Acta Limnologica Brasiliensia

Publication of the Brazilian Association of Limnology

Review Article

Acta Limnologica Brasiliensia, 2026, vol. 38, e5

https://doi.org/10.1590/S2179-975X3725

ISSN 2179-975X on-line version

Impact of unpaved roads on the fluvial ecosystems in the XXI century: a review

Impacto das estradas não pavimentadas no ecossistema fluvial no século XXI: uma revisão

Jeferson Eslei Mazur[1]*, Valdemir Antoneli[1] and Edivaldo Lopes Thomaz[1]

[1]Programa de Pós-graduação em Geografia, Laboratório de Erosão do Solo, Universidade Estadual do Centro-Oeste – UNICENTRO, Alameda Élio Antonio Dalla Vecchia, 838, Vila Carli, CEP 85040-167, Guarapuava, PR, Brasil

*e-mail: jeferson.mazur@gmail.com

Cite as: Mazur, J.E., Antoneli, V. and Thomaz, E.L. Impact of unpaved roads on the fluvial ecosystems in the XXI century: a review. *Acta Limnologica Brasiliensia*, 2026, vol. 38, e5. https://doi.org/10.1590/S2179-975X3725

Abstract: Aim: Considering the strategic role of water resources for ecosystem sustainability and the increasing anthropogenic pressure, particularly from roads, this study aimed to analyze the impacts of unpaved roads on fluvial ecosystems, with emphasis on erosion processes and related mechanisms. **Methods:** A systematic literature review was conducted using the Methodi Ordinatio, with searches in the Scopus and Web of Science databases. After applying the selection criteria, 29 articles published between 2001 and the present were analyzed. Initially, a scientometric analysis was carried out, followed by a knowledge synthesis and suggestions for future research directions. **Results:** The findings indicate a growing interest in the topic, with a geographic concentration of studies in countries such as the USA, China, and Australia, predominantly focused on forest roads in mountainous regions and streams. Most investigations addressed hydro-sedimentological dynamics and the effectiveness of best management practices (BMPs), while fewer studies examined direct impacts on water quality and aquatic biota. The studies showed that unpaved roads reduce infiltration, increase surface runoff, and intensify the production and delivery of fine sediments, with strong hydrological connectivity, especially at stream crossings and roadside ditches. BMPs such as road decommissioning, gravel surfacing, revegetation, and the establishment of riparian zones were effective in mitigating these impacts, particularly when well-implemented and adapted to local conditions. **Conclusions:** Although the reviewed studies provide evidence of the impacts of roads on fluvial systems, gaps remain in the literature. It is necessary to expand the geographical scope of investigations, deepen the evaluation of direct impacts on water quality and biodiversity, especially at a longitudinal scale, and test the effectiveness of BMPs under different environmental conditions to support the conservation of fluvial ecosystems in rural areas.

Keywords: soil erosion; rural roads; environmental impacts; water quality; best management practices.

Resumo: Objetivo: Considerando o papel estratégico dos recursos hídricos para a sustentabilidade dos ecossistemas e a crescente pressão antrópica, especialmente a partir das estradas, este estudo teve como objetivo analisar os impactos das estradas não pavimentadas nos ecossistemas fluviais, com ênfase nos processos erosivos e mecanismos relacionados. **Métodos:** Realizou-se uma revisão sistemática de literatura, a partir do *Methodi Ordinatio*, utilizando as bases Scopus e Web of Science. Após aplicação dos critérios de seleção, foram analisados 29 artigos publicados entre os anos 2001 e o presente. Inicialmente, foi realizada uma análise cienciométrica, seguida por uma síntese do conhecimento e indicações de futuras direções de pesquisa. **Resultados:** Os resultados apontam para um crescente interesse pela temática, com concentração geográfica das pesquisas em países como Estados Unidos, China, Brasil e Austrália, predominando estudos sobre estradas florestais em regiões montanhosas e riachos. Destacam-se investigações sobre a dinâmica hidrossedimentológica e a eficácia das boas práticas de manejo (BMPs), sendo mais escassas pesquisas que tratam dos impactos diretos sobre a qualidade da água e a biota aquática. Os estudos demonstraram que estradas não pavimentadas reduzem a infiltração, aumentam o escoamento superficial e intensificam a produção e entrega de sedimentos finos, com forte conectividade hidrológica, especialmente em travessias de riachos e valas. BMPs como descomissionamento de estradas, uso de cascalho, revegetação e implantação de zonas ripárias mostraram-se eficazes na mitigação desses impactos, sobretudo quando bem implementadas e ajustadas ao contexto local. **Conclusões:** Embora os estudos revisados forneçam evidências sobre os impactos das estradas nos sistemas fluviais, ainda há lacunas na literatura. É preciso ampliar o escopo geográfico das investigações, aprofundar a avaliação dos impactos diretos sobre a qualidade da água e a biodiversidade, especialmente em escala longitudinal, e testar a eficácia das BMPs em diferentes condições ambientais, visando à conservação dos ecossistemas aquáticos em áreas rurais.

Palavras-chave: erosão do solo; estradas rurais; impactos ambientais; qualidade da água; boas práticas de manejo.

1. Introduction

The advancement of economic activities and social development has driven a significant expansion of road infrastructure worldwide in recent decades (Xu et al., 2024a). This growth in the number of roads is directly related to the need to attend the increasing demands for mobility, territorial integration, access to essential services, and the flow of agricultural production. In particular, rural roads play a fundamental role in connecting productive areas and urban centers, enabling the transport of goods, inputs, and people, and are therefore strategic elements for regional development (Farias et al., 2019; Medeiros et al., 2022).

However, despite its socioeconomic importance, the expansion of road networks has been accompanied by a series of negative environmental impacts. Several studies highlight that road construction and use are associated with landscape fragmentation (Yang & Jin, 2024), changes in natural drainage patterns (Zhao et al., 2022a), intensified soil erosion (Ramos-Scharrón et al., 2022), and pollution of water bodies due to contaminated surface runoff (Zhao et al., 2022b). These impacts tend to be even more significant in regions with a predominance of unpaved roads, which are often built with little or no environmental control infrastructure and are subject to degradation processes due to lack of adequate maintenance (Xu et al., 2022).

Unpaved roads, common in rural areas, are highly susceptible to erosion processes (Ramos-Scharrón & Thomaz, 2017). They contribute substantially to sediment generation and increased surface runoff in watersheds (Farias et al., 2019; Valencia-Gallego & Montoya, 2024). This is primarily due to their high density and low infiltration rates, which lead to greater runoff generation (Liao et al., 2024; Xu et al., 2024a). As a result, these roads not only promote soil degradation (on-site) but also negatively impact water quality (off-site) by transporting sediment particles, nutrients, and contaminants to water bodies from ditches, culverts, and gullies (Thomaz et al., 2014; Navarro-Hevia et al., 2015; Wang et al., 2023; Xu et al., 2024a).

These effects become particularly critical when considering freshwater reservoirs, which are highly relevant hydraulic systems from social, economic, and environmental sustainability. The fluvial systems play essential roles both in supporting the society that depend on them, through the provision of ecosystem services, and in preserving biological communities (Martins et al., 2021). Therefore, to ensure water quality, watershed management strategies and Best Management Practices (BMPs) for soil erosion control must consider the hydrological changes induced by the presence and use of roads (Dangle et al., 2019; Xu et al., 2024b).

Although scientific attention to the environmental impacts of sediment generation in urban environments is growing – as seen in studies evaluating the presence of trace metals in road dust and their effects on water quality (Faisal et al., 2023; Jeong & Ra, 2023; Peng et al., 2024), - or investigations into the use of sediments deposited in rivers for road construction (Khudhur, 2021; Djeran-Maigre et al., 2022), research that comprehensively addresses the impacts of unpaved roads on fluvial ecosystems remains limited.

Soil erosion associated with roads is already well-documented (Lane & Sheridan, 2002; Brown et al., 2013; Yu et al., 2024), moreover studies have examined runoff generation and sediment production on unpaved roads, considering variables such as surface type, road characteristics, traffic, and rainfall patterns (Ramos-Scharrón & Thomaz, 2017; Farias et al., 2019; Valencia-Gallego & Montoya, 2024; Liao et al., 2024), and the effects of road erosion on soil degradation and nutrient transport (Li et al., 2020). However, a deeper understanding is still needed regarding the ecological impacts of unpaved roads, particularly considering the negative effects of sediments (e.g., nutrient, trace metals, organic matter etc.) on water quality and, consequently, on aquatic biota (Yu et al., 2024).

Given the strategic role of water resources in territorial sustainability and the increasing anthropogenic pressure on these systems, it is necessary to expand scientific knowledge on the interactions between rural roads and fluvial ecosystems. In this context, the present study aims to analyze the impacts of unpaved roads on fluvial ecosystems, with emphasis on erosion processes and related mechanism, through a systematic literature review using the *Methodi Ordinatio* method (Pagani et al., 2018). The objective is to characterize the scientific output on the topic, gather evidence on the direct and indirect effects of roads on fluvial systems, as well as to identify effective management practices that can mitigate the damage associated with erosion and sediment mobilization, contributing to the conservation of water resources and the promotion of environmental sustainability. Assessing these impacts and water resource conservation strategies is essential to mitigate the effects of roads on the integrity of aquatic habitats and the diversity of biological communities.

