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Data gaps in water-related ecosystem services for urban flood risk adaptation in Brazil: a national diagnostic and policy-oriented analysis

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Ana Feital Gjorup[1*]; Rachel Bardy Prado[2]; Joyce Maria Guimarães Monteiro[2]; Fernanda Helfer[3]

[1]Independent researcher, Alameda do Jequitiba, n° 565, 45a, CEP: 22785-055, Rio de Janeiro, RJ, Brazil.
[2]Departamento de Pesquisa. Embrapa Meio Ambiente (EMBRAPA), Rodovia SP-340, Km 127,5, Caixa Postal 69, CEP: 13918-110, Jaguariúna, SP, Brazil. E-mail: rachel.prado@embrapa.br, joyce.monteiro@embrapa.br
[3]Australian Rivers Institute. Griffith University, 170 Kessels Road, Nathan, QLD 4111, Australia. E-mail: f.helfer@griffith.edu.au
[*]Corresponding author. E-mail: ana_feital@id.uff.br
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ABSTRACT

Urban floods are among Brazil's most pressing climate-related risks, revealing limitations in conventional drainage systems and fragmented governance structures. This study provides a national diagnostic of how Water-related Ecosystem Services (WES) are addressed in the context of urban flood-risk adaptation in Brazil, based on the integration of three analytical components: a systematic literature review (2017–2025), a diagnostic assessment of national environmental datasets, and a comparative synthesis of city-level initiatives. The review of 94 peer-reviewed studies indicates that Brazilian research remains predominantly focused on watershed-scale management, while international literature increasingly advances operational approaches based on Nature-based Solutions (NbS) and Blue–Green Infrastructure (BGI). The analysis of environmental datasets reveals recent progress in data availability and spatial coverage, alongside persistent gaps related to interoperability and update frequency. A comparative synthesis of experiences from Curitiba, Recife, and São Paulo highlights that, although NbS initiatives are present and associated with flood-risk reduction efforts, their implementation remains largely pilot-based and weakly institutionalised. Overall, the diagnostic identifies three strategic pathways—data interoperability, institutional coordination, and equity-oriented monitoring—as key elements to strengthen the integration of WES into urban flood-risk adaptation and water resource management in Brazil.

Keywords: blue–green infrastructure, urban flood-risk adaptation, water-related ecosystem services.

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Lacunas de dados em serviços ecossistêmicos relacionados à água para a adaptação ao risco de inundações urbanas no Brasil: um diagnóstico nacional e uma análise orientada à gestão

RESUMO

As inundações urbanas figuram entre os riscos climáticos mais urgentes no Brasil, evidenciando limitações dos sistemas convencionais de drenagem e da governança fragmentada. Este estudo apresenta um diagnóstico nacional de como os Serviços Ecossistêmicos Relacionados à Água (SERA) são abordados no contexto da adaptação ao risco de inundações urbanas no Brasil, a partir da integração de três componentes analíticos: uma revisão sistemática da literatura (2017–2025), uma avaliação diagnóstica de bases de dados ambientais nacionais e uma síntese comparativa de iniciativas em nível urbano. A revisão de 94 estudos revisados por pares indica que a produção científica brasileira permanece predominantemente centrada na gestão em escala de bacias hidrográficas, enquanto a literatura internacional avança na operacionalização de Soluções Baseadas na Natureza (SbN) e Infraestrutura Azul–Verde (IAV). A análise das bases de dados revela avanços recentes na disponibilidade e na cobertura espacial das informações, bem como lacunas persistentes relacionadas à interoperabilidade e à frequência de atualização. A síntese comparativa de experiências em Curitiba, Recife e São Paulo indica que, embora existam iniciativas de SbN associadas à redução do risco de inundações, sua implementação ainda ocorre de forma pontual e com baixa institucionalização. De modo geral, o diagnóstico identifica três caminhos estratégicos — interoperabilidade de dados, coordenação institucional e monitoramento orientado à equidade — como elementos centrais para fortalecer a integração dos SERA às estratégias de adaptação ao risco de inundações e à gestão de recursos hídricos urbanos no Brasil.

Palavras-chave: adaptação ao risco de inundações urbanas, infraestrutura azul–verde, serviços ecossistêmicos relacionados à água.

1. INTRODUCTION

Urban flood events have intensified across Brazil in recent decades, causing severe social and economic losses. Flood-related disasters between 2000 and 2024 affected more than 7 million people and resulted in over US$30 billion in damage (CEPED UFSC, 2024). The 2022 landslides in Petrópolis and the 2024 floods in Rio Grande do Sul exposed critical shortcomings in drainage infrastructure, land-use regulation, and emergency coordination (Marengo and Alves, 2024). These recurrent disasters underscore the limitations of reactive, infrastructure-based responses and highlight the urgent need for preventive, ecosystem-based strategies that integrate data, governance, and planning.

Water-related Ecosystem Services (WES) provide essential regulating functions (such as infiltration, retention, and storage of surface runoff) which reduce flood risks and enhance climate resilience (Brauman *et al.*, 2007; Albert and von Haaren, 2011). Their incorporation into urban adaptation strategies primarily occurs through Nature-based Solutions (NbS) and Blue–Green Infrastructure (BGI), which complement conventional grey drainage systems (Maes and Jacobs, 2020; Seddon *et al.*, 2020). While international research has advanced in operationalizing NbS through hydrological modelling, long-term monitoring, and integration into statutory planning tools, Brazilian studies remain predominantly conceptual and less embedded in formal governance and planning processes (Nobre *et al.*, 2023; Brollo *et al.*, 2022; Silva *et al.*, 2024). International experiences such as Rotterdam's climate adaptation programme, Singapore's ABC Waters initiative, and Copenhagen's cloudburst management strategy illustrate how NbS and Blue–Green Infrastructure can be integrated into long-term urban planning and flood-risk governance. This contrast reflects ongoing challenges in translating ecological knowledge into actionable instruments for urban policy and decision-making. Although adaptation strategies are mainly implemented at the municipal level, large-scale disasters such as the 2024 floods in Rio Grande do Sul reveal how limited regional coordination and insufficient data integration amplify local vulnerabilities. National datasets, such as those maintained by the National Water and Sanitation Agency (ANA), the Brazilian Institute of Geography and Statistics (IBGE), and the MapBiomas project, have significantly expanded their spatial coverage and accessibility. However, their potential for operational use remains underexploited due to inconsistent metadata standards and overlapping institutional mandates. Strengthening the connection between national data governance and local adaptation needs is therefore essential for mainstreaming WES into urban planning and infrastructure management.

