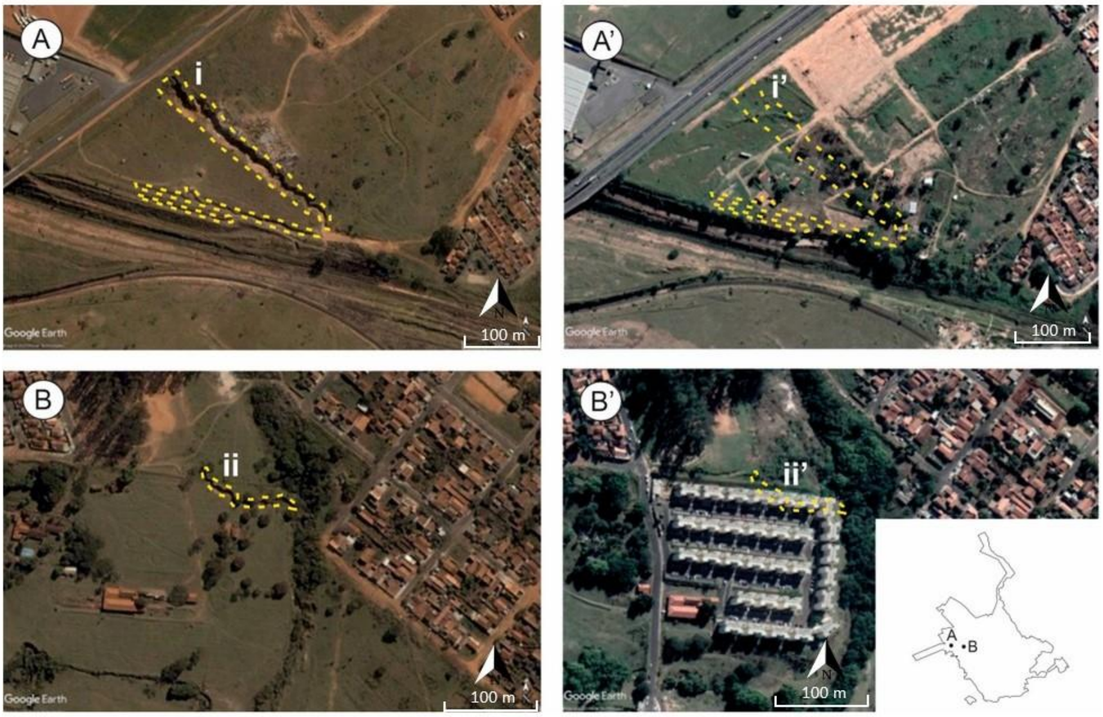


Figure 3: (A) large gully (i) active in 2004; (A') after remediation channel covered (i') and reintroduction of the area in the urban environment; (B) gully channel (ii) connected to a watercourse in 2004; (B'') area with social use recovered in 2020, after remediation of the area affected by gullies and the construction of residential buildings (ii').

Table 5: Areas where gullies were recovered between 2004 and 2020.

Gullies recovered between 2004 and 2020	**Number and percentages**		**Affected area m^2 percentages of total**	
Classified as “stable” in 2004	24	64.9%	21420	34.1%
Classified as “unstable” 2004	13	35.1%	41410	65.9%
Total	37		62830	

Between 2004 and 2020, 51 new gullies (Figure 4 A, B) were identified, most of which were already active in 2020. However, the number of new gullies is greater than the number of recovered gullies. The new gullies are smaller than the gullies that were recovered, which contributed to the reduction in the area affected by them. Most gullies that were not stabilized in 2004 showed changes in channel development in 2020. The gully-affected area in 2020 is lower than in 2004, but the number of existing gullies is higher (Table 6).

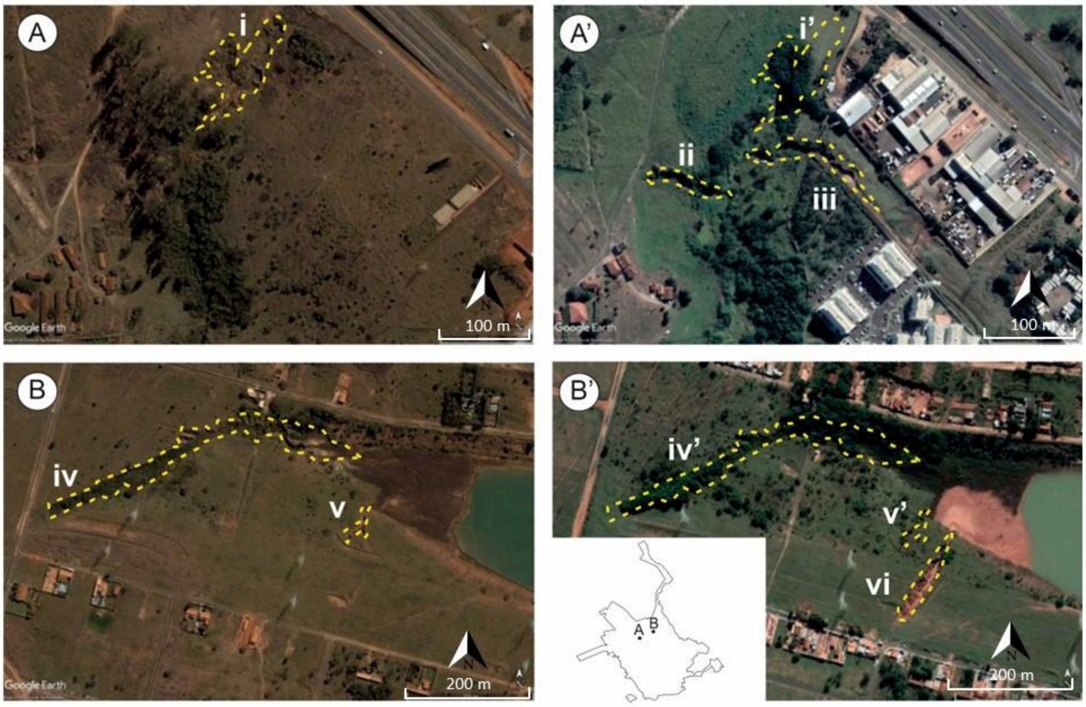


Figure 4: Some areas affected by new gullies between 2004 and 2020; (A) area with stable gully (i) in 2004; (A’) Gully channel development near residential condominium (iii) in 2020; (B) Quinta da Bela Olinda: area with two (iv and v) stable gullies in 2004; (B’) Quinta da Bela Olinda in 2020: area with two stable gullies (iv’ and v’) and a newly developed gully (vi).

