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Systematic Review

Nature-Based Solutions for Managing Urban Pluvial Flood Risk: A Systematic Review of Hazard Drivers, Modelling Approaches, and Climate Scenario Integration

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Abstract

Urban pluvial flood risk is intensifying under climate change, driving growing interest in nature-based solutions and blue–green infrastructure as adaptation measures. However, substantial heterogeneity in hazard characterisation, intervention types and design, modelling approaches, performance metrics, and climate scenario integration limits evidence comparability and policy applicability. This study systematically reviews 538 peer-reviewed articles (2000–2025) following PRISMA guidelines, with inter-rater reliability assessment confirming robust data extraction (Cohen's $\kappa = 0.76$–0.95). A three-tier framework was developed to evaluate climate scenario integration, alongside a quality-of-evidence assessment. Results show that 30% of studies incorporate formal IPCC climate scenarios (Tier-1), ~40% employ climate-informed but non-standardised approaches (Tier-2), and ~29% lack explicit climate scenario representation (Tier-3). High-emission pathways (RCP8.5/SSP5-8.5) dominate formal assessments, while CMIP6-based projections remain underrepresented. The Storm Water Management Model (SWMM) is the most widely applied modelling platform, with green roofs, bioretention systems, and permeable pavements being the most frequently evaluated interventions. Notably, only ~14% of studies provide high-confidence evidence combining calibrated modelling, formal climate scenarios, and quantitative performance evaluation. The review identifies persistent methodological inconsistencies and recommends harmonised climate scenario reporting, multi-pathway assessments, standardised performance metrics, and stronger empirical validation, particularly at catchment scales and under extreme and compound events. Addressing these gaps is essential to improving the robustness, transferability, and policy relevance of evidence supporting climate-resilient urban flood management.

Keywords: nature-based solutions (NBS); blue–green infrastructure (BGI); pluvial flooding; sustainable urban water management; sustainable urban drainage systems (SuDS); climate change

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1. Introduction

Urban areas are increasingly vulnerable to hydro-meteorological hazards, particularly pluvial and surface water flooding, driven by rapid urbanisation, expansion of impervious surfaces, and intensifying rainfall extremes under climate change [1–3]. Observed increases in short-duration, high-intensity precipitation events have amplified surface runoff generation and drainage system overload in many metropolitan regions [4,5]. Historically, hazard mitigation has relied primarily on conventional grey infrastructure approaches, including

pipe upsizing, detention tanks, levees, and channel modifications [6,7]. However, these measures are often constrained by high capital costs, ecological disruption, and reduced adaptability under non-stationary climatic conditions [8,9].

In response, blue–green infrastructure (BGI) and nature-based solutions (NBS) have emerged as adaptive and multifunctional strategies designed to replicate natural hydrological processes within urban environments [10,11]. Although these two terms are sometimes used interchangeably, nature-based solutions (NBS) is the broader ecological and policy concept, whereas blue–green infrastructure (BGI) refers to the physical blue–green measures that deliver these functions. As this review focuses on the physical stormwater measures used for urban flood mitigation, the combined term 'NBS/BGI' is used throughout to denote both, except where a distinction is explicitly drawn. Interventions such as green roofs, bioretention systems, infiltration trenches, permeable pavements, and retention ponds aim to enhance infiltration, delay runoff, and reduce peak discharge while delivering co-benefits including urban cooling, water quality improvement, and biodiversity enhancement [12–14]. Over the past two decades, a rapidly expanding body of research has evaluated the performance of these interventions across diverse climatic and geographical contexts [15–17]. Nevertheless, the literature remains methodologically heterogeneous. Studies employ a wide range of hydrological, hydraulic, ecohydrological, GIS-based, and optimisation models, with a pronounced dominance of SWMM-based modelling frameworks [13,16]. While SWMM provides detailed rainfall–runoff simulation and flexible integration of stormwater controls, its extensive data requirements and calibration complexity pose challenges, particularly in data-scarce regions [12].

Moreover, performance evaluation metrics vary substantially across studies, encompassing peak flow attenuation, runoff volume reduction, delay time, infiltration enhancement, pollutant removal, and resilience-based indicators [6,14,18]. Climate change integration also exhibits inconsistency. Although some studies adopt IPCC-aligned scenarios, such as Representative Concentration Pathway (RCP) RCP4.5 and RCP8.5 [1,3], many rely on simplified rainfall intensity increase approaches or baseline climatic conditions without explicit scenario justification [19]. This variability in modelling assumptions, indicator selection, and climate representation complicates cross-study comparability and limits the transferability of findings across regions [16,17].

While previous review studies have examined operational frameworks [16], modelling efficiency and economic evaluation [16], and global case study inventories [20], an integrated synthesis systematically linking hazard typology, stormwater control strategies, modelling platforms, performance indicators, and climate scenario incorporation remains limited. To address this gap, the present study systematically synthesises 538 peer-reviewed articles published between 2000 and 2025, following PRISMA 2020 guidelines [21]. Through quantitative and comparative analysis, this review identifies dominant hazard categories, most frequently applied stormwater controls, prevailing modelling tools, indicator selection patterns, and climate scenario practices. By examining methodological heterogeneity and analytical trends, the study provides a structured evidence base to support more standardised, transferable, and climate-resilient urban flood mitigation strategies.

2. Methodology

2.1. Review Framework and Literature Search Strategy

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [21], which provide a standard framework for transparent and reproducible evidence synthesis. The PRISMA framework structures the review into four sequential phases: identification, screening, eligibility assessment, and inclusion. In the identification phase, all potentially relevant

records are retrieved from the selected databases and supplementary sources. The screening phase removes duplicate records and excludes studies whose titles and abstracts fall outside the review scope. During the eligibility phase, the full texts of the remaining studies are assessed against predefined inclusion and exclusion criteria. The final inclusion phase retains only the studies that satisfy all criteria and are carried forward into the synthesis. This structured process reduces selection bias and allows other researchers to reproduce the review. The number of records retained and excluded at each phase is reported in the PRISMA flow diagram (Figure 1).

