

# Effects of extreme rainfall on urban streams: A systematic literature review based on the Nature-based Solutions concept

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## ABSTRACT

1. In the context of climate change, the vulnerability of natural ecosystems to extreme rainfall events (ER) is a well-documented issue. In urban areas, this exposure is further exacerbated by the pressures of rapid population growth and the concentration of settlements in flood-prone zones. Nature-based Solutions (NbS) offer a promising approach to mitigate the effects of both challenges by leveraging their capacity to provide essential ecosystem services.

2. This study employed a systematic review, following the PRISMA methodology, of 50 scientific publications to explore the current state of knowledge regarding the mitigation of the effects of ER occurrence in urban stream areas.

3. Results showed that modeling and thematic mapping (38%), as well as descriptive analyses, diagnostics and experimental case studies (32%) were the most frequently used methodologies to analyze the role of NbS in mitigating the effects of climate change in urban areas.

4. The reviewed studies were located principally in Europe (52% of the total manuscripts), South America and Asia (12% each). Regarding mitigation strategies, 40% of the analyzed cases proposed mitigation based on the implementation of green and blue infrastructure; 32% relied solely on green infrastructure; 22%, solely on blue infrastructure, and the remaining 6% on urban agriculture proposals.

5. The main actions identified in these studies were related to the restoration and renaturalization of urban rivers and streams in response to the threats posed by ER.

6. Implications. The review synthesizes current knowledge, revealing a predominance of specific methodological approaches and a marked geographical concentration of studies. This underscores the need to expand research and application of NbS in other regions to comprehensively address hydro-meteorological risks in urban environments.

[Keywords: prisma methodology, climate change, extreme events, floods, urban streams environments]

## RESUMEN. Efectos de eventos extremos de precipitación en arroyos urbanos: Una revisión sistemática de la literatura basada en el concepto de Soluciones basadas en la Naturaleza

1. En un contexto de cambio climático global, la vulnerabilidad de los ecosistemas naturales ante eventos extremos de precipitación es un tema bien documentado. En áreas urbanas, esta exposición se suma a la presión que ejercen el crecimiento acelerado de la población y su localización en áreas inundables. Las Soluciones basadas en la Naturaleza (SbN) se centran en su potencial respecto a la provisión de servicios ecosistémicos, y se presentan como una alternativa viable para mitigar los efectos de ambos procesos.

2. Este trabajo se basó en la metodología Prisma e incluyó una revisión sistemática de 50 publicaciones científicas orientada a explorar el estado actual del conocimiento en relación a la mitigación de los efectos de la ocurrencia de eventos extremos de precipitación en áreas de arroyos urbanos.

3. Los resultados mostraron que el modelado y la elaboración de cartografía temática (38%) y las descripciones, diagnósticos y estudios de caso experimentales (32%) fueron las metodologías usadas con más frecuencia para analizar el rol de las SbN en la mitigación de efectos del cambio climático en áreas urbanas.

4. Los estudios se localizaron, sobre todo, en Europa (52% de las publicaciones analizadas), Sudamérica y Asia (12% en cada caso). El 40% de los casos analizados planteó la mitigación basada en implementar infraestructuras verdes y azules; el 32%, solo infraestructuras verdes; el 22%, solo infraestructuras azules, y el 6% restante, propuestas de agricultura urbana.

5. Las principales acciones implementadas en los enfoques hallados se relacionaron con la restauración y la renaturalización de ríos y arroyos urbanos frente a las amenazas de eventos extremos de precipitación.

6. Implicancias. La revisión sistematiza el conocimiento actual, evidenciando una predominancia de enfoques metodológicos específicos y una marcada concentración geográfica de los estudios, lo que subraya la necesidad de ampliar la investigación y la aplicación de SbN en otras regiones para abordar de manera integral los riesgos hidrometeorológicos en entornos urbanos.

[Palabras clave: metodología prisma, cambio climático, eventos extremos, inundaciones, ambientes de arroyos urbanos]

## INTRODUCTION

In recent decades, both aquatic and terrestrial ecosystems have encountered growing environmental vulnerability (DeLong et al. 2018). Ecosystem vulnerability is an ecological response of the environment to external damage (Chen et al. 2023). Among the reasons explaining this situation are the accelerated population growth and, consequently, the urbanization processes that promote the occupation of unsuitable areas. Similarly, the development of economic activities that are incompatible with certain land uses can increase the vulnerability levels of ecosystems. From an academic perspective, there has been growing concern about the implementation of hybrid solutions that integrate blue, grey and green infrastructure (Liu et al. 2023). In this regard, the nature-based solutions (NbS) concept has gained notable visibility (Osaka et al. 2021) and is often adopted as an innovative and sustainable flood risk management method (Ruangpan et al. 2024).

Regarding NbS, the two most prominent definitions are from the International Union for Conservation of Nature (IUCN) (Cohen-Shacham et al. 2016) and the European Commission (EC 2015). NbS are considered an umbrella concept that encapsulates various ecosystem-based approaches, such as Ecosystem-based Adaptation (EbA), Ecosystem-based Disaster Risk Reduction (Eco-DRR), Green Infrastructure and Natural Infrastructure, used to address ecological degradation, risks from natural hazards and climate change adaptation (Shah et al. 2020).

These NbS are characterized by their potential, as their implementation brings multiple benefits in the short, medium and long term (e.g., protection, conservation, restoration, management, enhancement or imitation of natural ecosystems) for populations and ecosystems that increasingly show signs of fragility and environmental vulnerability (Osaka et al. 2021). In Urban Streams Environments (USE), NbS can contribute to mitigating heat islands, enhancing biodiversity, fostering community pride and cohesion and improving human health and wellbeing (Ferrario et al. 2024).

NbS are actions inspired by nature, designed to address a range of environmental challenges in an efficient and adaptable manner, while at the same time providing economic, social and environmental benefits (Van den Bosch and Sang 2017). There are various studies that

have focused on describing and analyzing NbS applied to different ecosystems and contexts with the aim of reducing their fragility and environmental vulnerability. The focus of these frameworks has been on addressing physical, socio-economic and environmental parameters. Such approaches are already well accepted within multilateral frameworks such as the United Nations (UN) Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD) and the Sendai Framework for Disaster Risk Reduction (SFDRR). As such, they are recognized as effective means for Climate Change Adaptation (CCA) and DRR and for the implementation of the Sustainable Development Goals (SDGs) (Ruangpan et al. 2024).

