REVISTA DCS
FUNDADA EN 2000

A GLANCE AT URBAN FLOOD RISK ASSESSMENT AND NATURE-BASED MITIGATION STRATEGIES IN RAPIDLY EXPANDING CITIES IN DEVELOPING REGIONS: RESEARCH DIRECTIONS

UMA ANÁLISE DA AVALIAÇÃO DE RISCO DE INUNDAÇÕES URBANAS E ESTRATÉGIAS DE MITIGAÇÃO BASEADAS NA NATUREZA EM CIDADES EM RÁPIDA EXPANSÃO EM REGIÕES EM DESENVOLVIMENTO: DIREÇÕES DE PESQUISA

UNA MIRADA A LA EVALUACIÓN DEL RIESGO DE INUNDACIONES URBANAS Y LAS ESTRATEGIAS DE MITIGACIÓN BASADAS EN LA NATURALEZA EN CIUDADES EN RÁPIDA EXPANSIÓN EN REGIONES EN DESARROLLO: DIRECCIONES DE INVESTIGACIÓN

Elvis Appiah[1], Nicole Amadeu Dias[2], Isabelle Stranburger Correia[3], Herlander Mata-Lima[4]

DOI: 10.54899/dcs.v22i82.3335
Recibido: 06/09/2025 | Aceptado: 08/09/2025 | Publicación en línea: 12/09/2025.

ABSTRACT

Urban flooding poses a growing threat to rapidly expanding cities, exacerbated by unregulated urban development, climate change, and inadequate drainage systems. Conventional grey infrastructure solutions, though widely implemented, often fall short in delivering adaptable, inclusive, and sustainable flood management. In response, this work proposes the development of an integrated, context-sensitive framework for assessing urban flood risk and evaluating the effectiveness of nature-based solutions (NbS) as a climate-resilient alternative. The work suggests a mixed-methods approach combining geospatial analysis, hydrological modeling (using GIS, SWMM, HEC-HMS, HEC-RAS, and Remote Sensing), and multi-criteria decision analysis to identify flood-prone zones and prioritize suitable NbS interventions—including bioretention, bioswales, rain gardens, permeable pavements, and urban retention basins. Stakeholder consultations and participatory mapping are also considered to complement the technical assessment, ensuring that local knowledge and social equity are embedded in the decision-making process. This work offers a contribution by bridging physical flood risk modeling with socio-environmental dimensions, resulting in a comprehensive decision-support tool for urban flood mitigation and, thus, build resilient cities. It promotes a hybrid infrastructure paradigm that integrates green and grey strategies to support adaptive and multifunctional flood resilience planning. Expected outcomes include spatially explicit flood risk maps, context-optimized NbS deployment strategies, and a replicable analytical framework applicable to all urban regions

[1] BS in Civil Engineering, Kwame Nkrumah University of Science and Technology (KNUST), Ghana.
E-mail: elvis.appiah.stu@gmail.com Orcid: https://orcid.org/0009-0004-1758-8741
[2] BS in Civil Engineering, Universidade Federal da Integracão Latino-Americana, Foz do Iguacu, Parana, Brazil.
E-mail: na.dias.2021@aluno.unila.edu.br
[3] BS in Architecture and Urban Planning, Universidade Federal da Integracão Latino-Americana, Foz do Iguacu, Parana, Brazil. E-mail: is.correia.2021@aluno.unila.edu.br
[4] PhD in Engineering Sciences, University of Lisbon (IST-UTL), Lisbon, Portugal.
E-mail: herlander.lima@unila.edu.br Orcid: https://orcid.org/0000-0001-9178-0046

facing similar challenges. The findings will directly support the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 6 (Clean Water and Sanitation).

Keywords: Urban Flooding. Nature-Based Solutions (NbS). Flood Risk Assessment. Hydrological Modeling. GIS. SWMM. Green Infrastructure. Climate Resilience. Sustainable Urban Planning. SDG.

RESUMO

As inundações urbanas representam uma ameaça crescente às cidades em rápida expansão, agravada pelo desenvolvimento urbano desregulado, pelas mudanças climáticas e pelos sistemas de drenagem inadequados. Soluções convencionais de infraestrutura cinza, embora amplamente implementadas, frequentemente não conseguem proporcionar uma gestão adaptável, inclusiva e sustentável das inundações. Em resposta, este trabalho propõe o desenvolvimento de uma estrutura integrada e contextualizada para avaliar o risco de inundações urbanas e a eficácia das soluções baseadas na natureza (SbN) como alternativa resiliente ao clima. O trabalho sugere uma abordagem de métodos mistos que combina análise geoespacial, modelagem hidrológica (usando SIG, SWMM, HEC-HMS, HEC-RAS e Sensoriamento Remoto) e análise de decisão multicritério para identificar zonas propensas a inundações e priorizar intervenções adequadas de SbN — incluindo biorretenção, valas biológicas, jardins de chuva, pavimentos permeáveis e bacias de retenção urbanas. Consultas às partes interessadas e mapeamento participativo também são considerados para complementar a avaliação técnica, garantindo que o conhecimento local e a equidade social sejam incorporados ao processo de tomada de decisão. Este trabalho contribui ao unir a modelagem física de risco de inundações com as dimensões socioambientais, resultando em uma ferramenta abrangente de apoio à decisão para a mitigação de inundações urbanas e, assim, a construção de cidades resilientes. Promove um paradigma de infraestrutura híbrida que integra estratégias verdes e cinzas para apoiar o planejamento adaptativo e multifuncional de resiliência a inundações. Os resultados esperados incluem mapas de risco de inundações espacialmente explícitos, estratégias de implantação de NbS otimizadas para o contexto e uma estrutura analítica replicável aplicável a todas as regiões urbanas que enfrentam desafios semelhantes. Os resultados apoiarão diretamente o alcance dos Objetivos de Desenvolvimento Sustentável (ODS) das Nações Unidas, particularmente o ODS 11 (Cidades e Comunidades Sustentáveis), o ODS 13 (Ação Climática) e o ODS 6 (Água Potável e Saneamento).

Palavras-chave: Inundações Urbanas. Soluções Baseadas na Natureza (SbN). Avaliação de Risco de Inundação. Modelagem Hidrológica. GIS. SWMM. Infraestrutura Verde. Resiliência Climática. Planejamento Urbano Sustentável. ODS.

RESUMEN

Las inundaciones urbanas suponen una amenaza creciente para las ciudades en rápida expansión, agravada por el desarrollo urbano no regulado, el cambio climático y los sistemas de drenaje inadecuados. Las soluciones convencionales de infraestructura gris, aunque ampliamente implementadas, a menudo no logran ofrecer una gestión de inundaciones adaptable, inclusiva y sostenible. En respuesta a ello, este trabajo propone el desarrollo de un marco integrado y sensible al contexto para evaluar el riesgo de inundaciones urbanas y la eficacia de las soluciones basadas en la naturaleza (NbS) como alternativa resistente al clima. El trabajo sugiere un enfoque de métodos mixtos que combina el análisis geoespacial, la modelización hidrológica (utilizando SIG, SWMM, HEC-HMS, HEC-RAS y teledetección) y el análisis de decisión multicriterio para identificar las zonas propensas a las inundaciones y priorizar las intervenciones NbS adecuadas, incluyendo la biorretención, los biofiltros, los jardines de lluvia, los pavimentos permeables y los depósitos de retención urbanos. También se tienen en cuenta las consultas con las partes interesadas y la cartografía participativa para complementar la evaluación técnica, garantizando que los conocimientos locales y la equidad social se incorporen al proceso de toma de decisiones. Este trabajo contribuye a tender un puente entre la modelización física del riesgo de inundaciones y las dimensiones socioambientales, lo que da como resultado una herramienta integral de apoyo a la toma de decisiones para la mitigación de las inundaciones urbanas y, por lo tanto, la construcción de ciudades resilientes. Promueve un paradigma de infraestructura híbrida que integra estrategias verdes y grises para apoyar una planificación adaptativa y multifuncional de la resiliencia ante las inundaciones. Los resultados esperados incluyen mapas de riesgo de inundaciones espacialmente explícitos, estrategias de implementación de NbS optimizadas para cada contexto y un marco analítico replicable aplicable a todas las regiones urbanas que enfrentan desafíos similares. Los hallazgos respaldarán directamente el logro de los Objetivos de Desarrollo Sostenible (ODS) de las Naciones Unidas, en particular el ODS 11 (Ciudades y comunidades sostenibles), el ODS 13 (Acción por el clima) y el ODS 6 (Agua limpia y saneamiento).