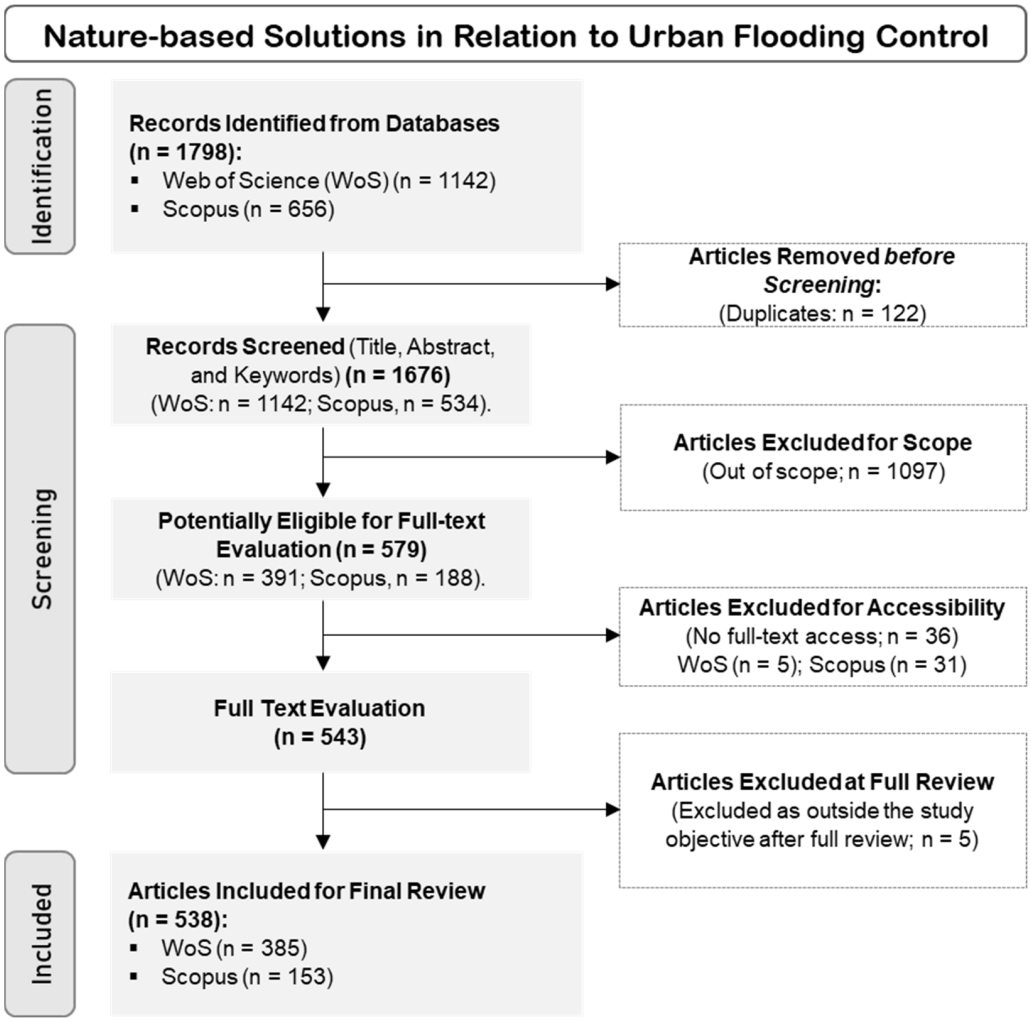


Figure 1. PRISMA flow diagram of the study selection process. Full PRISMA checklist is included in the Supplementary Materials (Table S3).

The primary objective of the review was to synthesise peer-reviewed literature on the application of nature-based solutions (NBS) and blue–green infrastructure (BGI) for urban flood mitigation under climate change conditions, with particular attention to hazard typology, stormwater control measures, modelling approaches, performance indicators, and climate scenario integration. The literature search was carried out using two major academic databases, Web of Science (WoS) and Scopus. These databases were selected because they index a wide range of high-quality peer-reviewed journals in environmental science, hydrology, climate change, and urban studies. The search was limited to English-language journal articles published between 1 January 2000 and 31 December 2025. A combination of keywords and Boolean operators was used to capture relevant studies: (*"blue-green infrastructure" OR "green infrastructure" OR "nature-based solutions" OR "Best*

Management Practices" OR "Water Sensitive Urban Design" OR "Sustainable Drainage" OR "Low Impact Development") AND ("urban flooding" OR "stormwater" OR "pluvial flooding") AND ("climate change" OR "climate adaptation" OR "extreme weather"). The search string was refined through pilot testing to balance sensitivity and specificity. Additional records were identified by manually screening the reference lists of key review papers, which helped ensure that relevant studies not captured by the database search were not missed.

2.2. Study Selection and Screening Process

The initial database search retrieved 1142 records from Web of Science and 656 records from Scopus. After removing duplicates, titles and abstracts were screened to exclude studies that did not directly address urban flooding, stormwater management, or the application of NBS.

A two-stage screening process was implemented: (1) title and abstract screening based on predefined inclusion and exclusion criteria; and (2) full-text assessment to confirm relevance, methodological quality, and alignment with the review objectives. Studies were included if they: (i) focused on urban flooding or stormwater management; (ii) evaluated nature-based or hybrid stormwater control measures; (iii) applied quantitative, modelling-based, or empirical analysis; and (iv) considered climate change, extreme rainfall, or future rainfall scenarios. Studies were excluded if they: (i) were review articles, conference papers, editorials, or technical reports; (ii) focused solely on rural catchments or riverine flooding; or (iii) lacked quantitative or analytical evaluation.

Following screening, a total of 538 articles were retained for final analysis (full list and key data extracted are detailed in the Supplementary Materials, Tables S1 and S2). The complete selection procedure is illustrated in the PRISMA flow diagram (Figure 1).

2.3. Automated Keyword-Based Screening and Validation

To enhance screening efficiency and consistency, an automated first-pass screening was implemented using Python 3.14 code applied to the exported records in Excel. For each record, the code read the title and abstract and evaluated them against the predefined inclusion and exclusion criteria, recording an explicit include/exclude decision, the criterion flags behind it, and a short justification. This produced a consistent, transparent, and fully reproducible screening log. To validate the reliability of the automated screening, a random subset of articles was manually reviewed and used as a reference dataset. The automated and manual classifications were compared using a confusion matrix, comprising true positives (TP), false positives (FP), false negatives (FN), and true negatives (TN). Screening performance was assessed using sensitivity (recall) and precision, defined as Equations (1) and (2):

$$\text{Sensitivity} = \frac{TP}{TP + FN} \quad (1)$$

$$\text{Precision} = \frac{TP}{TP + FP} \quad (2)$$

The automated screen was validated against an independent manual review of a sample of 125 records; records that were duplicates or whose full text was inaccessible were not used in the validation. Of these, the automated step correctly retained 35 relevant records (true positives) and correctly excluded 87 irrelevant records (true negatives), with no false positives and three false negatives. This gives a sensitivity (recall) of 92.1% (95% CI: 79.2–97.3%), a precision of 100% (95% CI: 90.1–100%), a specificity of 100% (95% CI: 95.8–100%), and an overall accuracy of 97.6% (95% CI: 93.2–99.2%), with an F1 score of 0.96. Agreement between the automated screen and the manual review was near-perfect (Cohen's $\kappa = 0.94$). The three false negatives were eligible studies initially excluded by the keyword step; these were identified during the manual review and retained, so the

two-stage design (automated screening followed by full manual review) prevented the small number of automated misses from propagating to the final dataset. Any discrepancies between automated and manual screening results were discussed and resolved through consensus. This validation procedure ensured a robust and reproducible screening process consistent with PRISMA 2020 recommendations.

2.4. Data Extraction and Classification Framework

A structured data extraction protocol was developed to ensure consistency across studies. For each included article, the following information was systematically recorded:

- Geographical location and climatic context
- Primary hazard type and flood category
- Stormwater control measures and NBS typologies
- Modelling tools and analytical approaches
- Performance indicators and evaluation metrics
- Climate change representation and scenario selection

Hazard categories were classified into thematic groups, including flood-related hazards, rainfall extremes, heat-related hazards, coastal hazards, drought and water scarcity, water quality degradation, and infrastructure failures. Stormwater controls were grouped into green, permeable, storage, grey, hybrid, and smart system categories. Modelling approaches were classified into hydrological–hydraulic models, ecohydrological models, climate and meteorological models, optimisation and artificial intelligence approaches, GIS-based models, statistical frameworks, and conceptual planning tools.