2. Methodology

A systematic literature review was conducted - a methodology that allows for the identification, extraction, and synthesis of data from relevant studies, providing a comprehensive understanding of the topic (Van Dinter et al., 2021). Systematic reviews follow rigorous methodological guidelines to select documents, assess the quality of studies, extract data, and synthesize findings, which ensures replicability (Denyer & Tranfield, 2009).

In this particular research, the systematic review method adopted was the *Methodi Ordinatio* (Pagani et al., 2018). This is a multicriteria decision-making methodology used to select studies, taking into account the number of citations of the article, the impact factor of the journal, and the year of publication. A total of nine steps were followed: 1. Definition of the research objective; 2. Preliminary search in scientific databases; 3. Selection of keyword combinations, databases, and time frame; 4. Final search execution; 5. Removal of duplicate articles and filtering; 6. Identification of impact factor, year of publication, and number of citations; 7. Ranking of articles using the *InOrdinatio equation* (Equation 1); 8. Retrieval of the articles; and 9. Systematic reading and analysis of the texts (Pagani et al., 2018).

After clearly defining the research objective and conducting preliminary searches in academic databases, the descriptors and their variations were selected to ensure a comprehensive and accurate search. The terms used were: *road, erosion, sediment; soil loss, river, stream, water, hydrodynamic, hydrologic, hydrous, silt, lake, floodplain, channel, watershed, pollution, pollutant, contamination, nutrient, best management practices,* and *BMP.* These terms were chosen based on their relevance to the topic, resulting in the retrieval of a significant number of studies aligned with the scope of the investigation. Boolean operators (*OR* and *AND*) were employed to combine descriptors, along with the truncation operator (*) to capture variations of the same term (Table 1).

For the definitive search, the Scopus and Web of Science databases were selected due to their comprehensiveness and relevance (Pranckutė, 2021). Filters were applied to restrict document type to journal articles and language to publications in Portuguese, English, or Spanish. To analyze the currently century of

Table 1. Search results from the databases.

Database	Search String	Total
Scopus	TITLE ((Road* AND (erosion OR sediment* OR "soil loss") AND (river OR stream OR water OR fluvial OR aquatic OR hydrodynamic OR hydrologic OR hydrous OR silt* OR lake* OR floodplain* OR channel OR watershed OR pollution OR pollutant* OR contamination OR nutrient* OR "best management practices" OR BMP)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "Portuguese") OR LIMIT-TO (LANGUAGE, "Spanish") OR LIMIT-TO (LANGUAGE, "English")). 2001-2025	156
Web of Science	Title Road* AND (erosion OR sediment* OR "soil loss") AND (river OR stream OR water OR fluvial OR aquatic OR hydrodynamic OR hydrologic OR hydrous OR silt* OR lake* OR floodplain* OR channel OR watershed OR pollution OR pollutant* OR contamination OR nutrient* OR "best management practices" OR BMP). Document Types: Article; Languages: English or Spanish or Portuguese. 2001-2024	143
Total		**299**

studies and capture recent developments on the topic, only articles published from 2001 to 2025. The search was conducted in April 2025 and initially retrieved 299 articles, as shown in Table 1.

In order to concentrate the information and results directly related to the research objective, the articles were submitted to filtering processes. Initially, duplicate articles were removed with the aid of the Zotero (version 6.0.36) reference manager. In total, 137 studies were excluded at this stage. Subsequently, the remaining articles were screened based on their titles, abstracts, and keywords, according to the following inclusion and exclusion criteria:

2.1. Inclusion criteria

Studies that assess the direct or indirect effects of rural roads on fluvial systems; Research that identifies BMPs to mitigate the impacts of unpaved road erosion on fluvial ecosystems.

2.2. Exclusion criteria

Research focused on urban areas and roads; Studies on the use of dredged river sediments as raw material for road construction; Investigations aimed at the lithological assessment of lakes and riverbeds; Studies on sediment production and surface runoff that analyze road characteristics, traffic, rainfall intensity, and other factors, focusing on surface hydrological impacts (on-site) rather than impacts on fluvial ecosystems (off-site); Research on erosion in cultivated surfaces or road construction sites; Studies on river erosion caused by temperature variation and/or chemical changes; Articles that apply or compare soil erosion and sediment delivery models; Studies that exclusively assess the presence of organic compounds, heavy metals, and other substances in soil and water, or that analyze the effects of erosion on soil degradation and nutrient transport.

After this screening process, 131 articles were excluded, leaving 31 studies for quality assessment. Additionally, a manual search was conducted based on the reference lists of the included articles and studies previously known by the research team, in order to ensure the comprehensiveness and relevance of the analyzed literature (Wohlin et al., 2022). Two additional studies were identified and included through this manual search, having been subjected to the same eligibility criteria adopted in the systematic selection.

These articles were organized in an Excel© spreadsheet, and the following data were extracted: year of publication, number of citations (from Google Scholar), and journal impact factor according to the Journal Citation Reports (JCR). The relevance analysis was conducted using the *InOrdinatio* equation (Pagani et al., 2018) (Equation 1):

$$\text{InOrdinatio}=\left(\frac{\text{Fi}}{1000}\right)+\text{a}^{*}\left[10-\left(\text{YearSearch-YearPub}\right)\right]+\left(\sum\text{Ci}\right) \quad (1)$$

where: Fi = Journal Impact Factor; a* = Coefficient assigned by the researcher to represent the relevance of the publication year, ranging from 1 to 10. In this case, a medium value of 5 was adopted, since the time frame (from the year 2001 onward) already defined a temporal relevance; YearSearch = The year in which the database search was conducted; YearPub = The publication year of the article; ∑ Ci = Number of citations of the study.

After applying the equation, four articles with negative scores (< 0) were excluded, resulting in a final portfolio of 29 studies. The methodological path for selecting the studies included in this systematic review is illustrated in Figure 1.

All articles were read in full, and their information was extracted and organized into analysis categories, including: year of publication, journal, authors, country of origin, road type, fluvial and hydrological components investigated, objective, methodology, and results. The first step of the analysis consisted of a scientometric approach, which involved the general characterization of the studies and the identification of thematic patterns through the formation of clusters based on the keywords of the articles, using the VOSviewer software (version 1.6.20). Subsequently, a knowledge synthesis was carried out based on the reading and interpretation of the contents. Finally, future directions regarding the implications of road impacts on fluvial systems are provided.

3. Study Characterization

The scientometric analysis of the final portfolio, composed of 29 scientific articles, made it possible to identify patterns regarding the temporal distribution, the geographical location of the studies, the scientific journals that most frequently published on the topic, the authors, and the main strategic focuses. An analysis of the distribution of articles over the years reveals a growing scientific interest in the impacts of rural roads on fluvial ecosystems, particularly from the second decade of the 2000s onward (Figure 2a). The period between 2015 and 2019 recorded the highest volume of publications, with 11 articles. Individually, 2017 stood out as the year with the highest number

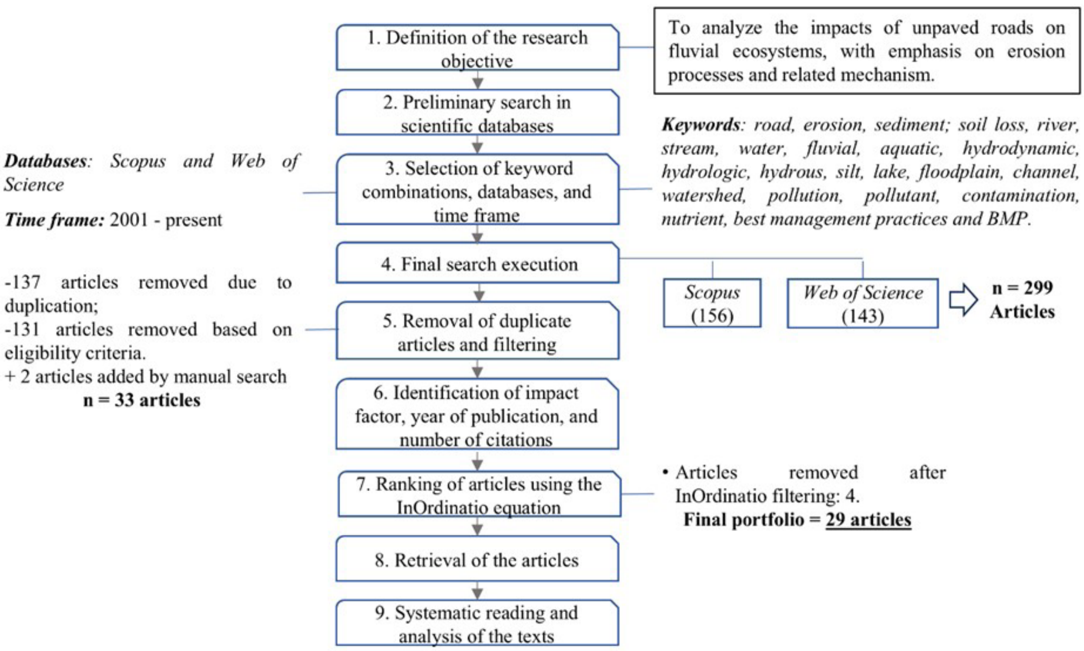

Figure 1. Methodological path of the systematic literature review – based on Pagani et al. (2018).

