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RESEARCH ARTICLE

Toward effective river restoration in Brazil: a systematic review of current practices, regional disparities, and success metrics

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Freshwater ecosystems in Brazil face critical threats from urbanization, industrialization, and agricultural expansion, leading to biodiversity loss and diminished ecosystem services. Restoration efforts are essential, yet a systematic overview of their distribution, objectives, and success metrics is lacking. Here, we conduct a systematic review of scientific literature and government-funded project reports to assess the current state of river and stream restoration in Brazil. We applied a structured approach to analyze 25 publications and 16 projects funded by the National Watershed Revitalization Program, classifying restoration efforts by scale, objectives, actions, and success evaluation. Results show that basin-scale restoration dominated over reach and sub-basin-scale projects, with most efforts concentrated in the Atlantic Forest and Cerrado savanna in the Southeastern region. Water quality improvement, particularly through pollution control and riparian vegetation restoration, was the primary objective. Success evaluation focused largely on water quality and habitat assessments; however, 40% of publications and 12.5% of projects lacked formal success control. Regional disparities in restoration distribution reflect economic and institutional imbalances, underscoring the need for standardized protocols and more equitable resource allocation. This review highlights the importance of adaptive management and community involvement to enhance restoration outcomes and ensure long-term sustainability in Brazil's freshwater ecosystems.

Key words: freshwater ecosystems, pollution control, riparian vegetation water quality, river restoration, watershed revitalization

Implications for Practice

- River restoration efforts in Brazil are concentrated in the Southeast. Expanding these efforts to other regions is important for balanced national restoration goals.
- Many restoration projects lack success control. Implementing consistent monitoring protocols would allow for adaptive river restoration and long-term sustainability.
- Engaging local communities and transferring technical knowledge on cost-effective, state-of-the-art practices could improve the outcomes of restoration projects at the municipal level.
- Due to the success of watershed-scale restoration regarding integrated water resource management, this approach should be prioritized to improve the environmental health and resilience of Brazilian freshwater ecosystems.

Introduction

In recent years, freshwater ecosystems have experienced unprecedented declines in biodiversity around the globe. This alarming trend is closely related to increases in urbanization, agricultural expansion and intensification, and the unregulated exploitation of water resources (Butchart et al. 2010). Anthropogenic disturbances, such as habitat fragmentation, hydromorphological degradation, riparian deforestation, and water pollution, are the main drivers of this decline (Stephenson 2001; Wantzen et al. 2019; Ranta et al. 2021), resulting in the loss of essential ecosystem services, such as water purification and food provisioning, which are vital to society (Díaz et al. 2018). Therefore, the restoration of running waters has become a common practice worldwide (González del Tánago et al. 2012; Feio et al. 2021).

Efforts to restore rivers in Europe and North America have been ongoing since the early twentieth century. For instance, in the United States, the initial focus was on esthetic and recreational aspects, such as introducing in-stream structures to enhance trout fishing (Wohl et al. 2015). From the 1970s onwards, these efforts

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expanded to include improving water quality, addressing point and then non-point sources of pollution first, and later, restoring riparian buffers and floodplains to improve pollutant retention and habitat quality (Craig et al. 2008; Campana et al. 2014). Common approaches in European rivers involve restoring more natural riverbanks and in-stream conditions, e.g. by large woody debris additions, increasing retention of fine sediments and nutrients through riparian buffer strips, and removing weirs and dams to enhance habitat resilience, increase biodiversity, and restore hydrological regimes (Poff & Zimmerman 2010; Feld et al. 2011). The success of these efforts depends on the scale and complexity of the implemented actions and, consequently, on the extent to which natural processes are recovered, as well as the time elapsed since restoration, given that biological recolonization and catchment responses are not immediate. Key factors include habitat availability resulting from riparian vegetation and channel restoration and addressing watershed-level issues such as water quality and recolonization potential (Jähnig et al. 2010; Gillmann et al. 2023).

In countries of the Global North, governmental agencies have been promoting the restoration of rivers and streams for decades. In the European Union, this is facilitated through the Water Framework Directive (WFD), while in the United States, the Clean Water Act serves a similar purpose. These directives aim to halt the degradation of aquatic ecosystems and achieve good water quality status (González del Tánago et al. 2012). In other developed countries, restoration practices have been implemented for over 50 years, with consolidated and effective legislation for urban sewage management (Feio et al. 2021). In contrast, the situation in developing countries is markedly different, and sanitation and sewage treatment remain inadequate or incomplete (Finkler et al. 2023). The hydromorphology of lotic systems in such countries is often still simplified and degraded, and the "urban stream syndrome" continues to be prevalent (Walsh et al. 2005).

In Brazil, the concept of restoration is still evolving in the context of water resources. Despite a growing number of projects in this area, legislation has no clear standardization (Veiga 2011). In this study, we adopted the term "restoration" as defined by the European Centre for River Restoration (ECRR), which describes river restoration as a range of ecological, physical, spatial, and water resource management practices aiming at reinstating natural processes such as flow regimes and sediment transport to restore biodiversity and ecosystem services (ECRR 2013).

To address river restoration at a broader scale, the Brazilian government launched the National Watershed Revitalization Program (Programa de Revitalização de Bacias Hidrográficas [PNRBH]) in 2001. The PNRBH aims to promote the revitalization and preservation of watersheds across Brazil through the integrated preservation, restoration, and sustainable management of water resources by fostering collaboration between governmental bodies, environmental agencies, civil society, and the private sector. The PNRBH prioritizes areas based on environmental degradation, socioeconomic importance, and water availability (República Federativa do Brasil 2022). However, implementing such large-scale projects has faced major obstacles, such as stakeholder conflicts, insufficient technical expertise, and the complexity of coordinating efforts across large and diverse river basins like the São Francisco (Machado 2008).