To assess the reliability of the multi-dimensional data extraction, a random subset of 125 articles (~23% of the dataset) was independently recoded by a second reviewer across all six extraction dimensions: hazard type, stormwater control category, modelling tool, performance indicator, climate change scenario tier, and geographical classification. Inter-rater agreement was evaluated using Cohen's kappa (κ) for each dimension (Equation (3)).

$$\kappa = \frac{P_o - P_e}{1 - P_e} \tag{3}$$

where P_o represents the observed proportion of agreement between reviewers and P_e represents the probability of agreement expected by chance alone. The results indicated substantial to near-perfect agreement across all categories: hazard type ($\kappa = 0.85$), stormwater control ($\kappa = 0.90$), modelling tool ($\kappa = 0.83$), performance indicator ($\kappa = 0.90$), climate scenario tier ($\kappa = 0.80$), and geographical classification ($\kappa = 0.95$). All values exceeded the $\kappa \geq 0.70$ threshold for substantial agreement [22]. Discrepancies were predominantly observed in boundary cases involving hybrid stormwater controls and multi-model studies and were resolved through discussion and consensus between the two reviewers. These results confirm the reproducibility of the extraction protocol and support the internal validity of the coded dataset.

2.5. Data Analysis and Synthesis

Quantitative bibliometric and comparative analyses were performed to identify temporal trends, geographical patterns, dominant modelling approaches, and stormwater control strategies. Frequency analysis, spatial mapping, and cross-tabulation were used to explore relationships between hazard types, stormwater control measures, modelling platforms, and climate scenario practices. Results were synthesised using descriptive statistics, comparative visualisation (graphs, heat maps, and matrices), and systematic thematic interpretation. This multi-dimensional analysis enabled the identification of prevailing research trends,

methodological gaps, and opportunities for advancing standardised and climate-resilient NBS implementation strategies.

3. Results and Findings

The 538 reviewed studies were characterised across six analytical dimensions: geographical distribution, publication trends, hazard typology, stormwater control selection, modelling approach, and climate scenario practice. Across all six dimensions, the evidence reveals a consistent pattern: research effort is concentrated in a narrow range of geographies, hazard types, modelling platforms, and BGI/NBS interventions, while climate scenario practice remains the dimension of greatest methodological fragmentation. The following subsections document each dimension in turn, with cross-dimensional relationships examined in Sections 3.5 and 3.6.

3.1. Geographical Distribution of Studies

The geographical distribution of the reviewed articles shows (Figure 2) that most research has been conducted in the United States (119 articles), closely followed by China (115 articles) and several European countries, most notably Italy (28 articles), Germany (22 articles), the United Kingdom (19 articles), Australia (19 articles), Canada (18 articles), and Spain (16 articles). At the continental scale, Asia (32.7%), Europe (30.8%), and North America (24.4%) account for the large majority of studies, while Oceania (5.3%), South America (4.0%), and Africa (2.8%) remain markedly underrepresented.

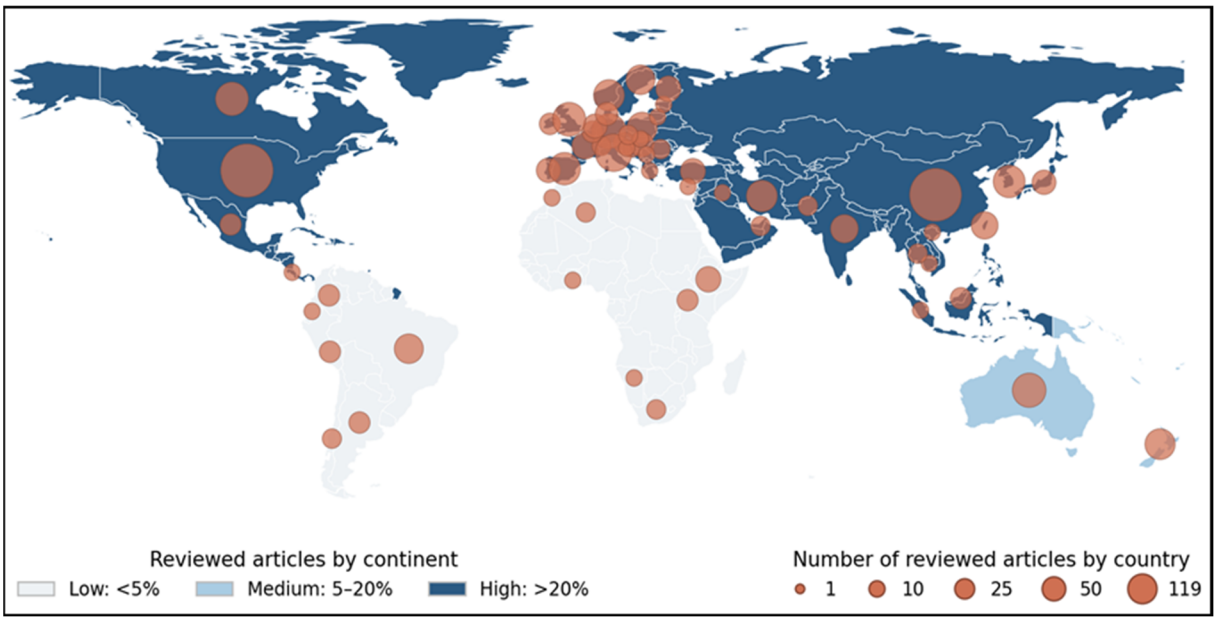


Figure 2. Geographical distribution of reviewed studies by country.

Case studies are widely used in NBS research to evaluate the effectiveness of stormwater management strategies under different climatic and urban conditions [23–25]. This spatial pattern reflects both the increasing exposure of these regions to urban flooding hazards and the availability of research funding, monitoring infrastructure, and modelling capacity. In contrast, relatively limited research output is observed in Africa (10 articles), South America (20 articles), and parts of Southeast Asia (9 articles), despite these regions facing rapid urbanisation and increasing climate-related flood risks. This geographical imbalance is likely driven by a combination of factors: the concentration of hydrological monitoring networks and high-resolution rainfall data in North America and Europe, the

availability of institutional funding for climate adaptation research, and publication-related barriers including language and journal access. The dominance of Chinese case studies further reflects the national-scale policy impetus of the Sponge City Programme, which has generated a substantial body of applied BGI research [26,27]. This highlights a significant geographical research gap and indicates the need for increased scientific attention and capacity-building efforts in developing and climate-vulnerable regions.

3.2. Temporal Trends in Publications

Figure 3 illustrates the annual distribution of published articles on urban flooding and nature-based solutions. A steady increase is observed from 2015 onward, with a pronounced growth after 2020.