In the Latin American context, urban spaces have undergone intense transformations marked by accelerated processes of urban expansion. This process has often taken place in environmentally fragile areas where watercourses and urban wetlands have emerged as the focal points of the main environmental conflicts (Jacobi et al. 2015; Ríos and Caruso 2021). In these areas, the occurrence of ER frequently leads to severe impacts, particularly for nearby residents, including flooding and overflows (Diep et al. 2022). It is noteworthy that most actions aimed at restoring urban rivers are common practice in the Global North, whereas in Latin America their effective planning and implementation remain scarce due to marked institutional, political and social limitations that hinder sustainable pathways (Graziano et al. 2019). Socio-urban inclusion projects often do not incorporate the environmental dimension as a key component of territorial interventions, as they primarily focus on addressing urgent issues related to other priorities (Ríos et al. 2024).

However, there are examples of countries that have implemented a paradigm shift by pioneering the integration of green and blue infrastructures into urban planning (Pradilla and Hack 2024). At the national level, several initiatives aim to implement green and blue infrastructure through the development of hybrid systems that reproduce natural absorption and retention processes, promoting more sustainable approaches to urban water management (Kozac et al. 2020). In this context, it is important to expand the understanding and knowledge of urban stream management through the application of NbS in the Global

South, particularly to better consider and integrate the needs and aspirations of local stakeholders in the planning and management of these solutions (de Souza and Torres 2021; Re et al. 2020).

The interest in conducting a systematic review of studies focused on NbS arises from the growing environmental issues occurring in aquatic and terrestrial ecosystems across various spatial and temporal scales. The need to implement environmentally friendly NbS has become an urgent requirement in the land management of these areas. The objective of this literature review was to explore the current state of knowledge on the application of NbS to mitigate the effects of Extreme Rainfall (ER) in USE, in order to identify future challenges, priorities and research directions.

This paper first presents the description of the applied methodology. Secondly, it shows the results through the analysis of the selected papers, considering: NbS definitions, objectives and general contributions. Thirdly, it presents the discussions and final conclusions to interpret the obtained results,

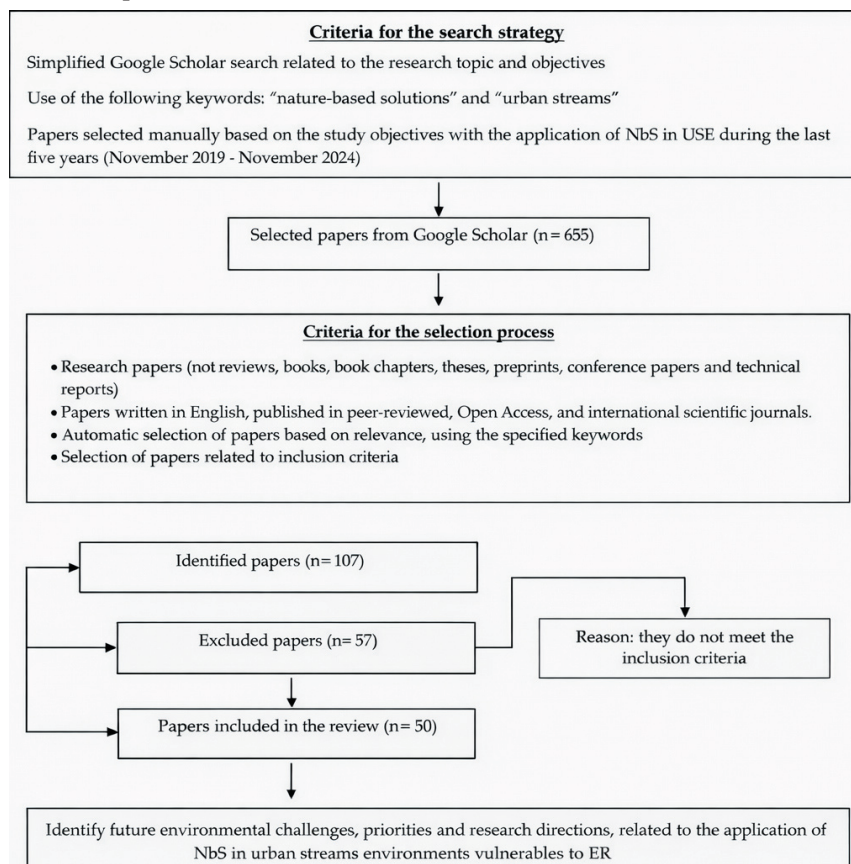
highlight common research areas and reflect on the potentialities and limitations derived from the application of the concept of NbS in USE.

## MATERIALS AND METHODS

A systematic literature review —based on the concepts of Liberati et al. (2009), Page et al. (2021) and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Page et al. 2021) methods— was conducted according to our objective. The process consisted of two main phases: 1) the execution of the search strategy and 2) the screening and filtering of all identified records based on the predefined inclusion and exclusion criteria (Figure 1).

### Search strategy

A Google Scholar search was conducted using keywords aligned with the research objectives. Since the concept appears under different names, the search targeted papers using the terms 'nature-based solutions' or its acronym 'NbS' in the context of 'urban streams'. The



**Figure 1.** Flow chart of the process of selecting papers for review.

**Figura 1.** Diagrama de flujo del proceso de selección de artículos para la revisión.

search string combined these concepts using Boolean operators: (“nature-based solutions” OR “nature based solutions” OR “NbS”) AND (“urban streams”) NOT (“reviews”).

To focus on recent developments in this relatively new field, the search was limited to the last five years (2019-2024). The search and subsequent download of PDFs were conducted on October 21-22, 2024, to ensure consistency given the dynamic nature of online databases. Google Scholar was chosen for its comprehensive coverage of the academic literature.

#### *Selection process*

The initial selection of papers was based on the results generated by Google Scholar, which were sorted by relevance using the specified keywords. First, titles, abstracts and keywords were screened. To visualize term frequency, a word cloud was generated using an interactive online tool (nubedepalabras.es).