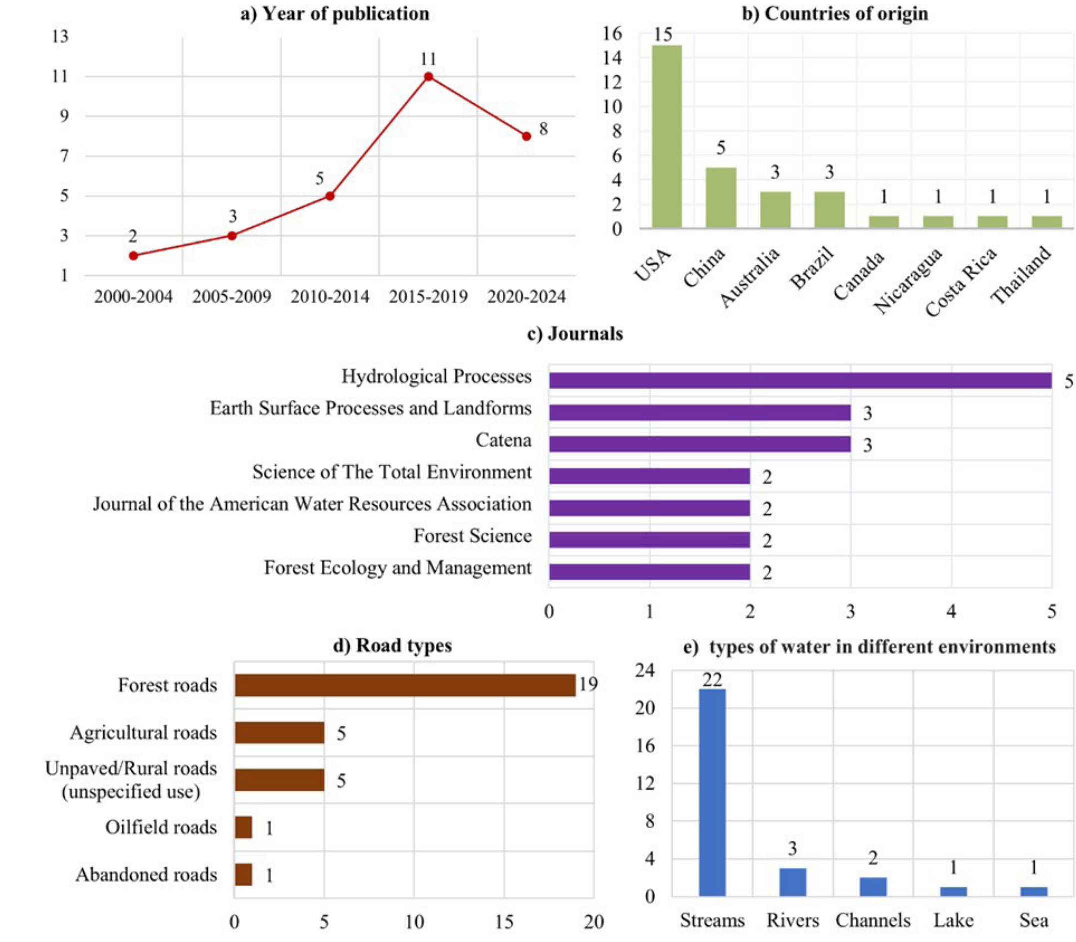

Figure 2. Characterization of selected studies.

of publications (four studies), followed by 2022 and 2024, with three articles each, indicating the ongoing development of research on this subject.

In terms of geographic distribution, Figure 2b shows a strong concentration of research conducted in the USA, where 15 of the 29 analyzed studies were carried out. China stands out next, with five publications, followed by Australia and Brazil with three studies each. Other countries, including Canada, Thailand, and one joint investigation between Nicaragua and Costa Rica, each contributed only one article, indicating a still limited scientific output on the topic in these contexts. These findings suggest that literature remains largely concentrated in countries with a well-established tradition in hydrological research (Rochman et al., 2024) and soil erosion studies (Yu et al., 2024), often justified by their climatic and/or geological characteristics. However, studies have also reinforced the role of roads as significant sources of sediment in tropical regions, including Latin America, highlighting that the protection of water resources from the impacts of rural roads is a critical issue, particularly in the Brazilian context (Thomaz et al., 2014).

Among the most frequently recurring journals, Hydrological Processes stood out with five publications, highlighting the emphasis on hydrological processes associated with rural roads (Figure 2c). This was followed by Catena and Earth Surface Processes and Landforms, each contributing three articles, both focused on soil science and geomorphology. Additionally, Science of The Total Environment, Forest Science, Forest Ecology and Management, and the Journal of the American Water Resources Association each published two articles, reinforcing the relevance of the topic in the fields of forest management and water resources. It is worth noting that ten other journals focused on soil, water, and environmental quality and management contributed only one article each.

When considering the types of roads addressed in the studies, it was observed that the majority of investigations focused on forest roads, which were present in 65.5% of the research. Agricultural roads were analyzed in five studies. Another five studies focused on unpaved roads without specifying a predominant use, encompassing regions with forested areas, pastures, and agricultural zones, for example. In addition, one article investigated agricultural, abandoned, and oilfield roads in an integrated manner (Figure 2d). Among these investigations, ten specifically analyzed stream crossing segments, highlighting the role of such structures in sediment transport and direct impacts on rivers. The predominance of studies focused on forest management areas can be explained by the geographical context in which most of the research was conducted, particularly in countries with a strong presence of forestry activities, such as the USA, Australia, and China. In these regions, the density of forest road networks is high, with roads often built in mountainous or conservation areas, which are characterized by high erosion potential and increased hydrological connectivity with water bodies (Madej, 2001; Lane & Sheridan, 2002; Sosa-Pérez & MacDonald, 2017a; Lang et al., 2018; Wang et al., 2023).

When evaluating the fluvial and hydrological components investigated in the studies, it is observed that the majority of the research (76%) focused their analyses on streams, including creeks and small watercourses. This emphasis may be associated with the greater sensitivity of these systems to sediment input generated by roads, especially at crossings and adjacent areas (Thomaz et al., 2014; Thomaz & Peretto, 2016; Sugden, 2018; Dangle et al., 2019). Rivers were examined in three studies, while two articles analyzed artificial channels or channel networks, usually related to surface runoff and drainage. Only one study investigated the impacts on a lake, and another focused on a marine ecosystem, specifically coral reefs. The distribution of these components is presented in Figure 2e.

Finally, the cluster analysis based on the keywords of the studies revealed three interrelated thematic areas (Figure 3). The first cluster (red) focuses on hydrosedimentological dynamics within watersheds and their indirect effects on fluvial systems. This theme addresses the physical origin of the problem, with key concerns including road-stream connectivity, soil erosion, infiltration and runoff processes, and sediment production and delivery (e.g., Falbo et al., 2013; Sosa-Pérez & MacDonald, 2017b; Medeiros et al., 2022; Wang et al., 2023; Xu et al., 2024a, b). In the second cluster (blue), there is a focus on the direct effects of sediment mobilization, transport, and road erosion on fluvial systems, particularly in streams (Lane & Sheridan, 2002; Sheridan & Noske, 2007a, b; Thomaz et al., 2014; Thomaz & Peretto, 2016; Reid et al., 2016; Arismendi et al., 2017; Touma et al., 2020). The third cluster (green), in turn, groups studies aimed at strategies and mitigation solutions for road impacts on water systems, with an emphasis on evaluating the effectiveness of BMPs, road management, and reducing sediment delivery to improve water quality (e.g., Madej, 2001; Brown et al., 2013, 2015; Sosa-

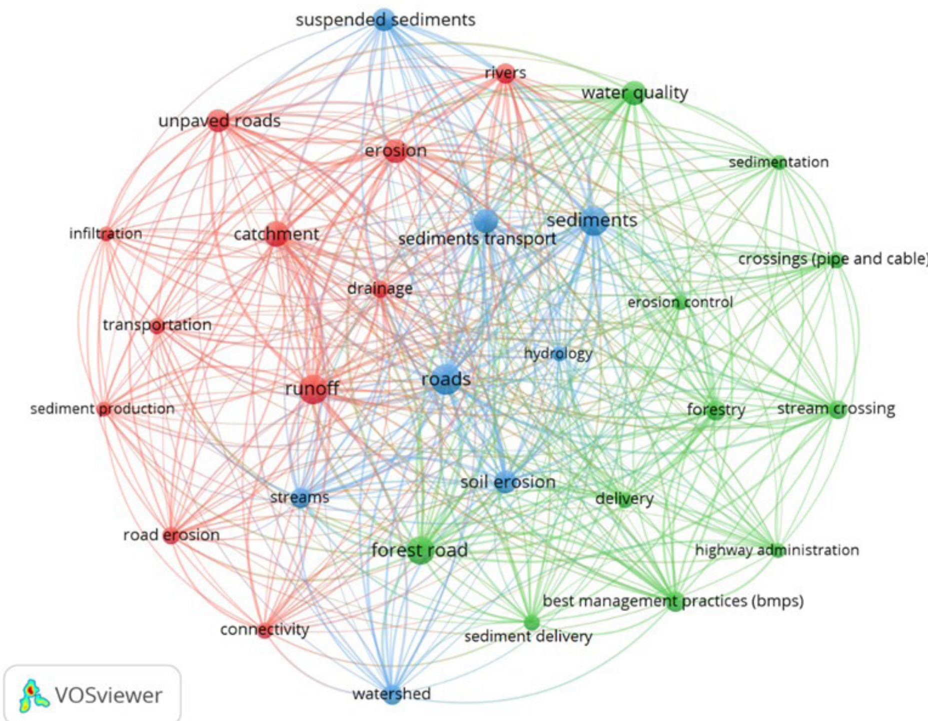

Figure 3. Thematic clusters from keyword co-occurrence analysis of studies on road impacts on fluvial systems. Red: watershed-scale hydrosedimentological processes; Blue: sediment mobilization and transport impacts on streams; Green: management and mitigation strategies (BMPs).