International frameworks, including the Intergovernmental Panel on Climate Change (IPCC), the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015), and Sustainable Development Goal 11 (Sustainable Cities and Communities), emphasise that effective climate adaptation not only requires physical interventions, but also institutional alignment and data-driven integration across scales (IPCC, 2022; UN, 2015). Evaluating the readiness of environmental datasets and governance structures is thus a critical step toward enabling equitable, evidence-based adaptation in Brazilian cities.

This study provides a national diagnostic of how Water-related Ecosystem Services (WES) can support urban flood-risk adaptation in Brazil by bridging gaps between data systems, governance mechanisms, and policy frameworks. It specifically aims to: (i) assess the thematic and methodological evolution of WES research; (ii) evaluate the readiness of national and subnational datasets to support WES indicators for urban adaptation; and (iii) identify governance innovations and policy pathways for mainstreaming WES and NbS into Brazil's urban resilience agenda. The analytical–methodological framework integrates bibliometric, dataset, and governance analyses to reveal how information systems and institutional arrangements shape the effectiveness of ecosystem-based adaptation.

2. MATERIAL AND METHODS

This study is based on a qualitative and descriptive analytical framework combining literature review, dataset screening, and comparative synthesis of urban experiences. This study combined three complementary phases: (i) a systematic literature review conducted using the PRISMA protocol; (ii) an assessment of national and subnational datasets relevant to Water-related Ecosystem Services (WES) and their readiness to support urban flood-risk adaptation; and (iii) a comparative synthesis of documented urban experiences illustrating governance and data challenges.

Together, these phases connect bibliometric, data, and policy analyses across national and municipal scales (Figure 1).

2.1. Phase I – Systematic Literature Review

The PRISMA protocol (Moher *et al.*, 2009) was applied to identify peer-reviewed studies published between 2017 and 2025 in Scopus and Web of Science. The following Boolean operators: (urban drainage OR urban flooding) AND (ecosystem services OR nature-based solutions) AND (flood regulation OR urban flood risk adaptation), captured both international and Brazilian research. Studies focused on urban areas and explicitly addressing WES, NbS, or BGI were included; rural-only and non-peer-reviewed works were excluded.