Table 6: Existing gullies in the study area in 2020.

Classification		**Gully number and percentages of total**		**Affected area m^2 percentages of total**	
Gullies that emerged between 2004 and 2020	stable	16	8.5%	11,077	1.8%
	unstable	35	18.5%	33,265	5.3%
Gullies classified as stable in 2004 and 2020		121	64%	451,005	72%

Situation in 2020 of gullies classified as under development in 2004	stable	2	1%	4,318	0.7%
	unstable	15	8%	126,262	20.2%
Total		189		625,927	

3.2. Classification of Priority gullies

Based on the analysis performed in the inventory, the existing gullies in 2020 were classified according to “local potential for business development”, “attractiveness and marketing”, and “environmental risks”.

3.2.1. Local potential for business development – Class 1

Seven parameters were analyzed (Figure 5 and Table 7). Regarding value per square metre, approximately 85% of gullies occurred in areas with costs between $6 and $60 US dollars. At least 50% of gullies are in areas with a population density of up to 500 people per hectare. In total, 54% are in areas of urban expansion with still open spaces. Approximately 50% of the areas with gullies are in regions close to educational institutions, and 59% are in regions with a complete sanitation structure, 51% have good transportation connections. The only parameter that did not obtain any parameter with values greater than 50% was health structures, the classification showed a distribution of the values between the parameters. The overall classification of this criterion indicated that the areas with the highest scores are in urban expansion zones or in urban open spaces (Figure 6).

Table 7: Relationship between identified gullies and parameters established in the methodology for “Local potential for business development” analysis.

Parameter	Score	Number of gullies	Percentage
Land Value per Square Metro	0	0	0.0%
	1	162	85.7%
	2	31	16.4%
	3	6	3.2%
Population density	0	96	50.8%
	1	60	31.7%
	2	24	12.7%
	3	9	4.8%
Educational indices	1	37	19.6%
	2	57	30.2%
	3	95	50.3%
Sanitation	1	67	35.4%
	2	2	1.1%
	3	112	59.3%
Land use	1	103	54.5%
	2	21	11.1%
	3	65	34.4%
Transportation connections	1	66	34.9%
	2	25	13.2%
	3	98	51.9%
Health structure	1	61	32.3%
	2	56	29.6%
	3	72	38.1%

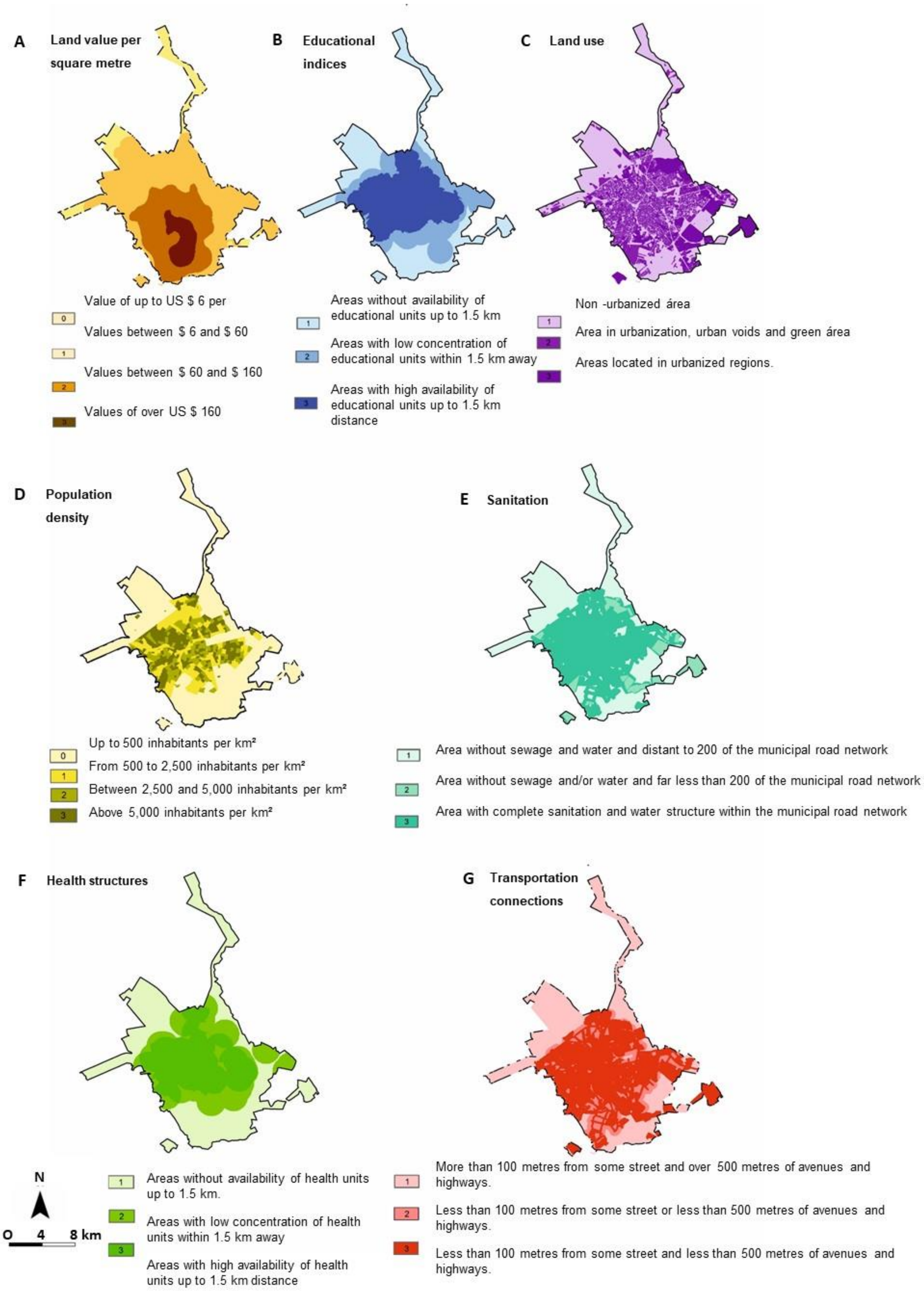


Figure 5: Analysis of the proposed parameters and scores in the work methodology for “Local potential for business development” classification: (A) Land Value per Square Metro; (B) Educational indices; (C) Land use; (D) Population density; (E) Sanitation; (F) Health structure; and (G) Transportation connections. Prepared based on the Master Plan maps [28].

