INTEGRATING HYDROLOGICAL MODELLING AND NATURE-BASED SOLUTIONS FOR SUSTAINABLE FLOOD MAPPING: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Objective: This study systematically reviews recent global research on the integration of hydrological modelling and nature-based solutions for sustainable flood mapping. It explores how models such as the Personal Computer Storm Water Management Model (PCSWMM) are used to simulate stormwater behavior under climate change conditions and how nature-based interventions enhance resilience, sustainability, and ecological restoration in urban areas vulnerable to flooding.

Research Method: A systematic literature review was conducted following PRISMA 2020 guidelines, focusing on peer-reviewed studies published between 2017 and 2025 obtained from Scopus and Google Scholar databases. After screening 1,037 records and applying the CASP quality appraisal, 21 eligible studies were analyzed through thematic synthesis to identify major trends, modelling approaches, and ecological strategies.

Findings: The findings indicate that integrating hydrological models with nature-based solutions provides a robust and adaptive framework for sustainable flood management. PCSWMM emerged as the most widely used model because of its flexibility, GIS integration, and high predictive reliability in simulating surface runoff and drainage efficiency. Studies show that coupling hydrological models with green infrastructures such as bioretention cells, permeable pavements, green roofs, and blue roofs significantly reduces flood volume, improves infiltration, and enhances water quality. Hybrid blue-green infrastructures were found to offset up to 167 percent of projected flood volume increases under climate change scenarios demonstrating substantial mitigation potential along with ecological co-benefits. Overall, this review contributes a comprehensive eco-hydrological framework that aligns engineering precision with ecological functionality, supporting global goals for climate resilience and sustainable flood adaptation.

Keywords: Flood, Mapping, Climate Change, PCSWMM, Nature-Based Solutions

1. INTRODUCTION

Flooding has become one of the most critical environmental challenges of the twenty-first century, posing severe threats to cities and human livelihoods. The growing frequency and intensity of floods are closely linked to climate change, urban expansion, and land-use alteration, which together accelerate the replacement of natural landscapes with impervious surfaces (Leopold, 1968; Lee and Heaney, 2003; Akter et al., 2018). When rainfall cannot infiltrate the ground, stormwater accumulates rapidly, overwhelming drainage systems and causing urban pluvial floods. These disasters not only destroy infrastructure and disrupt economies but also damage ecosystems and social stability. As the impact of climate variability intensifies, sustainable flood management has become a vital component of climate adaptation and urban resilience planning.

Traditional urban drainage systems rely on structural networks such as gutters, pipes, and tunnels to quickly discharge runoff into nearby waterways (Sohn et al., 2019; Tansar et al., 2022). However, these systems were originally designed based on stationary climate assumptions, using rainfall data from the past and without considering long-term variability (Arisz and Burrell, 2006). As urbanization increases impervious surface coverage, these outdated systems struggle to manage the growing volume and intensity of runoff, making cities more vulnerable to extreme precipitation (Pour et al., 2020; Yang et al., 2020). In addition, climate change has already intensified the frequency and magnitude of rainfall events (Martel et al., 2020; IPCC, 2021; Fowler et al., 2021). Consequently, the existing capacity of urban drainage infrastructure is proving inadequate, leading to more frequent and damaging flood events (Mailhot and Duchesne, 2010; Mamo, 2015; Martel et al., 2021).

In response to these challenges, many cities have begun adopting more flexible and sustainable approaches to stormwater management. Expanding the capacity of traditional drainage systems is often costly, impractical, and environmentally unsustainable, especially in densely developed areas (Qin et al., 2013; Dong et al., 2017). This has led to the growing adoption of Blue and Green Infrastructure (BGI), a climate-adaptive concept that combines engineered and ecological systems to manage water more naturally (Liu et al., 2019; Almaaitah et al., 2021). BGI integrates vegetated and non-vegetated elements that mimic natural hydrological cycles by promoting infiltration, evapotranspiration, and detention (Fletcher et al., 2015; Versini et al., 2018; USEPA, 2019). Beyond flood control, BGI also improves air quality, mitigates urban heat islands, and supports biodiversity, making it an essential tool for sustainable and resilient urban design (Liu et al., 2019).