Pérez & MacDonald, 2017a; Lang et al., 2018; Zhao et al., 2022b).

Based on this overview, the following sections organize the synthesis of knowledge around three main discussion axes: (i) the hydrosedimentological dynamics in river basins, focusing on infiltration and runoff, erosion and sediment delivery, and connectivity between roads and streams; (ii) the direct impacts of road erosion on water quality in fluvial systems; and (iii) best management practices aimed at mitigating these impacts.

4. Hydrosedimentological Dynamics: Erosion, Sediment Delivery and Road-stream Connectivity

Although unpaved roads facilitate economic and social aspects, such as the flow of production and rural mobility, they significantly affect the hydro-sedimentary dynamics of watersheds (Jing et al., 2022). By altering natural drainage patterns, these roads intensify surface runoff and sediment generation, becoming major sources of diffuse pollution in aquatic environments (Benda et al., 2019; Jing et al., 2022; Medeiros et al., 2022).

It is noted that infiltration rates on unpaved roads range from 4 to 11 mm h^{-1}, representing only 10-25% of the rates observed on undisturbed natural hillslopes. As a result, these roads generate runoff approximately five times more frequently than natural slopes, with surface flow beginning within two to four minutes after the onset of rainfall (~2 mm), directly contributing to sediment production (Ramos-Scharrón et al., 2024).

Sediment is one of the most prevalent water pollutants associated with erosion processes on unpaved roads. It can alter water chemistry, raise river temperatures, and increase turbidity, thereby degrading aquatic habitats and reducing biological diversity (Lang et al., 2018; Wang et al., 2023). In Culebra, Puerto Rico, erosion rates on such roads were observed to be 330 to 760 times higher than those on natural slopes, reaching up to 10.5 g m^{-2} mm^{-1}, with the potential to negatively impact the island's coral reefs (Ramos-Scharrón et al., 2024). These findings raise concern, particularly in high-rainfall regions where roads are poorly maintained and lack adequate containment infrastructure, such as in the Formoso River Watershed (MS), Brazil. In this location, the road network exceeds the natural drainage network by 41%, expanding runoff pathways and intensifying sediment loads that contribute to the turbidity of the region's scenic and touristic rivers (Medeiros et al., 2022).

The main sources of sediment include roadside slopes, which are responsible for the delivery of fine sediments, and cut and fill slopes, which contribute coarser material (Lane & Sheridan, 2002). Additionally, sediment production is influenced by factors such as road surface type, traffic intensity, precipitation levels, slope gradient, and the distance between the road and water bodies (Benda et al., 2019). In Culebra, for instance, roads with slopes greater than 20% that had recently been graded showed erosion rates of up to 26.8 Mg ha^{-1} yr^{-1} more than double the rates observed on roads with gentler slopes that had not been graded in the previous two years (11.7 Mg ha^{-1} yr^{-1}) (Ramos-Scharrón et al., 2024). Sheridan & Noske (2007a), in their study of forest roads in Australia, also found that the annual sediment load on natural soil roads with moderate traffic (5,373 mg m^{-2} mm^{-1}) was substantially higher than on well-maintained gravel roads with light traffic (216 mg m^{-2} mm^{-1}), indicating a potential to affect water quality, particularly in streams.

In addition to sediment production, hydrological connectivity emerges as an essential factor for the delivery of these materials to fluvial systems (Zhao et al., 2022b). The linkage between roads and streams is established through culverts, gullies, ditches, and crossings, which serve as channels for transporting both sediments and contaminants (Xu et al., 2024a). In a study examining the spatial relationships between road networks and rivers and the associated sediment connectivity within the Dongshuanghe (DSH) watershed in China, Jing et al. (2022) found that roads and rivers are strongly interconnected, with roads exerting a significant influence on sediment connectivity. The results revealed that the road-influenced sediment connectivity index (IC^R = -0.97) was notably higher than the conventional connectivity index (IC = -2.17). This enhanced connectivity is particularly evident in zones of abrupt transition between roads and streams, as highlighted by Sugden (2018), who reported that 25% of road-stream crossings accounted for up to 75% of the total sediment delivery in a network of legacy forest roads in the USA, and by Zhao et al. (2022b), who observed increased sediment connectivity near road-stream crossings.

Studies also indicate that sediment connectivity can be intensified by topographic and structural factors. According to Wang et al. (2023), sediment delivery pathways tend to form under steeper conditions and on surfaces with lower erosion resistance, with the slope of the downslope hillslope being one of the most influential factors, increasing the likelihood of gully formation by up to 34%. Lane & Sheridan (2002) also reported that gullies up to 30 cm deep and 12 meters long act as direct channels for sediment delivery to streams. On the Pikes Peak Highway (USA), Katz et al. (2014) estimated an annual sediment production of up to 101 m^3 yr^{-1} per gully.

Roadside ditches also play an important role in sediment connectivity. Falbo et al. (2013) demonstrated that these structures can efficiently transport sediments and fecal contaminants (such as *Escherichia coli*) to water bodies, particularly in agricultural areas. Through monitoring of roadside ditches in New York (USA), the authors observed that *E. coli* concentrations reached up to 241,000 MPN 100 mL^{-1} following rainfall events, compromising the water quality of receiving streams, even in small and predominantly rural watersheds.

Beyond structural connectivity, research has also examined functional hydrological connectivity, which considers the dynamics of runoff transfer driven by disturbance forces and the sensitivity of geomorphic systems, such as time, climate change, and human activities (Xu et al., 2024a). For instance, Xu et al. (2024a, b) demonstrated that intense rainfall events significantly enhance the connections between hillslopes, road surfaces, and downstream areas. In a study conducted in the agricultural Fangta watershed (China), under high-precipitation conditions, gully formation increased by up to 6.9 times, along with intensified erosion in connected segments. It was also found that Upslope-Road connections were responsible for 65.4% of landslides and 42% of slope failures (Xu et al., 2024a). When comparing different road types, agricultural roads showed greater susceptibility to this type of connection, whereas oilfield roads exhibited stronger Road-Downslope connectivity. Rainfall intensity (PI30) and road erosion were identified as the main factors associated with upslope and downslope connections, respectively. These findings underscore that intense rainfall events amplify sediment delivery and highlight the need for road-type-specific management strategies (Xu et al., 2024b).

Other factors, such as wildfires, can also be considered in the assessment of road-stream connectivity. Benda et al. (2019), in developing and applying a model to evaluate erosion and sediment delivery from roads to streams in areas affected by wildfires, demonstrated that the reduced infiltration resulting from burning increases both hydrological connectivity and sediment delivery. Similarly, in a study of 141 road segments in Colorado (USA), Sosa-Pérez & MacDonald (2017b) found that wildfire severity directly affects the frequency of rill formation and road-stream connectivity. After wildfires, all road segments located in areas of high and moderate burn severity exhibited connectivity, and up to 230 $kg\,yr^{-1}$ of sediment was produced on burned hillslopes - equivalent to seven times more than the typical value observed in unburned segments. The lack of drainage infrastructure and the steepness of the road segments further exacerbated these impacts.

Thus, it is evident that unpaved rural roads play a central role in the hydro-sedimentological dynamics of watersheds. Their low infiltration capacity, high sediment production, and strong structural and functional connectivity with water bodies significantly increase the risks of degradation to fluvial ecosystems. These conditions also contribute to direct impacts on water quality and fluvial systems, which will be presented and discussed in the following section.

5. Direct Impacts of Road Erosion on Water Quality in Fluvial Systems

In addition to the effects of unpaved roads on surface runoff, sediment generation, and hydrological connectivity, direct impacts on water quality are also observed. However, few studies have focused specifically on this dimension. Sheridan & Noske (2007a) had already pointed out that conceptualizing and investigating the impacts of management activities on water quality is challenging, due to the wide range of spatial and temporal scales involved, from pollution peaks that affect aquatic organisms to the gradual accumulation of sediments over the years.

When considering the impact of roads on water bodies, it was found that unpaved roads with moderate traffic on erodible soils are major sources of sediment that significantly affect water quality in small and sensitive streams. In a study conducted on forest roads in the Highlands region of Australia, the authors observed that larger streams (>500 $L\ s^{-1}$) showed only modest increases in sediment concentration (<2 $mg\ L^{-1}$), whereas smaller streams (~10 $L\ s^{-1}$) exhibited increases of up to 30 $mg\ L^{-1}$, with levels that can compromise aquatic biota, such as macroinvertebrate communities (Sheridan & Noske, 2007a).

In a subsequent study, Sheridan & Noske (2007b) evaluated the export of sediments and nutrients (phosphorus and nitrogen) from unpaved forest roads into streams and reservoirs at the watershed scale. The results indicated that 3.15 hectares of roads contributed approximately 50 tons of suspended sediments (4.4% of the total load), 22 kg of total phosphorus (1.8%), and 33 kg of total nitrogen (0.16%). Thus, although they represent a point source of pollution, forest roads showed a modest contribution to the overall watershed balance.