Palabras clave: Inundaciones Urbanas. Soluciones Basadas en la Naturaleza (NbS). Evaluación del Riesgo de Inundaciones. Modelización Hidrológica. SIG. SWMM. Infraestructura Verde. Resiliencia Climática. Planificación Urbana Sostenible. ODS.

BACKGROUND AND CONCEPTUALIZATION OF THE PROBLEM

Flooding stands as one of the most devastating and pervasive natural hazards globally (Gu et al., 2020), with impacts that have intensified in recent decades due to rapid urbanization (Hodgkins et al., 2019), climate change, and inadequate infrastructure (Chissende et al., 2025). According to recent analyses, floods accounted for the deaths of approximately 7,600 people worldwide in 2023, with annual death tolls fluctuating significantly depending on the severity of events—peaking at 35,000 in 1999 during catastrophic flooding in Venezuela (Statista, 2025; Save the Children, 2023). However, mortality figures only begin to capture the crisis's scale: in 2023, more than 30 million people were affected by floods globally, facing injury, displacement, or homelessness, while in 2010, nearly 200 million people were impacted by flooding events (Statista, 2025).

The economic toll of flooding is equally staggering. In Brazil, the 2024 floods in Rio Grande do Sul submerged 478 municipalities—over 95% of the state—resulting in 173 fatalities, the displacement of over 700,000 people at the peak, and an estimated US$3 billion in agricultural and soil recovery costs. The disaster is projected to cause a 4.2% contraction in the region's economic growth, with some municipalities experiencing economic losses exceeding 30% compared to the previous year (ILO, 2024; Faria and Skamvetsakis, 2025).

In Africa, Nigeria's 2024 floods affected 29 out of 36 states, displacing more than 225,000 people and causing over 200 deaths. The flooding destroyed over 115,000 hectares of farmland, exacerbating food insecurity in a country where one in six children already faces hunger (Save the Children, 2024). Neighboring Niger has also suffered, with over 649,000 individuals affected and more than 68,000 homes destroyed, highlighting the vulnerability of low-income populations to recurrent flood disasters (Save the Children, 2024). Ghana is not exempt from these challenges: in June 2024, severe flash floods in the Greater Accra and Central Regions displaced thousands, destroyed critical infrastructure, and caused at least 12 fatalities. The Ghana Meteorological Agency attributed the event to prolonged torrential rains compounded by poor drainage and unregulated urban expansion (Ghana News Agency, 2023).

Asia is particularly exposed, with countries like Bangladesh, Vietnam, and China facing persistent riverine and urban flood risks (Statista, 2025). The Intergovernmental Panel on Climate Change (IPCC) estimates that between 3.3 and 3.6 billion people—nearly half the world's population—live in areas highly vulnerable to climate change, with flood-prone regions in Africa, Asia, and South America experiencing the highest mortality rates from floods, droughts, and storms (IPCC, 2023). Between 2010 and 2020, human mortality from such events was 15 times higher in these highly vulnerable regions compared to less exposed areas (IPCC, 2023).

Looking ahead, the risks are projected to escalate. Recent research indicates that the global population exposed to a 1% annual risk (the so-called 100-year flood) represent 23% (1.81 billion peoples), with the most dramatic increases in low-income and rapidly urbanizing regions (Rentschler et al., 2022). The authors also highlighted that urban areas, in particular, are expected to see a substantial increase in flood exposure by century's end, with the poorest urban populations facing the greatest threat.

In response to these challenges, innovative approaches are emerging. China's "sponge city" initiative, launched in 2013, exemplifies efforts to integrate nature-based solutions (NbS) into urban stormwater management. By enhancing urban permeability, restoring wetlands, and implementing green infrastructure, sponge cities aim to absorb, store, and reuse rainwater, reducing flood risk and delivering co-benefits such as improved water quality and urban cooling (Chan et al., 2021).

In sum, flooding is a rapidly escalating global crisis, exacting a heavy toll on human lives, economies, and ecosystems. The disproportionate burden borne by low-income and urbanizing regions, coupled with the increasing frequency and severity of extreme weather events, highlights the urgent need for adaptive, sustainable, and context-sensitive flood risk management strategies. Hence, this work aims to propose an integrated flood management procedure that accounts for the principles entailed in Low Impact Development (LID), water sensitive urban design, and Sponge City which are (Maliva, 2019): (1) reduce impervious área; (2) desconnect impervious área; (3) intercept stormwater before it comes in contact with impervious áreas; and (4) detain and infiltrate on-site, as close as possible to the source. The application of the four principles, in turn, promotes aquifer recharge (infiltration supplies groundwater and maintains base flows to streams and wetland), protects groundwater quality, improves water and air quality, reduces the pollution impacts of stormwater runoff, mitigates urban heat island effect, and increases green space in urban environment, as stressed by Chikhi et al. (2023).

RATIONALE FOR RESEARCH FUNDING ON FLOOD MANAGEMENT

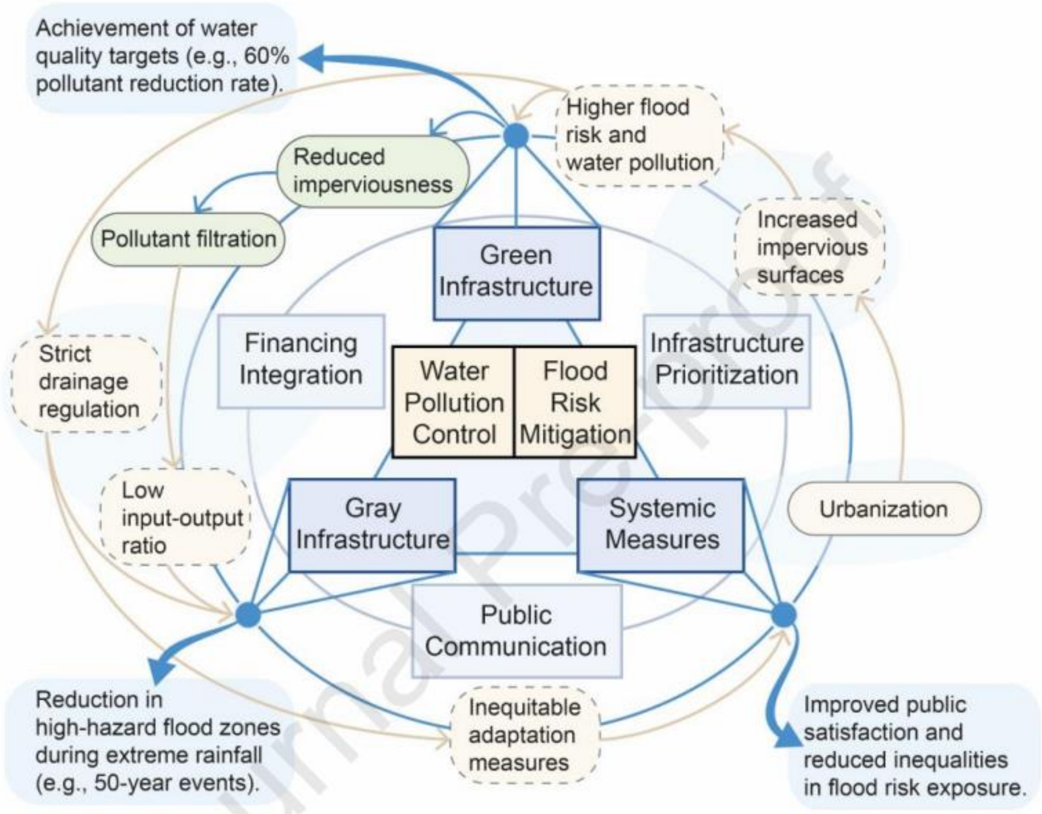
The process of rapid urbanization, coupled with climatic uncertainty and inadequate land use planning, has intensified both the occurrence and magnitude of urban floods globally, having significant environmental, social, and economic consequences. For instance, the recent flood occurrences in Brazil's southern Rio Grande do Sul state have left more than 150,000 persons homeless, scores dead, and missing (Reuters, 2024). Likewise, Nigeria suffers more than USD 4 billion in urban flood losses annually, with more than 300 deaths occurring in 2022 alone (Davies, 2022). These effects are compounded by the reality that most cities in the developing world lack resilient drainage systems, credible data, or governance structures that are coordinated to respond to flood threats in an effective manner (ECOWAS Commission, 2020).