Subsequently, the following predefined data were extracted from each paper: study area (continent), methodology and techniques applied according to type of work (i.e., experimental essay, theoretical development, technical report or project and study of regulations), physical characteristics of watercourses (i.e., relief, classification into permanent or intermittent rivers and streams, and channel modification) in cases where the papers included urban rivers and/or streams as case studies, type of NbS applied, results or benefits derived from them and objectives and main contributions of each paper.

The inclusion criteria were: a) research papers (not reviews, books, book chapters, theses, preprints, conference papers and technical reports); b) papers written in English from the last five years (November 2019- November 2024); c) papers published in peer-reviewed, open access and international scientific journals, and d) papers related to the objectives of the study; from the obtained papers by the Google scholar search, papers related to the objectives of the study were manually included.

## RESULTS

### *Review of NbS in relation to Extreme Rainfall effects in USE*

The initial search yielded 655 records. To refine the selection, only the first 11 pages of

results (sorted by relevance) were considered, comprising 109 papers. After removing two inaccessible records, 107 papers remained for full-text screening. From these, 50 papers met all inclusion criteria and were selected for analysis, while 57 were excluded. Of the 57 papers excluded, 52 were excluded based on document type. Among these, the largest share were reviews (20), followed by book chapters (17), theses (12), preprints (1), conference papers (1) and technical reports (1).

The reviewed literature reveals that the application of NbS in urban contexts is addressed under various conceptual frameworks and terminologies. Key related terms identified include: low-impact development, best management practices, water-sensitive urban design, sustainable urban drainage systems, green infrastructure, blue-green infrastructure, ecosystem-based adaptation and ecosystem-based disaster risk reduction (Ruangpan et al. 2020). The use of the NbS concept became frequent from the 2000s onward, integrating into frameworks for disaster risk reduction. The review also noted the influence of key institutional and legal frameworks — such as the 2030 Agenda for Sustainable Development (SDG), the European Climate Pact and EU sustainable development policies— in motivating the adoption of these solutions (Ruangpan et al. 2020).

Of the 50 papers reviewed, 40% focused on a single urban stream or river as a case study (Table 1a). Another 36% used multiple watercourses or urban areas for comparative or statistical analysis (Table 1b), while 24% did not specify a particular study area (Table 1c).

Regarding paper type, most were experimental studies (66%) (Table 2a), followed by theoretical papers (30%) (Table 2b) and analyses of regulations, projects or planning documents (4%) (Table 2c).

Among the most usual techniques and methodologies used are surveys, focus group discussions, workshops, modeling and mapping, multicriteria evaluation and description, diagnoses or case studies analysis. The most frequent techniques (used in 38% of the analyzed papers) were those related to modeling and mapping of variables, typically employing Geographic Information Systems (GIS) (Table 3a). Next, papers focused on the description and analysis of environmental variables to conduct diagnoses and evaluations

**Table 1.** Percentage of manuscripts by addressed topics and their references.**Tabla 1.** Porcentaje de manuscritos por temas tratados y sus referencias.

Topics addressed	%	References
a) Urban stream or river as a case study	40	Ourloglou et al. 2020; de Oliveira Campos et al. 2020; Alvareda et al. 2020; Ranta et al. 2021; Di Grazia et al. 2021; Gkiatas et al. 2021; da Silva et al. 2021; Chien and Saito 2021; Lemaire et al. 2022; de Oliveira Rolo et al. 2022; Moreau et al. 2022; Albert et al. 2021; Ersöz et al. 2022; Halecki et al. 2023; Luchauer et al. 2023; Koutalakis et al. 2023; Sretovic Brkovic and Djukic 2024; Rubi et al. 2024; Tavares Machado and Kim 2024
b) Rivers, streams, watersheds, subwatersheds and cities as case studies to making comparative analyses, associations, statistical analyses and generalizations	36	Ferreira et al. 2020; Croeser et al. 2021; Pradilla et al. 2021; Dinić-Branković et al. 2021; Wilczyńska et al. 2021; Kupilas et al. 2021; Zaręba et al. 2022; Gašparović et al. 2022; Diep et al. 2022; Prenner et al. 2022; Jutrović et al. 2023; Irvine et al. 2023; Huang and Gergel 2023; Halecki et al. 2023; Yaryan Hall and Bledsoe 2023; Lin et al. 2024; Li et al. 2023; Pradilla and Hack 2024
c) Did not specify a particular study area	24	Lechner et al. 2020; Oralet al. 2021; Langergraber et al. 2021; Canet-Martí et al. 2021; van Hullebusch et al. 2021; Ramísio et al. 2021; Jones et al. 2022; Wantzen et al. 2022; Bin Zaman et al. 2022; Ramísio et al. 2022; Delgado Lemus et al. 2022; Nawrath et al. 2024

**Table 2.** Percentage of analyzed manuscript and references, by applied methodology and techniques.**Tabla 2.** Porcentaje de manuscritos y referencias analizados, por metodología y técnicas aplicadas.

Type of paper	%	References
a) Experimental studies	66	Alvareda et al. 2020; Ourloglou et al. 2020; Santos Ferreira et al. 2020; de Oliveira Campos et al. 2020; Albert et al. 2021; Croeser et al. 2021; Langergraber et al. 2021; Ranta et al. 2021; Di Grazi et al. 2021; Kupilas et al. 2021; da Silva et al. 2021; Gkiatas et al. 2021; Pradilla et al. 2021; Wilczyńska et al. 2021; de Oliveira Rolo et al. 2022; Diep et al. 2022; Lemaire et al. 2022; Moreau et al. 2022; Prenner et al. 2022; Halecki et al. 2022; Halecki et al. 2023; Jutrović et al. 2023; Irvine et al. 2023; Huang and Gergel 2023; Yaryan Hall and Bledsoe 2023; Koutalakis et al. 2023; Luchauer et al. 2023; Li et al. 2023; Nawrath et al. 2024; Sretovic Brkovic and Djukic 2024; Rubi et al. 2024; Lin et al. 2024; Tavares Machado and Kim 2024
b) Theoretical papers	30	Lechner et al. 2020; Oralet al. 2021; Canet-Martí et al. 2021; Chien and Saito 2021; Jones et al. 2022; Dinić-Branković et al. 2021; van Hullebusch et al. 2021; Wantzen et al. 2022; Ramísio et al. 2021; Bin Zaman et al. 2022; Ramísio et al. 2022; Ersöz et al. 2022; Delgado Lemus et al. 2022; Zaręba et al. 2022; Gašparović et al. 2022
c) Analysis of regulatory frameworks, projects and urban planning documents	4	Denzell and Chappell 2022; Pradilla and Hack 2024