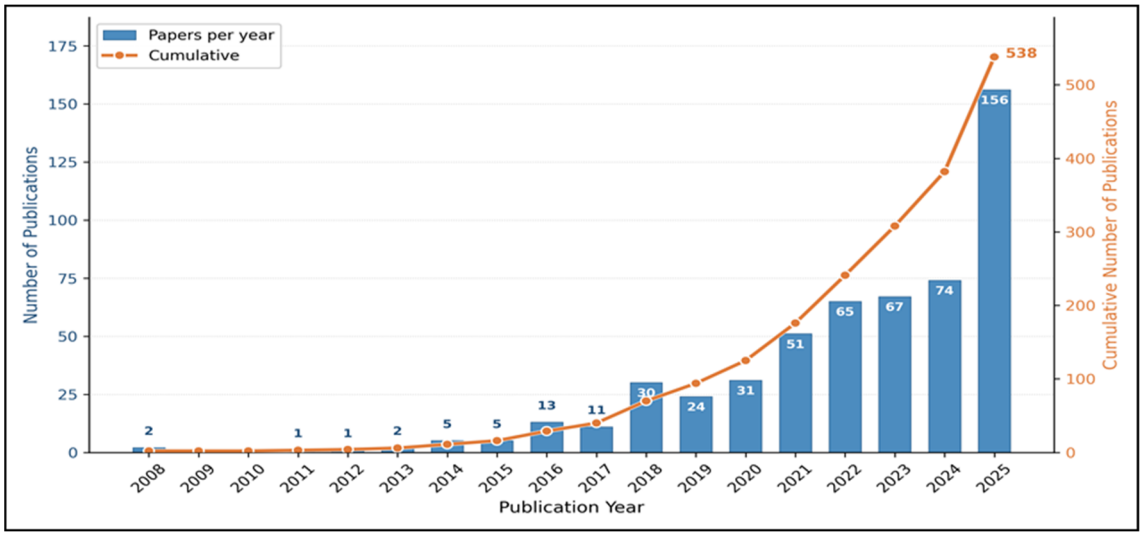


Figure 3. Annual and cumulative number of published articles per year.

This trend reflects the rising recognition of pluvial flooding as a major urban hazard and the growing interest in sustainable stormwater management strategies. The acceleration after 2015 corresponds to three convergent policy impulses: the Paris Agreement on climate change, which elevated urban adaptation as a national commitment across signatory states; the Sendai Framework for Disaster Risk Reduction (2015–2030), which established flood risk reduction as a measurable global target; and SDG 11 (Sustainable Cities and Communities), which linked urban resilience directly to infrastructure investment priorities [1]. In China specifically, the launch of the national Sponge City Programme in 2015 encompassing 30 pilot cities generated a discrete and substantial body of applied BGI research that is directly visible in the review data [26,27]. Notably, while publication volumes grew consistently throughout the review period, the adoption of SSP-based climate scenarios within the review data is almost entirely concentrated in papers published after 2021, suggesting that the most recent generation of BGI/NBS research has begun to engage with CMIP6-era climate projections, a shift examined in detail in Section Classification of Climate Change Scenario Approaches.

3.3. Hazard Categories and Regional Patterns

Urban flooding may originate from different hazard sources, including pluvial flooding caused by intense rainfall, fluvial flooding resulting from river overflow, and coastal flooding driven by storm surges and, in some coastal settings, tsunami-induced [28]. Identifying the type of hazard is therefore essential for understanding flood mechanisms and selecting appropriate modelling and mitigation strategies [29]. Pluvial flooding has become

increasingly important in urban environments, where high-intensity rainfall events can generate surface runoff that exceeds the capacity of urban drainage systems, especially in highly impervious areas [30]. Hazard assessment is therefore required to identify flood-prone areas and evaluate the magnitude and spatial distribution of pluvial flooding, which supports effective urban flood risk management and mitigation planning [31].

Figure 4 and Table 1 present the classification of hazard categories addressed in the reviewed studies. Urban flooding and pluvial flooding are the dominant hazards across all continents, reflecting their increasing frequency and impact in densely urbanised environments.

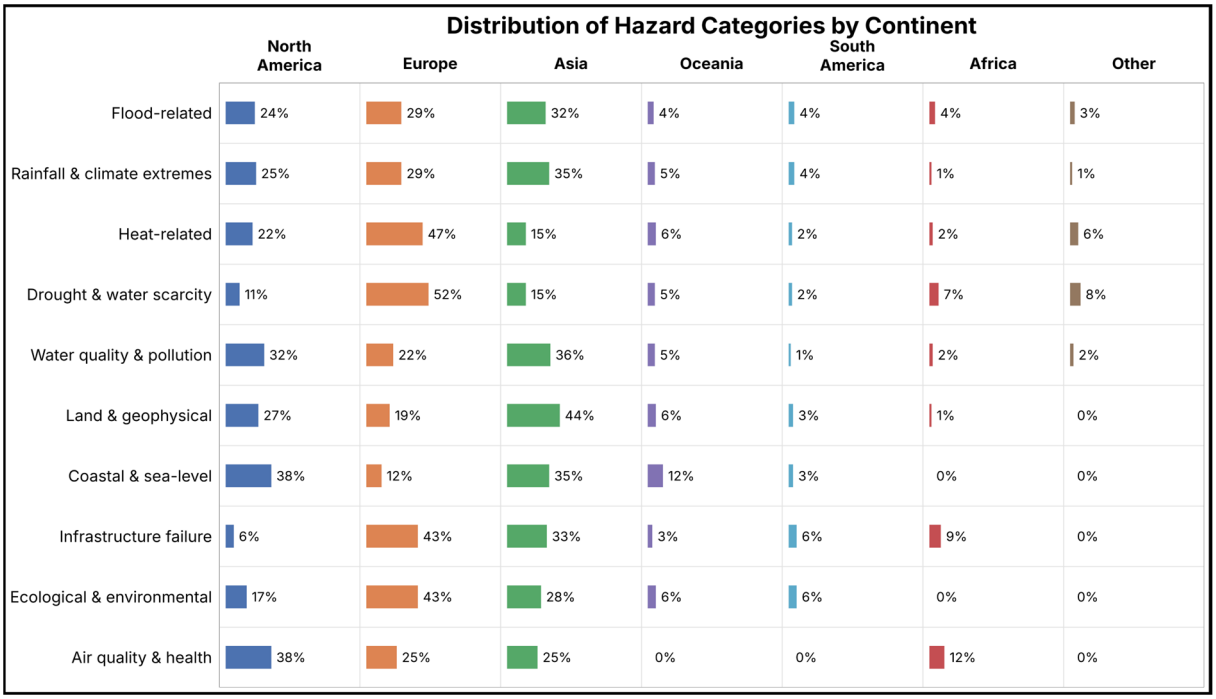


Figure 4. Hazard categories by continent.

Table 1. Hazard categories.