Numerous studies have explored the hydrological and environmental benefits of BGI using modeling approaches. Zahmatkesh et al. (2015) examined the effectiveness of rainwater harvesting, bioretention cells, and permeable pavements and reported that combined implementation could reduce annual runoff by 41 percent across climate change scenarios. Ahiablame and Shakya (2016) evaluated rain gardens, barrels, and permeable pavements in continuous 25-year simulations and found runoff and flood events reduced by up to 47 percent. Similarly, Ghodsi et al. (2020) determined that a combination of bioretention cells, vegetative swales, infiltration trenches, and permeable pavements could decrease runoff volume by 14 percent while minimizing cost. Samouei and Özger (2020) found that large-scale application of green roofs, permeable pavements, and bioretention systems reduced peak runoff by up to 24.7 percent and total runoff by 17 percent. These studies collectively highlight the efficiency of BGI practices in mitigating stormwater impacts across varying climatic and urban contexts.

Despite these advances, current research on sustainable flood mapping remains fragmented. Most hydrological modeling studies emphasize simulation and prediction but often exclude ecological variables that influence natural water retention, while ecological studies rarely employ quantitative models to assess hydraulic performance (Suleiman, 2021). This gap limits a full understanding of the capacity of BGI to adapt existing urban drainage systems to future climate conditions. A crucial question remains unanswered: to what extent can large-scale implementation of BGI counteract the impacts of projected increases in rainfall intensity? Benoit et al. (2025) addressed this issue by applying a calibrated Personal Computer Storm Water Management Model (PCSWMM) to assess how different BGI configurations could adapt an existing drainage system in Montreal to extreme rainfall conditions.

The novelty of the present study lies in its integration of high-resolution hydrological modeling with multiple BGI designs under climate-adjusted rainfall scenarios. Unlike earlier studies that focused on isolated interventions, this research evaluates the combined effect of bioretention cells, permeable pavements, green roofs, and blue roofs using a PCSWMM model of an actual drainage network. The analysis shows how these combined infrastructures can offset flood volume increases by up to 167 percent under climate change conditions, demonstrating that hybrid systems can not only mitigate but also improve the hydraulic performance of existing urban drainage infrastructure. This approach establishes a foundation for assessing both the technical and ecological efficiency of large-scale BGI implementation.

The significance of this review is twofold. First, it strengthens scientific understanding of how hydrological modeling tools can be harmonized with Nature-based Solutions (NbS) to design sustainable flood mapping systems. Second, it highlights how integrating PCSWMM simulations with NbS can improve resilience planning and guide the development of climate-adaptive policies. Accordingly, the study aims to analyze global trends in sustainable flood mapping that integrate hydrological models and BGI and to evaluate the role of PCSWMM in optimizing BGI designs within climate adaptation frameworks.

The structure of this paper follows a systematic and coherent flow. The introduction establishes the rationale and context of the study, followed by the methodology that outlines model selection, calibration, and simulation parameters. The results present quantitative findings on the hydraulic performance of various BGI implementations. The discussion interprets these findings in relation to climate uncertainty, cost-effectiveness, and system adaptability. The final section offers policy implications and recommendations for future research directions.

This study highlights that the integration of hydrological modeling and Nature-based Solutions provides a transformative path toward sustainable flood management. By combining technological precision with ecological resilience, this study offers a practical framework for rethinking urban stormwater design in the era of climate change. The findings reinforce the notion that adaptive BGI systems can serve not only as flood mitigation strategies but also as catalysts for building sustainable, resilient, and environmentally balanced cities for future generations.

2. METHODOLOGY

2.1 RESEARCH DESIGN

This study follows a Systematic Literature Review (SLR) design based on the PRISMA 2020 guidelines. The review identifies, evaluates, and synthesizes peer-reviewed studies published from 2017 to 2025 to capture the most recent developments in sustainable flood mapping and climate adaptation.

2.2 DATA SOURCES AND SEARCH STRATEGY

Articles were retrieved from Scopus and Google Scholar databases using the following keywords and Boolean combinations:

"flood mapping" OR "hydrological modelling" AND "PCSWMM" OR "stormwater management" AND "nature-based solutions" OR "green infrastructure" AND "climate change" OR "sustainability."