Other difficulties, such as the need for long-term monitoring and evaluation, limited incentives and budgets, and the involvement of entities with minimal scientific and ecological expertise, also undermine the few restoration efforts in Brazil. For example, short-term municipal efforts regarding pollution reduction and structural modifications can lead to unintended consequences, such as disrupted aquatic–riparian connectivity and infrastructure damage, compromising the long-term sustainability of restoration initiatives (Fig. 1). Additionally, the vast geographic and climatic diversity of Brazil poses unique challenges to the restoration of streams, rivers, and watersheds. Due to the country's heterogeneity in economic development, social inequality, land use, and climate, restoration efforts must be tailored to the specific conditions of different regions. In addition, restoration projects often face conflicts among government agencies, non-governmental organizations, private sector stakeholders, and traditional communities. These challenges are particularly pronounced in large river basins spanning different Brazilian regions or even states where competing interests and a lack of technical expertise have hindered the effective implementation and long-term monitoring of restoration efforts (Machado 2008).

The recent droughts and ongoing water crisis in Brazil, worsened by climate and land use changes, threaten the availability of freshwater resources and the resilience of aquatic ecosystems. This emphasizes the urgent need for effective watershed and stream restoration strategies. Recent studies have shown that while rehabilitated urban streams in Brazil have shown improvements in structure and function compared to degraded streams, they still do not fully recover the ecological conditions of reference streams (Bega et al. 2024; Madureira et al. 2024). This indicates that current restoration efforts often result in only partial recovery, highlighting the complexity of restoring urbanized and degraded streams and watersheds.

This study synthesizes the current status of stream and river restoration in Brazil, a megabiodiverse country with diverse environmental, economic, and social challenges. We structured our review around four questions: (1) What are the main targets and methods in Brazilian river restoration (Population)? (2) Which actions are implemented to restore freshwater ecosystems (Intervention)? (3) How do restoration efforts vary by region, and why (Comparator)? (4) What outcomes, especially in water quality and resilience, have been achieved (Outcome)? We reviewed scientific literature and government reports to analyze the challenges and opportunities for freshwater ecosystem restoration in Brazil.

Methods

Literature Search and Selection

This review applied a systematic approach to capture river and stream restoration projects across Brazil's biomes and regions. Searches were conducted in the Clarivate Web of Science and Google Scholar databases, including work published until the end of 2023, with iterative refinement of search terms based on initial

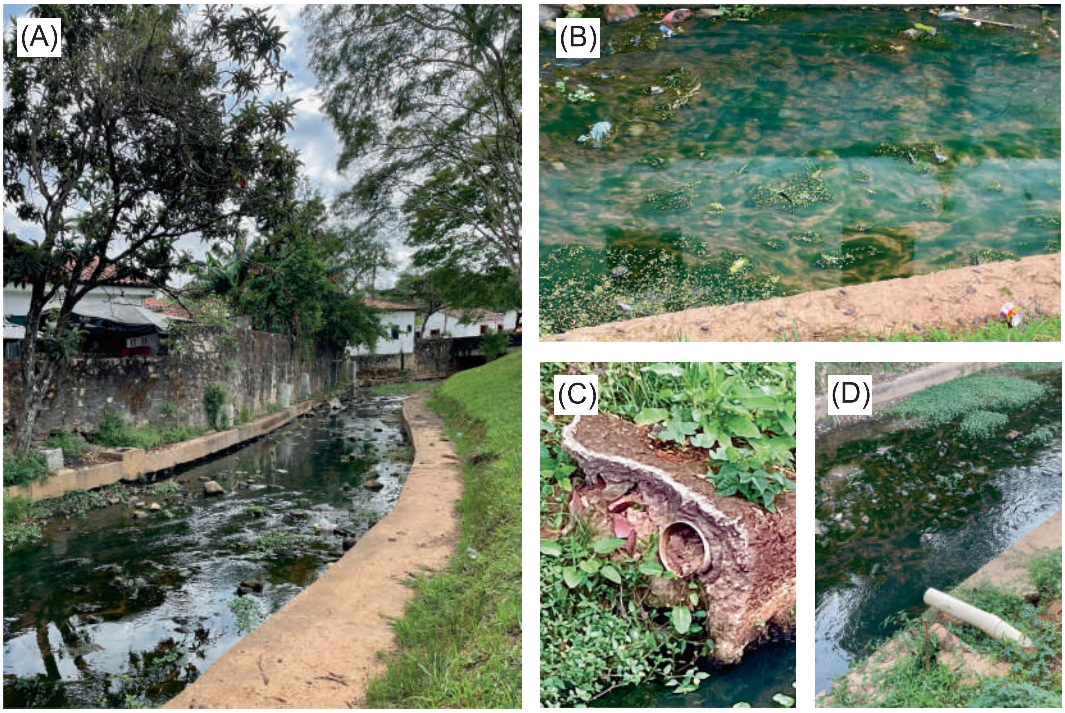

Figure 1. Restoration of the Santo Antônio stream in Tiradentes, Minas Gerais, Southeast Brazil (October, 2023). (A) To reduce pollution, domestic sewage collection systems were installed on both banks, characterized by concrete barriers that disrupted aquatic–riparian connectivity. (B) Proliferation of filamentous algae in response to eutrophication. (C) Damage to the sewage collection infrastructure a few years after installation. (D) Sewage pipes installed over the collection system.

findings and term co-occurrence analysis in VOSviewer. This analysis confirmed the robustness of our search, as it identified no additional unique records. The final English-language search string was:

(restor* OR rehabil* OR recover* OR revita* OR reclam* OR reclaim* OR requalify*) AND (stream* OR river* OR brook* OR creek* OR ditch* OR "running water*" OR catchment* OR watershed* OR basin*) AND (Brazil* OR Brasil* OR Cerrado OR Amazon* OR "Atlantic Forest" OR Pampa OR Pantanal OR Caatinga OR Acre OR Alagoas OR Amapa OR Bahia OR Ceara OR "Distrito Federal" OR "Espirito Santo" OR Goias OR Maranhao OR Mato Grosso OR "Mato Grosso do Sul" OR "Minas Gerais" OR Para OR Paraiba OR Parana OR Pernambuco OR Piaui OR "Rio de Janeiro" OR "Rio Grande do Norte" OR "Rio Grande do Sul" OR Rondonia OR Roraima OR "Santa Catarina" OR "São Paulo" OR Sergipe OR Tocantins).