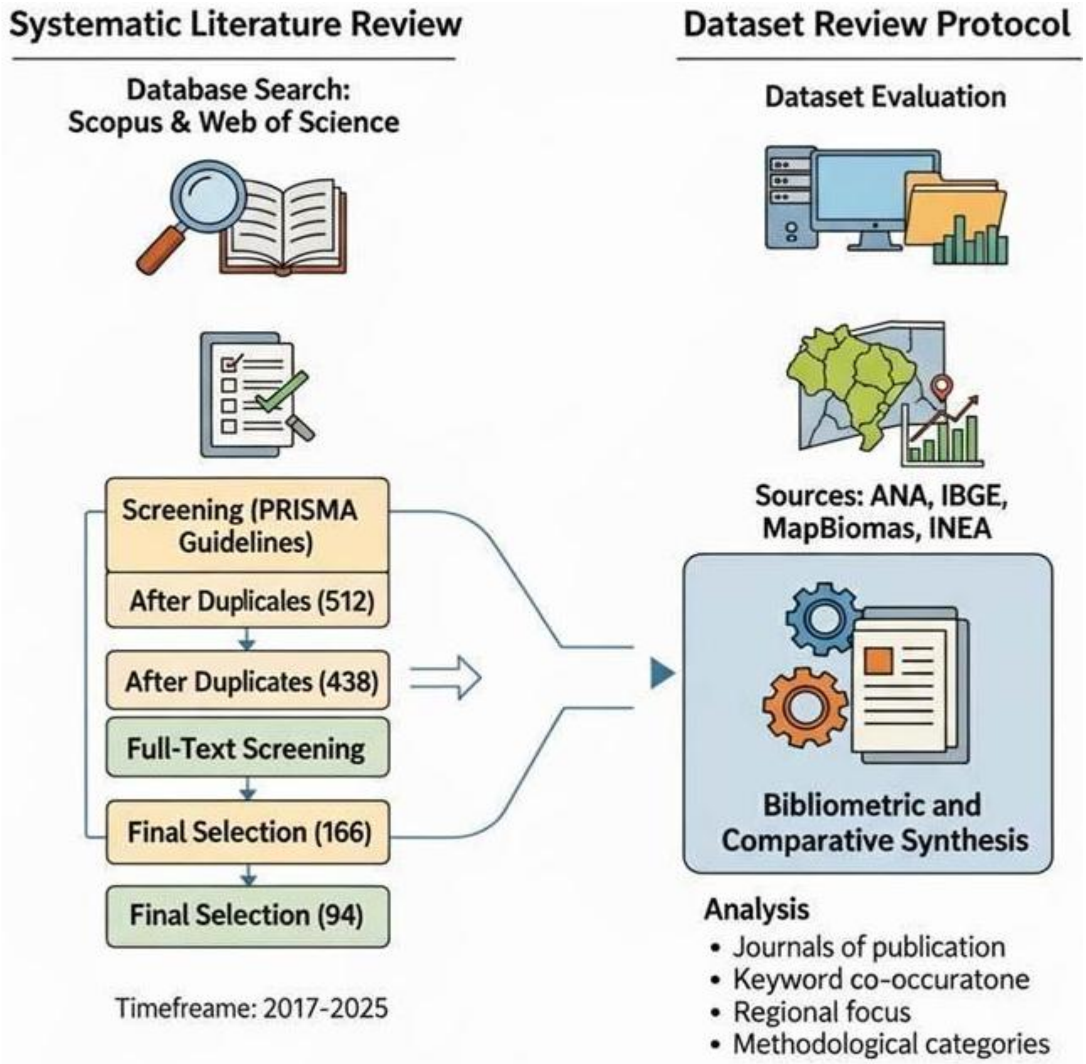


Figure 1. Analytical–methodological framework integrating the systematic literature review, dataset assessment, and comparative analysis stages.

A total of 438 unique records remained from the initial 512 after removing duplicates. Following title and abstract screening, 166 studies were retained for eligibility assessment, from which 94 met all inclusion criteria for full-text analysis (Figure 2). Metadata on study focus, methodology, geographic scope, and infrastructure type (grey, blue–green, or hybrid) were extracted from each paper to enable bibliometric and thematic analyses presented in the Results section.

2.2. Phase II – Dataset assessment

The second phase evaluated the readiness of national and subnational datasets to support WES indicators for urban flood-risk adaptation. Although Brazil hosts numerous environmental databases, their integration and usability for planning remain uncertain. The assessment covered 2017–2025 to ensure comparability with the literature review period.

2.2.1. Dataset selection and scope

Eight key datasets were selected according to three criteria: (i) relevance to WES assessment, including variables on land cover, hydrology, flood exposure, and socio-economic conditions; (ii) institutional significance, ensuring official maintenance under statutory mandates; and (iii) geographic coverage, representing at least one dataset at each governance level (national, state, and municipal).

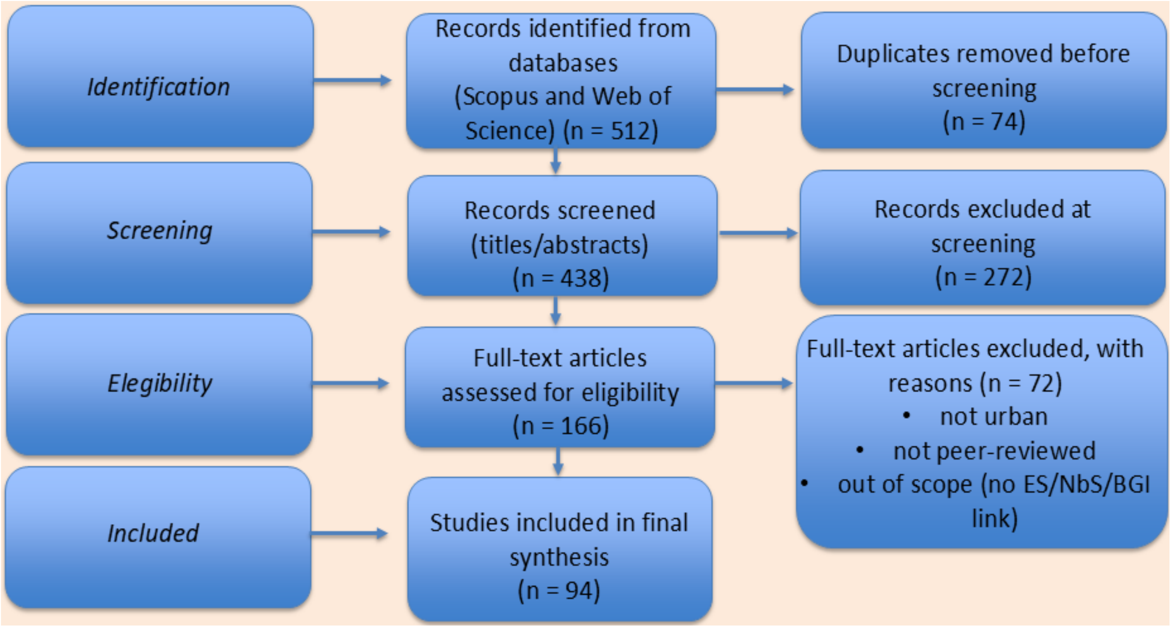


Figure 2. PRISMA flow diagram summarizing the systematic review process.
Source: adapted from Moher *et al.* (2009).

The selected datasets and their temporal coverage are summarised in Table 1, which provides an overview of the main platforms assessed in this phase.

2.2.2. Readiness assessment framework

Based on international data-quality frameworks (Wang and Strong, 1996; Batini and Scannapieco, 2016), each dataset was evaluated across five dimensions using a 1–5 qualitative scale (1 = very low, 5 = very high):

- **Availability** - existence and completeness of WES-related variables;
- **Accessibility** – openness, metadata quality, and usability;
- **Spatial Coverage** – geographic extent and resolution;
- **Interoperability** – capacity to integrate with other datasets;
- **Update Frequency** – regularity and timeliness of updates.

Scores were assigned through structured analysis of dataset documentation and metadata, with explicit descriptors ensuring consistency:

(1) datasets absent or irrelevant; (2) limited indicators (<25%); (3) partial coverage (25–50%); (4) most key indicators (50–75%); (5) comprehensive coverage (>75%), open access, and strong interoperability.

All ratings were based on comparative review of metadata, APIs, download structures, update protocols, and data dictionaries (see Supplementary Material). Observations were recorded in a comparative matrix to identify strengths and weaknesses across datasets. This qualitative approach ensured internal consistency while recognizing its non-statistical nature.