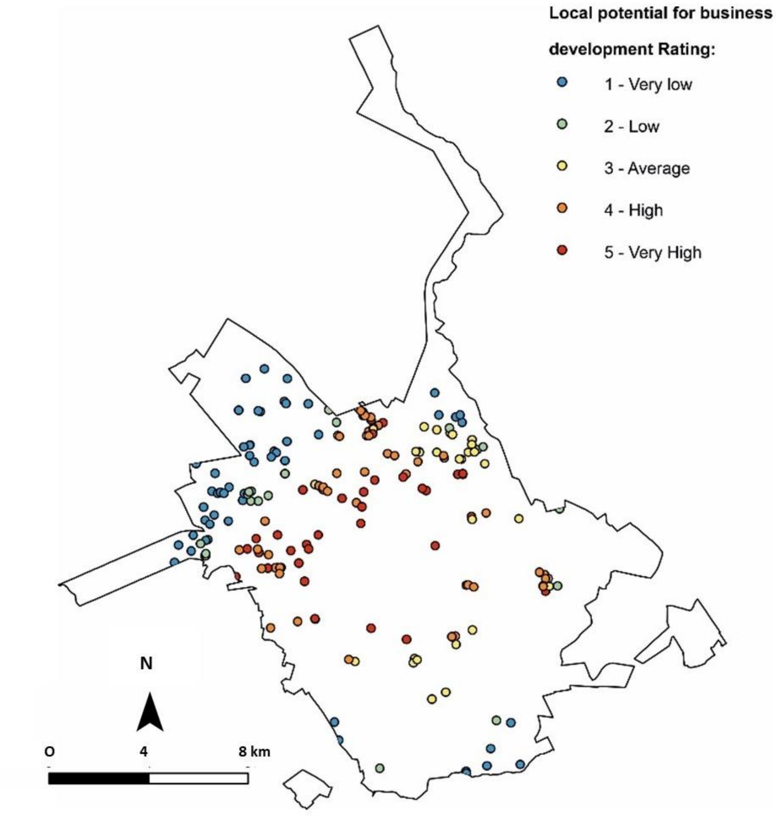


Figure 6: Map indicating the ranking of gullies in relation to the "Local potential for business development".

3.2.2. Attractiveness and marketing of the area affected by gullies – Class 2

The analysis of the attractiveness and marketing of areas affected by the gullies is shown in Figure 7 and Table 8. Some parameters indicated a correlation greater than 50% with areas affected by gullies.

Table 8: Relationship between identified gullies and parameters established in the methodology for attractiveness and marketing analysis.

Parameters	Score	Number	Percentage
Infrastructure	1	46	24.3%
	2	43	22.8%
	3	100	52.9%
Expected regeneration costs	1	12	6.3%
	2	53	28%
	3	124	65.6%
Ease of developing new enterprises	0	13	6.9%
	1	39	20.6%
	2	71	37.6%
	3	66	34.9%
Drainage	0	105	55.6%
	2	84	44.4%
Possibilities of future uses for residence	0	49	25.9%
	1	1	0.5%
	2	0	0%
	3	139	73.5%
	0	14	7.4%

Possibilities of future uses for trade	1	78	41.3%
	2	57	30.2%
	3	40	21.2%
Possibilities of future uses for industry	0	14	7.4%
	1	115	60.8%
	2	25	13.2%
	3	29	15.3%
	4	6	3.2%

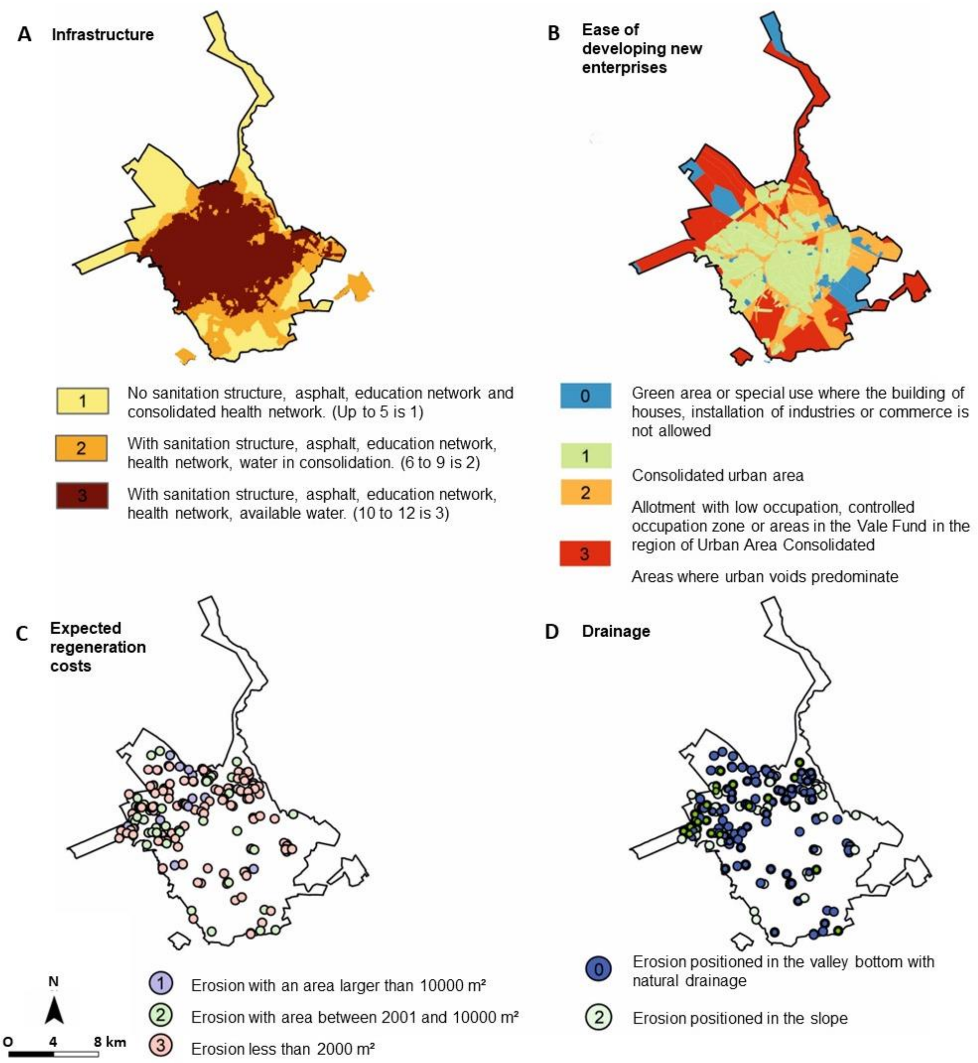


Figure 7: Maps produced for analysis of the proposed parameters and scores in the work methodology for classification of attractiveness and marketing: (A) infrastructure; (B) ease of developing new enterprises; (C) expected regeneration costs; and (D) drainage. Prepared based on the Master Plan maps [28].