Stream crossings, such as culverts, bridges, and fords, are also frequently recognized as critical points of sediment entry into water bodies (Brown et al., 2015; Lang et al., 2018; Dangle et al., 2019). For example, Sheridan & Noske (2007b) observed that only 10% of crossings were responsible for half of the sediment and phosphorus load in the Tyers River watershed (Australia). Similarly, Sugden (2018) found that 25% of road-stream crossings in mountainous regions of the USA accounted for 50 to 75% of the total sediment delivery. Lane & Sheridan (2002), in their investigation of a newly constructed crossing on the Latrobe River (Australia), reported a 3.5-fold increase in suspended sediment load downstream (from 0.78 t to 2.77 t), in addition to 2 to 3 tons of bed sediment added to the stream because of construction and subsequent erosion.

Thomaz et al. (2014) also evaluated the impact of six unpaved road-stream crossings on suspended sediment concentration (SSC) in rivers of different orders (3rd to 5th order) in the Guabiroba River catchment, southern Brazil. The authors observed that in 3rd and 4th order rivers with drainage areas smaller than 3 km^2, SSC downstream of the crossings was 3.5 to 10 times higher than upstream (with mean values of 0.10 $g\ L^{-1}$ and 0.04 $g\ L^{-1}$, respectively). On the other hand, no significant differences were observed in 5th order rivers with drainage areas ranging from 9.5 to 13.5 km^2. These findings highlight that the effects of river crossings on SSC are scale-dependent and reinforce the role of unpaved roads in increasing sediment loads in water bodies, particularly in low-order rivers.

In a complementary study, Thomaz & Peretto (2016) found that crossings in rural headwater regions lead to significant alterations in river dynamics. In the Rio das Pedras catchment, Brazil, the authors reported an increase of up to 50% in streamflow in reaches impacted by roads compared to unaffected segments. Increases in SSC ranged from 413% in 2nd order rivers to 145% in 3rd order rivers, and were even more pronounced when considering the total amount of sediment transferred, with increases between 2863% and 860%, respectively, compared to upstream i.e., no road effect. Secondary roads were responsible for 70% to 87% of the total sediment load delivered to rivers, while the main road contributed between 11% and 27%. The authors also highlighted the loss of filtering function of riparian vegetation in areas with crossings, demonstrating that the intensification of hydrogeomorphic connectivity promoted by roads significantly altered the hydrosedimentary dynamics of headwater stream systems.

The delivery of fine sediments from unpaved roads to water bodies is also particularly concerning due to its negative effects on aquatic biota and water quality, as it reduces light penetration and fills the interstitial spaces between larger particles in streambeds (Reid et al., 2016). Based on this concern, Arismendi et al. (2017) aimed to evaluate the effects of forest road construction and improvements, timber harvesting, and transportation on turbidity and Suspended Sediment Concentrations (SSC) in adjacent streams in the Trask River Basin (Oregon, USA). The results demonstrated only a minimal increase in turbidity and SSC values following the interventions (roads + harvesting and transportation) at the treated sites. Contrary to expectations, the reference site, which had no recent interventions, exhibited the highest increases in turbidity and SSC (up to 85% of the samples exceeded 3 mg L^{-1}, suggesting that local natural factors, such as treefall or bank erosion, may have influenced sediment concentrations.

In a similar line, Reid et al. (2016) investigated the delivery of fine sediments to river channels, focusing on a 425 m stretch of the Honna River (Canada). The study revealed that unpaved roads contributed approximately 18 ± 6% of the 105 ± 33 tons of suspended sediments transported, a value six times higher than that from bank erosion. Nevertheless, no significant accumulation of these sediments was detected in the riverbed, which may be attributed to the channel's transport capacity and the absence of extreme hydrological events during the sampling period.

Finally, Touma et al. (2020) identified significant impacts on aquatic communities associated with the input of fine sediments along the southern bank of the San Juan River (Nicaragua), where the Route 1856 highway was partially constructed. This bank exhibited greater deposition of fine sediments (8.5 mm) compared to the undisturbed northern bank (9.8 mm). Water temperature was also higher (27.27 °C on the southern bank vs. 25.9 °C on the northern bank), potentially affecting the quality of aquatic habitat. Additionally, there was lower periphyton biomass, as well as reduced richness and abundance of macroinvertebrates, with less diverse communities and absence of sensitive taxa such as Ephemeroptera, Plecoptera, and Trichoptera (EPT) on the southern bank. Thus, the study provided evidence that the construction of Route 1856 led to a degradation in the ecological quality of the affected water bodies.

The studies reviewed demonstrate that, although still underexplored in the literature, the direct effects of unpaved rural roads on water quality and fluvial ecosystems are real and warrant attention. This context requires the adoption of effective management strategies aimed at mitigating these impacts, a topic that will be addressed in the following section.

6. Best Management Practices: Implications for Fluvial Ecosystems

Best Management Practices (BMPs) have been widely adopted to reduce the production, delivery, and deposition of sediments in water bodies (Lang et al., 2018). These practices involve the use of both biological and engineering measures, such as ditches, sedimentation tanks, properly designed crossings, surface coverage with gravel or vegetation, and the relocation of roads away from streams (Sugden, 2018; Zhao et al., 2022b).

One strategy is the decommissioning of unnecessary roads, which may include treatments such as soil decompaction, culvert removal, excavation of embankments, drainage of ditches, application of mulch, and replanting of vegetation. Studies have shown that such interventions can reduce erosion and sediment delivery to streams by up to 75% compared to unrestored abandoned roads (Madej, 2001). In this same context, evaluations by Sosa-Pérez & MacDonald (2017a) found that after applying ripping and mulch, sediment production dropped to zero, and road-stream connectivity was reduced from 12% to just 2% following decommissioning.

In contrast to decommissioning, road reopening also requires the implementation of BMPs, especially at stream crossings. Studies conducted in Virginia (USA) showed that reopened road-stream approaches with exposed soil generated sediment delivery rates up to 7.5 times higher than those covered with gravel, with values ranging from 34 to 287 Mg ha^{-1} yr^{-1} on bare roads, compared to 10 to 16 Mg ha^{-1} yr^{-1} on graveled ones (Brown et al., 2013). When comparing different levels of surface coverage, a significant reduction in TSS production was also observed, decreasing from 2.84 g L^{-1} (no gravel) to 0.82 g L^{-1} (high gravel coverage), confirming graveling as a simple and cost-effective alternative to mitigate sediment input (Brown et al., 2015).

Additionally, BMPs such as drainage features, road graveling, revegetation of disturbed areas, and filtering near streams have also been shown to be effective on legacy forest road networks in the USA. The implementation of these measures led to an average reduction of 46% in sediment delivery and a decrease in mean connectivity from 6.4% to 4.1% of the total road length (Sugden, 2018).

The effectiveness of BMPs, however, also depends on their quality and level of implementation. On forest roads in Virginia (USA), stream crossings classified as low-BMP showed median sediment losses of 0.45 Mg yr^{-1}, a value 48 times higher than high-BMP sites (0.001 Mg yr^{-1}) and 3.5 times higher than standard-BMP sites (0.02 Mg yr^{-1}). These high values were associated with poorly positioned drainage, high soil exposure (>50%), and heavy truck traffic. In contrast, crossings with vegetation cover, lower traffic, and good location had minimal losses, even when directly connected to water bodies (Lang et al., 2018). Similar results were reported by Dangle et al. (2019), with average sediment losses of 14.5 Mg ha^{-1} yr^{-1} in low-BMP areas, 8.3 Mg ha^{-1} yr^{-1} in standard-BMP, and only 4.0 Mg ha^{-1} yr^{-1} in high-BMP. The use of gravel reduced sediment production by up to 25 times, and well-planned drainage structures, such as water diversions and wide depressions, contributed to lower losses, reinforcing the importance of quality in the application of BMPs for the protection of water quality.

In addition to stream crossings, the effectiveness of BMPs has also been evaluated in roadside ditches near streams. While these ditches function as drainage structures, they can also act as sources of erosion and sediment transport due to concentrated runoff. In a study of 60 ditch segments on forest roads in Virginia (USA), it was found that the treatment combining grass seeding with lime and an erosion control mat resulted in the lowest erosion rate (0.82 Mg ha^{-1} yr^{-1}) and the best cost-effectiveness (US$21.33 per treatment). In contrast, rock check dams were less effective, with a higher erosion rate (6.14 Mg ha^{-1} yr^{-1}) and higher cost (US$71.43). Ground cover was identified as the primary erosion control factor, with ditches having more than 50% vegetation cover showing a lower risk of accelerated erosion (Lang et al., 2017).

Natural riparian buffers have also shown positive results in sediment retention. In hillside areas in Thailand, Ziegler et al. (2006) found that a 30-meter strip of dense vegetation (primarily *Fimbristylis aphylla*) reduced SSC by 34 to 87%, especially of coarser particles. Most deposition occurred within the first 10 meters, and buffer efficiency declined under flow rates exceeding 10-13 L s^{-1}. In a watershed in China, Zhao et al. (2022b) confirmed that sediment connectivity decreases with increasing buffer width. Simulations showed that 64-meter-wide buffers combined with 30 sediment basins (each with a minimum area of 2 ha) provided the greatest reduction in the connectivity index, highlighting that the location, quantity, and scale of BMPs are key factors in mitigating sediment delivery and environmental impacts on fluvial systems.

Finally, some studies have advanced the development of decision-support tools for the implementation of BMPs. Efta & Chung (2014) created the BMP-SA model, based on simulated annealing, to identify the most effective combinations of BMPs, considering budget, maintenance, and equipment scheduling, to reduce erosion and sediment delivery to water bodies. Similarly, Benda et al. (2019) developed READI (Road Erosion and Delivery Index), a Geographic Information Systems (GIS)-based tool designed to predict erosion and sediment delivery from roads to streams, particularly useful in data-limited areas. Both models, therefore, support the prioritization of interventions and the integrated management of watersheds.