Table 1. Selected datasets and temporal coverage used for the readiness assessment (2017–2025).

Dataset / Platform	Maintaining Institution	Primary Coverage	Temporal Range
SNIRH / HydroWeb	ANA – National Water and Sanitation Agency (2025)	Hydrological monitoring	1930s–present (varies by station)
Environmental–Economic Accounts	IBGE – National Statistics Institute (2022)	Land use and water resources	2000–2020 (biennial)
MapBiomas Collection 9	MapBiomas (2024) Collaboration	Land-use classification and change	1985–2023 (annual)
MapBiomas Água	MapBiomas Collaboration	Surface-water dynamics and flood mapping	1985–2023 (monthly)
AdaptaBrasil	MCTI (Brasil, 2024)	Climate-risk and exposure indicators	2020–2050 (projections)
INDE Portal	IBGE (2023, coordinating federal agencies)	National geospatial infrastructure	Variable by layer
INEA-RJ Environmental Portal	INEA (2023) – Rio de Janeiro State Environmental Institute	State environmental monitoring	2010–present (irregular)
SNIS – Drainage Module	MDR – Ministry of Regional Development (2023)	Urban drainage and sanitation data	2015–2022 (annual)

2.2.3. Composite Readiness Index

A Composite Readiness Index (CRI) was calculated using weighted averages to support cross-dataset comparison, as per the following Equation 1:

$$\text{CRI} = (\text{Availability} \times 0.25) + (\text{Accessibility} \times 0.20) + (\text{Spatial Coverage} \times 0.25) + (\text{Interoperability} \times 0.20) + (\text{Update Frequency} \times 0.10) \tag{1}$$

Weights reflect the relative importance of each dimension for planning: data existence and coverage (25% each) were prioritised, followed by accessibility and interoperability (20% each), and update frequency (10%).

2.2.4. Results and readiness matrix

The readiness assessment synthesises progress and persistent gaps across Brazilian environmental datasets (Table 2).

Table 2. Dataset readiness assessment (2017–2025): availability, accessibility, spatial coverage, interoperability, and update frequency of key national and subnational datasets.

Dataset / Source	Availability	Accessibility	Spatial Coverage	Interoperability FH1	Update Frequency	Readiness 2017	Readiness 2025 FH2	Comments / Key advances
ANA – SNIRH	High	Moderate	National (watersheds, hydrological network)	Low	Continuous (daily–annual)	3/5	4/5	Improved interface and metadata documentation; still fragmented integration with IBGE and MapBiomas.
IBGE – Environmental and Territorial Indicators	High	High	National / state	Moderate	Decennial (Census, LULC updates)	2/5	4/5	Broadened scope of environmental indicators; partial metadata alignment.
MapBiomas – Land Use and Cover Collection	High	High	National (30 m resolution, annual)	High	Annual	3/5	5/5	Consistent time series (1985–2024); key dataset for WES indicators.
INEA – State Environmental Data Portal (RJ)	Moderate	Limited	State (Rio de Janeiro)	Low	Irregular	2/5	2/5	Limited updates and absence of interoperability protocols.
AdaptaBrasil / MCTI Platform	High	High	National (climate risk indicators)	Moderate	Continuous	-	3/5	Expanding climate risk and exposure indicators; growing potential for integration.
SNIS – National Sanitation Information System	High	High	National (municipal coverage)	Moderate	Annual	3/5	4/5	Valuable for drainage monitoring; spatial integration still limited.
INDE – National Spatial Data Infrastructure	Moderate	Moderate	National (metadata repository)	High	Continuous	3/5	4/5	Key institutional framework; limited adherence by sectoral agencies.
MapBiomas Água / Flood Mapping (2024)	High	High	National (hydrological and flood dynamics)	High	Annual	-	4/5	Newly available national flood mapping layer; strong integration potential.

*Scores based on a 1–5 scale (1 = very low; 5 = very high). The Composite Readiness Index (CRI) reflects the weighted average of criteria according to the formula described above.

2.3. Phase III – Comparative analysis and case studies

The third phase synthesised findings from the previous stages to examine how urban initiatives operationalise WES and NbS for flood-risk adaptation. Three Brazilian cities (Curitiba, Recife, and São Paulo) were selected for their documented experiences and policy relevance, representing diverse governance structures and data integration capacities. Rotterdam (Netherlands) and Singapore were included as reference cases for international benchmarking, recognised for long-term, cross-sectoral strategies integrating NbS and WES into statutory urban planning.

This phase does not constitute independent case studies, but a synthesis linking dataset readiness and bibliometric trends to real-world examples discussed in the literature. The comparative insights inform the policy recommendations presented in Sections 3.3.3 and 4.

3. RESULTS AND DISCUSSION

3.1. Results of the Systematic Literature Review (Phase I)

The systematic review identified 94 peer-reviewed studies published between 2017 and 2025 that examine the intersection of Water-related Ecosystem Services (WES), Nature-based Solutions (NbS), and urban flood-risk adaptation. Beyond bibliometric counting, the analysis assessed thematic patterns, methodological approaches, and evidence gaps in this emerging field.

Most studies conceptualise WES through NbS and Blue–Green Infrastructure (BGI) which enhance hydrological regulation, such as infiltration, runoff retention, and peak-flow attenuation, representing the ecological processes underpinning flood-risk mitigation.