2.3 INCLUSION AND EXCLUSION CRITERIA

To ensure the selection of high-quality and relevant studies, a clear set of inclusion and exclusion criteria was established. These criteria guided the screening and filtering process during the systematic literature review to maintain methodological rigor and thematic consistency. The inclusion criteria focused on studies related to flood mapping, hydrological modelling, and nature-based solutions that addressed sustainability or climate change within the 2017–2025 publication period. Conversely, studies that did not meet scientific standards, such as non-peer-reviewed materials, purely structural engineering research, or papers without a clear methodological framework, were excluded. The detailed criteria applied in this review are summarized in Table 1.

Table 1: Inclusion and Exclusion Criteria for the Selection of Studies in the Systematic Literature Review

Inclusion Criteria	Exclusion Criteria
Studies related to flood mapping, hydrological modelling, or NbS	Non-peer-reviewed materials such as news and blogs
Research that includes sustainability or climate change	Studies limited to structural engineering only
Publications in English, between 2017 –2025	Papers without a clear methodology or results

2.4 SCREENING AND QUALITY APPRAISAL

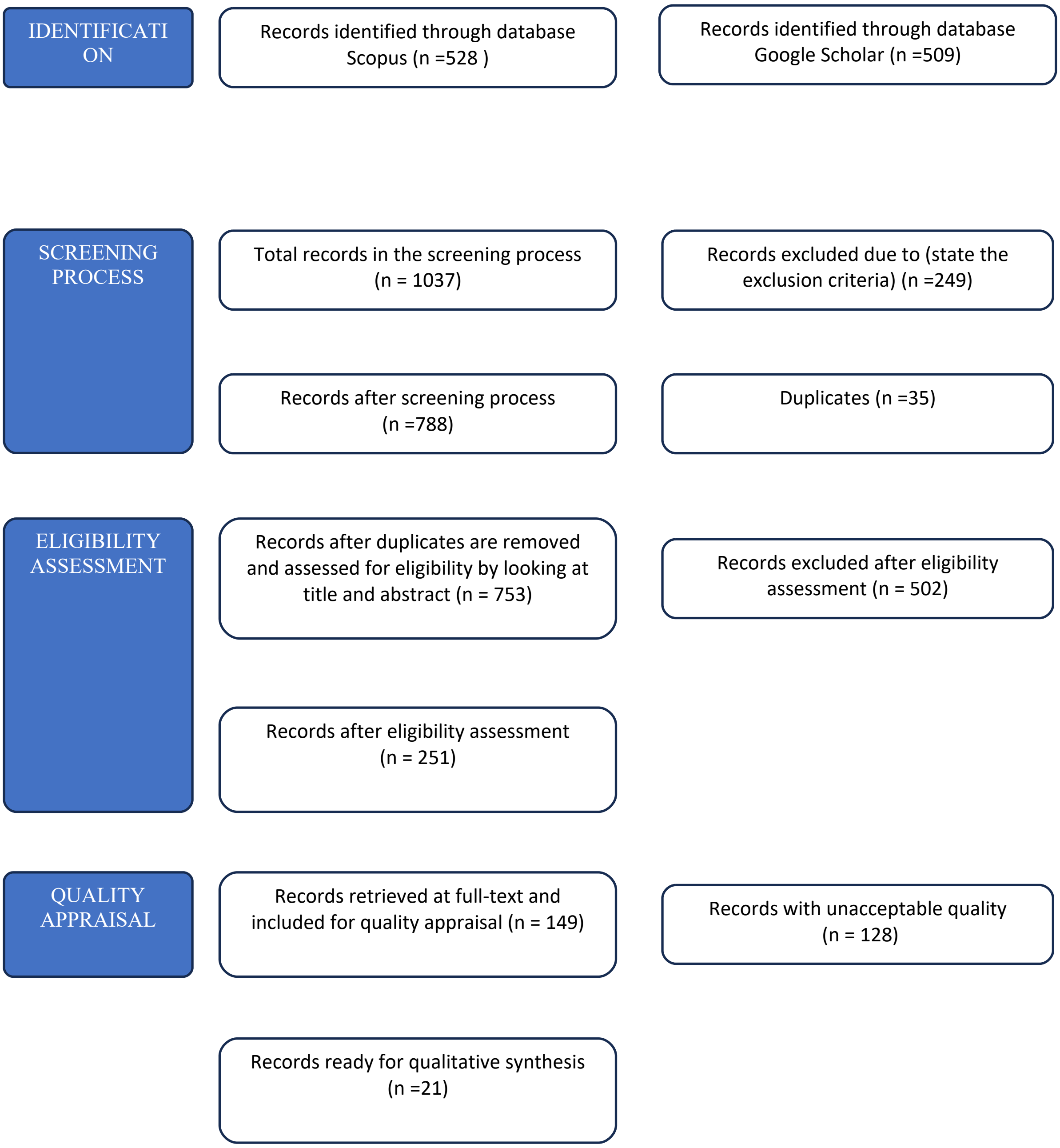

Figure 1: The Flow Diagram from Identification Process to Quality Appraisal

An initial search identified 1,037 studies. After removing duplicates, 149 articles were reviewed in full text. The Critical Appraisal Skills Programme (CASP) checklist was used to evaluate methodological clarity, data reliability, and validity. Only 21 studies met the minimum quality score of seven and were included in the synthesis.

2.5 DATA EXTRACTION AND ANALYSIS

Key data including author, year, study region, model used, NbS type, and main findings were extracted. Studies were coded into two thematic categories aligned with the research questions:

- Applications and effectiveness of hydrological models in flood mapping
- Integration of nature-based solutions into hydrological frameworks