Additionally, the same search terms were applied in Portuguese to capture non-English sources:

(restor* OR rehabil* OR recup* OR revita* OR requalifi*) AND (rio* OR riacho* OR corrego* OR manancia* OR bacia*) AND (Brasil* OR Cerrado OR Amazon* OR "Mata Atlântica" OR Pampa OR Pantanal OR Caatinga OR Acre OR Alagoas OR Amapa OR Bahia OR Ceara OR "Distrito Federal" OR "Espirito Santo" OR Goias OR Maranhao OR Mato Grosso OR "Mato Grosso do Sul" OR "Minas Gerais" OR Para OR Paraiba OR Parana OR Pernambuco OR Piaui OR "Rio de Janeiro" OR "Rio Grande do Norte" OR "Rio Grande do Sul" OR Rondonia OR Roraima OR "Santa Catarina" OR "São Paulo" OR Sergipe OR Tocantins).

We included only studies on stream and river restoration in Brazil, excluding other systems (e.g. reservoirs and terrestrial restoration). The study selection process, shown in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses diagram (Supplement S1), followed pre-established inclusion criteria for transparency and replicability. Briefly, we analyzed the titles of all publications obtained, excluding those clearly outside the scope of our study, such as studies from other research fields that did not address environmental restoration. This process resulted in 75 records, including scientific articles, book chapters, theses and dissertations, conference proceedings, and reports. Two researchers independently reviewed these publications, ultimately excluding 50 records that did not meet our criteria, retaining 25 records (Supplement S1). Restorations conducted outside Brazil or in other systems, like reservoirs or mangroves, were excluded. Terrestrial restoration efforts in watersheds and riparian vegetation restoration were included if they were directly related to stream or river objectives, such as improving water quality, aquatic biodiversity, habitat diversity, or natural hydrology.

To capture more recent restoration efforts not yet documented in the scientific literature, we also analyzed the 19 projects funded by the Federal Government of Brazil under the National Watershed Revitalization Program between 1987 and 2023. These projects were screened using the same exclusion criteria applied to the publications (Supplement S1), and only 16 projects explicitly aiming at restoring aspects of Brazilian streams or rivers were retained. We categorized the 25 scientific publications and 16 government-funded projects by restoration scale, objectives, specific actions, and success evaluation methods, detailed in Supplement S1. This framework aligns with widely used restoration metrics, such as water quality, biodiversity, and community involvement, allowing for clear comparisons across project types and scales. Classification criteria are based on key needs in Brazilian freshwater systems, providing transparency for future research.

Classification of Studies and Projects

We created a database summarizing each of the 41 records with entries including title, restored stream or watershed name, scale of restoration, objectives, restoration actions, success criteria, and additional comments. These additional comments included details such as river discharge, width, biome, vegetation type, and land use, which were used to characterize the range of rivers and catchments in the dataset. However, they were not included in further formal analysis due to missing data in some records and highly imbalanced category distributions. The records were further classified into categories: restoration proposals, experimental studies on aspects of stream restoration, and projects either completed or in progress. Key terms commonly used in restoration literature were then applied to classify the records according to the spatial scale, objectives, restoration actions, and success criteria of restoration efforts, as outlined in Supplement S1.

Spatial Analysis

For all records in our dataset, we retrieved spatial coordinates either from the original documents, by contacting the authors, or by locating the study sites in Google Earth. If large watersheds were restored, we considered the coordinates of the center of the watershed if the restored watershed was within a single federal state. Projects on watersheds spanning several states were represented by separate symbols at the center of the respective subwatershed in each state. Subsequently, we created a map of the restoration projects using Quantum Geographic Information System (version 3.32.0), classifying the records as "Finalized and executed projects" or "Proposals and planned projects" as extracted from the original texts. We also indicated whether the restoration projects were identified through the literature review or the PNRBH.

Term Co-Occurrence Analysis of Stream Restoration Literature

As an alternative to manually classifying the retrieved records according to restoration scale, objectives, and actions, we imported the bibliographic data of the records in our dataset that had titles and abstracts available in English into the software VOSviewer (version 1.6.20) and created term co-occurrence maps based on text data. In full counting mode, 747 terms were extracted from the titles and abstracts. After applying a minimum threshold of five occurrences across different references and excluding generic terms such as "Brazil" or "area," 17 terms were retained for the co-occurrence maps. With a minimum cluster size of four terms, 10 random starts, and 1000 iterations, we generated network, overlay, and cluster density co-occurrence maps.

Results

Dataset, restoration scale, objectives, actions, and success control in publications

After excluding publications outside the scope of our study, the 25 selected publications encompassed a broad range of river sizes (from approximately 100 L/s to 14,000 m^3/s discharge; Supplement S1), biomes (Atlantic Forest, Cerrado savanna, Caatinga arid land, Amazon Rainforest; Supplement S1), and catchment land uses (urban and rural, the latter including mixed agricultural catchments; Supplement S1). The publication dataset also covered a wide range of restoration scales, objectives, actions, and success control strategies (Fig. 2). There were more restorations at the river basin scale, with 10 published works, followed by the local reach and sub-basin scales, with 9 and 6, respectively.