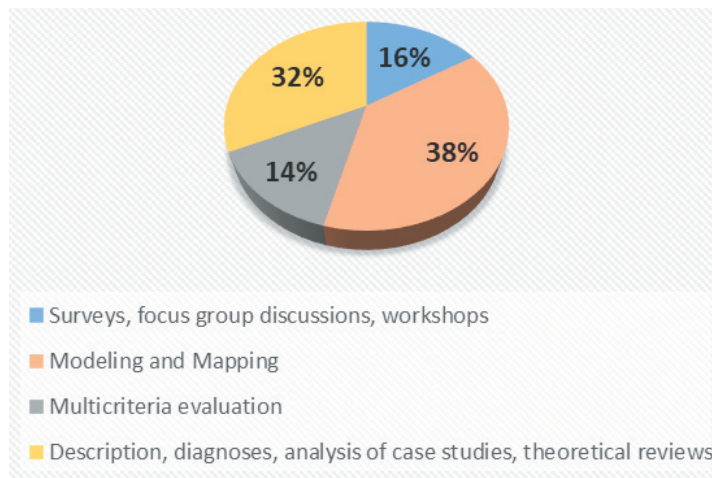
of suitable sites for NbS installation, as well as the case study approach, accounted for 32% (Table 3b). On the other hand, papers that applied surveys (questionnaires and interviews) and those that obtained information through participatory techniques (workshops, focus groups) represented 16% (Table 3c). Studies that conducted multicriteria evaluations to determine the optimal sites for NbS installation were found in the lowest percentage (14%) (Table 3c, Figure 2).

Although predefined keywords were used in the search criteria, it is important to highlight the prevalence of other words that were repeatedly mentioned in the analyzed research, reflecting the most usual research trends related to the topic under analysis. From the

keywords of the reviewed papers, it is possible to notice a predominance of words that contain the expression urban in relation to the general condition and management of urban streams (Alvareda et al. 2020; Ourloglou et al. 2020; Canet-Martí et al. 2021; Langergraber et al. 2021; de Oliveira Rolo et al. 2022; Ramísio et al. 2022; Wantzen et al. 2022; Halecki et al. 2023; Huang and Gergel 2023; and Sretovic Brkovic and Djukic 2024); "green infrastructure" (Jones et al. 2022; Li et al. 2023; Luchauer et al. 2023; Lin et al. 2024; Pradilla and Hack 2024); "blue green infrastructure" (Lechner et al. 2020; Dinić-Branković and Marković 2021; Kupilas et al. 2021; Oralet al. 2021; Pradilla et al. 2021; Ersöz et al. 2022; Gašparović et al. 2022; Zaręba et al. 2022); "nature-based solutions" (de Oliveira Campos et al. 2020; Di Grazia et

**Table 3.** Percentage of manuscripts and references by applied techniques and methodologies.**Tabla 3.** Porcentaje de manuscritos y referencias por técnicas y metodologías aplicadas.

Techniques and methodologies	%	References
a) Modeling and mapping	38	Ourloglou et al. 2020; Alvareda et al. 2020; Santos Ferreira et al. 2020; da Silva et al. 2021; Di Grazia et al. 2021; Kupilas et al. 2021; Wilczynska et al. 2021; Halecki et al. 2022; Prenner et al. 2022; Lemaire et al. 2022; Luchauer et al. 2023; Halecki et al. 2023; Jutrović et al. 2023; Irvine et al. 2023; Yaryan Hall and Bledsoe 2023; Koutalakis et al. 2023; Lia et al. 2023; Rubi et al. 2024; Tavares Machado and Kim 2024
b) Case studies approach	32	Oral et al. 2021; Canet-Martí et al. 2021; Dinić-Branković et al. 2021; van Hullebusch et al. 2021; Lechner et al. 2020; Chien and Saito 2021; Ramísio et al. 2021; Jones et al. 2022; Wantzen et al. 2022; Bin Zaman et al. 2022; Ramísio et al. 2022; Delgado-Lemus and Moreno-Calles 2022; Zareba et al. 2022; Gašparović et al. 2022 Pradilla and Hack 2024; Lin et al. 2024
c) Surveys and Participatory techniques (workshops, focus groups)	16	Albert et al. 2021; Pradilla et al. 2021; Diep et al. 2022; de Oliveira Rolo et al. 2022; Moreau et al. 2022; Denzell and Chappell 2022; Nawrath et al. 2024; Sretovic Brkovic and Djukic 2024
d) Multicriteria analysis	14	de Oliveira Campos et al. 2020; Croeser et al. 2021; Langergraber et al. 2021; Ranta et al. 2021; Gkiatas et al. 2021; Ersöz et al. 2022; Huang and Gergel 2023

**Figure 2.** Percentage of analyzed manuscript by applied methodology and techniques.**Figure 2.** Porcentaje de manuscritos analizados por técnicas y metodologías aplicadas.

al. 2021; Croeser et al. 2021; Langergraber et al. 2021; van Hullebusch et al. 2021; Delgado-Lemus and Moreno-Calles 2022; Diep et al. 2022; Ferreira et al. 2022; Halecki et al. 2022; S. Lemaire et al. 2022; Moreau et al. 2022; Irvine et al. 2023; Koutalakis et al. 2023; Rubi et al. 2024), and “ecosystem services” (Albert et al. 2021; Chien and Saito 2021; Di Grazia et al. 2021; Jones et al. 2022; Nawrath et al. 2024) such as the most representative ones (Figure 3). This aspect demonstrates the interest of the reviewed studies in the application of NbS to reduce the effects caused by ER. For example, some cases address the restoration of urban areas by applying bioengineering techniques and using natural materials to protect urban ecosystems, rather than relying on traditional engineering methods such as channelization or piping of water bodies (Ourloglou et al. 2020; Jutrović et al. 2023). They also include the creation of green and blue infrastructure.