Thus, it is observed that BMPs play a relevant role in mitigating the impacts of rural roads on fluvial ecosystems. Relatively simple improvements, such as gravel surfacing and drainage structures, have proven to be cost-effective measures for reducing erosion. It was also observed that the effectiveness of these practices depends not only on their adoption but also on the quality of implementation and their suitability to local conditions. When well-planned and applied, BMPs can significantly reduce sediment production and delivery, contributing to the conservation of water quality and the integrity of fluvial systems. These findings therefore reinforce the importance of strategies and investments aimed at the restoration and sustainable management of unpaved roads, especially in environmentally sensitive areas.

7. Implication of Road Impact on River Ecosystem and Future Research Directions

The interdependence between human systems and river ecosystems creates a complex chain of cause and effect. Land use, especially road construction, directly influences the abiotic components of the system. Roads alter the channel's hydrology by increasing flow, flow velocity, and flood peaks, making the river more responsive in their presence (Thomaz & Peretto, 2016). As a result, the river channel adjusts to the new hydraulic conditions, changing its geometry, including width, depth, hydraulic radius, bed roughness, and wetted perimeter. Additionally, roads directly impact water quality and habitats by introducing nutrients, organic matter, and both fine and coarse sediments (Lorenz et al., 1997; Forman et al., 2003).

Consequently, the presence of roads leads to changes in the abiotic components of river ecosystems. These changes, in turn, directly influence biotic components, particularly affecting functional characteristics such as matter flow, excess, retention, and transfer, as well as structural characteristics like habitats, species diversity, abundance, and distribution. Thus, by impacting the abiotic system, unpaved roads can affect macroinvertebrates and the zonation of fish and benthic fauna (Gordon et al., 2004; Lorenz et al., 1997).

Nonetheless, the potential effects of roads on aquatic biota deserve examination across the diverse Brazilian biomes. Headwaters, identified as stream orders 1-3, are likely the most susceptible to road infrastructure. Because this hydro-geoecological system serves as a zone for the production and transfer of matter and energy within the drainage basin. Such processes occur at this scale due to the strong coupling between the hillslope, the riparian zone, and river ecosystem. As a result, headwaters are particularly sensitive, and the impact of roads on this system may have repercussions throughout the entire river ecosystem (Bilby et al., 1989; Thomaz et al., 2014).

The riparian zone, associated with the riparian buffer zone (e.g., vegetation strip), plays a vital role in reducing the diffuse transfer of nutrients (nitrates, nitrogen, and phosphorus), sediments, and pesticides from agricultural areas (Vidon et al., 2019; Stutter et al., 2021). However, the riparian-buffer zone becomes ineffective in limiting contaminant transfer when the connection is direct or punctual (Bilby et al., 1989; Thomaz & Peretto, 2016). In the context of road-stream connectivity, this connection is established punctually through culverts, gullies, ditches, and crossings.

For example, in a catchment where riparian forests cover 10.2% and annual crops occupy about 64% of the total area, unpaved roads were identified as the main source of sediment, contributing with 41.3 ± 19.2% of the total sediment budget. This is notable given that the road area was relatively small, at just 1.9 hectares, making up only 1.3% of the total catchment area (Tiecher et al., 2017). In more extreme scenarios at the farm scale, only 2-8% of the total sediment was linked to cultivated hillslopes, while unpaved roads, which constitute 15% of the total area, accounted for over 90% of the sediment budget (Ramos-Scharrón & Thomaz, 2017).

In Brazil, numerous studies have highlighted the influence of land use and the significance of riparian zones on water quality and aquatic biodiversity (Feijó-Lima et al., 2019; Linares et al., 2021; Hepp et al., 2023). A comprehensive review of the role of riparian zones in water quality within Atlantic forest biome identified the primary land use types as agriculture, pasture, urbanization, mining, forestry, and bare soil (Ebling & Padial, 2024). Interestingly, roads are not categorized as a specific land use, despite their hydro-geomorphological characteristics and functions being crucial to the river ecosystem quality. Consequently, generalizing the impact of pasture, forestry, and agricultural use on the river ecosystem may lead to misunderstandings regarding the role of unpaved roads.

In 2010, the global road network extends over 33.8 million kilometers, resulting in a road density of 0.23 kilometers per square kilometer. Notably, seven countries – the USA, China, India, Brazil, Japan, Canada, France, and Russia – accounted for 59% of the world's road infrastructure. Due to population growth and the rising demand for food and consumer goods, it is expected that between 1 and 2 million kilometers of roads will be constructed every decade from 2000 to 2050 (Faiz et al., 2012).

Brazil, being a large country, holds the fourth position in terms of road networks, contributing about 5% to the global total. The current and planned road network in Brazil, around to 1.692 million kilometers, results in a road density of 0.198 km km^{-2} (Thomaz, 2019). Therefore, road will continue to cause landscape fragmentation and impacting the aquatic system in Brazil.

Given this context, it is recommended that future research expand the geographic scope of investigations, including different types of roads and regions, especially agricultural areas in tropical and subtropical contexts. It is necessary to deepen studies on the direct effects of unpaved roads on water quality and fluvial ecosystems, incorporating indicators such as impact on biodiversity and ecosystem services. Longitudinal studies are also recommended to assess long-term effects, considering different maintenance conditions, surface types, and adverse environmental conditions.

Research that quantifies the volume of sediments, nutrients, and pollutants transported from roads to streams is equally important, especially considering its effects on macroinvertebrates and the zonation of fish and benthic fauna. Finally, evaluating the effectiveness of BMPs across diverse environmental contexts is essential to promote the sustainability of road infrastructure and the conservation of water resources and aquatic biota in rural areas.

8. Conclusions

This study aimed to analyze the impacts of unpaved roads on fluvial ecosystems, with emphasis on erosion processes and related mechanism, through a systematic literature review conducted using the *Methodi Ordinatio*. A total of 29 articles were selected and analyzed based on criteria of relevance, methodological rigor, and thematic scope. Initially, the scientometric analysis allowed for the characterization of the selected studies and the identification of patterns in the types of roads and fluvial components addressed. Subsequently, the knowledge synthesis contributed to the understanding of the investigative approaches, providing insights for future research directions.

The characterization of the studies revealed a growing interest in the topic over the years, especially since 2010. The journal *Hydrological Processes* stood out with five publications on the subject. A geographical concentration of research was also observed, with a predominance of studies conducted in the USA, China, Brazil and Australia, mainly focusing on forest roads in mountainous regions and streams, which are more sensitive to sediment delivery.

The thematic analysis, based on studies of hydro-sedimentological dynamics, revealed the indirect impacts of unpaved rural roads on fluvial systems. These roads were found to have lower infiltration rates, higher surface runoff, and intensified erosion and sediment transport from various sources. Roads with steeper slopes, recent grading, higher traffic, lack of gravel cover, and location in areas with high rainfall were more susceptible to erosion processes and, consequently, to negative impacts on water quality. Hydrological connectivity also played a significant role in sediment delivery to water bodies, particularly at stream crossings, roadside ditches, and under conditions of major disturbances such as heavy rainfall and wildfires.

Regarding direct impacts, the studies indicate that the input of fine sediments from roads compromises water quality and negatively affects aquatic communities. The presence of these roads alters runoff dynamics and intensifies sediment delivery to streams. Observed effects include increased turbidity, deposition of particles on the streambed, higher flow rates, elevated water temperature, and reduced biodiversity. Stream crossings and roadside ditches were identified as critical points of sediment input, particularly in small watercourses, where the impacts tend to be more pronounced.

Studies on BMPs, in turn, revealed the effectiveness of several interventions in mitigating erosion and controlling sediment mobilization. Strategies such as road decommissioning, revegetation, gravel application, and the implementation of drainage features, such as ditches and riparian buffers, proved effective in reducing sediment production and road-to-stream connectivity. The results also indicated that the effectiveness of these practices depends on the quality and level of BMP implementation, as well as their suitability to the local context. Support tools such as the BMP-SA and READI models also stood out as useful instruments for planning and prioritizing interventions.

Despite the relevant contributions, literature still presents some limitations. Most studies remain concentrated in mountainous regions and forest roads, with a lack of research focused on tropical countries and agricultural areas. There is also a shortage of investigations evaluating the cumulative and long-term effects of roads on fluvial ecosystems, as well as more conclusive studies on the direct impacts of road-derived sediments on water bodies and water quality. Furthermore, most research focuses on physical and chemical parameters, with few approaches addressing biotic responses or the affected ecosystem services. For these reasons, further studies are encouraged to address these gaps and expand the understanding of road impacts on fluvial systems, thereby contributing to the promotion of sustainable practices in rural landscapes.

Data availability

The entire dataset supporting the results of this study was published in the article itself.

References

Arismendi, I., Groom, J.D., Reiter, M., Johnson, S.L., Dent, L., Meleason, M., Argerich, A., & Skaugset, A.E., 2017. Suspended sediment and turbidity after road construction/improvement and forest harvest in streams of the Trask River Watershed Study, Oregon. Water Resour. Res. 53(8), 6763-6783. https://doi.org/10.1002/2016WR020198.