Hazard Category	Specific Hazards	Studies (*n*)	% of 538 Studies
Flood-Related Hazards	Pluvial flooding (surface water flooding); urban flooding; flash floods; basement flooding; waterlogging; nuisance flooding; combined sewer overflows (CSOs); stormwater system overload/sewer surcharge; stream overflow; flood risk and flood vulnerability	497	92.4%
Rainfall and Climate Extremes	Extreme rainfall; heavy precipitation; short-duration high-intensity rainfall; cloudburst events; monsoon-driven rainfall; typhoon-related rainfall; extreme weather events; climate-change-driven precipitation extremes; non-stationary rainfall patterns	217	40.3%
Water Quality and Pollution Hazards	Stormwater pollution; nutrient pollution (nitrogen, phosphorus); heavy metals contamination; microplastics; organic contaminants; pathogens and faecal contamination; waterborne disease risk; declining water quality	119	22.1%
Heat-Related Hazards	Urban heat island (UHI); urban heat stress; heat waves/extreme heat; rising urban temperatures; heat–flood compound events	87	16.2%

Table 1. *Cont.*

Hazard Category	Specific Hazards	Studies (*n*)	% of 538 Studies
Land and Geophysical Hazards	Landslides; land subsidence; soil erosion; surface sealing/imperviousness; reduced infiltration; sedimentation	67	12.5%
Drought and Water Scarcity	Drought; water scarcity; prolonged dry spells; drought–flood variability; water supply stress	61	11.3%
Coastal and Sea-Level Hazards	Sea-level rise (SLR); storm surges; high-tide flooding; coastal subsidence interactions	34	6.3%
Infrastructure and Urban System Failures	Drainage system failure; ageing infrastructure; blockages and structural collapse; insufficient drainage capacity; stormwater network surcharge; infrastructure overload	33	6.1%
Ecological and Environmental Degradation	Biodiversity loss; habitat fragmentation; vegetation stress; ecosystem degradation; loss of green cover; urban ecological disruption	18	3.3%
Air Quality and Health Hazards	Air pollution (NO_2, O_3, particulates); heat-related health risks; waterborne diseases; public safety risks during floods	8	1.5%

Note: Studies (n) and % are derived from the 538-study dataset; a study can address more than one hazard, so values do not sum to 100%.

These hazards are strongly linked to short-duration, high-intensity rainfall events and the expansion of impervious surfaces. In Asia, studies frequently focus on extreme rainfall, monsoon-driven precipitation, flash floods, and compound flood events, while European research often emphasises surface water flooding, combined sewer overflows (CSOs), and urban heat-related hazards. In coastal regions, sea-level rise and storm surge interactions are increasingly incorporated into urban flood risk assessments.

Despite the breadth of hazard categories identified in Table 1, spanning ten types from pluvial flooding to compound heat–flood events and coastal surge interactions, the reviewed literature is structurally concentrated on a single hazard type. Pluvial flooding dominates the review data across all regions, and fewer than 5% of reviewed studies assess BGI performance under compound or cascading hazard conditions. This concentration means that the current evidence base, however extensive, describes BGI effectiveness under a narrower range of conditions than practitioners in coastal, fluvial, or multi-hazard urban environments face. The compound hazard gap is examined further in Section 3.7.

3.4. Distribution of Stormwater Control Measures (SCMs)

Stormwater control measures (SCMs) are a broad set of techniques used to capture, treat, and infiltrate stormwater runoff from impervious areas [6]. Identifying the different types of SCMs across various locations enables planners and designers to select more appropriate solutions in relation to climate change impacts and site-specific land characteristics. Therefore, the distribution of SCMs is presented in Figure 5 and Table 2.

The distribution of stormwater control measures across continents shows that North America has a high proportion of smart and non-structural measures (61%), which suggests a stronger focus on technological and data-driven approaches. Europe, by contrast, present a more balanced distribution, with a noticeable use of permeable and infiltration techniques (31% of that category), reflecting the influence of SuDS-based planning.

In Asia, hybrid and grey infrastructure are now strongly represented (at 43% and 39% in those categories, respectively) alongside green and permeable measures, indicating a transitional stage between conventional and sustainable approaches. In contrast, Africa, South America, and Oceania show relatively low representation across most categories.

This is likely related to the limited number of studies available in these regions rather than the actual absence of stormwater measures. The regional variation in SCM adoption reflects not only differences in physical and climatic context but in institutional capacity, regulatory tradition, and research investment history. North America's concentration of smart and non-structural measures and Europe's higher infiltration and permeable features representation suggest that the maturity of a region's BGI evidence base is itself shaped by governance history, a factor that any attempt to transfer findings across contexts must account for explicitly.

Table 2. Stormwater control categories and their specific measures. Categories reflect the dominant hydrological function of each measure; multi-functional measures (e.g., detention ponds, bioswales) may appear in more than one category by design.

Stormwater Control Category	Specific Stormwater Controls	Studies (*n*)	% of 538 Studies
Green/Nature-Based Controls	Green roofs (extensive, intensive, blue roofs, eco-roofs); green walls/living walls/vertical greening; rain gardens; bioretention cells/basins (biofilters); bioswales/vegetated swales; vegetated infiltration swales; tree pits/tree trenches; street trees and urban tree planting; urban forests and green corridors; parks, green spaces, green belts; green streets/green bus stops; green channels; constructed wetlands; wetlands and wetland parks; retention ponds/wet ponds; detention ponds; floodplain restoration; living shorelines; vegetated filter strips; afforestation/canopy enhancement; phytoremediation systems.	445	82.7%
Permeable and Infiltration Controls	Permeable pavements; porous pavements; pervious pavements; permeable interlocking concrete pavers (PICP); grass pavers/gravel beds; infiltration basins; infiltration trenches/beds; infiltration shafts; soakaways/soakaway wells; dry wells; subsurface infiltration systems; unsealing/desealing of paved areas.	339	63.0%
Storage, Retention, and Harvesting	Rainwater harvesting systems; rainwater tanks/cisterns; rain barrels; retention tanks; retention crates; detention basins; retention basins; underground storage reservoirs; stormwater ponds; smart retention ponds (sensor-controlled); internal water storage (IWS).	172	32.0%
Grey/Structural Controls	Pipes and sewer networks; pipe upsizing/diameter enlargement; pump stations; levees; dams; channel widening and deepening; sea walls; stormwater reservoirs; detention tanks; storage vaults; weirs/underflow weirs; flood storage basins.	83	15.4%
Hybrid (Green–Grey/Blue–Green) Systems	Integrated grey–green infrastructure (IGGI); hybrid BGI/GI systems; Sponge City systems; sustainable urban drainage systems (SuDS/WSUD); low-impact development (LID); nature-based solutions (NBS); modular hybrid green infrastructure; blue–green corridors; combined CSO mitigation systems.	156	29.0%
Smart, Operational, and Non-Structural Measures	Real-time control (RTC); model predictive control (MPC); soil-moisture-based active control; stormwater planters; pre-treatment units (gross pollutant traps, filters); oil and pollutant separators; flood forecasting and early-warning systems; land-use planning and zoning; maintenance and upgrading of drainage systems.	18	3.3%

Note: Studies (n) and % are derived from the 538-study dataset; a study often applies more than one control type, so values do not sum to 100%.