Most gullies, 52%, are in areas with good municipal urban structure. Approximately 65% of gullies affect an area less than 2,000 m², and most gullies are in slope areas without contact with natural drainage. The ease of developing new ventures has not indicated any correlation.

Among the possible uses for the areas (Figure 8), most of them, 73%, can be used for different residential uses. Use for small business or industrial activities compatible with residential use is indicated in 41% and 60%, respectively. As three distinct analyses of use were applied, residential, commercial and industrial, three different rating were also generated (Figure 9). The result indicates the three different classifications for the “attractiveness and marketing potential” class, according to the existing municipal master plan restrictions for residential, commercial or industrial use.

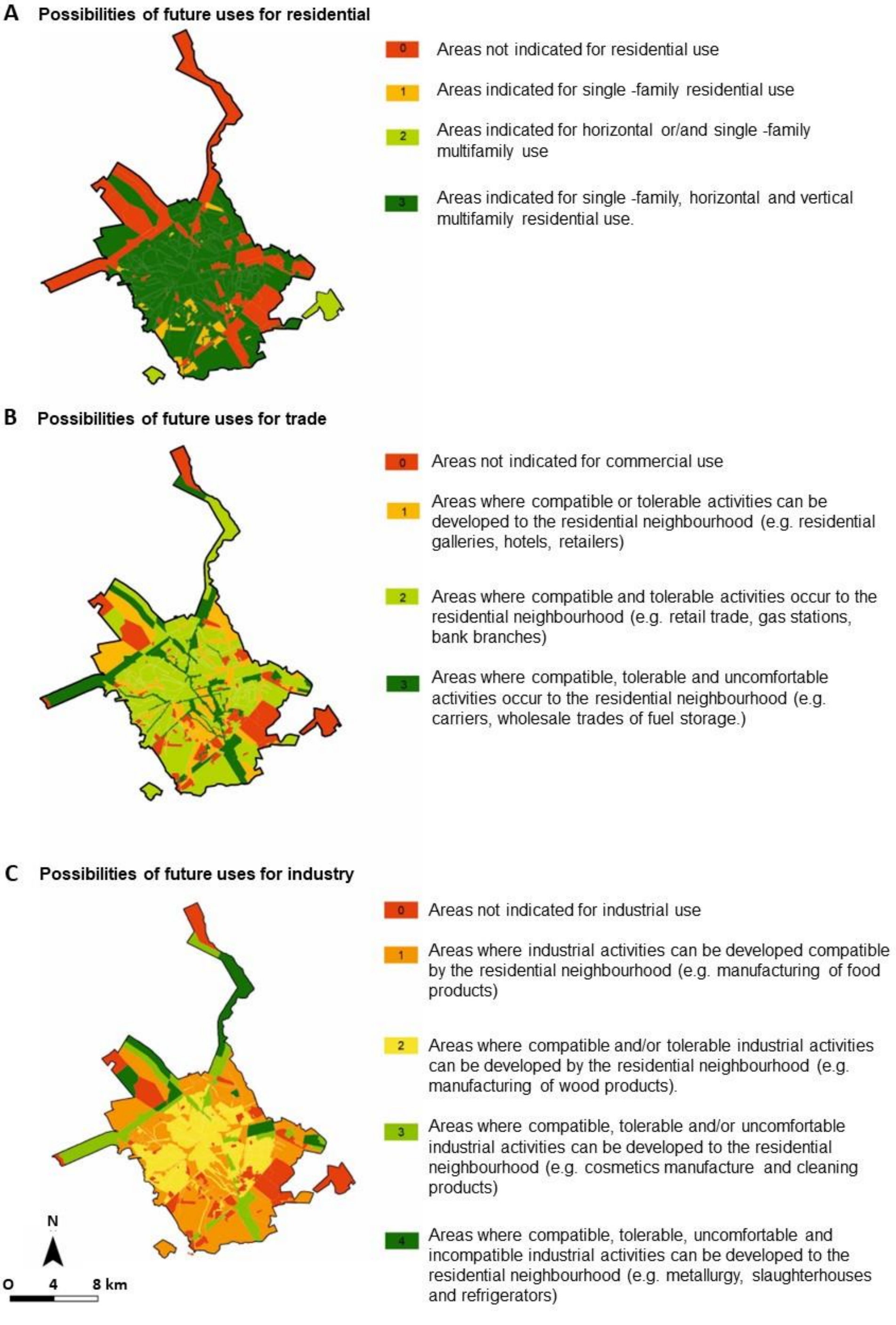


Figure 8: Map with the different possible uses, as indicated in the Municipal Master Plan for each region of the city, considering the (A) possibilities of future uses for residence; (B) possibilities of future uses for trade; and (C) possibilities of future uses for industry [28]