Benda, L., James, C., Miller, D., & Andras, K., 2019. Road Erosion and Delivery Index (READI): a model for evaluating unpaved road erosion and stream sediment delivery. J. Am. Water Resour. Assoc. 55(2), 459-484. https://doi.org/10.1111/1752-1688.12729.

Bilby, R.E., Sullivan, K., & Duncan, S.H., 1989. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. For. Sci. 35(2), 453-468. https://doi.org/10.1093/forestscience/35.2.453.

Brown, K.R., Aust, W.M., & McGuire, K.J., 2013. Sediment delivery from bare and graveled forest road stream crossing approaches in the Virginia Piedmont. For. Ecol. Manage. 310, 836-846. https://doi.org/10.1016/j.foreco.2013.09.031.

Brown, K.R., McGuire, K.J., Aust, W.M., Hession, W.C., & Dolloff, C.A., 2015. The effect of increasing gravel cover on forest roads for reduced sediment delivery to stream crossings. Hydrol. Processes 29(6), 1129-1140. https://doi.org/10.1002/hyp.10232.

Dangle, C.L., Bolding, M.C., Aust, W.M., Barrett, S.M., & Schilling, E.B., 2019. Best Management Practices influence modeled erosion rates at forest haul road stream crossings in Virginia. J. Am. Water Resour. Assoc. 55(5), 1169-1182. https://doi.org/10.1111/1752-1688.12762.

Denyer, D., & Tranfield, D., 2009. Producing a systematic review. In: Buchanan, D.A., & Bryman, A., eds. The Sage handbook of organizational research methods. Thousand Oaks: Sage Publications, 671-689.

Djeran-Maigre, I., Morsel, A., Briançon, L., Delfosse, E., Levacher, D., & Razakamanantsoa, A.R., 2022. Uses of Usumacinta River sediments as a sustainable resource for unpaved roads: an experimental study on a full-scale pilot unit. Transp. Eng. 9, 100136. https://doi.org/10.1016/j.treng.2022.100136.

Ebling, L.A., & Padial, A.A., 2024. The connections between riparian vegetation and water quality in the Atlantic Forest. Oecol. Aust. 28(4), 256-271. https://doi.org/10.4257/oeco.2024.2804.03.

Efta, J.A., & Chung, W., 2014. Planning best management practices to reduce sediment delivery from forest roads using WEPP: road erosion modeling and simulated annealing optimization. Croat. J. For. Eng. 35(2), 167-178.

Faisal, M., You, Z.-J., Akram, M.Z., & Ali, S., 2023. Quantifying the influence of urban road surface roughness on heavy metals pollution in road-deposited sediment's accumulation and wash-off. Water Sci. Technol. 88(10), 2594-2610. PMid:38017680. https://doi.org/10.2166/wst.2023.338.

Faiz, A., Faiz, A., Wang, W., & Bennett, C., 2012. Sustainable rural roads for livelihoods and livability. Procedia Soc. Behav. Sci. 53, 1-8. https://doi.org/10.1016/j.sbspro.2012.09.854.

Falbo, K., Schneider, R.L., Buckley, D.H., Walter, M.T., Bergholz, P.W., & Buchanan, B.P., 2013. Roadside ditches as conduits of fecal indicator organisms and sediment: implications for water quality management. J. Environ. Manage. 128, 1050-1059. PMid:23933218. https://doi.org/10.1016/j.jenvman.2013.05.021.

Farias, T.R.L., Medeiros, P.H.A., Navarro-Hevia, J., & Araújo, J.C., 2019. Unpaved rural roads as source areas of sediment in a watershed of the Brazilian semi-arid region. Int. J. Sediment Res. 34(5), 475-485. https://doi.org/10.1016/j.ijsrc.2019.03.002.

Feijó-Lima, R., Zandonà, E., Silva, B.S., Tromboni, F., Moulton, T.P., & Thomas, S.A., 2019. Longitudinal dimensions of land-use impacts in riverine ecosystems. Acta Limnol. Bras. 31, 1-8. https://doi.org/10.1590/s2179-975x4519.

Forman, R.T.T., Sperling, D., Bissonette, J.A., Clevenger, A.P., Cutshall, C.D., Dale, V.H., Fahrig, L., France, R., Goldman, C.R., & Heanue, K., 2003. Road ecology: science and Solutions. Washington, D.C: Island Press.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., Gippel, C.J., & Nathan, R.J., 2004. Stream hydrology: an introduction for ecologists. Hoboken: John Wiley & Sons.

Hepp, L.U., Milesi, S.V., Picolotto, R.C., Decian, V.S., Restello, R.M., Huiñocana, J.S., & Albertoni, E.F., 2023. Agriculture affects functional diversity of aquatic insects in Subtropical Atlantic Forest streams. Acta Limnol. Bras. 35, 1-12. https://doi.org/10.1590/s2179-975x2323.

Jeong, H., & Ra, K., 2023. Pollution and ecological risk assessments for heavy metals in coastal, river, and road-deposited sediments from Apia City in Upolu Island, Samoa. Mar. Pollut. Bull. 188, 114596. PMid:36706545. https://doi.org/10.1016/j.marpolbul.2023.114596.

Jing, Y., Zhao, Q., Lu, M., Wang, A., Yu, J., Liu, Y., & Ding, S., 2022. Effects of road and river networks on sediment connectivity in mountainous watersheds. Sci. Total Environ. 826, 154189. PMid:35240168. https://doi.org/10.1016/j.scitotenv.2022.154189.

Katz, H.A., Daniels, J.M., & Ryan, S., 2014. Slope-area thresholds of road-induced gully erosion and consequent hillslope-channel interactions. Earth Surf. Process. Landf. 39(3), 285-295. https://doi.org/10.1002/esp.3443.

Khudhur, M.E., 2021. The suitability of Tigris River sediments from Tikrit, Northern Iraq, for concrete production and road construction purposes. Iraqi J. Sci. 62(4), 1177-1187. https://doi.org/10.24996/ijs.2021.62.4.14.

Lane, P.N.J., & Sheridan, G.J., 2002. Impact of an unsealed forest road stream crossing: water quality and sediment sources. Hydrol. Processes 16(13), 2599-2612. https://doi.org/10.1002/hyp.1050.

Lang, A.J., Aust, W.M., Bolding, M.C., McGuire, K.J., & Schilling, E.B., 2017. Forestry best management practices for erosion control in haul road ditches near stream crossings. J. Soil Water Conserv. 72(6), 607-618. https://doi.org/10.2489/jswc.72.6.607.

Lang, A.J., Aust, W.M., Bolding, M.C., McGuire, K.J., & Schilling, E.B., 2018. Best Management Practices influence sediment delivery from road stream crossings to mountain and Piedmont streams. For. Sci. 64(6), 682-695. https://doi.org/10.1093/forsci/fxy019.

Li, Y., Are, K.S., Qin, Z., Huang, Z., Abegunrin, T.P., Houssou, A.A., Guo, H., Gu, M., & Wei, L., 2020. Farmland size increase significantly accelerates road surface rill erosion and nutrient losses in southern subtropics of China. Soil Tillage Res. 204, 104689. https://doi.org/10.1016/j.still.2020.104689.

Liao, R., Fu, S., Wei, J., Zeng, R., Su, X., & Zhang, G., 2024. Annual soil erosion characteristics of unpaved roads in the Loess Plateau hilly and gully region, China. Catena 247, 108483. https://doi.org/10.1016/j.catena.2024.108483.

Linares, M.S., Santos, L.B., Callisto, M., & Santos, J.C., 2021. Do wider riparian zones alter benthic macroinvertebrate assemblages' diversity and taxonomic composition in neotropical headwater streams? Acta Limnol. Bras. 33, 1-12. https://doi.org/10.1590/s2179-975x3821.

Lorenz, C.M., Van Dijk, G.M., Van Hattum, A.G.M., & Cofino, W.P., 1997. Concepts in river ecology: implications for indicator development. Regul. Rivers 13(6), 501-516. https://doi.org/10.1002/(SICI)1099-1646(199711/12)13:6<501::AID-RRR479>3.0.CO;2-1.

Madej, M.A., 2001. Erosion and sediment delivery following removal of forest roads. Earth Surf. Process. Landf. 26(2), 175-190. https://doi.org/10.1002/1096-9837(200102)26:2<175::AID-ESP174>3.0.CO;2-N.

Martins, T.F.G., Ferreira, K.S., Rani-Borges, B., Biamont-Rojas, I.E., Cardoso-Silva, S., Moschini-Carlos, V., & Pompêo, M.L.M., 2021. Land use, spatial heterogeneity of organic matter, granulometric fractions and metal complexation in reservoir sediments. Acta Limnol. Bras. 33, 1-15. https://doi.org/10.1590/s2179-975x3521.

Medeiros, R.B., Jesus, A.D., & Alves, L.B., 2022. Erosões em estradas não-pavimentadas da bacia hidrográfica do Rio Formoso, Bonito/MS: diagnóstico e medidas de controle. Confins Rev. Fr. Bras. Geogr. 57, https://doi.org/10.4000/confins.50005.

Navarro-Hevia, J., Lima-Farias, T.R., Araújo, J.C., Osorio-Peláez, C., & Pando, V., 2015. Soil erosion in steep road cut slopes in Palencia (Spain). Land Degrad. Dev. 27(2), 190-199. https://doi.org/10.1002/ldr.2459.

Pagani, R.N., Kovaleski, J.L., & de Resende, L.M.M., 2018. Avanços na composição da Methodi Ordinatio para revisão sistemática de literatura. Cienc. Inf. 46(2), 161-187. https://doi.org/10.18225/ci.inf.v46i2.1886.