The analysis of restoration objectives shows that riparian reforestation was a prominent focus, appearing in 12 studies. Other objectives were less represented: water quality improvement was the focus of nine studies, and enhancing biodiversity and fish habitat appeared in six studies. Participative restoration, that is, the objective of raising awareness, motivating, and actively including local communities, was identified in five studies (Fig. 2). In general, the restoration objectives were closely aligned with the environmental issues and human impacts identified at the restoration sites in the respective studies.

Among the restoration actions identified in the publications, 13 mentioned pollution control and sanitation (Fig. 2). Riparian vegetation restoration was highlighted in 12 publications. Restoration actions such as hydromorphological improvements and erosion and sedimentation control were each present in five projects. Environmental education was less frequently addressed, appearing in three publications only. Management and monitoring were identified in three publications. Additionally, enhancing carbon sequestration and implementing Nature-Based Solutions (NBS) approaches were mentioned in single publications.

Among the 25 publications, 13 report completed restorations, 7 are restoration proposals, and 5 report experimental work related to stream and river restoration. The primary success control methods reported were assessments of water quality characteristics and pollution levels (12) and those related to habitat quality and biodiversity, including the use of bioindicators (10; Fig. 2). Assessments of hydromorphological and riverbank conditions were mentioned in four records. Notably, 10 papers did not report any plans for success control.

Dataset, Restoration Scale, Objectives, Actions, and Success Control in PNRBH Projects

Sixteen watershed restoration projects funded by the Federal Brazilian Government through the National Watershed

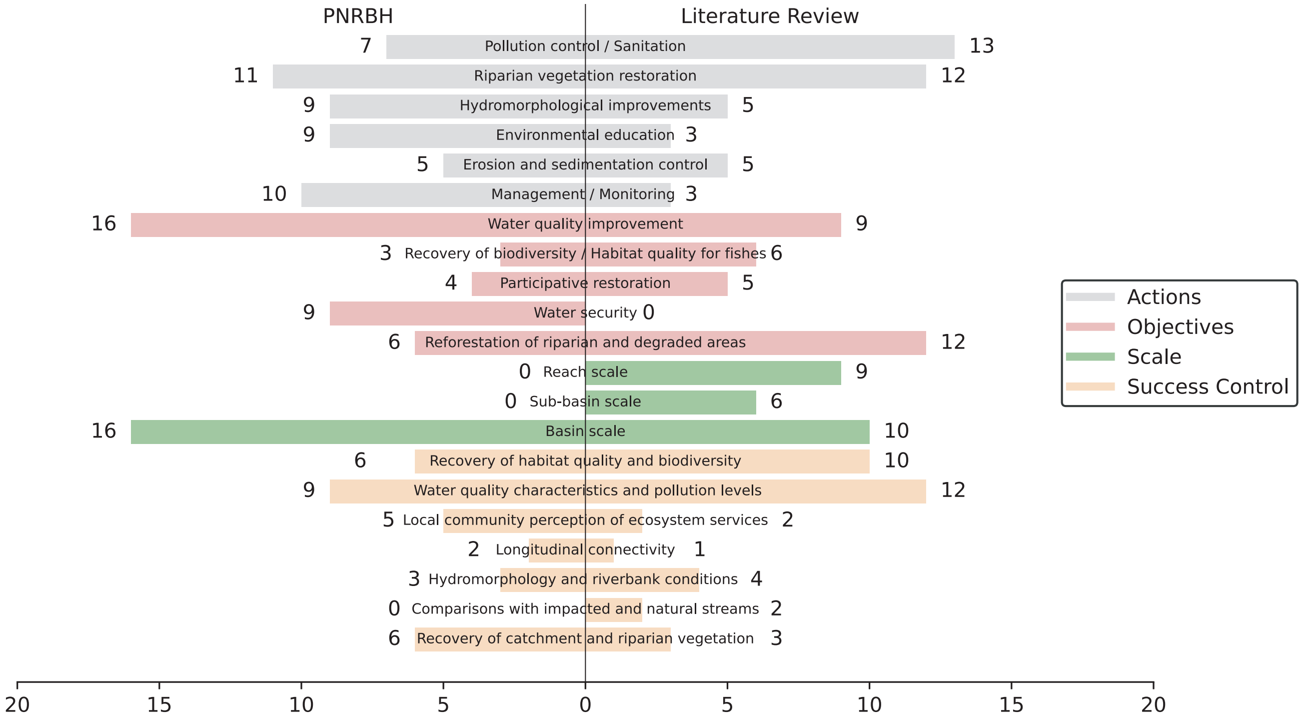

Figure 2. Restoration actions, objectives, scale, and success control in the records from the literature review and projects funded by the Brazilian National Watershed Revitalization Program (PNRBH). Numbers indicate the number of publications or projects that include each specific item.

Revitalization Program (PNRBH) over the past 20 years were included in our study. These projects encompassed a broad range of river sizes (from <1 to 18,000 m^3/s discharge; Supplement S1), biomes (Atlantic Forest, Cerrado savanna, Caatinga arid land, and Pampa grassland; Supplement S1), and catchment land uses (urban and rural, the latter incl. mixed agricultural catchments; Supplement S1). Although all 16 projects were focused on basin-scale restoration efforts (Fig. 2), as expected from the Funding Guidelines of the PNRBH, the high diversity of project objectives reflected different emphases and priorities within the overall effort to revitalize watersheds. Water quality improvement was the most frequently cited objective, appearing in all 16 projects. Water security was an objective in nine projects. Reforestation of riparian areas (six projects), participative restoration (four), and biodiversity and habitat enhancement (three) were other key objectives.

Regarding restoration actions, the restoration and preservation of riparian areas stood out, with 11 projects mentioning these actions. Environmental education and hydromorphological improvements were components in nine projects, while pollution control and sanitation were featured in seven projects. Erosion and sedimentation control appeared in five projects. Management and monitoring, with a strong focus on the effective administration of water resources and establishing permanent protection areas, were mentioned in 10 projects.