In spite of the increased focus on the subject, traditional flood risk analysis models are still insufficient to represent the spatial and temporal dynamics of flood events in the context of rapidly urbanizing communities. The models are commonly based on outdated hydrometeorological information, do not account for real-time urbanization trends, and do not reflect informal settlements or socio-spatial disparities (Merz et al., 2010; world Bank, 2018;

Rojas-Lesmes et al., 2025). For example, the paucity of observational networks and lack of data sharing constrains the reliability of hydrological simulations and early warning systems in Sub-Saharan Africa, thus undermining timely responses (ECOWAS Commission, 2020; Chavula et al., 2025). Besides, expert-driven evaluations that lack participatory contributions from affected communities tend to miss context-specific vulnerabilities and indigenous coping strategies (Martins et al., 2025). In the context of rapidly urbanizing áreas (e.g. sub-Saharan Africa, South America, and Asia), cities can address climate change as they develop, adopting Nature-based Solutions (NbS) in the most effective combinations with grey infrastructure and in ways that maximize locally valued co-benefits (Mguni, Herslund, and Jensen, 2016; Hobbie and Grimm, 2020).

Hence, NbS have been developed as innovative, multi-functional solutions that utilize natural processes—such as infiltration, evapotranspiration, and ecosystem restoration—to mitigate flood risk. Green roofing, vegetated swales, and wetland restoration have proven effective at mitigating runoff, increasing biodiversity, and improving climate resilience (Díaz et al., 2019). Yet, widespread implementation of NbS is held back by the absence of standardized methods for evaluating their effectiveness, maintenance problems, and lack of good long-term monitoring practice (Moosavi, Browne, and Bush, 2021; Zarei and Shahab, 2025). Additionally, NbS by themselves may not be sufficient to manage extreme weather events, and therefore hybrid solutions combining both green and grey infrastructure are required for greater resilience (Li et al., 2024; Feng et al., 2025).

Figure 1. Coordination Governance Framework for flood risk management.



Source: adapted from Feng et al. (2025)

In light of these constraints, the justification of this proposal is the pressing need for an integrated, flexible, and scalable system for flood risk assessment and mitigation—one that effectively conveys the complex interaction between urbanization, climatic extremes, and local-specific vulnerabilities. An integrated framework would combine state-of-the-art hydrodynamic modeling, spatially explicit analysis, and stakeholder-engaged priority-setting to map high-risk zones and quantify the efficacy of NbS in varied urban contexts (Almeida et al., 2020; Prashar et al., 2023). By incorporating sustainability metrics and equity into decision-making, this article aims to propose a research approach that enhance technical flood forecasting while simultaneously enabling equitable and climate-resilient urban planning.

Ultimately, this article seeks to fill a key gap in the existing urban flood management policy and practice framework: the lack of context-specific, system-level models for informing the effective use of Nature-based Solutions (NbS) and hybrid infrastructure planning in rapidly urbanizing settings. Consequently, the article share with academic community and practitioners a research strategy that is both timely and required to support more resilient, evidence-based, and sustainable approaches that are consistent with global development aspirations, including the Sustainable Development Goals (SDGs 11, 13, and 6).

RESEARCH SCOPE

Hereby is proposed a research procedure focused on the assessment and mitigation of urban flood risk in rapidly expanding cities, with a particular emphasis on the application and evaluation of NbS. While numerous studies and frameworks exist for sustainable development in the context of building construction—such as the USGBC's LEED metric for residential, commercial, and institutional projects—this study deliberately narrows its scope to address the unique challenges and opportunities present in urban flood risk management, rather than general sustainable construction practices.

Delimitations

Respecting to geographical focus the research is urgent for rapidly urbanizing cities in regions with high flood vulnerability in developing areas (e.g., Africa, Asia, and South America) and also in Small Island Developing States (SIDS). These regions are chosen due to their pronounced exposure to flood hazards, rapid population growth, and evolving urban landscapes (Mata-Lima et al., 2016). For thematic Boundaries one stresses (a) the assessment of current flood risk using state-of-the-art hazard and vulnerability modeling tools; (b) evaluation of the effectiveness of nature-based solutions - NbS (e.g., green roofs, permeable pavements, restored wetlands, urban forests, and others features of sponge city) for flood mitigation; (c) comparison of NbS with conventional (grey) infrastructure and hybrid approaches; and (d) identifying barriers and enablers for mainstreaming NbS in urban planning and policy.

Rationale for Scope

Hereby, the scope is designed to fill critical knowledge and practice gaps in urban flood risk management, where the integration of NbS remains limited despite growing evidence of their co-benefits. By focusing on urban environments and the intersection of rapid urbanization, climate change, and innovative mitigation strategies, the research should provide actionable insights for city planners, policymakers, and stakeholders seeking to enhance urban resilience (Díaz, Smith and Thompson, 2019).

INNOVATIVE CONTRIBUTIONS

The research must contributes to advance the field of urban flood risk management by addressing critical methodological and practical gaps identified in recent literature, covering both structural and non-structural measures (table 1).

Table 1. Flood management measures.

Action or Measure	Description
Structural	Keeping water away from populations, for flood hazard reduction. Measures include dams, dikes, levees, weirs, seawalls, dykes, reservoirs, pump stations, embankments, tidal gates, diversion channels, etc.
Non-structural	Keeping populations away from water bodies, for flood vulnerability reduction. Measures include policies and laws, raising public awareness, flood forecasting and warnings, evacuation, training and education, land use adjustment, regulations and insurance, funding and subsidies, spatial and flood management plans, etc.

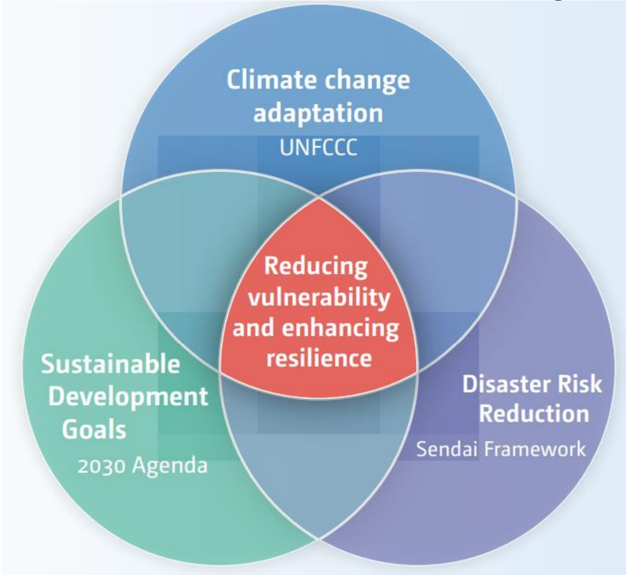
Source: authors based on Sayers et al. (2013), and Wang et al. (2022)

Considering the limitations of existing assessment tools and the need for integrated, context-sensitive approaches, the study should offers several key innovative contributions:

Integrated Assessment Framework

The integrated framework suitable for developing regions should integrates hydrodynamic modeling, spatial vulnerability analysis, and nature-based solutions (NbS) assessment, providing a multi-dimensional tool (including indicators) to evaluate both physical and socio-ecological dimensions of flood risk in order to reduce the vulnerability and increase the resilience (Chavula et al., 2025), as depicted in figure 2.