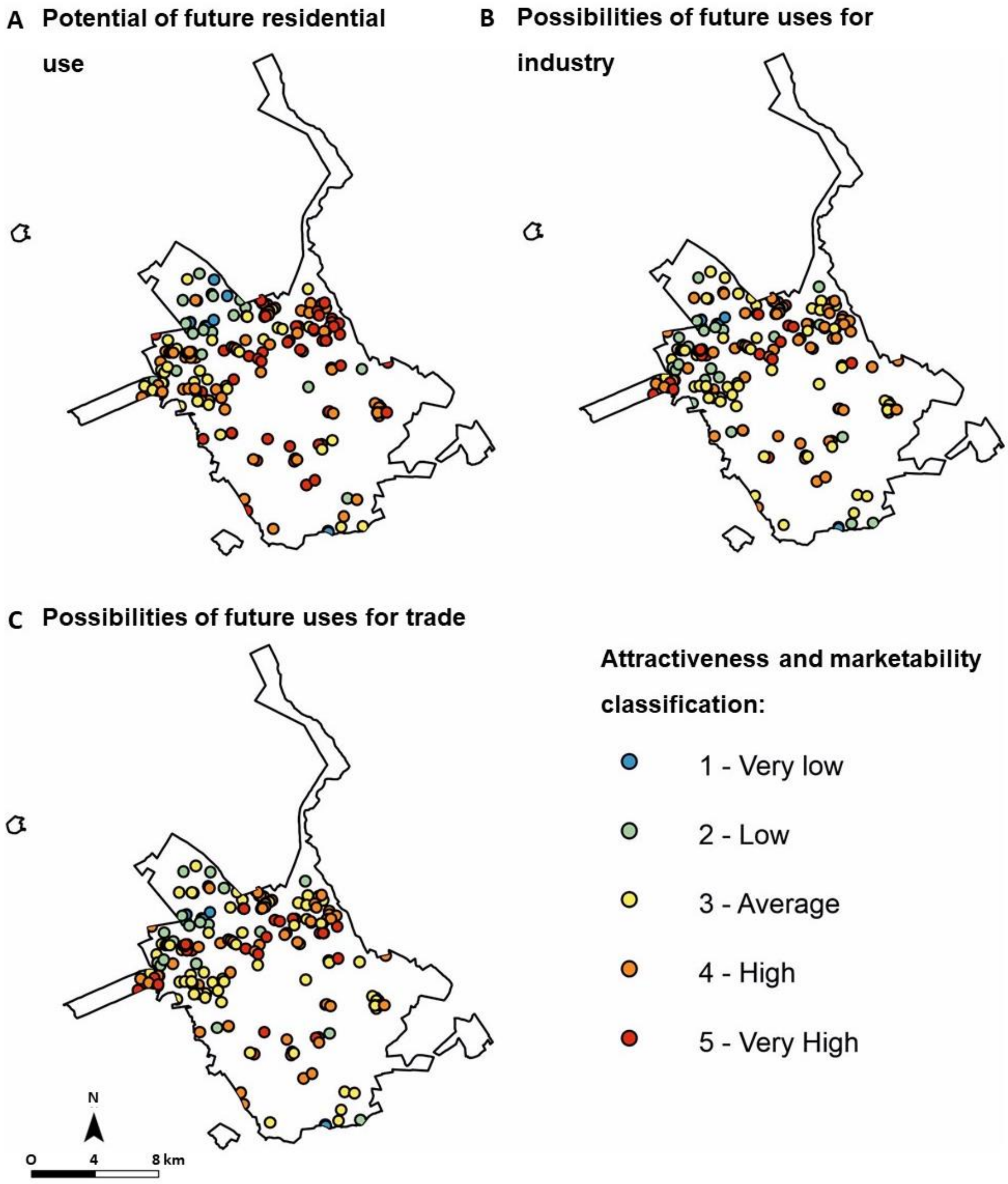


Figure 9: Map indicating the rating of gullies regarding "attractiveness and marketing potential" class, considering the possibilities of (A) residential, (B) industrial and (C) trade use.

3.2.3 Environmental risks - Class 3

Four parameters were analyzed (Table 9 and Figure 10). Environmental risk analyses considered the size of the area of gully; whether gully was active or still developing, urban zoning in relation to urbanized areas, areas with urban voids and nonurbanized areas and green areas, and, in the risk analysis, proximity to urban structures was considered.

Most gullies, 65%, have an area of less than 2,000 m². The analysis indicates a correlation with gully activity, and 73% of gullies are classified as stable. In the zoning class, there was no strong correlation with any of the classes. All gullies analysed are at least 300 metres from some public or private infrastructure. Based on the criteria analysed, gullies were classified in relation to environmental risks (Figure 11).

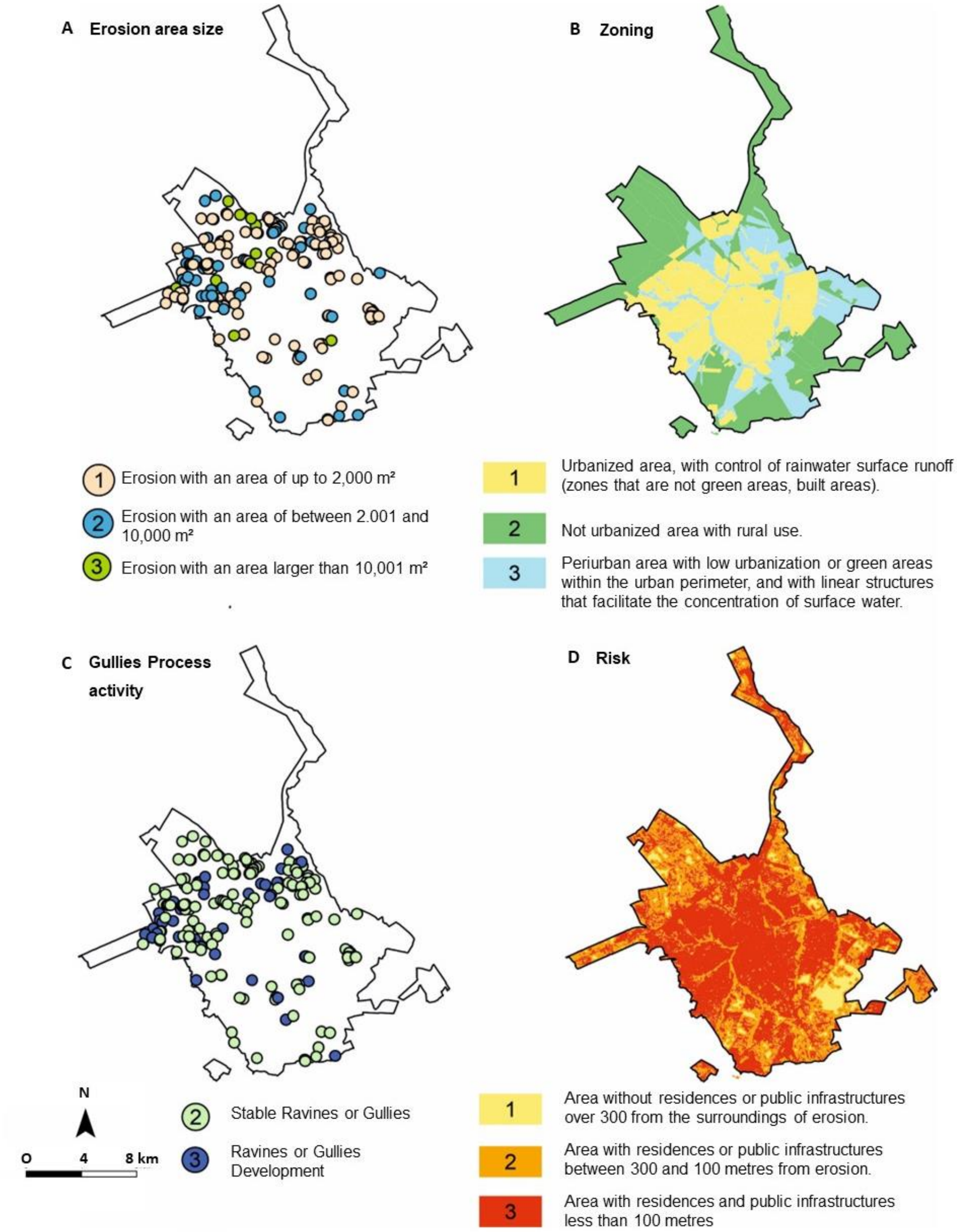


Figure 10: Maps produced for analysis of the proposed parameters and scores in the work methodology for environmental risk classification: (A) gullies area size; (B) zoning; (C) gullies process activity; and (D) risk: proximity with urban structures. Prepared based on the Master Plan maps [28].