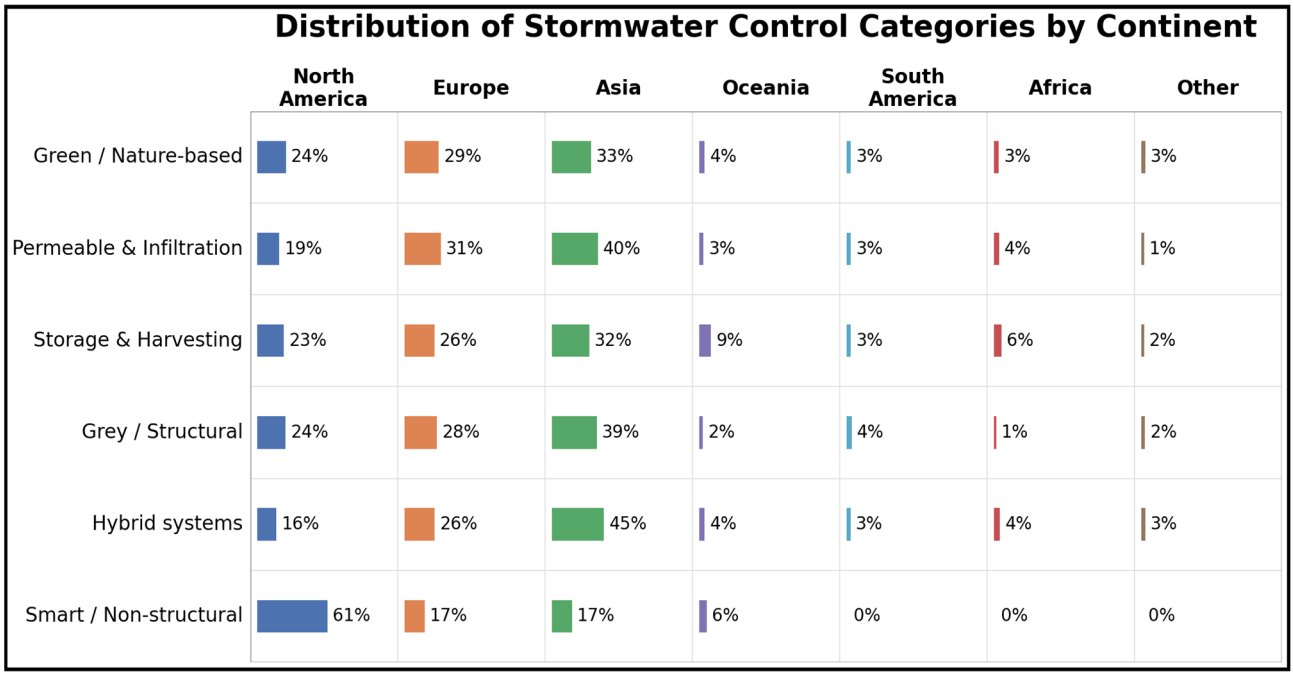


Figure 5. Distribution of stormwater controls by continent.

The distribution of stormwater control measures across different hazard categories shows a consistent dominance of green and nature-based controls (Figure 6). These measures represent the highest proportion in all hazard types, ranging from around 30% in infrastructure-related hazards to approximately 50% in ecological and environmental hazards. This indicates that nature-based solutions are widely applied regardless of the hazard type, particularly where ecological benefits co-occur with flood risk reduction objectives. Bona et al. (2024) [32] report that NBS adoption in European cities is consistently highest in contexts combining flood risk reduction with ecological restoration goals, while Mugume and Nakyanzi (2024) [33] demonstrate that BGI effectiveness in pluvial flood reduction is maintained across a range of urban typologies under both current and future climate conditions.

Permeable and infiltration controls form the second most common group, with relatively high contributions across most categories, approaching or exceeding 30% in air quality and health (33.3%), heat-related hazards (29.6%), and drought and water scarcity (28.9%). This reflects their importance in reducing runoff and enhancing infiltration, which is also emphasised in studies assessing watershed-scale green infrastructure performance and hydrological optimisation [34,35]. Storage and harvesting systems show moderate representation, particularly in coastal and sea-level (18.1%) and infrastructure failure (18.8%) contexts, where water retention and reuse play a role under changing climate conditions [36].

In contrast, grey or structural controls have a relatively low share across all hazard categories, generally remaining below 10% and peaking at 9.6% for coastal and sea-level hazards, indicating a reduced reliance on conventional infrastructure compared to more integrated approaches. Hybrid systems show limited but notable contributions, particularly in ecological and environmental hazards (15.6%), suggesting an increasing integration of green and grey solutions, as discussed in studies on blue–green infrastructure implementation and optimisation [37,38]. Smart and non-structural measures remain the least represented across all categories, with values typically below 3%, which suggests that their application is still limited.

The dominance of green and infiltration-based measures across all ten hazard categories is consistent with the depth of the existing evidence base for these interventions. However, the near absence of smart and real-time control systems, below 3% across all hazard categories and stable across the review period, represents not merely a research gap but a potential implementation risk. As urban drainage systems face increasingly non-stationary rainfall regimes, the most operationally flexible SCM category remains the least studied, and the evidence base available to practitioners considering adaptive control strategies is negligible.

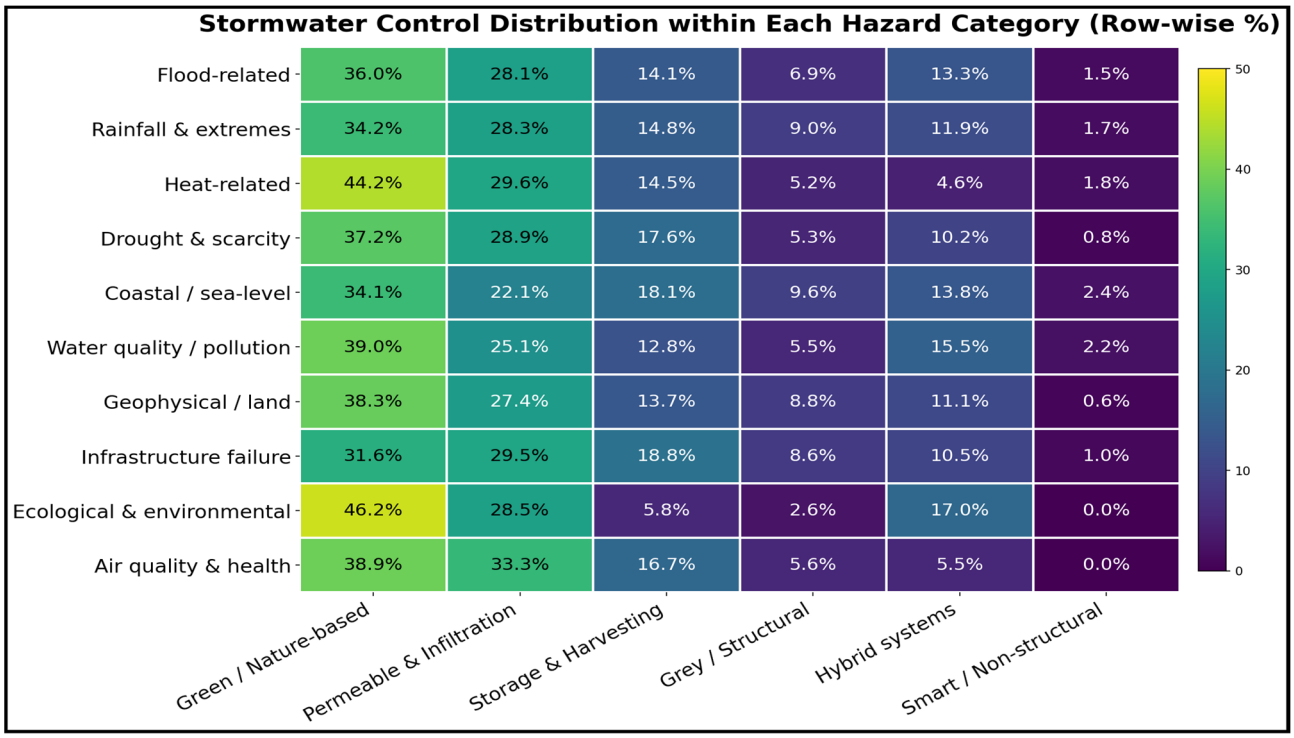


Figure 6. Stormwater control distribution within each hazard category.