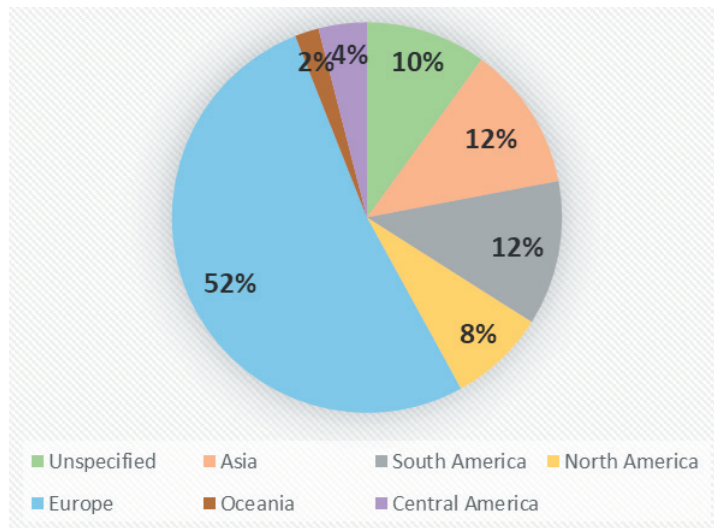
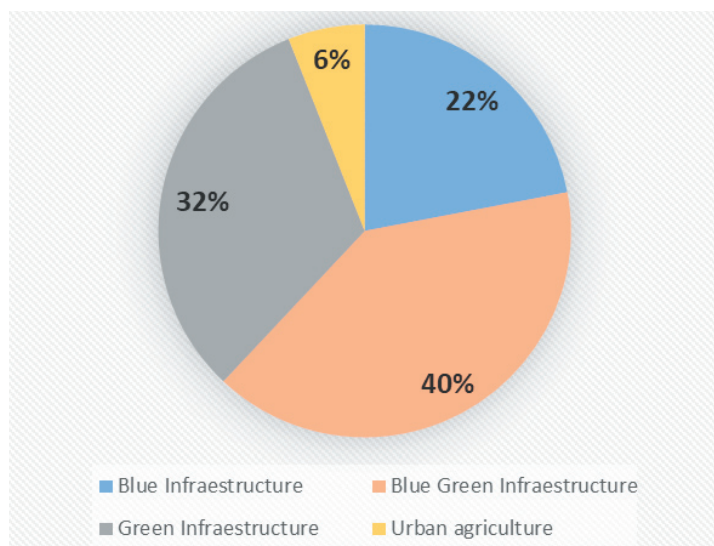
Among these, concrete examples include rainwater retention and infiltration systems, creation of multifunctional green spaces (e.g., corridors and linear parks, restored riparian zones) (Diep et al. 2022), implementation of urban gardens (Canet-Martí et al. 2021), construction of weirs in urban stream channels for flow control (Santos Ferreira et al. 2020), permeable urban infrastructure (permeable pavements and green roofs), storage and reuse systems (creation of wetlands, pipes and urban ditches) (Irvine et al. 2023) and infiltration trenches and permeable pavements, among others (Croeser et al. 2021).

From a geographical distribution perspective, based on the searching criteria of selection of papers in this review —research papers written in English, from the last five years, published in peer-reviewed, open access and international scientific journals and related to



**Table 5.** Percentage of NbS types proposed in the analyzed papers and their references.**Tabla 5.** Porcentaje de tipos de NbS propuestos en los artículos analizados y sus referencias.

NbS type	%	References
a) Blue-Green Infrastructures	40	Lechner et al. 2020; de Oliveira Campos et al. 2020; Croeser et al. 2021; Kupilas et al. 2021; Pradilla et al. 2021; Gkiatas et al. 2021; da Silva et al. 2021; Wilczynska et al. 2021; Ramísio et al. 2022; Gašparovic et al. 2022; Zaręba et al. 2022; Lemaire et al. 2022; Prenner et al. 2022; de Oliveira Rolo et al. 2022; Ersöz et al. 2022; Huang and Gergel 2023; Luchauer et al. 2023; Sretovic Brkovic and Djukic 2024; Pradilla and Hack 2024
b) Green Infrastructures	32	Ourloglou et al. 2020; Langergrab et al. 2021; van Hullebusch et al. 2021; Di Grazia et al. 2021; Dinić-Branković and Marković 2021; Ranta et al. 2021; Oral et al. 2021; Diep et al. 2022; Jones et al. 2022; Moreau et al. 2022; Jutrović et al. 2023; Halecki et al. 2023; Yaryan Hall and Bledsoe 2023; Tavares Machado and Kim 2024; Nawrath et al. 2024
c) Blue Infrastructures	22	Alvareda et al. 2020; Santos Ferreira et al. 2020; Albert et al. 2021; Chien and Saito 2021; Wantzen et al. 2022; Bin Zaman et al. 2022; Delgado-Lemus and Moreno-Calles 2022; Denzell and Chappell 2022; Halecki et al. 2022; Irvine et al. 2023; Koutalakis et al. 2023; Rubi et al. 2024
d) Urban Agriculture	6	Canet-Martí et al. 2021; Li et al. 2023 Lin et al. 2024

**Figure 4.** Percentage of manuscripts by studied areas (continents).**Figure 4.** Porcentaje de manuscritos por áreas de estudio (continentes).**Figure 5.** Percentage of NbS types proposed in the analyzed papers.**Figure 5.** Porcentaje de tipos de SbN propuestos en los trabajos analizados.

ponds, streams) (22%) (Table 5c) and Urban Agriculture (UA) (6%) (Table 5d, Figure 5).

Regarding the aforementioned feature, it is important to highlight that the implementation of UA contributes to improving water management throughout its entire cycle, strengthening resilience by promoting practices that increase infiltration, retention and sustainable use of water resources. In this way, permeable surfaces are increased, water is temporarily retained and stored and soil absorption capacity is enhanced. It also helps reduce the effects of ER, the urban heat island and enables the recycling and reuse of rainwater, among other benefits.