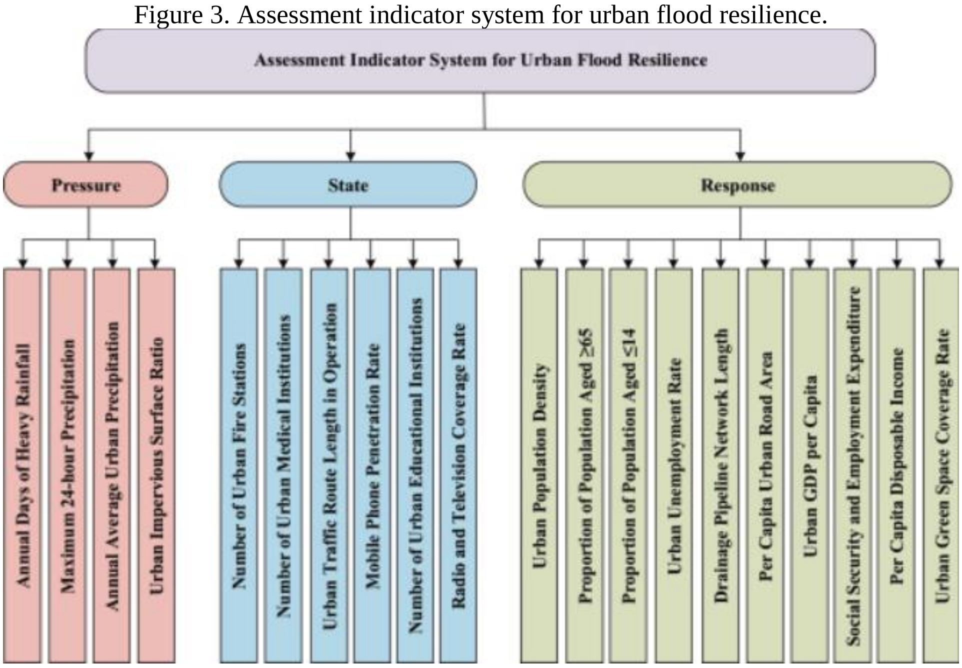
Figure 2. Intersection of the SDGs, Disaster Risk Reduction, and Climate Change Adaptation agendas 2015-2030.



Source: adapted from UNFCCC (2017)

Multi-Dimensional Indicators: encompass a set of indicators that capture hydrological, infrastructural, and socio-economic vulnerabilities. It addresses key shortcomings in existing models by reflecting the dynamic interactions between urban growth, land use change, and community resilience (Fu et al., 2024; Liu et al., 2025).

Figure 3. Assessment indicator system for urban flood resilience.



Source: adapted from Liu et al. (2025)

Advancing the Mainstreaming of Nature-Based Solutions: the research ought to be done to systematically evaluates the effectiveness of NbS for urban flood mitigation, adopting a holistic social-ecological systems (SES). It highlights co-benefits such as biodiversity enhancement, urban cooling, and social cohesion, moving beyond conventional engineering-focused evaluations (Li et al., 2024; Liu et al., 2025). By comparing the performance of NbS, grey infrastructure, and hybrid solutions, it is possible to provide practical insights for decision-makers on integrated urban flood mitigation strategies (Prado et al., 2024).

Incorporation of Flexible, Data-Informed Modeling Approaches

(a) ***Use of Modern Tools***: Where feasible, the proposed framework allows the integration of advanced spatial tools—including remote sensing, GIS, and potentially machine learning—to enhance flood prediction, hot spot detection, and land-use forecasting. Future works or interdisciplinary collaboration may incorporate machine learning to improve accuracy and decision-support.

(b) ***Participatory Mapping and Stakeholder Engagement***: Recognizing the importance of local knowledge, the research should integrates participatory mapping and stakeholder engagement into the framework. This ensures that outputs are not only technically robust but also socially responsive and context-sensitive (Forrester et al., 2015; Minucci et al., 2020; Gnecco et al., 2024).

Bridging Methodological and Practical Gaps

(a) ***Filling Knowledge Gaps in Urban NbS Assessment*****:** This work addresses the lack of integrated frameworks that combine physical flood modeling with NbS evaluation and social vulnerability mapping.

(b) ***Relevance for Policy and Urban Planning*****:** The proposed framework is designed to be practical, replicable, and scalable. It offers decision-support for local governments and urban planners in high-risk cities, contributing to more resilient and sustainable urban futures aligned with SDGs 11 (Sustainable Cities), 13 (Climate Action), and 6 (Clean Water and Sanitation).

RESEARCH QUESTIONS

The proposed framework seeks to address critical knowledge gaps at the intersection of urban flood risk, nature-based solutions (NbS), and sustainable urban development. To achieve this, the approach should be guided by the following key questions:

Primary Research Question: How can an integrated, context-sensitive framework be developed to assess urban flood risks and evaluate the effectiveness of nature-based mitigation strategies in rapidly expanding cities under conditions of climate variability and data scarcity?

Secondary Research Questions:

Flood Risk Assessment Dimension

What are the dominant physical, social, and institutional drivers of urban flood risk in rapidly growing cities?

How can hazard, exposure, vulnerability, and adaptive capacity be spatially quantified using a multi-criteria and GIS-based approach?

Nature-Based Solutions (NbS) Dimension

What types of NbS are most effective in mitigating urban flood risks in tropical, rapidly urbanizing contexts?

How do these NbS interventions perform under different land-use and climate scenarios, particularly extreme rainfall events?

Modeling and Framework Integration

How can hydrological, spatial, and socio-economic data be integrated into a coherent decision-support tool that accommodates both detailed and data-scarce environments?

What indicators can be used to monitor the long-term performance, co-benefits, and trade-offs of NbS implementation?

Sustainability and Policy Relevance

How does the proposed framework align with global sustainable development goals (e.g., SDGs 6, 11, 13)?

What policy mechanisms and institutional arrangements are needed to support the mainstreaming and upscaling of NbS in developing cities?

These questions will guide both the conceptual development and the empirical validation of the integrated framework. Collectively, they ensure the research is problem-driven, solutionoriented, and aligned with global calls for climate-resilient and sustainable urban transformation.

LINK WITH SUSTAINABLE DEVELOPMENT GOALS (SDGS)

This research directly contributes to several targets outlined in the United Nations 2030 Agenda for Sustainable Development, particularly in the context of building climate-resilient infrastructure, promoting sustainable urban development, and safeguarding water-related ecosystems. The project's integrated framework for flood risk assessment and nature-based mitigation is aligned with the following key SDGs:

SDG 11: Sustainable Cities and Communities

Target 11.5: *"By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses caused by disasters, including water-related disasters…"*

By enhancing the capacity of urban areas to assess and manage flood risks using nature-based interventions, the research directly supports disaster risk reduction and urban resilience planning.

Target 11.3: *"Enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management."*

The stakeholder-oriented framework promotes inclusive urban planning through participatory GIS and community-based risk assessment tools.

SDG 13: Climate Action

Target 13.1: *"Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries."*

The proposed framework enables cities to adapt to increasing flood hazards driven by climate change, particularly through the integration of nature-based solutions which enhance natural water retention and mitigate urban heat.

Target 13.3: *"Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction…"*

The research outputs, including decision-support tools and policy briefs, will strengthen institutional knowledge and capacity for climate adaptation planning.

SDG 6: Clean Water and Sanitation

Target 6.6: *"By 2020, protect and restore water-related ecosystems, including* *mountains, forests, wetlands, rivers, aquifers and lakes."*

NbS such as wetland restoration, vegetated swales, and permeable surfaces help rehabilitate degraded urban watersheds and enhance groundwater recharge, supporting this target.

Target 6.5: *"Implement integrated water resources management at all levels."*

The framework encourages integrated urban water and flood management through cross-sectoral planning approaches, bridging engineering, ecology, and governance.