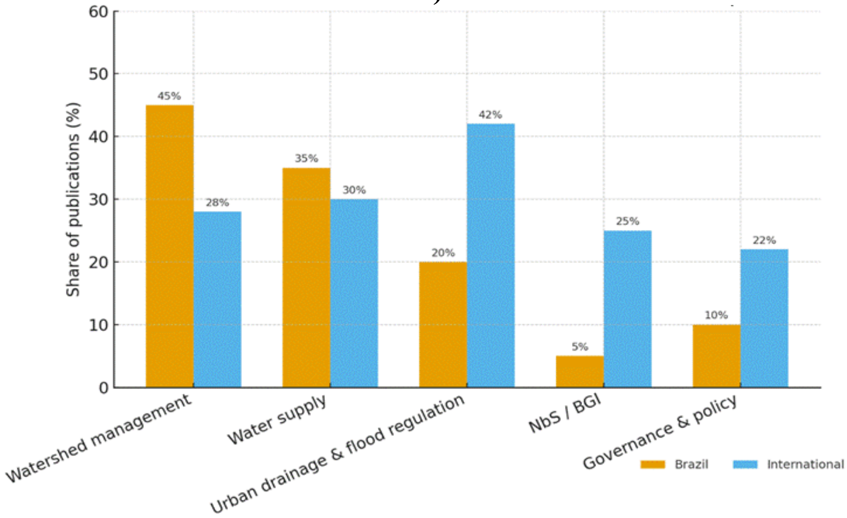
Clear contrasts emerged between Brazilian and international research. Brazilian studies remain concentrated on watershed management (≈44%) and water supply (≈33%), while international literature places greater emphasis on urban drainage, flood regulation (≈40%), and NbS implementation (≈26%). Although conceptual advances exist in Brazil, flood regulation has not yet become a consolidated urban agenda. International publications more frequently apply hydrological modelling, GIS-based prioritization, and resilience indicators that integrate ecological and socio-economic dimensions (e.g., Azadgar *et al.*, 2024; Cao *et al.*, 2023; Khodadad *et al.*, 2023). In contrast, Brazilian studies generally rely on descriptive analyses and small-scale pilots, reflecting persistent data and methodological limitations.

Figure 3 synthesises the main trends: (a) thematic distribution of WES studies, (b) temporal evolution of publication output, and (c) journals publishing on WES and flood regulation. International output sharply accelerated after 2018 following the IPCC Special Report on 1.5°C and the launch of the UN Decade on Ecosystem Restoration (2021–2030), while Brazilian production only modestly increased after 2020, constrained by limited funding and fragmented research networks. International studies are concentrated in high-impact journals (e.g., Journal of Hydrology, Sustainable Cities and Society), whereas Brazilian publications are dispersed across regional outlets, reducing global visibility.

3.1.1. Thematic analysis

Table 3 summarises the thematic distribution of the 94 studies, highlighting key differences in research focus and methodological maturity between Brazilian and international publications.

3a)



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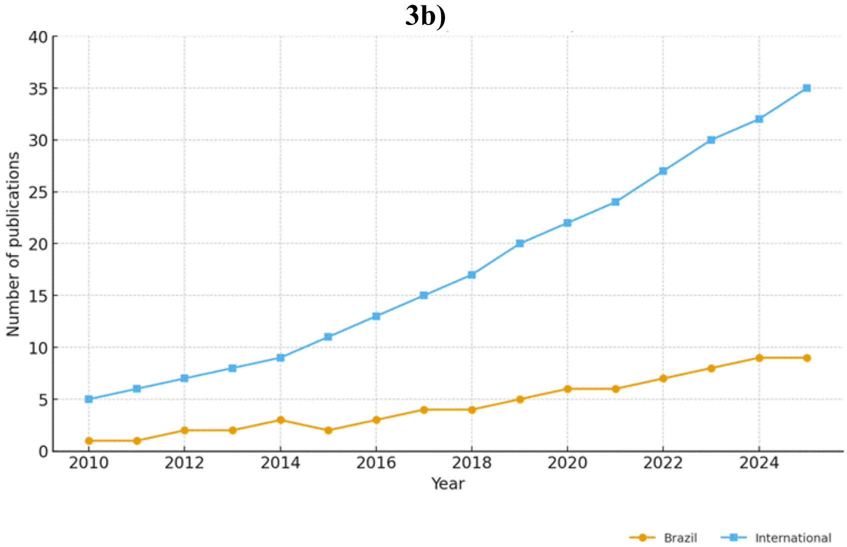

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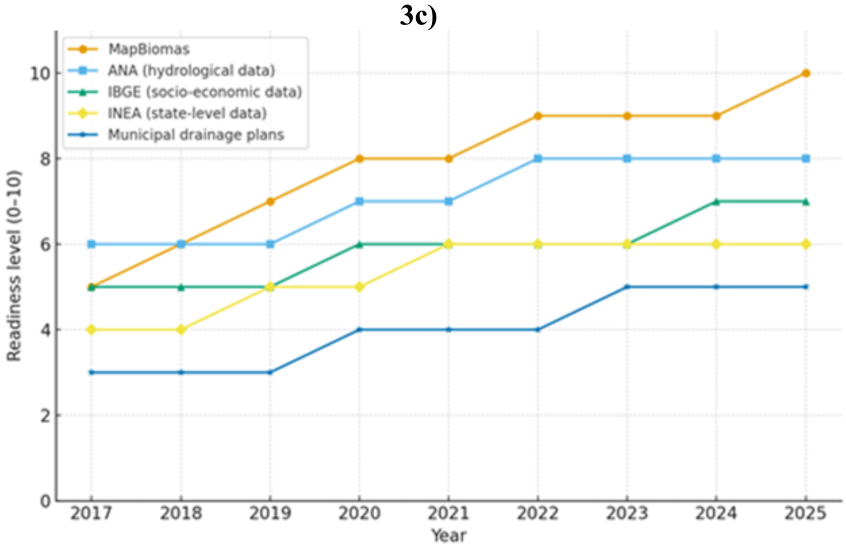

Figure 3. Thematic distribution and publication trends of Water-related Ecosystem Services (WES) studies (2010–2025). (a) Thematic distribution of WES studies in Brazilian and international literature. (b) Publication trends comparing Brazilian and international outputs. (c) Journals publishing WES and flood-regulation studies.
Source: Author's elaboration.