The data were analyzed through a thematic synthesis approach to identify key patterns, gaps, and trends.

3. RESULTS

This section presents findings from the systematic literature review that are structured around two main themes: the application of hydrological modelling for sustainable flood mapping and the integration of Nature-based Solutions (NbS) into these models. The analysis is based on 21 selected journal articles published between 2017 and 2025, which provide empirical insights into various modelling techniques, drainage designs, and ecological interventions for urban flood management. These studies collectively explore how tools such as PCSWMM, SWMM, and GIS-based models have been used to simulate flood scenarios, assess drainage performance, and evaluate the effectiveness of NbS in enhancing climate resilience and sustainability.

Table 2: Summary of Reviewed Articles on Hydrological Modelling and Nature-Based Solutions for Sustainable Flood Management

No.	Author(s)	Article Title	Journal Title	Year
1	Thomas Benoit, Jean-Luc Martel, Émilie Bilodeau, François Brissette, Alain Charron, Dominic Brulé, Gilles Rivard, Simon Deslauriers	Limits of Blue and Green Infrastructures to Adapt Actual Urban Drainage Systems to the Impact of Climate Change	*Journal of Irrigation and Drainage Engineering*	2025
2	Barsha Neupane, Tue M. Vu, Ashok K. Mishra	Evaluation of Land-Use, Climate Change, and Low-Impact Development Practices on Urban Flooding	*Hydrological Sciences Journal*	2021
3	Olbert A.I., Comer J., Nash S., Hartnett M.	High-Resolution Multi-Scale Modelling of Coastal Flooding Due to Tides, Storm Surges and Rivers Inflows: A Cork City Example	*Coastal Engineering*	2017
4	Xu H., Zhang X., Guan X., Wang T., Ma C., Yan D.	Amplification of Flood Risks by the Compound Effects of Precipitation and Storm Tides under the Nonstationary Scenario in the Coastal City of Haikou, China	*International Journal of Disaster Risk Science*	2022
5	Wu Z., Zhou Y., Wang H., Jiang Z.	Depth Prediction of Urban Flood under Different Rainfall Return	*Science of the Total Environment*	2020