The dominance of BGI solutions highlights their central role in addressing the multifaceted challenges cities face from ER. The most frequently cited solutions involved creating green parks, trails, interconnected natural networks and hybrid systems that combine these with traditional engineering. Integrating water resources and vegetation in urban areas offers a range of ecosystem services that help mitigate ER associated with climate change and urbanization, while simultaneously boosting biodiversity and enhancing residents' quality of life (Pradilla et al. 2021).

The reviewed literature highlights the potential of combining green infrastructure (plants and vegetation) with blue infrastructure (drainage systems) to capture, filter rainwater and reduce flood risk (Croeser et al. 2021; Oral et al. 2021; Jones et al. 2022; Jutrović et al. 2023). For instance, green roofs and spaces both mitigate urban heat and manage rainwater. When integrated with storage systems like cisterns, they further reduce runoff volume, helping to prevent flooding.

#### *Overview of NbS concept and general contributions from the reviewed papers*

**Analysis of NbS concept: objectives and theoretical-methodological frameworks.** There are various NbS concepts developed from different disciplines. From the 50 selected papers, 27 explicitly outlined one or more definitions of the NbS concept (de Oliveira Campos et al. 2020; Lechner et al. 2020; Ourloglou et al. 2020; Santos Ferreira et al. 2020; Canet-Martí et al. 2021; Croeser et al. 2021; Hullebusch et al. 2021; Langergrab et al. 2021; Oral et al. 2021; Ramísio et al. 2021; van Albert et al. 2021; Wilczynska et al. 2021; Bin Zaman et al. 2022; de Oliveira Rolo et al. 2022;

Delgado-Lemus and Moreno-Calles 2022; Diep et al. 2022; Halecki et al. 2022; Jones et al. 2022; Moreau et al. 2022; Prenner et al. 2022; Ramísio et al. 2022; Jutrović et al. 2023; Koutalakis et al. 2023; Yaryan Hall and Bledsoe 2023; Lin et al. 2024; Nawrath et al. 2024; Rubi et al. 2024).

As for the definitions found, the most frequently used definition was the one outlined by the EC (2015), followed by the IUCN (Cohen-Shacham et al. 2016): "Solutions that aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by; supported by or copied from nature; both using and enhancing existing solutions to challenges as well as exploring more novel solutions. Nature-based solutions use the features and complex system processes of nature; such as its ability to store carbon and regulate water flows; in order to achieve desired outcomes; such as reduced disaster risk and an environment that improves human well-being and socially inclusive green growth" (EC 2015). "Nature-based solutions (NbS) are actions aimed at sustainably protecting; managing and restoring natural or modified ecosystems that help society cope with the adverse effects of climate change in an effective and adaptive manner; while simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al. 2016).

These definitions highlight the role of NbS in providing societies with multiple benefits to address climate change challenges in cities. In doing so, they reiterate key concepts such as well-being, social inclusion, environmental/social/economic co-benefits, mimicking nature, green growth, climate adaptation and effectiveness. The analysis shows that the EC (2015) conceptualization is broader, focusing on the variety of challenges addressed by NbS. In contrast, the IUCN (2016) definition focuses more specifically on protecting, managing and restoring ecosystems to help society cope with climate change.

Beyond these core definitions, the 27 reviewed works highlight aspects that enrich the analysis, providing key elements that complement the EC and IUCN definitions. In this context, NbS are recognized as an alternative for reducing flood risk and enhancing ecological quality (Ourloglou et al. 2020); an overarching framework linking ecosystem services to urban challenges through concepts like green infrastructure

and ecosystem-based adaptation (de Oliveira Campos et al. 2020); an approach that integrates green, blue and grey infrastructure to improve urban conditions (Lechner et al. 2020); a source of flexible, cost-effective solutions that mimic natural processes to bolster resilience (Ferreira et al. 2020); a viable alternative to grey infrastructure development (Koutalakis et al. 2023) and a highly valued strategy for addressing urbanization challenges while providing multiple co-benefits (Nawrath et al. 2024).

The rest of the analyzed papers (N=23), although addressed the concept indirectly, have not defined it explicitly. They have focused on other types of key concepts, such as stream restoration, blue-green infrastructure, integral solutions, urban circularity challenges, urban sustainability, ecosystem services, EbA measures, sponge cities and water sensitive urban design (Alvareda et al. 2020; Chien and Saito 2021; da Silva et al. 2021; Di Grazia et al. 2021; Dinić-Branković and Marković 2021; Gkiatas et al. 2021; Kupilas et al. 2021; Pradilla et al. 2021; Ranta et al. 2021; Denzell and Chappell 2022; Ersöz et al. 2022; Gašparović et al. 2022; Lemaire et al. 2022; Wantzen et al. 2022; Zaręba et al. 2022; Halecki et al. 2023; Huang and Gergel 2023; Irvine et al. 2023; Li et al. 2023; Luchauer et al. 2023; Pradilla and Hack 2024; Sretovic Brkovic and Djukic 2024; Tavares Machado and Kim 2024).

The analysis of the selected papers revealed various methodologies (Figure 2) that have advanced knowledge on applying NbS to specific case studies. Diep et al. (2022) explored NbS for stream restoration in 'informal' settlements — flood-prone areas with severe habitat and housing deficits — showing how riparian margins have become conflict zones. A key contribution is their emphasis on incorporating marginalized groups into NbS planning. Oral et al. (2021) presented results from five international scoping workshops used to examine NbS effectiveness in restoring and maintaining the water cycle, fostering implementation for circular urban water management. Pradilla et al. (2021) tested a rapid visual social-ecological stream assessment method for restoration planning, complemented by a citizen survey on perceptions and uses of blue-green infrastructure. Their work enabled the identification of areas ranging from well-preserved to critically degraded based on hydromorphological and sociocultural

conditions and assessed demand for green and blue infrastructure. Other contributions have focused on the analysis of social perceptions in order to assess the potential of the ecosystem services offered by scenarios with and without the application of NbS (Ribeiro et al. 2022) and in understanding the opinion of specialists and decision-makers regarding the bank management of urban streams through in-depth interviews (Moreau et al. 2022).