SDG 15: Life on Land

Target 15.1 & 15.3: *Conserve ecosystems and combat land degradation.*

Urban NbS directly support biodiversity conservation, reduce soil erosion, and stabilize land that may otherwise be degraded due to rapid urbanization and runoff.

Cross-Cutting Contributions

Equity & Inclusion: By identifying flood-prone, vulnerable communities, the framework promotes equitable adaptation strategies and prioritizes resource allocation where most needed.

Innovation & Policy Impact: The research will generate open-access tools and evidence to influence local and national policies on urban flood resilience and land-use planning.

This alignment with the SDGs reinforces the global relevance of the research and ensures that its outcomes contribute to both scientific advancement and real-world sustainable development impacts.

OBJECTIVES

General Objective

In this work objectives have been made to help research community and practitioners developing an integrated framework for assessing urban flood risks and evaluating the effectiveness of nature-based mitigation strategies in rapidly expanding cities, with a focus on climate resilience, sustainable urban planning, and alignment with the Sustainable Development Goals (SDGs).

Specific Objectives

The objectives should be set to:

(1) identify and map flood-prone zones in rapidly urbanizing areas using geospatial tools and historical flood data;

(2) analyze land use change and urban expansion patterns that contribute to increased flood risk, using remote sensing and GIS-based spatial analysis;

(3) simulate stormwater runoff and flood scenarios under various rainfall and land use conditions using hydrological models such as SWMM or HEC-RAS

(4) evaluate the performance of selected Nature-Based Solutions (NBS)—such as bioswales, rain gardens, and permeable pavements—in mitigating flood impacts through scenario-based modeling;

(5) propose a decision-support framework that integrates environmental, hydrological, and socio-economic indicators for guiding sustainable flood management in developing urban contexts;

(6) assess the contribution of NBS-based urban flood mitigation to SDG 11 (Sustainable Cities), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action).

BRIEF LITERATURE REVIEW

Urban flood risk management has evolved significantly over the past century, transitioning from rigid engineering paradigms to adaptive, sustainable, and inclusive frameworks. This section synthesizes the development of key theories, technologies, and governance approaches that underpin contemporary strategies—especially those involving Nature-based Solutions (NbS). It provides a critical overview of the field's evolution and highlights current advancements in flood mitigation science, with particular attention to integrated, context-sensitive, and resilience-oriented approaches.

Evolution of Urban Flood Risk Management

Early Approaches: Grey Infrastructure Dominance

Historically, flood management strategies were grounded in structural solutions such as levees, culverts, and concrete channels designed to remove water rapidly from urban areas (Ashley et al., 2007; Brown and Clarke, 2007). These grey infrastructures provided short-term flood protection but frequently resulted in ecological degradation, increased downstream flooding, and long-term maintenance challenges (Butler and Davies, 2011; Fletcher et al., 2015).

Recognition of Limitations and the Shift to Resilience

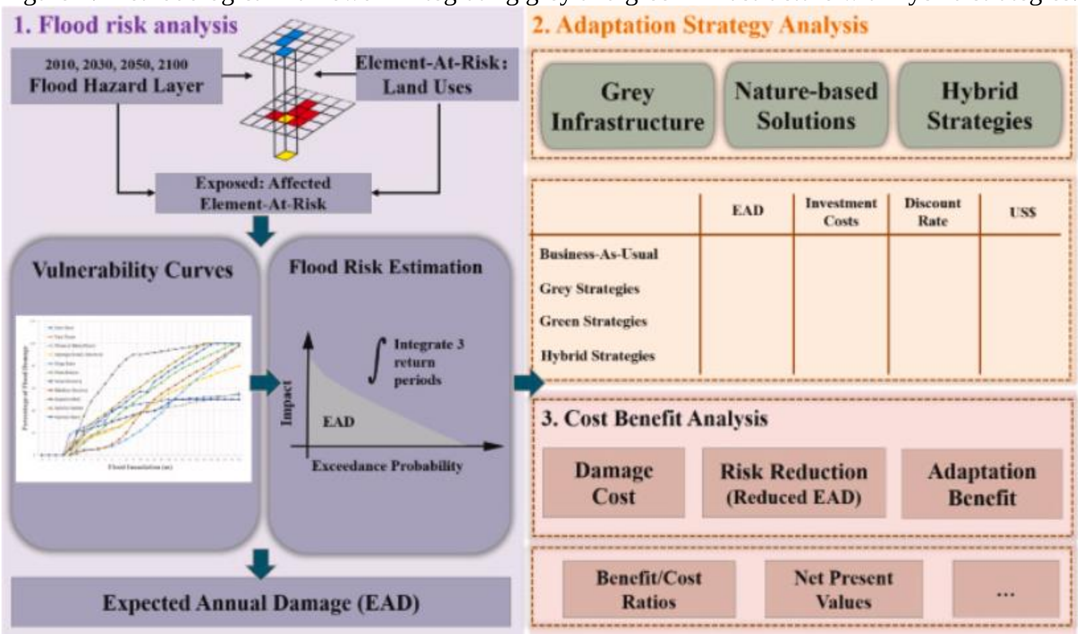
By the late 1990s and early 2000s, intensified rainfall, urban sprawl, and climate variability revealed the rigidity and unsustainability of grey systems (Sobhaninia et al., 2025; Chen et al., 2026). Scholars and planners began to adopt risk-based approaches that accounted for hazard exposure, social vulnerability, and adaptive capacity (Merz et al., 2007;-Rözer et al., 2022; Zhang et al., 2023). This shift laid the groundwork for resilience-oriented frameworks, where urban systems are designed to coexist with floods rather than resist them outright (Qin, 2020; Dong et al., 2024).

The Rise of Nature-Based Solutions (NbS)

NbS emerged in the 1990s as multifunctional alternatives or complements to traditional engineering (Díaz et al., 2019). Examples include rain gardens, bioswales, green roofs, constructed wetlands, and reforested catchments—designed to restore hydrological cycles, absorb stormwater, and deliver ecosystem co-benefits such as biodiversity enhancement, temperature regulation, and community recreation (Azadgar et al., 2025).

Recent literature confirms that NbS are effective in mitigating frequent, low-to-moderate intensity urban floods (Qin, 2020; Azadgar et al., 2025). However, during high-intensity or short-duration events, their effectiveness is diminished—leading to the emergence of hybrid strategies that combine NbS with engineered solutions (Shan et al., 2025).

Figure 4. Methodological framework integrating grey and green infrastructure with hybrid strategies.



Source: adapted from Shan et al. (2025)

Advances in Urban Flood Risk Assessment

Contemporary frameworks now integrate hydrological modeling (e.g., SWMM, HEC-RAS), spatial multi-criteria analysis (SMCA), GIS, and remote sensing tools to assess flood hazards, vulnerabilities, and exposure (Dong et al., 2024; Zhang et al., 2020). This enables fine-resolution risk mapping under different climate and land use scenarios. Notably, data-scarce contexts—especially in the Global South—are adopting open-source tools, satellite rainfall datasets, and participatory mapping to overcome information barriers (Merz et al., 2007; Mekhloufi et al., 2025). These frameworks increasingly embed socio-economic factors and community narratives, recognizing that technical precision must be matched by social relevance.

Social Equity, Citizen Science, and Community Engagement

There is growing recognition that flood impacts disproportionately affect marginalized communities, including residents of informal settlements and low-income neighborhoods (Winter and Karvonen, 2022; Juma et al., 2023). These populations often inhabit high-risk areas without access to protective infrastructure or early warning systems.

Recent studies have emphasized equity-driven adaptation and participatory governance (Rözer et al., 2022). Citizen science initiatives—including crowd-sourced flood reporting, community-based monitoring, and participatory GIS—enhance data collection and empower local stakeholders in decision-making (Gharesifard et al., 2019). These approaches not only bridge data gaps but also enhance the legitimacy and effectiveness of urban resilience strategies.

Remaining Limitations and Research Gaps

Despite progress, four major challenges persist:

(1) Performance Under Extreme Events: NbS are less effective during intense storms, and empirical evaluations of their performance under future climate conditions remain limited (Azadgar et al., 2025).