Similar to the results from the literature review, the primary success control strategies reported in the funded projects were assessments of water quality characteristics and pollution levels (nine) as well as those related to habitat quality and biodiversity, including the use of bioindicators (six; Fig. 2). However, assessments of vegetation recovery (six) and community perceptions of ecosystem service improvement (five) were also important. Notably, two funded projects did not report any plans for success control.

Spatial Distribution of Stream and River Restoration in Brazil

Stream restoration efforts were primarily concentrated in the Atlantic Forest (Supplement S1) in the Southeastern region (Fig. 3), with projects in the states of São Paulo (11 projects), Minas Gerais (8), Rio de Janeiro (2), and Espírito Santo (2). In the Northeast region, there were four records in Bahia, Pernambuco, Sergipe, and Alagoas. In the Southern region, there were two records in Paraná and Santa Catarina. The Central-Western region had two projects in the state of Goiás and the Federal District. There was only one project in the North (Tocantins).

Regarding the National Watershed Revitalization Program (PNRBH), projects were concentrated both in the Southeast (10), with 8 projects in Minas Gerais, 1 in São Paulo, and 1 in Rio de Janeiro, and in the Northeast region (10), with 2 each in Bahia, Ceará, and Pernambuco, and single projects in Alagoas, Sergipe, Piauí, and Paraíba. There were three projects in the South, in Paraná (two) and Rio Grande do Sul (one), and one project in the northern state of Tocantins. There were no projects in the Central-West region. Projects

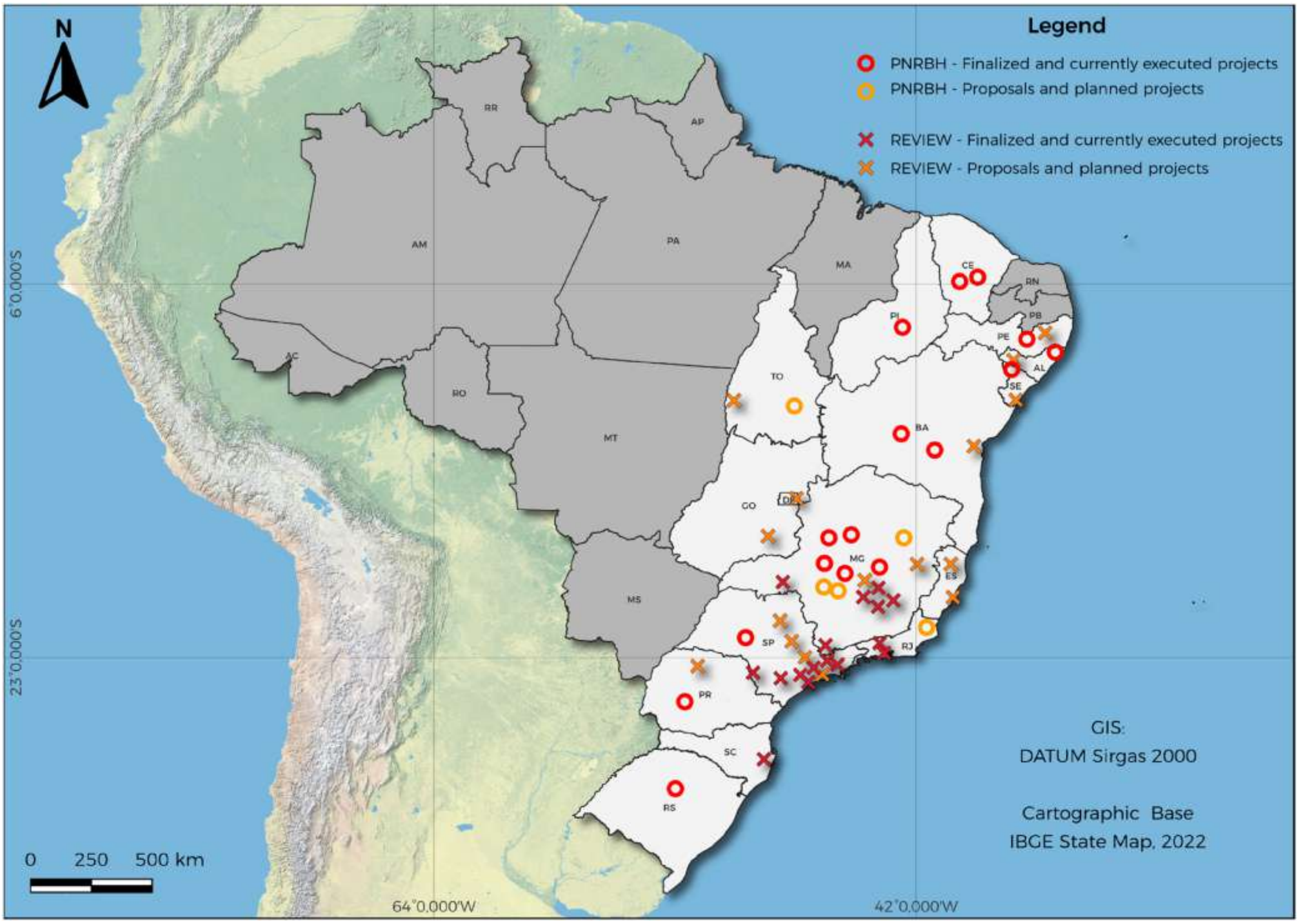

Figure 3. Location of restoration projects and studies from the literature review and projects funded by the Brazilian National Watershed Revitalization Program (PNRBH). Projects on watersheds spanning several federal states are indicated with separate symbols in the center of the respective watershed in each state. States without restoration projects and studies are indicated in gray.

mainly considered the Atlantic Forest and Cerrado savanna biomes (Supplement S1).