No.	Author(s)	Article Title	Journal Title	Year
		Periods Based on Deep Learning and Data Warehouse		
6	Bermúdez M., Ntegeka V., Wolfs V., Willems P.	Development and Comparison of Two Fast Surrogate Models for Urban Pluvial Flood Simulations	*Water Resources Management*	2018
7	Kabir S., Patidar S., Xia X., Liang Q., Neal J., Pender G.	A Deep Convolutional Neural Network Model for Rapid Prediction of Fluvial Flood Inundation	*Journal of Hydrology*	2020
8	Dai W., Cai Z.	Predicting Coastal Urban Floods Using Artificial Neural Network: The Case Study of Macau, China	*Applied Water Science*	2021
9	Fang J., Liu W., Yang S., Brown S., Nicholls R.J., Hinkel J., Shi X., Shi P.	Spatial-Temporal Changes of Coastal and Marine Disaster Risks and Impacts in Mainland China	*Ocean and Coastal Management*	2017
10	Xu H., Xu K., Lian J., Ma C.	Compound Effects of Rainfall and Storm Tides on Coastal Flooding Risk	*Stochastic Environmental Research and Risk Assessment*	2019
11	Abdelrahman Y.T., El Moustafa A.M., Elfawy M.	Simulating Flood Urban Drainage Networks Through 1D/2D Model Analysis	*Journal of Water Management Modeling*	2018
12	Bhusal A., Thakur B., Kalra A., Benjankar R., Shrestha A.	Evaluating the Effectiveness of Best Management Practices in Adapting the Impacts of Climate Change-Induced Urban Flooding	*Atmosphere*	2024
13	Bibi T.S., Kara K.G.	Evaluation of Climate Change, Urbanization, and Low-Impact Development Practices on Urban Flooding	*Heliyon*	2023
14	Binesh N., Niksokhan M.H., Sarang A., Rauch W.	Improving Sustainability of Urban Drainage Systems for Climate Change Adaptation Using Best Management Practices: A Case Study of Tehran, Iran	*Hydrological Sciences Journal*	2019
15	Custódio D.A., Ghisi E.	Impact of Residential Rainwater Harvesting on Stormwater Runoff	*Journal of Environmental Management*	2023
16	Ekmekcioglu Ö., Yılmaz M., Özger M.,	Investigation of the Low Impact Development	*Water Science and Technology*	2021

No.	Author(s)	Article Title	Journal Title	Year
	Tosunog F.	Strategies for Highly Urbanized Area via Auto-Calibrated Storm Water Management Model (SWMM)		
17	Feng B., Zhang Y., Bourke R.	Urbanization Impacts on Flood Risks Based on Urban Growth Data and Coupled Flood Models	*Natural Hazards*	2021
18	Sagar Kumar M., Umamahesh N.V.	Integrated Assessment of Future Climate and Land Use Changes on Urban Floods: A Markov Chain and PCSWMM-Based Approach for Hyderabad	*Water Science and Technology*	2024
19	Taji S.G., Regulwar D.G.	LID Coupled Design of Drainage Model Using GIS and SWMM	*ISH Journal of Hydraulic Engineering*	2019
20	Vemula S., Srinivasa Raju K., Sai Veena S.	Modelling Impact of Future Climate and Land Use Land Cover on Flood Vulnerability for Policy Support – Hyderabad, India	*Water Policy*	2020
21	Xu K., Zhuang Y., Yan X., Bin L., Shen R.	Real Options Analysis for Urban Flood Mitigation under Environmental Change	*Sustainable Cities and Society*	2023

3.1 HYDROLOGICAL MODELLING FOR SUSTAINABLE FLOOD MAPPING

Hydrological modelling has evolved from static simulations into dynamic, data-driven systems that integrate rainfall, land-use change, and drainage networks to support sustainable flood mapping. Among these, the Personal Computer Storm Water Management Model (PCSWMM) has proven the most efficient due to its flexibility, user-friendly interface, and capability to simulate surface runoff, infiltration, and drainage performance across diverse climate scenarios (Benoit et al., 2025). Through its modular design and compatibility with GIS and remote sensing data, PCSWMM allows detailed visualization and quantification of flood-prone areas, enabling engineers and planners to assess potential interventions with high spatial accuracy.