Table 3. Thematic distribution of WES and flood-adaptation studies (2017–2025).

Theme	Brazilian Studies (n = 26)	%	International Studies (n = 68)	%	Key Distinction
Watershed hydrology & water allocation	11	42	8	12	Basin-scale focus dominates Brazilian research.
Nature-based Solutions (NbS) for flood regulation	6	23	31	46	International literature leads NbS implementation research.
Blue–Green Infrastructure (BGI) design & performance	3	12	18	27	Engineering-based performance studies mostly international.
Ecosystem-service valuation & economic analysis	2	8	14	21	Economic valuation underdeveloped in Brazil.
Data systems & monitoring for WES assessment	1	4	9	13	Critical data-governance gap in Brazil.
Governance & policy integration	3	11	10	15	Institutional fragmentation common to both contexts.

Brazilian research remains dominated by watershed-scale approaches (42%), where flood regulation is treated as a secondary outcome of water-supply management. Only 23% of Brazilian papers address NbS implementation, compared to 46% internationally, underscoring the gap between conceptual understanding and applied practice. Economic valuation of WES appears in fewer than 10% of Brazilian publications, limiting cost–benefit arguments for investment. Moreover, just one Brazilian study explicitly examines data systems or interoperability, mirroring the dataset gaps identified in Section 2.2.

Overall, the findings indicate that awareness of WES is increasing, but its empirical integration into urban planning and decision-making remains incipient. Advancing this agenda will require bridging scientific, institutional, and data-governance divides to translate NbS and BGI into operational WES outcomes for flood-risk adaptation.

3.1.2. Evidence of NbS/BGI effectiveness

Empirical evidence of NbS and BGI performance was identified in 37 studies reporting hydrological outcomes such as runoff reduction and flood-peak attenuation. Table 4 synthesises how different interventions deliver Water-related Ecosystem Services (WES) related to flood regulation through infiltration enhancement, runoff reduction, and temporary water storage, translating ecological processes into measurable hydrological outcomes.

Overall, the reviewed studies report that NbS and BGI are associated with reductions in peak flows and enhanced infiltration. Effectiveness varies by context and scale: small-scale measures such as rain gardens and green roofs show high relative efficiency but limited coverage, while larger systems like wetlands and floodable parks provide moderate yet city-relevant mitigation. Despite promising hydrological results, only 11% of studies combine performance data with socio-economic indicators, revealing a persistent focus on engineering aspects rather than integrated socio-environmental evaluation.

Table 4. Reported effectiveness of NbS/BGI for flood regulation.

Intervention Type	Studies Reporting Outcomes	Typical Effectiveness Range	Context
Bioretention cells / rain gardens	11 (8 international, 3 Brazilian)	35–80% peak-flow reduction	Small urban catchments (<10 ha)
Green roofs	7 (6 international, 1 Brazilian)	40–70% runoff retention	Individual buildings
Permeable pavements	6 (5 international, 1 Brazilian)	25–60% runoff reduction	Parking lots, low-traffic streets
Urban wetlands / detention basins	8 (4 international, 4 Brazilian)	20–50% peak-flow attenuation	Neighbourhood–catchment scale
Riparian forest restoration	5 (2 international, 3 Brazilian)	10–35% downstream flood reduction	Watershed scale (>100 km²)
Floodable parks	4 (2 international, 2 Brazilian)	15–40% localised flood reduction	Urban park systems (5–50 ha)

3.1.3. Knowledge gaps identified

The review highlights five overarching gaps and four Brazil-specific limitations that constrain the mainstreaming of WES and NbS.

Gap 1 – Monitoring and performance continuity: Only 6% of studies track results beyond five years, and maintenance effects are rarely evaluated, hindering life-cycle assessments.

Gap 2 – Scalability and replication: Most analyses remain confined to isolated pilots; only three studies explore replication mechanisms, exposing the absence of pathways for scaling NbS citywide.

Gap 3 – Social co-benefits and trade-offs: Over 75% of publications solely focus on hydrological outcomes, neglecting co-benefits such as recreation, biodiversity, health, and heat mitigation.

Gap 4 – Implementation barriers: Few studies examine governance, financing, and institutional limitations, explaining why many technically viable NbS remain unimplemented.

Brazil-specific limitations: Research is absent in rapidly urbanizing Amazonian cities, scarce in informal settlements despite high vulnerability, lacks cost data for Brazilian NbS/BGI projects (most use international proxies), and reveals persistent disconnects between national datasets (ANA, IBGE, MapBiomas) and municipal planning tools.

Together, these gaps emphasise the need for long-term monitoring, interoperable data systems, and equity-oriented evaluation frameworks to consolidate WES-based adaptation. Advancing this agenda requires both robust hydrological evidence and institutional capacity to operationalise NbS at scale.

3.2. Dataset readiness and data governance (Phase II)

The dataset readiness assessment (Table 2) reveals clear advances in environmental data availability and spatial coverage in Brazil between 2017 and 2025, but persistent weaknesses in interoperability, metadata alignment, and update frequency.

National datasets such as MapBiomas, ANA/SNIRH, and IBGE Environmental Accounts scored high in availability and accessibility, reflecting significant progress in open-data platforms and time-series consistency. MapBiomas provides near-comprehensive land-use and land-cover (LULC) data at 30-meter resolution and annual frequency, enabling derivation of ecosystem indicators for infiltration and imperviousness analysis. Similarly, ANA's hydrological time series through SNIRH and HydroWeb support flow and precipitation modelling across multiple basins, while IBGE's Environmental–Economic Accounts offer complementary land-use and water-resource indicators.

However, interoperability remains the weakest dimension. Inconsistent spatial identifiers, metadata formats, and the absence of shared protocols continue to limit integration across agencies. Socio-economic datasets from IBGE, though comprehensive, are not easily linked to hydrological or land-use data, constraining socio-hydrological analyses and vulnerability mapping.