Term Co-Occurrence Analysis

The cluster density map (Fig. 4A) highlights the distribution and concentration of key terms across the literature on stream restoration in Brazil. The analysis identified three prominent clusters. The first cluster (red in Fig. 4; upper panel) has the highest density of terms associated with "stream," "reach," "experiment," and "greenway," indicating a strong emphasis on experimental work and assessments at the stream reach scale. The second cluster (green in Fig. 4A) shows high term densities associated with "city," "resilience," "sewage," "urban stream," and "ecosystem service." This cluster includes restoration publications primarily from Southeastern cities in the states of São Paulo and Minas Gerais, suggesting a focus on urban stream restoration in larger cities, particularly on pollution control. The third cluster (blue in Fig. 4A) is characterized by high term densities associated with "watershed," "recovery," "environment," and the urban river restoration index "URRIX," indicating a focus on assessments of watershed-scale vegetation recovery.

The network map (Fig. 4B) shows the relationships between the identified terms, illustrating their frequency of co-occurrence within the dataset. The map reveals tightly connected cores within each cluster: "stream," "reach," and "experiment" form the core of cluster 1; "city," "resilience," and "sewage" form the core of cluster 2; and "watershed," "environment," and "time" are central in cluster 3. This suggests that the literature on stream restoration in Brazil is particularly concentrated around these themes. Some terms, such as "greenway," "physical habitat," and "recovery," exhibit significant connections across various cluster cores. For instance, "greenway" is linked to all three clusters, underscoring the importance of urban stream corridor restorations. On the other hand, "URRIX" (cluster 3) and "experiment" (cluster 1) appear as peripheral terms with limited connections to other clusters, likely representing more specialized topics within their respective clusters.

The temporal overlay map (Fig. 4C) provides insights into the evolution of stream restoration research in Brazil over time. The analysis shows a temporal progression within

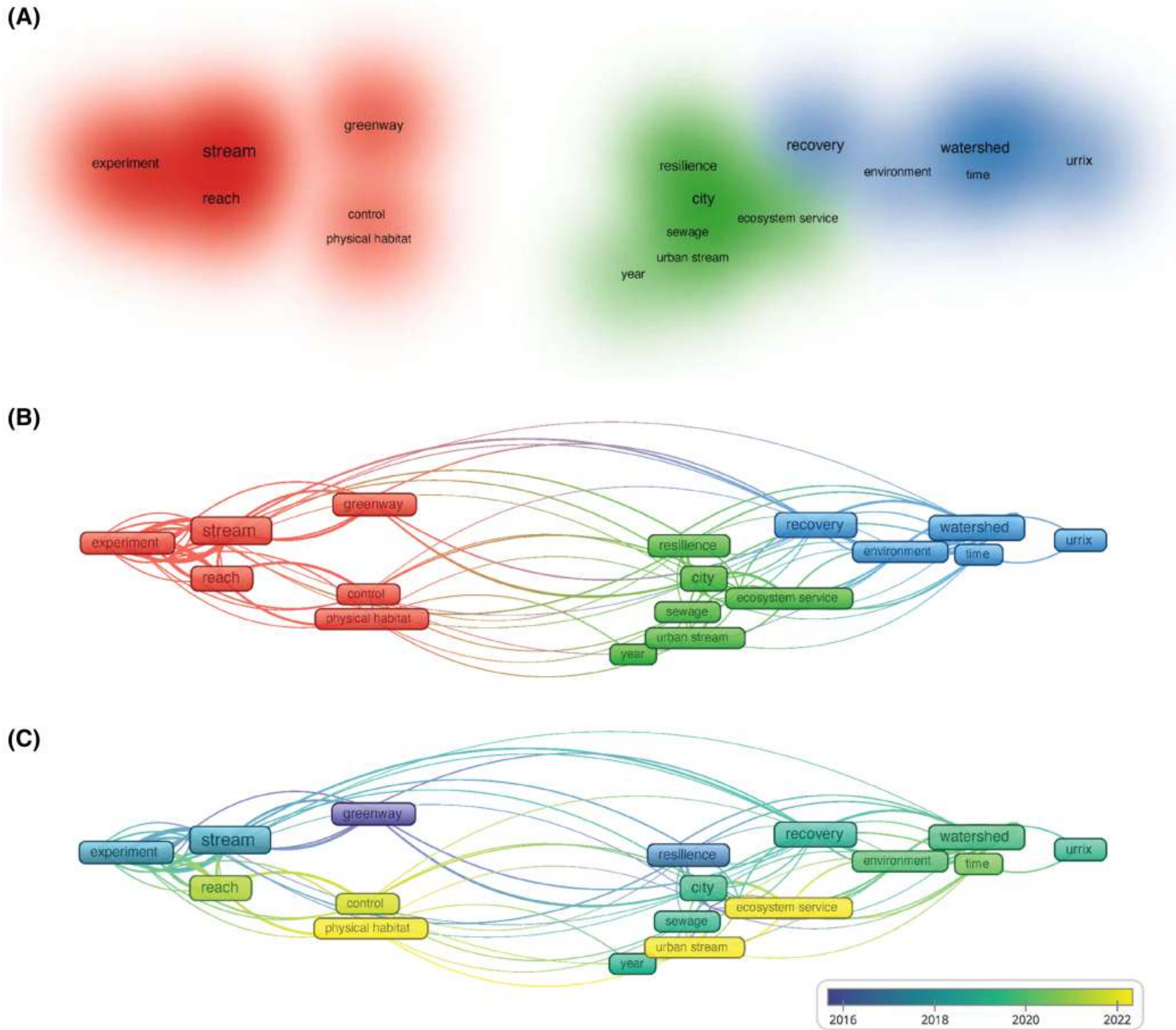

Figure 4. Cluster density (A), network (B), and temporal overlay (C) VOSviewer co-occurrence maps of terms in record titles and abstracts.

the relatively short span of literature on stream restoration, with earlier publications (around 2016) focusing on topics such as "greenway," "resilience," "stream," and "experiment." More recent publications increasingly address issues like "urban stream," "physical habitat," and "ecosystem service." This trend suggests a growing specialization and refinement in the field of stream restoration, with a shift toward addressing more complex and targeted ecological challenges related to ecosystem services and habitat structure in urban streams in recent years.