Table 9: Relationship between identified gullies and parameters established in the methodology for environmental risk analysis.

Parameters	**Score**	**Number**	**Percentage**
Gullies area size	1	124	65.6%
	2	53	28%
	3	12	6.3%
Gullies Process activity	2	139	73.5%
	3	50	26.5%
Zoning	1	39	20.6%
	2	78	41.3%
	3	72	38.1%
Risk: Proximity with urban structures	1	0	0%
	2	95	50.3%
	3	94	49.7%

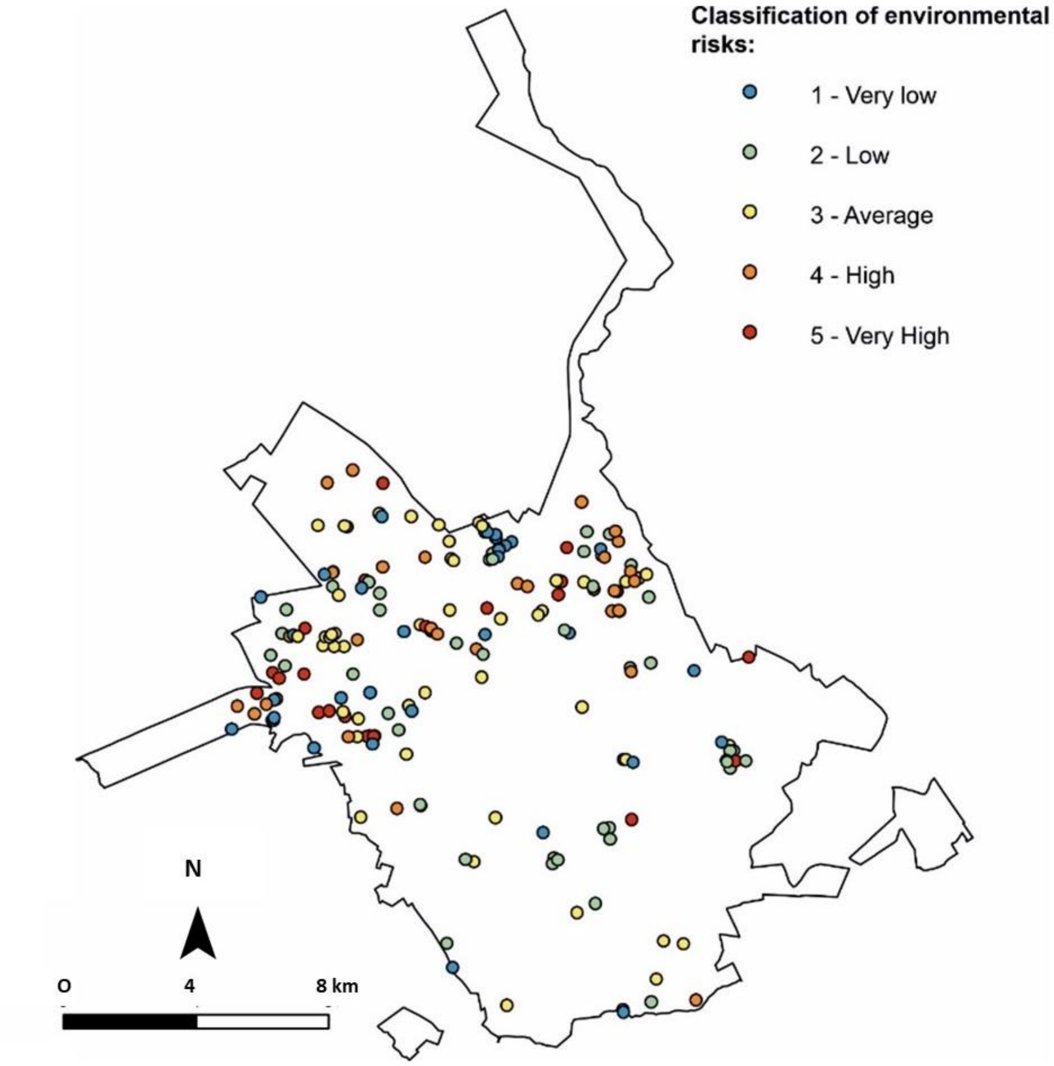


Figure 11: Map indicating the classification of gullies in relation to environmental risks.

3.3 Analysis of priority areas

The classification can be analysed individually for each of the 3 classes or analysed in an integrated way. Gullies that have a high rating considering the 3 classes, are cases where, if prioritized, they can at the same time reduce the risk and present economic gains if the area is reintroduced for urban use.

The 30 best classified gullies when adding the rating of the 3 classes analysed are concentrated mostly in urban expansions, northwest of the city (Figure 12 A). The 7 gullies with the highest potential are concentrated in the Quinta da Bela Olinda region (Figure 4 C and D). The data indicate that this is the area with the highest development potential today and has gully with the highest risk of activities.

When considering the 30 best classified gullies with an area greater than 5000 m² (Figure 12 B), although there is still a larger concentration of gullies in the northwest sector of the city, well-classified gullies also occur in other sectors, indicating a greater dispersion of erosive processes.