3.5. Modelling Tools and Analytical Methods

The selection and investigation of modelling approaches are essential in urban flooding and stormwater management studies, as the reliability of the results depends on the ability of the models to represent complex hydrological processes and system interactions. Numerical models are widely used to evaluate drainage performance and green infrastructure; however, their applicability varies with spatial scale, input requirements, and underlying assumptions [39]. Plot-scale models can capture detailed physical processes, while urban-scale models provide a broader system perspective, indicating that model choice directly influences the interpretation of results and that no single model is sufficient to represent all processes [39]. In addition, commonly used models may simplify key interactions, introducing uncertainties that can affect the accuracy of flood assessments, which highlights the need for careful evaluation of modelling approaches [39].

Furthermore, simplified modelling practices or reliance on limited parameters may lead to overestimation or misrepresentation of system performance, particularly under changing climatic conditions [35]. Limitations in existing software-based approaches and gaps in accurately representing both qualitative and quantitative aspects of stormwater systems have also been reported, reinforcing the importance of selecting appropriate and well evaluated models [40]. Moreover, the balance between model accuracy and computational efficiency remains a key consideration, as highly detailed models require extensive data and

resources, while simplified methods may not adequately capture complex hydrodynamic behaviour [41].

Based on the models used in the research articles, the methods are categorised into eight different groups. This classification is to show the use of each model in different continents, in order to lead designers and stakeholders to a better understanding. Figures 7 and 8 and Table 3 present the modelling tools and analytical methods used in the reviewed studies.

Table 3. Methods and hydraulic models.

Model/Method Category	Specific Models and Approaches	Studies (*n*)	% of 538 Studies
Hydrological and Stormwater Models	SWMM (including PySWMM, PCSWMM, Rhodium-SWMM, RECARGA + SWMM); MIKE family (MIKE URBAN, MIKE21, MIKE SHE, MIKE+); HEC models (HEC-HMS, HEC-RAS, HEC-HMS + GIS); InfoWorks ICM; MUSIC; TUFLOW; RORB; HSPF; LEAFlood; CityCAT; FloodMap 2D; ParFlow-CLM; RHESSys; TELEMAC-2D; GR2L (Green Roof 2-Layer model); UrbanBEATS	275	51.1%
GIS, Remote Sensing, and Spatial Models	GIS platforms (ArcGIS, QGIS); GIS–SWMM coupling; GIS + InVEST integration; remote-sensing-based LULC models; GeoDetector Model (GDM); Moran's I; geographically weighted regression (GWR); OLS and spatial regression; Circuitscape.	143	26.6%
Statistical, Econometric, and Decision Models	Regression models (OLS, logistic, ordinal, mixed-effects); PCA; ANOVA; difference-in-differences; hedonic price models; analytic hierarchy process (AHP); TOPSIS; multi-criteria analysis (MCA); SWOT analysis; contingent valuation; structural equation modelling (SEM).	96	17.8%
Hydraulic, Empirical, and Design Methods	SCS curve number (CN) method; TR-55; rational method; analytical–probabilistic models; empirical runoff coefficient models; laboratory hydraulic experiments; lysimeter-based experiments; ASTM infiltration tests; Błaszczyk rainfall formula; Maag infiltration model.	83	15.4%
Climate and Meteorological Models/Data Sources	NA-CORDEX regional climate models; Cal-Adapt statistical downscaling; NOAA Atlas 14; IDF-based rainfall models; HYRAS/KOSTRA-DWD datasets; Chicago storm hyetograph; Sentinel-2/Copernicus datasets.	69	12.8%
Optimisation, AI, and Advanced Computational Methods	NSGA-II/NSGA-III; particle swarm optimization (PSO/MOPSO); copula-based joint probability models; Bayesian mixed-effects models; cellular automata; machine learning (classification, regression, clustering); real-time control (RTC); model predictive control (MPC).	57	10.6%
Conceptual, Framework, and Non-Simulation Approaches	Conceptual frameworks; ecosystem services framework; resilience assessment framework; policy arrangement approach; system dynamics models; nature-based solutions (NBS) planning frameworks; survey-based and qualitative models; participatory mapping approaches.	52	9.7%
Green Infrastructure and Ecohydrological Models	InVEST (UFRM, Urban Cooling, GIS-integrated variants); ECO-PRO ecohydrological model; green roof water balance models; i-Tree/i-Tree HydroPlus; Tethys–Chloris (T&C); ABIMO; FITNAH urban climate model; UrbClim; ENVI-met; LIDMOD2.	26	4.8%

Note: Studies (n) and % are derived from the 538-study dataset by keyword classification of the reported model/method; a study can use more than one method, so values do not sum to 100%.