Peng, X., Zhang, X., Chen, H., Zhang, X., Tan, C., Bai, X., Gong, Y., Qu, Y., Li, H., & Zhang, Z., 2024. Investigation the existence and mechanism of Cu(II)-sulfamethoxazole co-pollution by road-deposited sediments in stormwater runoff. Sci. Total Environ. 924, 171634. PMid:38471585. https://doi.org/10.1016/j.scitotenv.2024.171634.

Pranckutė, R., 2021. Web of Science (WoS) and Scopus: the titans of bibliographic information in today's academic world. Publications 9(1), 12. https://doi.org/10.3390/publications9010012.

Ramos-Scharrón, C.E., & Thomaz, E.L., 2017. Runoff development and soil erosion in a wet tropical montane setting under coffee cultivation. Land Degrad. Dev. 28(3), 936-945. https://doi.org/10.1002/ldr.2567.

Ramos-Scharrón, C.E., Alicea-Díaz, E.E., Figueroa-Sánchez, Y.A., & Viqueira-Ríos, R., 2022. Road cutslope erosion and control treatments in an actively-cultivated tropical montane setting. Catena 209, 105814. https://doi.org/10.1016/j.catena.2021.105814.

Ramos-Scharrón, C.E., McLaughlin, P., & Figueroa-Sánchez, Y., 2024. Impacts of unpaved roads on runoff and erosion in a dry tropical setting: Isla De Culebra, Puerto Rico. J. Soils Sediments 24(3), 1420-1430. https://doi.org/10.1007/s11368-024-03749-2.

Reid, D.A., Hassan, M.A., & Floyd, W., 2016. Reach-scale contributions of road-surface sediment to the Honna River, Haida Gwaii, BC. Hydrol. Processes 30(19), 3450-3465. https://doi.org/10.1002/hyp.10874.

Rochman, S., Rustaman, N., Ramalis, T.R., Amri, K., Zukmadini, A.Y., Ismail, I., & Putra, A.H., 2024. How bibliometric analysis using VOSviewer based on artificial intelligence data (using ResearchRabbit data): explore research trends in hydrology content. ASEAN J. Sci. Eng. 4(2), 251-294. https://doi.org/10.17509/ajse.v4i2.71567.

Sheridan, G.J., & Noske, P.J., 2007a. A quantitative study of sediment delivery and stream pollution from different forest road types. Hydrol. Processes 21(3), 387-398. https://doi.org/10.1002/hyp.6244.

Sheridan, G.J., & Noske, P.J., 2007b. Catchment-scale contribution of forest roads to stream exports of sediment, phosphorus and nitrogen. Hydrol. Processes 21(23), 3107-3122. https://doi.org/10.1002/hyp.6531.

Sosa-Pérez, G., & MacDonald, L.H., 2017a. Reductions in road sediment production and road-stream connectivity from two decommissioning treatments. For. Ecol. Manage. 398, 116-129. https://doi.org/10.1016/j.foreco.2017.04.031.

Sosa-Pérez, G., & MacDonald, L., 2017b. Wildfire effects on road surface erosion, deposition, and road-stream connectivity. Earth Surf. Process. Landf. 42(5), 735-748. https://doi.org/10.1002/esp.4018.

Stutter, M., Costa, F.B., & Ó hUallacháin, D., 2021. The interactions of site-specific factors on riparian buffer effectiveness across multiple pollutants: a review. Sci. Total Environ. 798, 149238. PMid:34325145. https://doi.org/10.1016/j.scitotenv.2021.149238.

Sugden, B.D., 2018. Estimated sediment reduction with forestry best management practices implementation on a legacy forest road network in the northern Rocky Mountains. For. Sci. 64(2), 214-224. https://doi.org/10.1093/forsci/fxx006.

Thomaz, E.L., Vestena, L.R., & Ramos-Scharrón, C.E., 2014. The effects of unpaved roads on suspended sediment concentration at varying spatial scales: a case study from Southern Brazil. Water Environ. J. 28(4), 547-555. https://doi.org/10.1111/wej.12070.

Thomaz, E.L., & Peretto, G.T., 2016. Hydrogeomorphic connectivity on roads crossing in rural headwaters and its effect on stream dynamics. Sci. Total Environ. 550, 547-555. PMid:26849320. https://doi.org/10.1016/j.scitotenv.2016.01.100.

Thomaz, E.L. 2019. Erosão do solo: teorias, métodos e perspectivas. Curitiba: CRV.

Tiecher, T., Caner, L., Minella, J.P.G., Pellegrini, A., Capoane, V., Rasche, J.W.A., Schaefer, G.L., & Rheinheimer, D.S., 2017. Tracing sediment sources in two paired agricultural catchments with different riparian forest and wetland proportion in southern Brazil. Geoderma 285, 225-239. https://doi.org/10.1016/j.geoderma.2016.10.008.

Touma, B.R., Kondolf, G.M., & Walls, S., 2020. Impacts of sediment derived from erosion of partially-constructed road on aquatic organisms in a tropical river: the Río San Juan, Nicaragua and Costa Rica. PLoS One 15(11), e0242356. PMid:33201898. https://doi.org/10.1371/journal.pone.0242356.

Valencia-Gallego, V., & Montoya, L.-J., 2024. Erosion mechanisms in unpaved roads: effects of slope, rainfall, and soil type. Air Soil Water Res. 17, 1-10. https://doi.org/10.1177/11786221241272396.

Van Dinter, R., Tekinerdogan, B., & Catal, C., 2021. Automation of systematic literature reviews: a systematic literature review. Inf. Softw. Technol. 136, 106589. https://doi.org/10.1016/j.infsof.2021.106589.

Vidon, P.G., Welsh, M.K., & Hassanzadeh, Y.T., 2019. Twenty years of riparian zone research (1997-2017): where to next? J. Environ. Qual. 48(2), 248-260. PMid:30951128. https://doi.org/10.2134/jeq2018.01.0009.

Wang, A., Zhao, Q., Yu, Z., Yu, J., Liu, Y., Wang, P., Zhang, G., Zhou, J., & Ding, S., 2023. Factors and thresholds determining sediment delivery pathways between forest road and stream in mountainous watershed. Catena 224, 106976. https://doi.org/10.1016/j.catena.2023.106976.

Wohlin, C., Kalinowski, M., Romero Felizardo, K., & Mendes, E., 2022. Successful combination of database search and snowballing for identification of primary studies in systematic literature studies. Inf. Softw. Technol. 147, 106908. https://doi.org/10.1016/j.infsof.2022.106908.

Xu, Q., Li, M., Jiang, X., Zhang, Z., Jiao, J., Jian, J., Li, J., Yan, X., Liang, Y., Chen, T., Chen, Y., Qi, H., & Zhang, Z., 2022. Response of rill erosion to rainfall types and maintenance on the Loess Plateau: implications for road erosion control. Catena 219, 106642. https://doi.org/10.1016/j.catena.2022.106642.

Xu, Q., Jiao, J., Yan, Z., Liao, J., Zhang, Z., Li, M., Yan, X., Chen, Y., Li, J., & Jian, J., 2024a. Response of road erosion to hydrological connectivity under a heavy rainstorm in an agricultural watershed on the Loess Plateau. Catena 240, 107991. https://doi.org/10.1016/j.catena.2024.107991.

Xu, Q., Jiao, J., Zhang, Z., Li, M., Yan, X., Chen, Y., Liao, J., & Yan, Z., 2024b. Functional connectivity related to road linear erosion at rainfall event scale in an agricultural watershed on the Loess Plateau. Catena 243, 108170. https://doi.org/10.1016/j.catena.2024.108170.

Yang, S., & Jin, Z., 2024. Impact of road network expansion on landscape ecological risk and soil erosion sensitivity on the Luochuan Tableland of the Chinese Loess Plateau. Reg. Environ. Change 24(2), 37. https://doi.org/10.1007/s10113-024-02202-x.

Yu, Z., Zhao, Q., Liu, Y., Yu, J., Wang, A., & Ding, S., 2024. Soil erosion associated with roads: A global review and statistical analysis. Land Degrad. Dev. 35(11), 3509-3522. https://doi.org/10.1002/ldr.5159.

Zhao, Q., Jing, Y., Wang, A., Yu, Z., Liu, Y., Yu, J., Liu, G., & Ding, S., 2022a. Response of sediment connectivity to altered convergence processes induced by forest roads in mountainous watershed. Remote Sens. (Basel) 14(15), 3603. https://doi.org/10.3390/rs14153603.

Zhao, Q., Wang, A., Jing, Y., Zhang, G., Yu, Z., Yu, J., Liu, Y., & Ding, S., 2022b. Optimizing management practices to reduce sediment connectivity between forest roads and streams in a mountainous watershed. Remote Sens. (Basel) 14(19), 4897. https://doi.org/10.3390/rs14194897.

Ziegler, A.D., Negishi, J., Sidle, R.C., Preechapanya, P., Sutherland, R.A., Giambelluca, T.W., & Jaiaree, S., 2006. Reduction of stream sediment concentration by a riparian buffer: filtering of road runoff in disturbed headwater basins of Montane Mainland Southeast Asia. J. Environ. Qual. 35(1), 151-162. PMid:16391286. https://doi.org/10.2134/jeq2005.0103.

Received: 08 May 2025
Accepted: 06 January 2026

Associate Editor: Andre Andrian Padial.