(2) Adaptation Gaps and Institutional Barriers: Many cities face logistical, technical, and policy obstacles that prevent effective NbS integration, especially in low-resource settings (Chappin et al., 2024; Martin et al., 2025).

(3) Monitoring and Data Limitations: The long-term hydrological, ecological, and socio-economic impacts of NbS are under-monitored, making it difficult to optimize or replicate interventions (Dong et al., 2024).

(4) Equity and Inclusion Challenges: The equitable distribution of NbS benefits, as well as sustained community engagement, remains an unresolved issue, especially in diverse and rapidly expanding urban environments (Rözer et al., 2022).

The literature on urban flood risk management reveals a clear evolution from traditional, hazard-centric approaches dominated by grey infrastructure to more integrated and adaptive strategies that emphasize resilience, sustainability, and inclusivity. NbS have emerged as viable alternatives or complements to conventional systems, offering hydrological, ecological, and social co-benefits. Advanced assessment frameworks now incorporate spatial modeling, stakeholder engagement, and multi-criteria decision-making to better reflect complex urban realities. However, challenges remain in mainstreaming NbS, particularly in the Global South, due to data limitations, institutional fragmentation, performance under extreme events, and barriers to equitable implementation. Addressing these gaps requires interdisciplinary innovation, community participation, and long-term investment in hybrid and context-sensitive solutions.

MATERIAL AND METHODS

Study Area

This work proposes a framework to cope with hydrological problems on a rapidly urbanizing metropolitan area that exemplifies common characteristics of urban flood vulnerability in developing regions—namely, high population growth, inadequate drainage infrastructure, and significant impervious surface expansion. While specific study areas will be finalized in consultation with local stakeholders and data availability, candidate sites include peri-urban zones in Sub-Saharan Africa, Latin America, and Asia where flooding is recurrent and spatial data is accessible. Site selection criteria will include:

Documented history of flood events

Availability of hydrological and meteorological data

Presence of unplanned settlements and high impervious surface ratios

Institutional openness to nature-based infrastructure pilot projects.

Description of Methods

The methodology is designed to integrate hydrological modeling, spatial analysis, and multi-criteria decision frameworks to identify, simulate, and assess NbS for flood mitigation.

Data Collection and Sources

Topographic and Land Use Data: Sourced from satellite imagery (e.g., Sentinel-2, Landsat 8) and OpenStreetMap. These will support land cover classification and imperviousness mapping.

Hydrological Data: Historical rainfall, streamflow, and evapotranspiration data will be obtained from national hydromet agencies or open datasets (e.g., CHIRPS, TRMM, ERA5).

Soil and Geological Data: Acquired from FAO Soil Maps or national geological surveys to parameterize infiltration and runoff processes.

Socio-economic and Infrastructure Data: Collected via field surveys, municipal databases, and census records to understand vulnerability and exposure.

Flood Incident Records: Sourced from disaster management agencies, NGOs, and crowd-sourced platforms (e.g., FLOODLIST, local news archives).

Hydrological Modeling

A physically-based, distributed hydrological model (e.g., **SWMM**, **HEC-HMS**) should be calibrated to simulate stormwater behavior across the urban watershed.

Model inputs should be include rainfall intensity-duration-frequency (IDF) curves, catchment delineation, infiltration rates, and runoff coefficients (land use cover).

Model calibration and verification should be conducted using observed flood events, optimizing model performance metrics such as Nash–Sutcliffe efficiency (NSE) and root mean square error (RMSE).

Scenario Development

Three urban flood risk scenarios should be developed:

Baseline Scenario: Simulates current land-use and stormwater infrastructure under historical rainfall conditions.

Climate Change Scenario: Models future rainfall intensities using downscaled RCP 4.5 and 8.5 climate projections.

Nature-Based Mitigation Scenario: Simulates the integration of NbS interventions (e.g., green roofs, bioswales, retention ponds, urban jungle).

Spatial Multi-Criteria Analysis (SMCA)

To prioritize NbS placement, SMCA should be employed by integrating layers such as: Flood susceptibility; Population density; Land availability; Ecosystem sensitivity; and Cost-effectiveness.

Weights for each criterion should be determined using the **Analytic Hierarchy Process (AHP)** in consultation with local planners, engineers, and community stakeholders.

Stakeholder Engagement and Validation

Participatory workshops should be conducted with municipal authorities, NGOs, and residents to: validate model results; co-design NbS interventions; Identify implementation barriers and enablers.

This participatory approach ensures contextual relevance, enhances social acceptance, and builds local ownership of interventions.

Evaluation of NbS Effectiveness

The modeled performance of NbS should be evaluated using both technical and co-benefit indicators as synthesized in table 2.

Table 2. Indicators to assess model performance.

Dimension	Indicator
Hydrological	Peak runoff reduction, time to peak, inundation depth
Environmental	Green cover increase, biodiversity potential
Socio-economic	Property risk reduction, beneficiary population size
Climate Resilience	Impact under Representative Concentration Pathways (RCP) scenarios

Source: Authors

Tools and Software Available

- GIS & Remote Sensing: QGIS, ArcGIS Pro, Google Earth Engine
- Hydrological Modeling: EPA-SWMM, HEC-HMS, HEC-RAS
- Statistical Analysis: R, SPSS
- Decision Analysis: AHP software, MATLAB, or Python.

FINAL REMARKS

The framework proposed in this work is expected to produce a combination of technical, scientific, and societal outcomes that contribute meaningfully to the sustainable management of urban flood risk. The anticipated results are categorized as described below.

Technical Results

High-Resolution Urban Flood Risk Maps

Spatially explicit maps indicating areas of high flood exposure, vulnerability, and infrastructure deficits will be generated using GIS and hydrological modeling tools. These maps will help municipal planners prioritize intervention zones.

Calibrated Urban Flood Models

A validated hydrological model (e.g., SWMM, MIKE URBAN) tailored to the selected case study will be developed. This model will simulate the behavior of stormwater under various rainfall and land-use scenarios, enabling predictive analysis.

Scenario-Based Flood Mitigation Plans

Three urban flood management scenarios will be evaluated—baseline (no intervention), climate change (increased rainfall intensity), and NbS-enhanced infrastructure. Quantitative comparisons will demonstrate the cost-effectiveness and performance of NbS versus traditional approaches.

Optimized NbS Deployment Strategy

Using multi-criteria decision analysis, the project will deliver a prioritized framework for NbS implementation. This includes location suitability maps, typology of interventions (e.g., bioswales, retention ponds), and cost-benefit estimates.

Monitoring and Evaluation Indicators

A performance indicator framework will be developed to track hydrological, ecological, and socio-economic impacts of NbS interventions over time—paving the way for long-term monitoring and adaptive management.

Scientific and Academic Contributions

Open-Access Datasets and Model Code

Hydrological input data, land-use classifications, and model code should be made openly available via platforms like GitHub or institutional repositories, encouraging transparency and reproducibility.

Policy Briefs and Technical Reports

Simplified outputs targeting local governments and urban planning departments will be developed, including policy briefs and reports on NbS viability, benefits, and challenges specific to rapidly urbanizing regions.

Societal and Sustainability Impacts

Increased Institutional Capacity.

Local stakeholders (e.g., municipal engineers, urban planners) will be trained in flood modeling and NbS planning through participatory workshops—promoting knowledge transfer and technical capacity-building.

Enhanced Urban Resilience.

The research will support municipal adaptation strategies to climate-induced urban flooding, contributing to reduced flood losses, improved public safety, and enhanced quality of life in vulnerable communities.

Alignment with Sustainable Development Goals (SDGs).

The project supports the achievement of several SDGs, particularly:

- SDG 6: Clean Water and Sanitation
- SDG 11: Sustainable Cities and Communities
- SDG 13: Climate Action
- SDG 15: Life on Land.

The application of the integrated procedure proposed hereby will contribute to enhance Risk Management Strategies via measures that lead to (i) Resilience enhancement, and (ii) Risk reducing.