In the study by Benoit et al. (2025), a calibrated PCSWMM model representing a 20 km^2 urban drainage network in Montreal was used to simulate eight distinct Blue-Green Infrastructure (BGI) scenarios. The analysis demonstrated that climate change, represented by an 18 percent increase in rainfall intensity, could elevate total runoff volume by 32 percent and flood volume by 136 percent relative to baseline conditions. These results confirm that traditional drainage systems are increasingly unable to absorb or redirect excessive stormwater under intensified precipitation patterns. However, PCSWMM's scenario-based structure enabled the evaluation of different mitigation measures, identifying those most capable of offsetting climate impacts. The model calibration achieved Nash–Sutcliffe efficiency (NSE) values ranging from 0.67 to 0.91, confirming its high reliability and predictive strength, consistent with accepted hydrological performance benchmarks (Moriasi et al., 2007; Shamsi and Koran, 2017, as cited in Benoit et al., 2025).

Furthermore, Benoit et al. (2025) emphasized that PCSWMM not only predicts runoff and flooding but also functions as a decision-support platform for long-term adaptation planning. It enables local authorities to explore a range of climate and infrastructure combinations, assessing both their hydraulic and economic implications. Despite these strengths, limitations were observed, including the model's dependence on high-quality spatial data, its time-consuming calibration process, and its limited capacity to represent ecological dynamics within hydrological systems. These challenges underline the need for further coupling between hydrological and ecological modeling approaches to achieve more holistic and sustainable flood management strategies.

Overall, the findings illustrate that hydrological modelling tools such as PCSWMM are integral to designing adaptive and sustainable flood management systems. They offer reliable predictions under climate variability, guide investment decisions, and foster data-driven urban resilience planning, particularly in regions where physical experimentation is constrained by financial or spatial limitations.

3.2 INTEGRATION OF NATURE-BASED SOLUTIONS INTO HYDROLOGICAL MODELLING (RQ 2)

The integration of Nature-based Solutions (NbS) into hydrological models has emerged as an innovative approach to improving flood resilience while enhancing ecological sustainability. By embedding NbS elements within simulation platforms like PCSWMM, recent studies have demonstrated significant reductions in both runoff volume and peak flow. In Benoit et al. (2025), multiple configurations of Blue-Green Infrastructure were tested, including bioretention cells, permeable pavements, green roofs, and blue roofs. The combination of blue roofs, permeable pavements, and bioretention cells (BGIs scenario) offset up to 162 to 167 percent of climate-induced flood volume increases, while the configuration of green roofs, permeable pavements, and bioretention cells (GIs scenario) achieved a 99 percent climate-change offset indicator (CCO). These results highlight the capacity of NbS to outperform traditional grey infrastructures when strategically designed and distributed across urban catchments.

The study also revealed that bioretention cells provided the most consistent performance across multiple rainfall intensities, primarily due to their capacity to manage both direct precipitation and surface runoff from adjacent areas. In contrast, green roofs, while effective in moderate rainfall conditions, showed limited infiltration capacity during extreme events, leading to performance saturation. Further sensitivity analysis by Benoit et al. (2025) demonstrated that increasing the soil conductivity of green roofs from 12.5 to 100 mm/h could significantly enhance their infiltration efficiency, outperforming blue roof systems in peak attenuation. This finding suggests that design parameters such as soil permeability and retention depth are critical in optimizing NbS performance within hydrological frameworks.

Moreover, the incorporation of NbS into PCSWMM modeling provides an interdisciplinary advantage by linking engineering precision with ecological insight. The integration of GIS-based topographic and land-use layers allowed a more accurate estimation of hydrological responses and facilitated flood-risk zoning and infrastructure prioritization. However, Benoit et al. (2025) observed that relatively few studies incorporate both hydrological and ecological assessments simultaneously, indicating a gap in interdisciplinary integration that limits the full understanding of NbS potential. Bridging this gap will require more hybrid frameworks that combine hydrological simulation with ecological monitoring, cost-benefit analysis, and socio-environmental evaluation.

From a practical standpoint, the study confirmed that NbS, when coupled with robust hydrological modeling, provides no-regret solutions for cities seeking cost-effective and environmentally responsible flood mitigation. Even partial implementation of BGI practices could offset nearly half of the projected flood volume increase caused by climate change. This reinforces the role of NbS not only as supplementary structures but as central components of adaptive water management systems capable of restoring hydrological balance and urban livability.