The main contributions of these papers derive from the richness associated with the evaluation of the applicability of NbS through participatory techniques that can be replicated in other urban environments. Ultimately, the contribution of using participatory experiences lies in using ecosystem services perception by different stakeholders as a proxy for evaluating the effectiveness of EbA measures. Moreover, through the use of these techniques, firsthand information can be obtained that is often not available in official sources (Albert et al. 2021; Pradilla et al. 2021; de Oliveira Rolo et al. 2022; Denzell and Chappell 2022; Diep et al. 2022; Moreau et al. 2022; Nawrath et al. 2024; Sretovic Brkovic and Djukic 2024).

One notable study described the development and use of a multi-criteria decision analysis (MCDA) tool to guide NbS selection in cities. Its main contribution lies in MCDA's potential to set and balance priorities from a long list of options, make robust and plausible recommendations under uncertainty and play a valuable role in supporting planning processes (Croeser et al. 2021). Another study developed a holistic assessment tool with multiple indicators for urban rivers, designed to support decision-makers in developing restoration measures (Ranata et al. 2021).

Other studies address ecological problems in USE resulting from human activities by applying various indices (Huang and Gergel 2023). By integrating remote sensing (e.g., vegetation indices) with field observations, these studies provide valuable insights into stream ecological conditions and offer practical guidelines for improving restoration practices (Tavares Machado and Kim 2024).

The analyzed studies generally applied methodologies aimed at promoting the ecological health of urban rivers and streams amid intense urban expansion. As stated by Ramísio et al. (2022), climate change and the need for efficient resource use are exerting additional pressures that cannot be addressed

with 'business-as-usual' solutions. However, a key challenge is the lack of practical knowledge on implementing academic recommendations. Similarly, limited budgets and a lack of local community support hinder the implementation of these strategies.

Examples of targeted interventions to mitigate ER. The reviewed studies indicate that NbS are a relatively recent concept with significant potential for adoption in urban planning. When applied to mitigate flood risk, NbS offer a range of social, cultural and economic benefits. In the review, it was observed that the most frequently mentioned interventions in urban watercourses include: reforestation/afforestation plans; retention ponds; renaturalization of watercourses (Ruangpan et al. 2024); greening of grey surfaces (green rooftops, green walls or greened brownfields); integrated broad scale climate change mitigation and adaptation measures (natural flood control and constructed wetlands) (Van den Bosch and Sang 2017); construction of wetlands and bioengineering techniques that employ natural materials (riparian vegetation) to mimic the natural characteristics and features of rivers (Ourloglou et al. 2019); daylighting (Wantzen et al. 2022); planning green infrastructure (Albert et al. 2021; Pradilla et al. 2021; Jones et al. 2022) and NbS incorporate connected green (vegetation), blue (water) and grey (unsealed roads) infrastructure in order to improve environmental, social, cultural and economic conditions in cities (Lechner et al. 2020) and ecosystem restoration.

Regarding the aforementioned aspect, it is important to note that the application of NbS for the restoration of urban rivers and streams was one of the main objectives found in most of the papers analyzed (Ourloglou et al. 2020; Santos Ferreira et al. 2020; Pradilla et al. 2021; Diep et al. 2022; Jutrović et al. 2023). The focus on preserving open ecosystems has grown, highlighting the need to enhance resilience in urban riverside areas for effective ecosystem restoration (Ribeiro et al. 2022; Halecki et al. 2023). Many of the studies mentioned that river restoration projects are increasing, but many lack strategic planning and monitoring (Pradilla and Hack 2024).

Concerning the urbanization of stream ecosystems with the purpose of managing flash-flood events, Ourloglou et al. (2020) demonstrated the effects of a NbS for managing an urban stream, based on the

use of bioengineering materials (plants for bioremediation) and the implementation of actions that restore the stream to its natural form (channel widening). The authors concluded that the application of NbS is more economical, efficient and beneficial than other traditional practices (concrete channelization).

Jones et al. (2022) analyzed optimal NbS location within a holistic urban design framework. Spatial models should be appropriate for assessing the scale and reach of NbS, considering their operational mechanisms and any threshold-dependent effects (Di Grazia et al. 2021). Jutrović et al. (2023) explored sustainable NbS as an alternative to grey infrastructure for waterway management, analyzing different locations to assess options for safeguarding, revitalizing and developing blue-green infrastructure. Similarly, Prenner et al. (2022) analyzed suitable locations by considering stream hydrological potential and urban microclimatic sensitivity. In another study, Gkiatas et al. (2021) evaluated the current state of urban streams using GIS to recommend functional improvements and raise community awareness.

There are also studies that provide suggestions of how planning NbS can be conceptualized and applied in practice (Albert et al. 2021) or explored the potential of NbS for flood hazard mitigation (Ferreira et al. 2020). In this last topic, it is concluded that decreases in water depth provided by NbS are useful in flood mitigation and adaptation within the peri-urban catchment. They also emphasize that a network of NbS, rather than small isolated strategies, needs to be created for efficient flood-risk management at a larger scale (Ferreira et al. 2020). In this regard, it has been concluded that the integration of water management systems and green spaces in USE offers significant potential for climate change adaptation and the mitigation of extreme weather events (Halecki et al. 2023).

Advances in the development of analytical criteria. The review identified papers focusing on theoretical analyses related to NbS application. A frequently mentioned topic was the need to protect and plan hydrological networks, integrating them with urban green spaces (Ersöz et al. 2022).

Irvine et al. (2023) reviewed NbS research and design practices to identify knowledge gaps hindering effective implementation

for managing particle-bound metals. They concluded that NbS are an emerging urban design focus which, with multidisciplinary guidance, can provide effective water management balanced with habitat creation and community wellbeing. Ramísio et al. (2022) reflected on the opportunities NbS provide for including BGI in urban planning. They noted that this integrated approach contributes to sustainable urban water management and enhances the resilience of Urban Stream Environments (USE) and water services to climate change, while delivering social co-benefits.

Langergraber et al. (2021) addressed the challenges of applying NbS for urban circularity across different sectors and land uses. They concluded that most NbS are interconnected and provide co-benefits for other resource cycles. Thus, they suggest that a holistic, systemic approach can facilitate circular resource use in cities. Another work (Lechner et al. 2020) identified five key challenges for NbS application: a) urbanization characteristics; b) biophysical and climatic context; c) environmental risks and restoration challenges; d) human-nature relationships and conflicts, and e) policy and governance context. While these challenges were identified for urban regions in Southeast Asia, the authors argued that they can be replicated in other urban contexts.