ACKNOWLEDGEMENT

The authors gratefully acknowledge financial support from PRPPG-UNILA, and CAPES.

REFERENCES

ALMEIDA, M.C., TELHADO, M.J., MORAIS, M., BARREIRO, J., LOPES, R. Urban resilience to flooding: Triangulation of methods for hazard identification in urban areas. **Sustainability**, 12(6), 2227, 2020. https://doi.org/10.3390/su12062227

ASHLEY, R., BALMFORTH, D., SAUL, A. AND BLANSKBY, J. Flooding in the future–predicting climate change, risks and responses in urban areas. **Water Science and Technology**, 52(5), pp.265–273, 2007. https://doi.org/10.2166/wst.2005.0142

AZADGAR, A., RAHIMI, S., KHAN, A. AND YU, D. Optimizing nature-based solutions for urban flood risk mitigation. **Science of the Total Environment**, 963, 178303, 2025. https://doi.org/10.1016/j.scitotenv.2024.178303

BROWN, R.R., CLARKE, J.M. **The transition towards Water Sensitive Urban Design**: The story of Melbourne. Report No. 07/01, Facility for Advancing Water Biofiltration, Monash University, 2007.

Butler, D., Davies, J.W. **Urban Drainage**. 3rd ed. London: Spon Press, 2011.

CHAN, F.K.S., GRIFFITHS, J.A., HIGGITT, D., XU, S., ZHU, F., TANG, Y-T., XU, Y., THORNE, C.R. “Sponge City” in China—A breakthrough of planning and flood risk management in the urban context. **Land Use Policy**, 243, p.772–778, 2021. https://doi.org/10.1016/j.landusepol.2018.03.005

CHAPPIN, M.M.H. How can networks address barriers to nature-based solutions? The case of agriculture and construction in the Netherlands. **Landscape and Urban Planning**, 251, 105147, 2024. https://doi.org/10.1016/j.landurbplan.2024.105147

CHAVULA, P., KAYUSI, F., LUNGU, G., UWIMBABAZI, A. The current landscape of early warning systems and traditional approaches to disaster detection. **LatIA**, 3(77), p. 3-21, 2025. https://doi.org/10.62486/latia202577

CHEN, W. et al. Scalable impact of urban green infrastructure on urban climate: A critical review. **Renewable and Sustainable Energy Reviews**, 226, 116259, 2026. https://doi.org/10.1016/j.rser.2025.116259

CHISSENDE, A., MEHMOOD, M.S., HUO, A., LOU, P., WANG, Z. Riverine flood susceptibility assessment using drainage basin morphometry in the Bahe River. **International Journal of Disaster Risk Reduction**, 117, 105181, 2025. https://doi.org/10.1016/j.ijdrr.2025.105181

CHIKHI, F., LI, C., JI, Q., ZHOU, X. Review of Sponge City implementation in China: performance and policy. **Water Science & Technology**, 88(10), 2499–2520, 2023. https://doi.org/10.2166/wst.2023.312

DAVIES, R. Floods in Nigeria, June to September 2022. Copernicus. *Available at:* <https://global-flood.emergency.copernicus.eu/news/110-floods-in-nigeria-june-to-september-2022/>. Accessed on: 15 August 2025

DÍAZ, S., SETTELE, J., BRONDÍZIO, E.S., NGO, H.T., AGARD, J., ARNETH, A., et al. **Summary for policymakers of the global assessment report on biodiversity and ecosystem services**. Bonn: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Secretariat, 2019. *Available at:* <https://zenodo.org/records/3553579>. Accessed on: 20 August 2025

DONG, B., HUANG, B., TAN, C. Comprehensive urban flood risk assessment using 1D/2D coupled hydrodinamic model. **Proceedings of the 24th IAHR-APD Congress**, 14-17 October 2024, Wuhan, China, 2024. *Available at:* <https://www.iahr.org/library/infor?pid=31331>. Accessed on: 13 August 2025

ECOWAS Commission. **Disaster Risk Reduction Policy for West Africa**. Abuja: Economic Community of West African States, 2020.

FARIA, N.M.X., SKAMVETSAKIS, A. Extreme weather events in Rio Grande do Sul and their impacts on Workers' Health. **Revista Brasileira de Saúde Ocupacional**, 50, p. 1-14, 2025. https://doi.org/10.1590/2317-6369/18024en2025v50eddsst8

FENG, W. et al. Synergizing Flood Mitigation and Water Quality Goals through Green Infrastructure in Dali City, China. **International Journal of Disaster Risk Reduction**, 2025 https://doi.org/10.1016/j.ijdrr.2025.105785

FLETCHER, T.D., ANDRIEU, H., HAMEL, P. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. **Advances in Water Resources**, 51, p. 261–279, 2013. https://doi.org/10.1016/j.advwatres.2012.09.001

FORRESTER, J., COOK, B., BRACKEN, L., CINDERBY, S., DONALDSON, A. Combining participatory mapping with Q-methodology to map stakeholder perceptions of complex environmental problems. **Applied Geography**, 56, p. 199-208, 2015. https://doi.org/10.1016/j.apgeog.2014.11.019

FU, X. et al. A coupled PSR-based framework for holistic modeling and flood resilience assessment: A case study of the 2022 flood events in five southern provinces of China. **Journal of Hydrology**, 636, 131255, 2024. https://doi.org/10.1016/j.jhydrol.2024.131255

GHANA NEWS AGENCY. About 270 dead and thousands displaced by floods in the horn of Africa, 2023. Available at: <https://www.newsghana.com.gh/about-270-dead-and-thousands-displaced-by-floods-in-the-horn-of-africa/>. Accessed on: 23 August 2025

GHARESIFARD, M., WEHN, U., VAN DER ZAAG, P. Context matters: A baseline analysis of contextual realities for two community-based monitoring initiatives of water and environment in Europe and Africa. **Journal of Hydrology**, 579, 124144, 2019.

https://doi.org/10.1016/j.jhydrol.2019.124144

GNECCO, I. et al. Participatory mapping for enhancing flood risk resilient and sustainable urban drainage: A collaborative approach for the Genoa case study. **Sustainability**, 16(5), 1936, 2024. https://doi.org/10.3390/su16051936

GU, X.H., ZHANG, Q., LI, J.F., CHEN, D.L., SINGH, V.P. et al. Impacts *of anthropogenic warming and uneven regional socio-economic development on global river flood risk.* ***Journal of Hydrology****, 590, 125262 , 2020. https://doi.org/10.1016/j.jhydrol.2020.125262*

HOBBIE, S.E., GRIMM, N.B. Nature-based approaches to managing climate change impacts in cities. ***Philosophical Transactions of the Royal Society B****, 375, 20190124, 2020. https://doi.org/10.1098/rstb.2019.0124*

HODGKINS, G.A., DUDLEY, R.W., ARCHFIELD, S.A., RENARD, B. Effects of climate, regulation, and urbanization on historical flood trends in the United States. ***Journal of Hydrology****, 573, p. 697-709, 2019.* https://doi.org/*10.1016/j.jhydrol.2019.03.102*

ILO, 2024. **Brazil floods: Hundreds of Rio Grande do Sul towns submerged**. International Labour Organization. https://www.ilo.org/resource/article/ilos-emergency-response-rio-grande-do-sul-floods

IPCC. Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, 2023. Available at: <https://doi.org/10.59327/IPCC/AR6-9789291691647.001>. Accessed on: 13 August 2025

JUMA, B. et al. Flooding in the urban fringes: Analysis of flood inundation and hazard levels within the informal settlement of Kibera in Nairobi, Kenya. ***Physics and Chemistry of the Earth, Parts A/B/C****, 132, 103499, 2023. https://doi.org/10.1016/j.pce.2023.103499*

LI, S., LEITÃO, J.P., WANG, Z., BACH, P.M. A drainage network-based impact matrix to support targeted blue-green-grey stormwater management solutions. **Science of The Total Environment**, 912, 168623, 2024. https://doi.org/10.1016/j.scitotenv.2023.168623

LIU, Y., JIANG, Y., DENG, Y. A framework for urban flood resilience assessment: Integrating multidimensional indicators and dynamic adaptation strategies. **Journal of Environmental Management,** 392, 126841, 2025. https://doi.org/10.1016/j.jenvman.2025.126841

MALIVA, R.G. **Anthropogenic aquifer recharge**: WSP methods in water resources evaluation. Series no. 5. Springer, Cham, 2019.