Discussion

Here, we provide a systematic overview of stream and river restoration efforts in Brazil, analyzing the current state of practice, key challenges, and future directions. We found that restoration initiatives are concentrated in the Southeastern region, particularly in the states of São Paulo and Minas Gerais, likely due to disparities in economic development and institutional capacities between Brazilian states and regions, with wealthier regions having greater access to the resources needed to implement and sustain restoration projects. The concentration of stream and river restoration plans in the Southeastern region mirrors the pattern observed in other restoration initiatives across Brazil. Brazil has pledged to restore 12 million hectares of degraded land by 2030 as part of its commitment to the United Nations Decade on Ecosystem Restoration. This initiative, the National Plan for the Recovery of Native Vegetation (MMA 2017), plans for active restoration efforts covering 20–50% of Brazil's degraded areas. A 2022 study conducted by the Brazilian

Society for Ecological Restoration (SOBRE), the Atlantic Forest Restoration Pact, the Alliance for the Restoration of the Amazon, and the Brazilian Coalition on Climate, Forest, and Agriculture revealed that most restoration initiatives were concentrated in the Southeastern region of Brazil (61%), with 30% occurring in the state of São Paulo (Brancalion et al. 2022). This uneven distribution of restoration initiatives across Brazilian regions was more strongly associated with the states' gross primary product than with the legal deficit of native vegetation. Therefore, a more equitable allocation of governmental resources, alongside greater political recognition that ecosystem restoration is an emerging economic sector with the potential to create jobs and generate income, especially for local organizations and communities, could help expand restoration initiatives to other regions (Brancalion et al. 2022).

Restoration Scale, Objectives, and Actions

Restoration efforts in Brazil show a strong emphasis on pollution control, sanitation, and riparian forest restoration. These actions are crucial in addressing ongoing water quality problems and deforestation, which remain severe challenges in many parts of the country (e.g. Gücker et al. 2016; Ríos-Villamizar et al. 2017). The prevalence of basin-scale restoration efforts is particularly promising, as they may facilitate integrated water resource management and a broader understanding of large-scale ecosystem processes (Gregersen et al. 2007). However, our study also shows that many projects lack systematic evaluations of outcomes. As a crucial prerequisite for adaptive management and long-term sustainability, there is a need for a more consistent inclusion of success control mechanisms in restoration projects (Gregory et al. 2006). While the success of river restoration in Brazil is typically evaluated by monitoring the physical and chemical characteristics of river water, macroinvertebrate community structure, aquatic plants, fish diversity and biomass, and physical habitat structure (Pompeu et al. 2004; Hughes 2019; Al-Zankana et al. 2020), aspects of ecosystem functioning are rarely considered. While some of these aspects, such as gross primary production, recover in the short term following riparian vegetation restoration, other critical functions, such as ecosystem respiration and nutrient uptake, may take much longer to recover (Bega et al. 2024). This suggests that restoration efforts must be evaluated over extended periods to assess their success accurately (Palmer & Ruhi 2019).

Comparison with Global North Practices

Unlike the Global North, where restoration is supported by strong legislative frameworks like the European Union's WFD and the United States Clean Water Act (Wohl et al. 2015), Brazil's regulatory landscape is more fragmented. This lack of standardized guidance introduces inconsistencies in project implementation and monitoring, which may reduce long-term effectiveness. Brazilian projects often prioritize short-term goals like pollution control, while Global North projects typically focus on broader ecosystem recovery supported by water quality and ecological health metrics. A cohesive national framework for Brazilian river restoration, integrating both ecological and social objectives, would improve consistency and impact.

The absence of a standardized legal framework and regulations, as well as manuals and practical guides for stream and river restoration in the Portuguese language considering local restoration priorities (unpublished study), can result in inconsistencies in the implementation and monitoring of restoration projects, potentially undermining their long-term success. Since there is already a commitment to restoring native vegetation in degraded areas (MMA 2017), incorporating a stronger watershed perspective into current policies could create a synergistic effect between reforestation and stream and river restoration. Additionally, while community involvement is a component of restoration efforts in the Global North, Brazilian projects like the Programa Produtor de Água have uniquely integrated local communities, particularly rural producers, into the restoration process. This participatory approach has proven effective in ensuring the sustainability of restoration actions by facilitating local ownership and engagement (González del Tánago et al. 2012).

Our results indicate several peculiarities of restoration efforts in Brazil, probably typical for other countries in the Global South. The most prominent is the significant regional disparity in the spatial distribution of restoration projects, potentially driven by differences in financial resources and institutional capacity rather than the spatial distribution of river degradation (Brancalion et al. 2022). While the Southeast exhibits more robust economic development and infrastructure, the North and some Northeastern regions may face socioeconomic and logistical challenges that limit the implementation of restoration initiatives, highlighting the need for targeted investments and policy interventions to promote restoration efforts across the entire country and ensure that regions with fewer resources are included (Neeson et al. 2015). However, our results also reveal a surprisingly low number of restoration projects in the more developed South despite the region's recent severe water crises and flooding issues. This suggests that political and societal factors play a significant role in implementing river restoration initiatives.