Collectively, the results address both research questions. For RQ 1, hydrological models such as PCSWMM demonstrate strong capacity to simulate and analyze flood behavior under multiple climate and land-use scenarios, offering a scientific foundation for adaptive planning and sustainable flood mapping. For RQ 2, the integration of Nature-based Solutions within these models substantially enhances flood resilience by reducing runoff and flood volume, while also contributing to ecological restoration. Together, these insights indicate that the combination of advanced hydrological modeling and NbS constitutes a viable and forward-looking strategy for achieving sustainable urban flood management in the context of accelerating climate change.

4. DISCUSSIONS

The findings of this systematic review affirm that sustainable flood mapping requires an integrated framework that unites engineering precision with ecological sensitivity. Hydrological modelling has evolved into a powerful scientific tool that enables the simulation of rainfall–runoff processes, drainage network dynamics, and surface inundation patterns with high accuracy. Among the various modelling platforms, PCSWMM emerged as the most widely adopted due to its capacity to analyze multiple scenarios involving land-use change and climate variability (Benoit et al., 2025; Zahmatkesh et al., 2015; Rahman et al., 2021). The Montreal case study by Benoit et al. (2025) demonstrated that under a projected 18 percent increase in rainfall intensity, runoff volumes rose by 32 percent and flood volumes by 136 percent, confirming that the combined effects of urbanization and climate change significantly increase hydrological pressure on existing drainage systems.

Key findings from the reviewed literature reveal that hydrological modelling, when integrated with Blue and Green Infrastructure (BGI), can effectively offset climate-induced increases in runoff and flooding. Benoit et al. (2025) showed that integrating permeable pavements, blue roofs, and bioretention cells achieved up to 167 percent flood volume reduction, confirming that the implementation of distributed BGI measures within urban catchments produces measurable hydrological and ecological benefits. This observation aligns with the findings of Zahmatkesh et al. (2015), Ghodsi et al. (2020), and Samouei and Özger (2020), who also reported significant reductions in runoff when low-impact development measures were integrated into hydrological simulations. Other studies, including Li et al. (2023), Xu et al. (2022), and Chua et al. (2024), provided similar empirical validation that coupling hydrological models with NbS enhances model performance and contributes to sustainable adaptation strategies.

These outcomes collectively emphasize that integrating hydrological models with nature-based measures contributes to both hydraulic efficiency and ecological resilience. Benoit et al. (2025) observed that bioretention cells displayed the highest mitigation potential because they received runoff directly from impervious surfaces and promoted infiltration and evapotranspiration. Permeable pavements, by contrast, reduced surface runoff and delayed peak discharge by retaining water in their sub-layers, as also noted by Ekmekcioglu et al. (2021) and Binesh et al. (2019). Meanwhile, blue and green roofs contributed primarily to volume control on rooftop catchments, but their efficiency depended on soil permeability and maintenance. When soil conductivity was increased from 12.5 to 100 mm/h, green roofs outperformed blue roofs in reducing runoff volume (Benoit et al., 2025). This performance sensitivity illustrates the importance of biophysical parameters and construction materials in enhancing BGI functionality under variable rainfall conditions.

Despite this progress, significant research and implementation gaps remain. The integration of ecological parameters into hydrological models is still limited, and most PCSWMM applications rely on empirical formulas that do not fully represent the complexity of vegetation, soil structure, and microclimatic feedbacks (Suleiman, 2021; Martel et al., 2021). Benoit et al. (2025) highlighted that calibration uncertainties and data scarcity often restrict model accuracy, especially in regions lacking long-term rainfall or topographic records. Moreover, inconsistencies in defining and quantifying BGI parameters, such as infiltration rate or storage capacity, hinder model comparability between case studies (Xu et al., 2019; Wu et al., 2020; Fang et al., 2017). Institutional fragmentation and the absence of standardized modelling frameworks also contribute to the slow adoption of NbS within urban planning practices.