MARTIN, J.G.C. et al. The nature-based solution implementation gap: A review of nature-based solution governance barriers and enablers. **Journal of Environmental Management**, 388, 126007, 2025. https://doi.org/10.1016/j.jenvman.2025.126007

MARTINS, M.H.M., LIMA-SILVA, F., CRUZ, C., CUNHA, M.A.V. Risk communication in flood-prone communities: memories, informal practices and public action in Brazil. **Interface (Botucatu)**, 29, p. 1-19, 2025. https://doi.org/10.1590/interface.230660

MATA-LIMA, H., ALVINO-BORBA, A., AGUIAR, R., DRUMOND, J. Factors Affecting Flood Disasters in Small Island Developing States and Potential Adaptation Measures: The Case of Funchal City, Portugal. **Environmental Quality Management**, 25(3), p. 37-51, 2016. https://doi.org/10.1002/tqem.21458

MEKHLOUFI, N., AQUILINO, M., BAZIZ, A., RICHIARDI, C., ADAMO, M. Free satellite data and open-source tools for urban green spaces and temperature pattern analysis in Algiers. **International Journal of Applied Earth Observation and Geoinformation**, 139, 104482, 2025. https://doi.org/10.1016/j.jag.2025.104482

MERZ, B., THIEKEN, A.H. AND GOCHT, M. Flood risk mapping at the local scale: Concepts and challenges. S. Begum et al. (eds.), **Flood Risk Management in Europe**, 231–251, Springer, 2007.

MERZ, B., HALL, J., DISSE, M., SCHUMANN, A. Flood risk ~~analysis~~ management in a changing world. **Natural Hazards and Earth System Sciences**, 10(3), p. 509–527, 2010.

MGUNI, P., HERSLUND, L., JENSEN, M.B. Sustainable urban drainage systems: examining the potential for green infrastructure-based stormwater management for Sub-Saharan cities. **Natural Hazards**, 82, p. 241–257, 2016. https://doi.org/10.1007/s11069-016-2309-x

MINUCCI, G., MOLINARI, D., GEMINI, G., PEZZOLI, S. Enhancing flood risk maps by a participatory and collaborative design process. **International Journal of Disaster Risk Reduction**, 50, 101747, 2020. https://doi.org/10.1016/j.ijdrr.2020.101747

MOOSAVI, S., BROWNE, G., BUSH, J. Perceptions of nature-based solutions for Urban Water challenges: Insights from Australian researchers and practitioners. **Urban Forestry & Urban Greening**, 57(1), 126937, 2021. https://doi.org/10.1016/j.ufug.2020.126937

PRASHAR, N., LAKRA, H.S., SHAW, R., KAUR, H. Urban flood resilience: A comprehensive review of assessment methods, tools, and techniques to manage disaster. **Progress in Disaster Science**, 20, 100299, 2023. https://doi.org/10.1016/j.pdisas.2023.100299

PRADO, H.A. et al. Designing nature to be a solution for climate change in cities: A meta-analysis. **Science of The Total Environment**, 954, 176735, 2024. https://doi.org/10.1016/j.scitotenv.2024.176735

QIN, Y., 2020. Urban flooding mitigation techniques: A systematic review. **Water**, *12*(12), 3579, 2020. https://doi.org/10.3390/w12123579

RENTSCHLER, J., SALHAB, M., JAFINO, B. A. Flood exposure and poverty in 188 countries. **Nature Communications**, 13, Article No. 3527, 2022. https://doi.org/10.1038/s41467-022-30727-4

REUTERS. Floods in Brazil's south leave over 150,000 homeless, scores dead or missing, 2024. *Available at:* <https://www.reuters.com/business/environment/brazil-floods-leave-150000-homeless-scores-dead-or-missing-2024-05-07/>. Accessed on: 24 August 2025

ROJAS-LESMES, D. et al. National Water Level Forecast (NWLF): An open-source customizable web application for the GEOGLOWS ECMWF global hydrological model. **Information Geography**, 1, 100008, 2025. https://doi.org/10.1016/j.infgeo.2025.100008

RÖZER, V., MEHRYAR, S., SURMINSKI, S. From managing risk to increasing resilience: a review on the development of urban flood resilience, its assessment and the implications for decision making. **Environmental Research Letters**, 17(12), 123006, 2022. https://doi.org/10.1088/1748-9326/aca8bc

SAVE THE CHILDREN. **Number of people affected by floods worldwide from 1990 to 2023**., 2023. *Available at:* <https://www.savethechildren.net/news/2023-review-climate-disasters-claimed-12000-lives-globally-2023>. Accessed on: 09 August 2025

SAVE THE CHILDREN. **West Africa Floods**: More Than 950,000 People Displaced, and Children Sheltering in Schools Weeks Before School Term Starts, 2024. *Available at:* <https://www.savethechildren.org/us/about-us/media-and-news/2024-press-releases/west-africa-floods-people-displaced-and-children-sheltering-in-schools>. Accessed on: 11 August 2025

SAYERS, P., YUANYUAN, L., GALLOWAY, G., PENNING-ROWSELL, E., FUXIN, S., KANG, W., LE QUESNE, L. **Flood risk management**: a strategic approach. Asian Development Bank, GIWP, UNESCO and WWF-UK. May 2013. *Available at:* <https://www.adb.org/publications/flood-risk-management-strategic-approach>. Accessed on: 07 August 2025

SHAN, X. et al. Integrating nature-based solutions for compound flood risk mitigation in China: A case study of Shanghai. **Journal of Environmental Management**, 380, 125155, 2025. https://doi.org/10.1016/j.jenvman.2025.125155

SOBHANINIA, S. et al. Where should the green go? A systematic literature review of methods for siting green infrastructure to mitigate rising heat and stormwater risks in cities worldwide. **Urban Forestry & Urban Greening**, 107, 128790, 2025. https://doi.org/10.1016/j.ufug.2025.128790

STATISTA. **Annual number of flood fatalities and affected persons globally from 1990 to 2023**, 2025. *Available at:* <https://www.statista.com/statistics/1293353/global-number-of-people-affected-by-floods/>. Accessed on: 07 July 2025

UNFCCC. **Opportunities and options for integrating climate change adaptation with the Sustainable Development Goals and the Sendai Framework for Disaster Risk Reduction 2015–2030**. Bonn: United Nations Climate Change Secretariat, 2017. *Available at:* <https://unfccc.int/sites/default/files/resource/techpaper_adaptation.pdf>. Accessed on: 26 August 2025

WANG, L. et al. A review of the flood management: from flood control to flood resilience. **Helyon**, 8(11), e11763, 2022. https://doi.org/10.1016/j.heliyon.2022.e11763

WINTER, A.K., KARVONEN, A. Climate governance at the fringes: Peri-urban flooding drivers and responses. **Land Use Policy**,117, 106124, 2022.

https://doi.org/10.1016/j.landusepol.2022.106124

WORLD BANK. **Assessment of the state of hydrological services in developing countries**. Washington: International Bank for Reconstruction and Development/The World Bank, 2018. *Available at:* <https://www.gfdrr.org/sites/default/files/publication/state-of-hydrological-services_web.pdf>. Accessed on: 02 August 2025

ZAREI, M., SHAHAB, S. Nature-Based Solutions in Urban Green Infrastructure: A Systematic Review of Success Factors and Implementation Challenges. **Land**, 14(4), 818, 2025. https://doi.org/10.3390/land14040818

ZHANG, W. et al. Urban Flood Risk Assessment through the Integration of Natural and Human Resilience Based on Machine Learning Models. **Remote Sensing**. 15(14), 3678, 2023. https://doi.org/10.3390/rs15143678