Additionally, restoration efforts in Brazil must address both urban and rural degradation (Gücker et al. 2024). In urban areas, restoration often focuses on mitigating severe environmental degradation and improving water security, while in rural areas, the emphasis is on maintaining the functionality of critical ecosystems that support agriculture and other livelihoods, but also biodiversity. Therefore, a flexible and context-specific approach to restoration, adapted to the needs and conditions of different regions, is needed (Palmer & Filoso 2009). Finally, we suspect there are numerous undocumented, often ill-conceived, urban stream restoration attempts at the municipal level that could greatly benefit from the transfer of knowledge and guidance on state-of-the-art, cost-effective restoration practices to local practitioners.

Adaptive Restoration for Future Climate Change

In Brazil, general precipitation patterns, climatic variability, and extreme events are projected to intensify (Avila-Diaz et al. 2020), and the hydrological regimes of many rivers are expected to shift due to climate change. Thus, conventional restoration techniques may no longer suffice (Palmer et al. 2005, 2014), and adaptive restoration strategies could become important to ensure the resilience of aquatic ecosystems. A strategic focus on riverscapes as natural infrastructure (Skidmore & Wheaton 2022) could enhance the ability of restored rivers to withstand climate change impacts by providing critical ecosystem services, such as flood regulation and water quality improvements. Adaptive restoration involves implementing flexible management practices that can be adjusted in response to changing environmental conditions. Key strategies include the use of native species that are resilient to a broader range of environmental conditions, the restoration of natural hydrological processes, especially in floodplains, to buffer against extreme flow events, and the integration of climate projections into restoration planning. Process-based restoration, which focuses on reinstating natural processes such as sediment transport and flow regimes, is crucial in this context as it enhances the capacity of ecosystems to self-regulate and adapt to future changes (Wohl et al. 2015). Moreover, adaptive management, involving continuous monitoring and feedback loops that allow for timely adjustments in restoration activities and their intensity, could enhance the long-term sustainability of restoration efforts and ensure their effectiveness under future climate scenarios. However, resources for restoration initiatives are still rather limited in Brazil, and therefore, it may be important to focus on NBS that maximize the resilience of restored systems with minimal interventions and need for monitoring, ensuring that restoration projects are sustainable in the face of political change and ongoing environmental changes (Kollmann et al. 2016).

River Restoration Based on the Monitoring of Ecosystem Functions and Services

A critical aspect of modern river restoration is including a focus on restoring and monitoring ecosystem functions and services rather than merely characteristics of ecosystem structure or biotic community composition. In Brazil, a megadiverse developing country where rivers provide important ecosystem services such as water purification, flood regulation, food provisioning, and habitat for biodiversity, restoration and conservation efforts should prioritize the ecosystem functions underlying these services to enhance ecosystem resilience and human well-being. Monitoring ecosystem functions, such as nutrient cycling, primary production, and sediment transport, provides valuable insights into the ecosystem health of restored rivers (Bega et al. 2024). For example, the recovery of ecosystem metabolism and nutrient uptake is crucial for maintaining water quality and supporting aquatic communities. However, some of these functions may recover over longer timescales than structural elements like vegetation cover, highlighting the need for long-term monitoring to fully understand the success of restoration efforts (Palmer & Ruhi 2019; Bega et al. 2024).

Restoring ecosystem functions of rivers and the services they promote directly benefits local communities and contributes to broader societal goals such as poverty alleviation and sustainable development. Therefore, integrating ecosystem services into restoration planning and monitoring can ensure that restoration efforts deliver tangible benefits to both nature and people (González del Tánago et al. 2012). Important interdisciplinary approaches combine ecological with socioeconomic sciences, including engaging local communities in the restoration process. In Brazil, where many restoration projects already involve community participation, expanding this engagement to include the co-monitoring of ecosystem services could enhance the impact and sustainability of restoration outcomes (Cunha et al. 2019).

Fish Bypasses and the Brazilian Forest Code

While not considered in the present literature review, two related topics with significant implications for running water restoration in Brazil were frequently encountered while screening the literature. The first topic is the implementation of fish bypass systems, such as fish ladders, which are designed to facilitate the migration of fish species across barriers like hydroelectric dams that are numerous in Brazil. These systems may be crucial for maintaining fish populations, especially regarding migratory fishes, but they also present challenges, including high costs, maintenance difficulties, predation risk, and potential disruptions to the natural behavior of some species, which can impact their reproductive success (Lennox et al. 2019). The second topic, and a critical aspect of Brazil's environmental management, is the Brazilian Forest Code, established by Law No. 12.651/2012, which mandates the protection and restoration of riparian forests and headwaters. The Forest Code requires the preservation and recovery of native vegetation in Areas of Permanent Preservation along rivers, streams, and springs, and the maintenance of Legal Reserves in rural properties. Although recently significantly weakened, this legislation still plays an important role in the conservation of running waters and maintaining watershed connectivity, and thus, river restoration (Sparovek et al. 2012).

In summary, river and watershed restoration in Brazil poses a complex and challenging task that requires an interdisciplinary approach. Although there has been notable progress, especially in the Southeastern region, restoration projects are still relatively scarce compared to those in the Global North. Furthermore, the variations in restoration efforts across Brazilian states indicate the need for a more equitable allocation of resources and institutional support. Brazil could enhance its river restoration agenda and serve as a model for other developing countries by involving local communities, adapting to climate change, and utilizing existing legal frameworks such as the Brazilian Forest Code and the National Plan for the Recovery of Native Vegetation. Continuous research, along with knowledge transfer and the implementation of practical and adaptive restoration strategies, could help overcome obstacles and ensure the long-term success of restoration efforts in Brazil.

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Conflict of Interest Statement

The authors declare that they have no conflicts of interest regarding this research.

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Supporting Information

The following information may be found in the online version of this article:

Supplement S1. Supplementary information on the literature and project review, search strategy, record classification, and river characteristics.

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