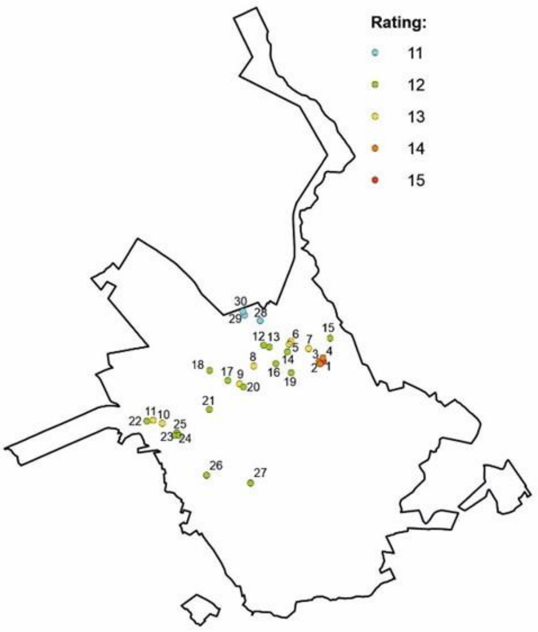
4. Discussion

The inventory indicated an increase in the number of gullies between 2004 and 2020 from 175 to 189. The area directly affected by gully channels decreased from 64.1 hectares to 62.5 hectares. The contrast between the increased number of gullies and the reduced area is the result of the remediation of large channels among the 37 recovered gullies; most small gullies (51 new channels) emerged between 2004 and 2020, indicating that gullies will increase in number, but these gullies still have a smaller size. Although the reduction in the affected area is good news, the existence of a greater number of gullies may indicate a growth trend in the medium term.

Brownfields are found in urban centers and have potential land resources that can be important areas to reduce land scarcity [30]. Brownfield can be areas of old factories, buildings, railways, military areas, but there are also authors who consider mining areas, semi-urban areas and agricultural areas [31, 32]. Gullies are generated by natural and anthropogenic factors [33], and in urban areas they are related to inadequate land use [4, 8]. In other cities in Brazil and around the world, gullies also occupy significant areas and are a challenge for the development of cities, due to the creation of abandoned areas [4, 8, 33, 34, 35]. Gullies can therefore be classified as a form of Brownfield, as they are generated due to inadequate soil use, making the use of land in areas that could previously be occupied unfeasible, but in the same way as occurs with other Brownfields, if the necessary interventions, these areas can be reinserted for land use.

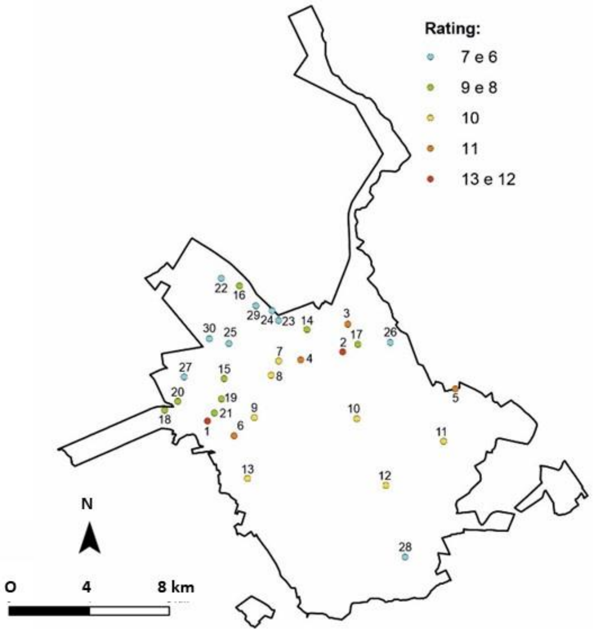
Although the area directly affected by gully channels is 62.5 hectares, the surrounding area indirectly affected can easily be 10 times larger, as the gullies make the use of the surrounding area unfeasible. This demonstrates that gullies represent a problem with very significant dimensions. Reintroducing these spaces for urban use is crucial in city management. Although they are a significant challenge, the existence of large urban areas without occupation is also an opportunity, and the size of brownfields in hectares was a positive parameter for areas to be recovered [36]. The recovery of areas affected by gully also prevents new damage in the vicinity. The inventory indicated that the areas of urban expansion have the largest number of gullies, while in consolidated urban areas, new gullies in most cases are related to inadequate drainage structures.

A Classification of the 30 priority erosions



Number	Area (m²)	Class 1	Class 2	Class 3	Ranking
1	114	5	5	5	15
2	177	5	5	4	14
3	1354	5	5	4	14
4	236	5	5	4	14
5	45	3	5	5	13
6	104	3	5	5	13
7	2906	4	4	5	13
8	289	5	5	3	13
9	276	4	5	4	13
10	808	5	3	5	13
11	5858	5	3	5	13
12	199	4	4	4	12
13	124	4	4	4	12
14	5563	4	3	5	12
15	901	3	5	4	12
16	891	5	4	3	12
17	1898	5	5	2	12
18	2271	4	3	5	12
19	534	5	5	2	12
20	839	5	5	2	12
21	1626	5	4	3	12
22	2701	4	3	5	12
23	392	4	3	5	12
24	337	4	3	5	12
25	153	4	3	5	12
26	240	5	5	2	12
27	481	5	4	3	12
28	1685	5	5	1	11
29	425	4	4	3	11
30	398	4	4	3	11

B Classification of the 30 priority erosions greater than 5000 m²



Number	Area (m²)	Class 1	Class 2	Class 3	Ranking
1	5858	5	3	5	13
2	5563	4	3	5	12
3	9774	3	3	5	11
4	11949	4	2	5	11
5	6908	2	4	5	11
6	40070	4	2	5	11
7	50666	4	3	3	10
8	21972	4	2	4	10
9	5337	5	2	3	10
10	7327	5	2	3	10
11	9721	4	3	3	10
12	15284	3	2	5	10
13	42385	4	2	4	10
14	5511	5	3	1	9
15	6275	2	3	4	9
16	11684	1	2	5	8
17	6955	3	2	3	8
18	9334	1	2	5	8
19	19087	4	2	2	8
20	12119	1	2	5	8
21	5650	5	2	1	8
22	5537	1	2	4	7
23	58596	2	2	3	7
24	13349	2	2	3	7
25	8627	1	1	5	7
26	7175	2	2	3	7
27	5853	1	2	4	7
28	7341	2	2	3	7
29	12162	1	2	3	6
30	6099	1	1	4	6

Figure 12: Considering the three classes considered: local potential for business development (Class 1); attractiveness and marketing potential (Class 2); and environmental risks (Class 3), the figure shows the classification of priority gullies: a) map with the 30 best classified gullies; B) map with the 30 gully larger than 5000 m² better classified.

Regarding the class "local potential for business development", among the parameters, the strongest correlation was in relation to costs per square metre between $6 and $60, which was one of the lowest scores in the analysis. This indicates a relationship between the existence of gully and the low value of the property. However, this correlation can also indicate an opportunity. Low land prices increase attractiveness for potential investors [17]. However, the data also indicated that most areas affected by gully are in places close to educational institutions and with public sanitation and good transportation calls. Thus, the recovery of areas affected by gullies can be a good opportunity considering the existing public infrastructures in the surroundings. In the long run, the trend is that the areas affected by gullies that are not considered today for new enterprises become attractive due to their location in the city. Local potential analyses developed in this work can accelerate this process due to the creation of indicators that demonstrate the competitive differences of each area.