Data readiness is even more uneven at the subnational level. State portals such as INEA-RJ show irregular updates and poor metadata documentation, while the National Spatial Data Infrastructure (INDE) provides a coordination framework that remains underutilised by municipalities. These limitations reduce the practical use of otherwise high-quality national datasets for local adaptation planning.

Overall, Table 2 demonstrates that while availability and accessibility have advanced substantially, these gains remain underexploited without standardised interoperability and regular updates. The findings point to the need for a unified interoperability protocol, harmonised metadata standards, and shared spatial keys, with these recommendations being further developed in Section 3.3.3.

National open-data platforms (ANA, IBGE, MapBiomas) illustrate growing institutional transparency and technical capacity. Yet subnational repositories remain fragmented and inconsistently updated, highlighting the importance of metadata harmonization under INDE, secure maintenance funding, and inter-agency data-sharing protocols to transform Brazil's expanding data ecosystem into a reliable foundation for WES-based planning and monitoring.

3.3. Comparative synthesis of urban experiences (Phase III)

This phase synthesises how Water-related Ecosystem Services (WES) and Nature-based Solutions (NbS) are implemented at the urban level in Brazil and compares these experiences with international benchmarks to identify common challenges and transferable lessons for flood-risk adaptation. Rather than individual case studies, this section provides a comparative synthesis connecting city-level initiatives, governance structures, and data systems.

Three Brazilian cities (Curitiba, Recife, and São Paulo) were selected for their documented and policy-relevant experiences, each illustrating distinct approaches to ecosystem-based flood management. Rotterdam (Netherlands) and Singapore were included as reference cases for international benchmarking, recognised for long-term, cross-sectoral integration of NbS and WES into statutory urban planning.

Implementation of NbS and WES has advanced across the three Brazilian cities since 2017, but remains constrained by fragmented governance, unequal data interoperability, and inconsistent performance monitoring.

Curitiba demonstrates a technically robust, continuity-driven approach linking hydrological design with land-use control and ecosystem restoration through its linear park network.

Recife represents a socially innovative model emphasizing coastal restoration, urban wetlands, and participatory design through the *Parque Capibaribe* initiative, though coordination between state and municipal agencies remains weak.

São Paulo shows mainstreaming potential at metropolitan scale, with over 1,200 hectares of NbS-linked interventions embedded in drainage planning, yet vulnerable neighbourhoods, especially informal settlements, still face recurrent flooding.

These examples collectively confirm that data integration capacity, institutional continuity, and cross-sectoral coordination are decisive for operationalizing ecosystem-based adaptation in Brazil. The insights reinforce national patterns identified in the dataset readiness assessment: progress in data coverage and accessibility contrasts with enduring gaps in interoperability, monitoring, and equity-oriented scaling.

Subsection 3.3.2 extends this analysis to international benchmarks (Rotterdam and Singapore), highlighting governance and financing mechanisms which have enabled these cities to institutionalise NbS within statutory urban frameworks.

3.3.1. Integration of NbS into urban planning

Brazilian cities demonstrate diverse pathways for embedding Water-related Ecosystem Services (WES) and Nature-based Solutions (NbS) into statutory planning. Recife incorporated rain gardens (*jardins filtrantes*) into its Drainage Master Plan, one of Brazil's first formal NbS adoptions. Curitiba's floodable parks integrate flood regulation, recreation, and biodiversity corridors, while São Paulo has requalified detention reservoirs (*piscinões*) and canalised rivers into multifunctional blue–green corridors, exemplifying gray–green hybridization. By embedding NbS and BGI into planning instruments, these initiatives operationalise WES such as infiltration, retention, and flow regulation within urban frameworks. Figure 4 illustrates representative examples of these NbS/BGI interventions.

a) b)

c)

Figure 4. Examples of Nature-based Solutions (NbS) and Blue–Green Infrastructure (BGI) initiatives in Brazilian cities: (a) Rain gardens incorporated into Recife's Drainage Master Plan; (b) Floodable parks in Curitiba integrating flood regulation, recreation, and biodiversity corridors; (c) Requalification of detention reservoirs in São Paulo, combining green–blue multifunctionality with existing drainage systems. **Source:** Recife (2023); Curitiba (2022); São Paulo – SIURB (2023).

3.3.2. Institutional governance in urban adaptation

Whereas data governance defines how information is produced and shared, institutional governance determines how ecosystem-based approaches are embedded into planning and regulation (Müller *et al.*, 2022; Silva *et al.*, 2024). Fragmented mandates for drainage, land use, and environmental protection across government levels in Brazil hinder integration of WES and NbS into long-term adaptation strategies (Scarano, 2017).

In contrast, Rotterdam and Singapore illustrate how multi-level coordination, predictable financing, and performance-based monitoring enable mainstreaming (Frantzeskaki *et al.*, 2019; 2022). Water boards and municipalities around Rotterdam share legal mandates and budgets for flood control and green infrastructure, while Singapore's *ABC Waters Programme* integrates NbS principles into regulatory standards and national investments by the Public Utilities Board (PUB, 2023).

Brazilian initiatives (such as Recife's rain gardens and Curitiba's floodable parks) remain pilot-scale and seldom institutionalised beyond the municipal level (Travassos *et al.*, 2022; Brollo *et al.*, 2022). Bridging data and institutional governance is therefore essential to move from reactive, project-based actions toward preventive, system-wide resilience.

3.3.3. Data integration and policy recommendations for equity-oriented adaptation

Equitable, evidence-based adaptation depends on the integration of hydrological, socio-economic, and land-use datasets to inform the design, prioritisation, and monitoring of urban flood-risk management strategies. Internationally, socio-hydrological frameworks increasingly link biophysical modelling with exposure and vulnerability indicators to advance climate-just adaptation (Meerow and Newell, 2022). In Brazil, however, few platforms currently achieve this level of integration. The Ministry of Regional Development's *Visão 360°* initiative represents a relevant step forward, but still prioritises data transparency over operational interoperability.