The novelty of Benoit et al. (2025) lies in the simultaneous evaluation of multiple BGI configurations within a single calibrated PCSWMM model covering 9,000 subcatchments in Montreal. This multi-scenario approach, which tested eight configurations under climate-adjusted rainfall conditions, provided a rigorous quantitative assessment of how different BGI strategies interact hydrologically. The study moved beyond theoretical modelling by applying real-world design parameters derived from existing urban infrastructure. Its emphasis on combining blue and green roofs, permeable pavements, and bioretention cells established an integrated analytical framework that could be replicated in other climate-impacted regions (Neupane et al., 2021; Xu et al., 2023). This methodological innovation represents a clear advance in understanding how engineered and ecological systems can co-function to reduce flood risks and enhance long-term water sustainability.

The implications of these findings are substantial for both science and policy. The evidence confirms that BGI measures not only mitigate flooding but also provide co-benefits including temperature regulation, improved water quality, and biodiversity enhancement (Fletcher et al., 2015; Liu et al., 2019; Almaaitah et al., 2021). Benoit et al. (2025) concluded that by strategically combining different types of green infrastructure, cities can compensate for much of the hydraulic deficit caused by climate change without relying solely on expensive grey infrastructure upgrades. This conclusion supports previous results by Dai and Cai (2021) and Vemula et al. (2020), who observed that nature-based adaptation is particularly effective when coupled with precise hydrological simulations. The Montreal study also underscored that adopting NbS improves resilience in older urban drainage systems where space or cost constraints limit full system replacement.

From a methodological perspective, Benoit et al. (2025) demonstrated that sensitivity analysis is crucial in optimizing model calibration and parameterization. Variations in infiltration rates, roughness coefficients, and subcatchment discretization substantially influenced model performance and outcomes. These findings emphasize the need for international calibration protocols and open-source datasets to improve comparability among studies. Establishing shared data repositories and integrating high-resolution remote sensing with PCSWMM could enhance predictive capability and reduce modelling uncertainty. Other researchers, including Bermúdez et al. (2018) and Kabir et al. (2020), have also highlighted that data interoperability and real-time rainfall integration are essential to improve urban flood modelling accuracy.

Looking forward, future research should focus on expanding interdisciplinary collaboration among hydrologists, ecologists, and urban planners to ensure that ecological variables are embedded into hydrological algorithms. Long-term field monitoring of implemented BGI systems is required to validate model projections and refine parameter estimation (Custódio and Ghisi, 2023; Bibi and Kara, 2023). Comparative studies across different climatic regions such as tropical, arid, and coastal environments would reveal how hydrological–ecological interactions differ under varying rainfall regimes (Olbert et al., 2017; Xu et al., 2022). In addition, the inclusion of economic valuation, maintenance cost, and social perception metrics within hydrological models could provide a more holistic understanding of sustainability outcomes. By incorporating these interdisciplinary dimensions, future flood-mapping research can evolve into a more adaptive, data-informed, and ecologically balanced approach to urban resilience planning.

5. CONCLUSIONS

Hydrological modelling and nature-based solutions represent two complementary pillars of sustainable flood management, and their integration offers a promising pathway toward adaptive and eco-hydrological systems that are both technically efficient and environmentally restorative. This study aimed to examine how these two approaches can be unified to strengthen flood resilience, focusing particularly on the application of hydrological models such as PCSWMM and the role of nature-based solutions in enhancing system adaptability. The findings from twenty-one reviewed studies reveal that hydrological models provide reliable predictive accuracy in simulating surface runoff, drainage behavior, and rainfall impacts under various climate and land-use conditions, while nature-based interventions such as bioretention cells, permeable pavements, green roofs, and blue roofs improve infiltration, storage, and ecological functionality. When combined, these frameworks not only reduce flood volume and peak discharge but also promote biodiversity, improve water quality, and align with global climate adaptation and sustainability goals. The integration of precision and ecological understanding thus marks a significant advancement in flood modelling research, contributing to a more holistic understanding of urban hydrology that balances structural control with natural processes. This review contributes to the field by emphasizing that sustainable flood management must evolve beyond conventional infrastructure toward interdisciplinary approaches that unite technology, ecology, and community participation. Future flood mapping frameworks should prioritize long-term monitoring, open data collaboration, and model interoperability to ensure that hydrological tools and nature-based systems work synergistically to create cities that are resilient, adaptive, and environmentally harmonious.

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