The class “attractiveness and marketing” showed that most gullies are positioned in places with good urban infrastructure and have a scar with an area of less than 2000 m². According to [37], small gullies have not only lower costs for regeneration but also less technical complexity than large gullies. Regarding the ease of development of new enterprises, a strong correlation with any proposed class was not indicated. However, large urban voids may provide excellent opportunities for large enterprises, which helps to cover eventual remediation costs [36].

The analysis of attractiveness and marketing allows us to relate gullies to the possibilities provided for in the city's master plan. This is interesting to identify areas most suitable for specific use according to municipal standards. Residential use was the most suitable in 73% of cases, but small industries and trades were also possible in 60% and 41% of areas, respectively. If enterprises seek the construction of large industries and trades, the map produced also allows an easy view of the areas possible to develop this activity.Low potential areas for these three uses (residential, industries and trades) can be used as green space or left as brownfield, which does not involve the construction of infrastructure [38]. Alternative uses may be connected to geotourism and education programs [39]. Municipal public policies and tax incentives can assist in more sustainable land use, allowing the best option to be taken for the urban community [17].

Risk analysis has indicated that all existing gullies in the area are at least 300 metres from some public or private infrastructure. This indicates the need for monitoring all gullies, as in some cases, these gullies may have a rapid evolution, and if mediation measures are not performed, they can destroy infrastructures and even cause fatalities. Most gullies are less than 2000 m² and classified as stable, so the reactivation of these channels or the rapid growth of smaller channels may occur when soil use and occupation change or extreme weather events occur.The three priority categories can be analysed separately according to the user's interest; for example, if the interest is to find areas with good local potential, only class 1 should be considered, but if the goal is to analyse or monitor the evolution of the gully risk, class 3 will indicate priority gullies that may cause significant economic or environmental damage.The final priority analysis indicated that the area of Quinta da Bela Olinda has better classified gullies, considering the sum of the three priority categories. This reinforces the analysis performed by [11], who estimated that approximately 80.7 hectares in that region are affected due to the existence of gullies. The environmental and economic impacts calculated by the authors demonstrate that losses exceed $76.4 Million over the last few decades. The area was planned for residential use, but the development of gullies over the last three decades made it impossible to use the site. Reintegrating this area into the urban environment represents a good opportunity for municipal entrepreneurs and managers, but this requires creating marketing strategies to convince local actors. The creation of databases that bring together information on the techniques used to regenerate the areas, existing costs and monitoring measures applied may represent a risk reduction factor and improve agility in decision-making and application of resources more assertively.

The analysis carried out by applying the TIMBRE methodology allows us to visualize which areas affected by gullies have the greatest potential to return them to use. The classification can indicate among hundreds of gullies which of them are in areas with high potential for urban use. After the classification carried out by the methodology, it is necessary to carry out on-site analyses of the priority gullies. Geomorphology (slope, drainage basin size, strand shape), Geology (rock type, aquifer characteristics), soil (cohesion, permeability, erodibility, soil thickness) and other factors such as characteristic of vegetation and anthropogenic changes in land use, can be important conditions in the gullies analysis, to view details related to any technical difficulties existing in the area [2, 3, 4, 12, 13].

The inventory demonstrated that several areas were reintroduced into the urban environment in the municipality of Bauru during the time interval analysed, thus indicating that the reintroduction of gully brownfields is possible. However, the creation of urban green areas in places affected by gullies is also an alternative. The TIMBRE methodology applied to gully classification can be an important ally for managers' decision-making.Although the data collected in this study provide important information on the areas with the highest potential, it is necessary to consult the population and local managers to build consensus and establish priorities for use for the affected areas. This will also depend on land ownership (public vs. private land).

To convince stakeholders, dialogue strategies must be developed. [40] identified five groups interested in brownfield regeneration: site owners, authorities, neighbours and others interested in the problems related to the area, service providers, and scientific community. These same authors propose a participatory methodology consisting of five phases, which involves (i) planning and preparatory work, (ii) mapping of stakeholders, (iii) development of activities such as workshops and lectures to foster engagement, (iv) application of a devolutionary questionnaire and (V) feedback for each of the stakeholders involved.

The establishment of a governance strategy through policies is another factor that can help in the regeneration of Brownfields, as the time required for complete implementation of a municipal or even project strategy may be longer than the period of managers' electoral mandates [41]. The classification presented here provides an important indicator for gully brownfield management, just as it is already done with other types of brownfield portfolios. To identify the variables that are most relevant for area recovery. The construction of databases assisting the analysis of territorial evolution can be an important metric to make decision-making increasingly assertive.

Application of this method to other places is possible provided it is adjusted to local data. The development of decision support systems (DSS) for gullies management in urban areas can help solve the complexity involved in the areas, as proposed for contaminated areas [42]. Tools also help identify and manage the specific opportunities and risks of each remediation project [43].

The methodology can also help other types of analysis, for example, for insurance companies to establish the prices for lands or buildings according to the risk scores. It can also help investors to define the risks that exist for investments in areas affected by gullies. Thus, the proposed method's main strength is the ability to visualize and classify many gullies in a wide area. However, this regional analysis is based on simplifications, which is a limitation of the work. Therefore, after choosing the priority gullies, it is necessary to detail the characteristics related to the physical and social environment of each of them.

5. Conclusions

This work demonstrated that the TIMBRE method can be successfully adapted for the analysis brownfields caused by gullies. This adaptation allows for an investigation of which are the priority areas for gully development, facilitating decision-making by managers, communities and investors in cities where this problem is relevant. The use of this type of analysis can help in the reintroduction of important idle spaces in cities in developing countries, where the disorderly growth of urban areas has favoured the creation of gully-derived brownfields.

The inventory performed by this work showed an increase in the number of gullies in the urban perimeter; however, the area affected by gully scars was reduced by approximately 2 hectares. The recovery of areas affected by gully was mainly due to urban structure works and residential construction. Brownfields are concentrated in peripheral regions and in the urban growth zone. However, many of these areas have a good urban infrastructure and several services nearby. Creating pathways that facilitate reintroduction reduces the cost of development of new housing, industries or trade.

The adaptation of the gullies analysis methodology is a first step, but further research needs to be performed to create more complete databases that allow sharing knowledge between different cities and countries that have gully-derived brownfield problems. The construction of this type of database allows for an analysis of good practices or even the registration and study of unsuccessful cases.

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