The dataset assessment (Section 2.2) showed that, although MapBiomas, ANA/SNIRH, and IBGE datasets have improved in terms of availability and spatial coverage, they remain limited with respect to interoperability, metadata alignment, and update frequency. These constraints hinder the effective use of Water-related Ecosystem Services (WES) indicators in planning processes and may reinforce inequalities, as municipalities with lower technical capacity face greater barriers to accessing and harmonising essential data.

Data integration and policy recommendations derived from the dataset readiness results (Tables 1–2) and the governance analysis (Section 3.3.2) are organised into three strategic areas: (i) data interoperability and governance alignment; (ii) institutional coordination and financing mechanisms; and (iii) monitoring and evaluation approaches oriented toward social equity.

The first strategic area addresses data governance challenges. Establishing a national interoperability protocol through INDE and SNIRH would support the harmonisation of spatial identifiers and metadata standards across institutions, reducing duplication of efforts and implementation costs. In parallel, open-data registration of municipal drainage maps would improve access to subnational infrastructure information and facilitate cross-sectoral analysis.

The second strategic area focuses on institutional integration. Mandating WES indicators within master plans and drainage by-laws would embed ecosystem-service metrics into statutory planning instruments, while the institutionalisation of hydrological modelling within plan approval processes could strengthen technical rigour, transparency, and accountability in decision-making.

The third strategic area emphasises monitoring and scalability. Developing NbS/BGI monitoring dashboards aligned with dataset update cycles (e.g., annual MapBiomas products and continuous ANA hydrological series) would support the operational tracking of ecosystem performance across governance levels. In addition, federal co-financing mechanisms linked to standardised indicators could incentivise municipalities to adopt data-informed NbS portfolios and facilitate the replication of successful pilot initiatives, such as those implemented in Curitiba and Recife.

Finally, the development of a National Urban Flood Adaptation Atlas could integrate hydrological, ecological, and socio-economic datasets into a unified open-access platform, supporting benchmarking, policy learning, and public accountability. Collectively, these measures highlight the potential of coordinated data governance and institutional alignment to enhance data-driven decision-making, expand the adoption of NbS, and strengthen climate-resilient urban planning in Brazil over the medium to long term.

3.3.4. Comparative insights and scaling challenges

The cross-case synthesis presented in this section compares Brazilian urban experiences with selected international benchmarks to identify structural gaps and transferable lessons for mainstreaming Nature-based Solutions (NbS). This comparative analysis builds on the governance and technical dimensions identified in the literature review (Section 3.1) and the institutional analysis (Section 3.3.2), and is cross-referenced with established international NbS frameworks (Frantzeskaki *et al.*, 2019; Kabisch *et al.*, 2016; Seddon *et al.*, 2020).

The analysis indicates that international cases such as Rotterdam, Singapore, and Copenhagen have institutionalised NbS through integrated governance arrangements, stable funding mechanisms, and performance-based monitoring systems. In contrast, Brazilian initiatives remain largely fragmented and project-based, with limited continuity across planning cycles. Six interrelated dimensions — governance, technical integration, scalability, hybridisation, monitoring, and equity — collectively shape the maturity of NbS strategies across contexts.

In the Brazilian context, fragmented governance structures and the absence of national NbS frameworks contrast with the institutional continuity observed in European and Asian benchmarks. Advancing NbS mainstreaming therefore requires the alignment of data governance, intersectoral coordination, and stable financing mechanisms. Among these dimensions, governance continuity and data interoperability emerge as the most critical gaps, as their absence constrains the long-term sustainability of NbS initiatives. In addition, the limited use of standardised monitoring frameworks and social-equity indicators restricts accountability and inclusiveness. Addressing these challenges is essential not only for scaling NbS, but also for securing the Water-related Ecosystem Services (WES) that underpin long-term urban resilience.

4. CONCLUSIONS

The results indicate that, despite recent advances in environmental monitoring, land-use mapping, and the conceptual incorporation of Nature-based Solutions (NbS) and Blue–Green Infrastructure (BGI), the operational integration of Water-related Ecosystem Services (WES) into statutory urban planning and flood-risk management remains limited.

In relation to the study objectives, three cross-cutting patterns emerge from the analysis. First, regarding the assessment of environmental data and monitoring systems, fragmented governance arrangements and limited interoperability among hydrological, socio-economic, and land-use datasets constrain the effective use of information in decision-making processes. Second, concerning the incorporation of NbS and WES into urban planning and flood-risk management, NbS and WES-related initiatives are predominantly implemented at pilot scales, often lacking institutional continuity, standardized indicators, and stable funding mechanisms. Third, with respect to governance and institutional arrangements, the interface between data systems, governance structures, and planning instruments remains weakly developed, limiting the mainstreaming of ecosystem-based approaches in urban flood adaptation.

By synthesizing these findings, the study contributes a structured diagnostic of data and governance constraints shaping the feasibility of WES-based adaptation strategies in Brazil. While the analysis is predominantly qualitative, it highlights the importance of strengthening data integration, institutional coordination, and monitoring practices as enabling conditions for advancing ecosystem-based adaptation in urban contexts. Future research may build on this diagnostic by incorporating quantitative performance assessments, equity-focused evaluations, and comparative applications in other Global South settings. Overall, the findings reinforce that improving the alignment between environmental data systems, governance arrangements, and urban planning processes is a critical step toward enhancing the resilience of Brazilian cities to flood-related risks.

5. DATA AVAILABILITY STATEMENT

Data availability not informed.

6. ACKNOWLEDGEMENTS

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