Notable contributions include those addressing problems in small urban streams and creeks, exploring how their revitalization can foster community resilience (Dinić-Branković and Marković 2021). Others present implemented NbS units for resource recovery from urban waste streams, along with supporting units to enhance quality and minimize hazards at the source (e.g., for concentrated fertilizers or disinfected products) (van Hullebusch et al. 2021).

Thus, NbS serve as an innovative tool to reduce ecosystem vulnerability to climate risks while fostering more livable urban areas (Shah et al. 2020; Ferrario et al. 2024). They also help maintain ecological balance amid climate change and human impacts. However, a major implementation challenge is obtaining data to assess the multiple hazards, exposure and vulnerability of socio-ecological systems at project sites (Chen et al. 2023), a concept highlighting the reciprocal relationships between ecosystem health and human wellbeing.

## DISCUSSION

This paper presented a systematic review of research aimed at mitigating extreme rainfall (ER) effects in urban stream environments (USE), identifying future challenges, priorities and research directions. The systematic review method helps to limit the scope of the work and provides useful direction for defining research gaps, as it enables the collection of papers from a broad range of sources (Ruangpan et al. 2024).

The reviewed studies were categorized into three primary areas based on their methodologies: 1) analysis of the NbS concept, its objectives and theoretical-methodological frameworks; 2) examples of targeted interventions for ER mitigation, and 3) advancements in analytical criteria development. While these three analytical categories were established, a limitation of the search process was the frequent inclusion of topics not directly related to ER occurrence and NbS application in USE.

Furthermore, the selection criteria may have introduced bias into the search process. For example, the geographical concentration of selected papers does not imply a lack of relevant studies in other regions. Similarly, limiting the search to 2019-2024 or to open access publications may exclude relevant work. However, given the exploratory nature of this review, it was appropriate to limit the scope initially (e.g., by excluding non-English papers or broader time frames) even though expanding keywords and spatiotemporal horizons would be valuable for future work. This non-exhaustive approach provides a foundation for deeper investigation in future contributions.

The review of 50 articles confirmed a growing tendency toward NbS frameworks that integrate experimental and theoretical work, with only a few studies focusing on regulations, standards or urban projects. The analysis shows a rise in publications since 2018, peaking in 2023, primarily in journals covering environmental sciences, water resources, technology, management, governance and environmental engineering. Nevertheless, significant challenges persist and various research avenues remain open.

Considering the diverse aims of the papers, it is important to highlight that a large part of them have focused on demonstrating NbS effects for managing urban streams as an

alternative to conventional grey infrastructure and exploring their potential for flood hazard mitigation (Santos Ferreira et al. 2020; Ramísio et al. 2022; Jutróvic et al. 2023). This reflects a growing global interest, both theoretical and applied, in NbS for ER mitigation. A key limitation is the geographic bias in paper provenance, which shapes the resulting theoretical frameworks, methodologies and techniques, often excluding realities of the Global South. Consequently, recommendations from specific European contexts (Ourloglou et al. 2020; Croeser et al. 2021; Halecki et al. 2022; Jutrović et al. 2023; Sretovic Brkovic and Djukic 2024) often cannot be directly transferred to regions with different financial, legal and political realities. This disparity is highlighted by Pradilla and Hack (2024), who note that while urban stream restoration is widespread in the Global North, it remains limited in the Global South, where focus is often on water quality, river habitats and watershed assessment.

In Argentina, the predominant model of hydraulic management was oriented towards water evacuation, without prioritizing its potential to create sustainable public spaces (Kozac et al. 2023). It is important to highlight the case of the RMBA (Región Metropolitana de Buenos Aires), where watercourses and urban water bodies have historically been focal points of environmental conflicts leading to their artificialization (Williams et al. 2018). In response, remediation and restoration initiatives have been implemented through various local actors (Ríos et al. 2024).

For example, initiatives in the RMBA include: a) proposals to design green spaces based on complex systems, biodiversity and sustainable development (Garay and Fernández 2013); b) revegetation of riparian corridors with native phytoremediator species in the Matanza-Riachuelo basin (de Cabo et al. 2020); c) a community-based project to prevent the channelization of the San Francisco stream in Claypole, testing plant-based water treatment systems (Graziano et al. 2019; Aimo et al. 2024; Gómez et al. 2025), and d) watershed-scale interventions in the El Gato stream (La Plata) after the 2013 flood, aimed at reducing degradation, pollution and flood risk (Rotger 2017).

Thus, it is essential to contextualize studies both spatially and temporally to identify region-specific environmental issues and establish suitable solutions. Creating spaces for reflection and new practices to reshape

current urban paradigms has become a priority to guide the implementation of environmentally respectful solutions in USE.

## CONCLUSIONS

A large part of the studies analyzed have focused on addressing, from different perspectives, the application of NbS for the restoration of urban rivers and streams. The consideration of green and BI as an alternative to traditional interventions, which are solely focused on grey infrastructures, has been the most recurrent option. The application of the PRISMA methodology was effective for conducting the systematic review, as it guided the search for papers and the analysis process based on predefined steps, aligned with the objectives of the study and inclusion criteria.

It is important to add that a large part of these initiatives generally come from European countries, which is related to the level of progress in these countries regarding the design and implementation of such nature-friendly solutions. One of the causes of this lies in the characteristics of the problems faced by these countries related to climate change, the pressures arising from intense urbanization processes and the occupation of flood-prone areas near rivers, streams and wetlands. This has led to the development of the main international agreements, frameworks and standards related to the application of NbS initially being created in this context.

Considering the benefits derived from the application of NbS, those related to the restoration of urban rivers have been identified first, followed by flood risk reduction. This explains the prominence the topic has gained in recent years due to the occurrence of ER in the context of global climate change. Regarding the studies that focused on rivers or streams, it is notable that, in general, these have been watercourses that have been intervened through the construction of dams, channels, pipes, among other grey infrastructures. This has been a recurring topic and motivates the consideration of NbS in various restoration and regeneration projects of urban streams in cities.

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