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PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS E MEIO AMBIENTE

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

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Instituto de Geociências e Ciências Exatas
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Rio Claro – SP

2024

UNIVERSIDADE ESTADUAL PAULISTA
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METHODOLOGY TO DETERMINE THE SOCIOECONOMIC IMPACT AND ECOSYSTEM SERVICES LOSS CAUSED BY RAVINES AND GULLIES

CAIUBI EMANUEL SOUZA KUHN

Tese de Doutorado em cotutela com a Universidade de Tübingen (Alemanha)

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Orientador: Prof. Dr. Fábio Augusto Gomes Vieira Reis (UNESP)

Orientador: Prof. Dr. Peter Grathwohl (Universidade de Tübingen)

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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.

Keyword: Evaluation, Impact analysis, Civil defense, Brownfields, Soil.

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.

Palavras chaves: Avaliação, Análise de impacto, Defesa civil, Brownfields, Solo.

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.

Stichwort: Evaluation, Wirkungsanalyse, Zivilschutz, Brachflächen, Boden.

List of accepted publications

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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List of submitted publications

III. **Kuhn CES**, Reis FAGV, Furegatti SA, Zarfl C, Peixoto ASP (*under 1st review*) Economic impacts of an urban gully are driven by land degradation. Natural Hazards.

*Individual 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.*

IV. **Kuhn CES**, Reis FAGV, Santos FRP, Cabral V, Zarfl C, Grathwohl P (*under 1st review*) Adaptation of the Timbre methodology for gully erosion analysis in urban areas. Heliyon.

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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).

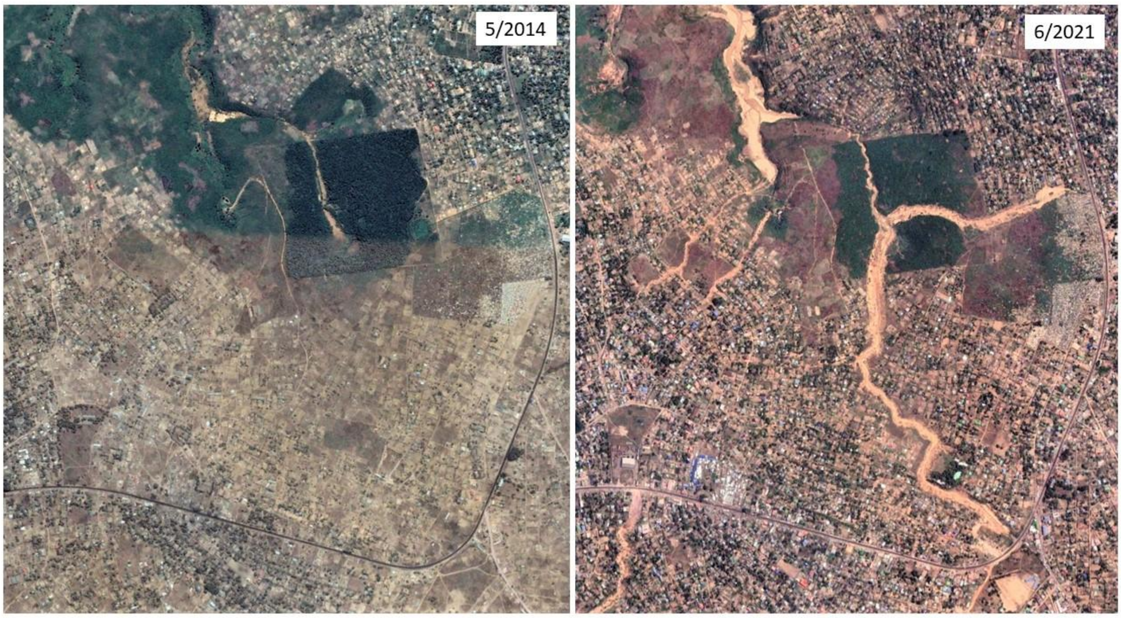

Figure 1. Comparison of two images of the same area, the first from 2014, where the erosive process development of the ravines is clearly visible between 2014 and 2021, in an area with high population density in Kinshasa, the Republic Democratic Republic of Congo. Images extracted from Google Earth (Lat. 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 m^3 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.

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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