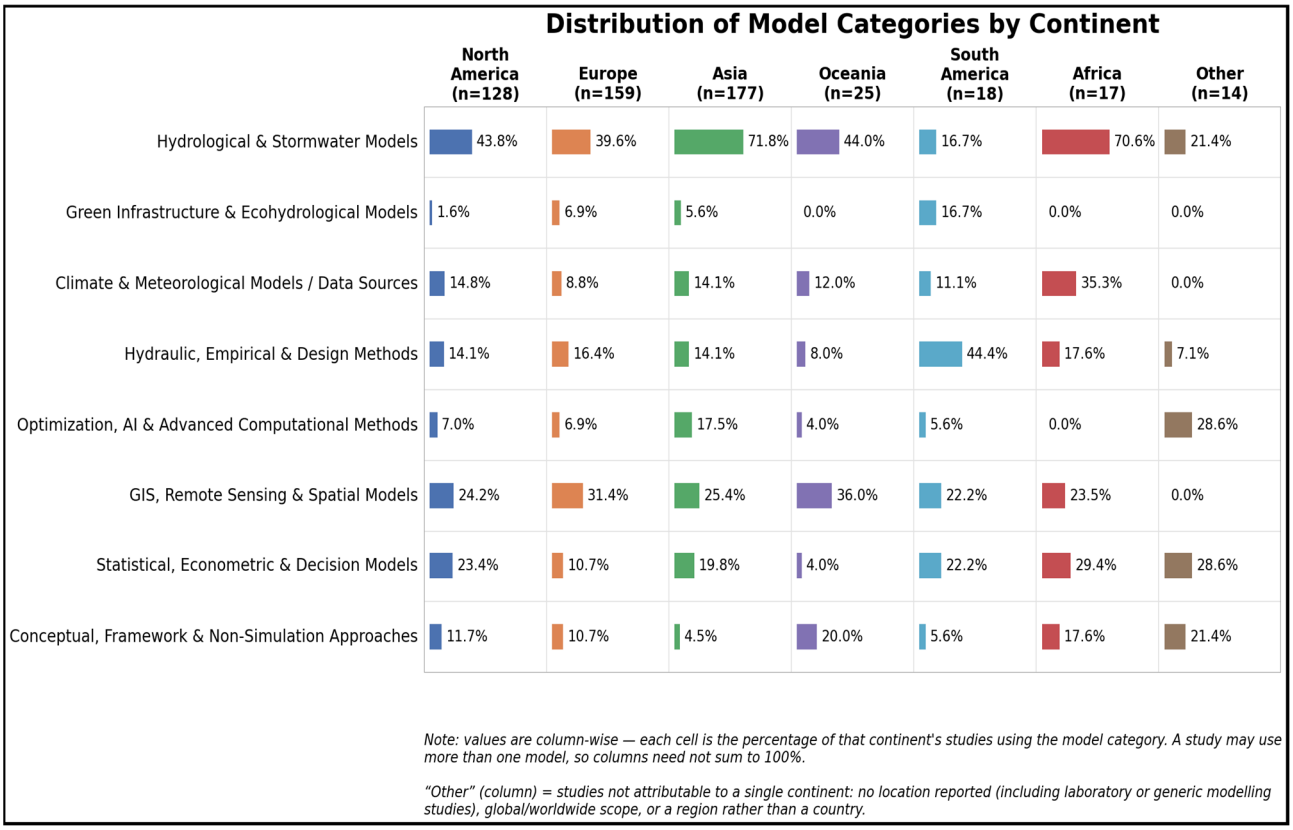


Figure 7. Distribution of model categories by continent.

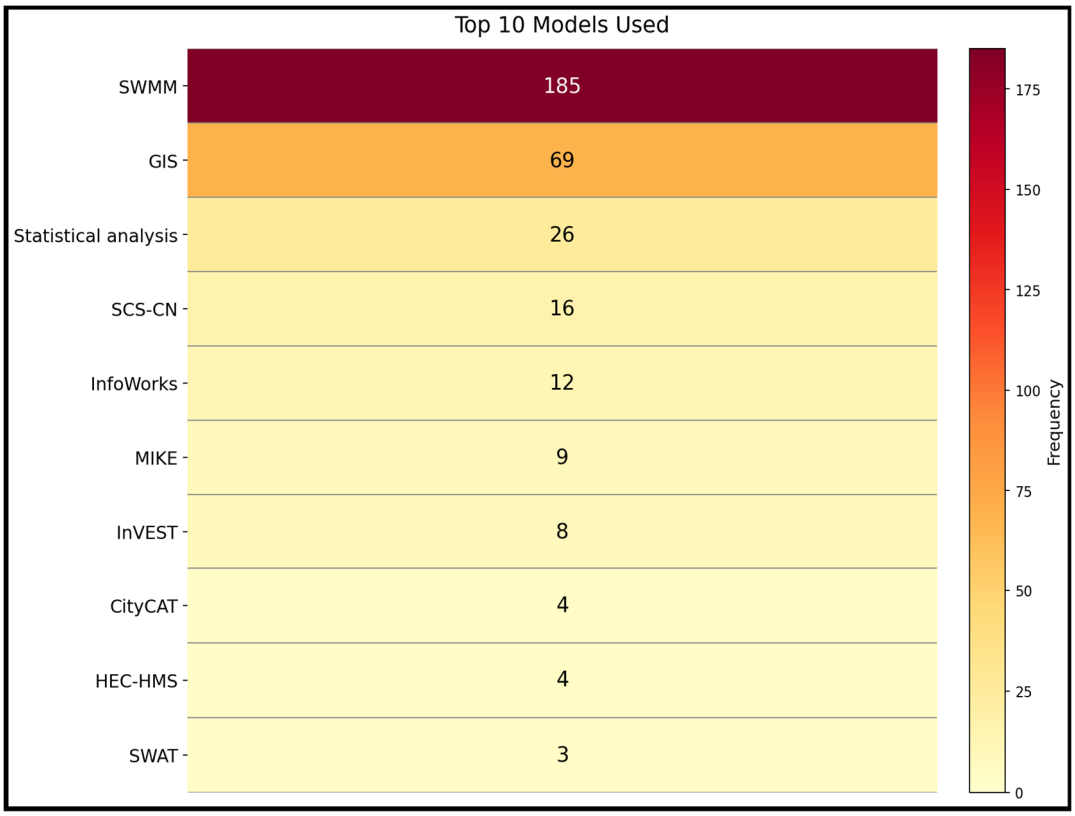


Figure 8. Most frequently used models for urban flooding assessment.

SWMM's dominance reflects its ability to simulate rainfall–runoff processes, drainage networks, and stormwater control measures with a high level of detail. GIS-based approaches are also frequently applied, mainly for spatial analysis, flood mapping, and site selection of stormwater controls.

Figure 8 shows that SWMM is the most frequently applied model across the reviewed studies. This dominance is attributable to three reinforcing factors: (i) technical capability, as SWMM can simulate rainfall–runoff processes, drainage networks, and surface water flooding in urban environments with a high level of detail; (ii) open-source accessibility, which lowers adoption barriers for researchers in low-resource settings; and (iii) institutional path dependency, whereby the availability of existing calibration datasets, training materials, and established workflows [33,36,42] sustains model selection regardless of whether SWMM is optimal for a given research question [43]. In addition, SWMM allows the integration of different stormwater control measures and nature-based solutions, making it suitable for assessing their performance under various rainfall scenarios [44].

However, despite its advantages, the use of SWMM also presents some limitations [39]. Several studies report that SWMM requires extensive data input and calibration, which may not always be available, especially in data-scarce regions [44]. Moreover, the model can be computationally demanding and may not fully capture complex interactions between surface and subsurface processes without coupling with other models or tools [43]. In particular, SWMM is primarily a one-dimensional (1D) hydrological–hydraulic model. Compared with two- and three-dimensional (2D/3D) hydrodynamic models (for example, TUFLOW, MIKE 21, CityCAT, and TELEMAC-2D), it has a limited ability to represent complex overland surface routing and the interaction of multiple flood drivers in compound events. This constraint is most consequential under extreme, high-intensity rainfall, and it contributes to the methodological gaps in extreme-event and compound-flood modelling discussed later in this review. Nevertheless, due to its flexibility, robustness, and wide acceptance in the scientific community, SWMM remains the dominant model used for urban flooding assessments, as reflected in the selected articles [43,45].

Figure 9 presents the cross-tabulation between the most frequently used modelling tools and the stormwater control measures evaluated in the reviewed studies. The results confirm that the EPA Storm Water Management Model (SWMM) is the most widely applied platform, covering the broadest range of stormwater controls. SWMM is used in conjunction with permeable pavements (139 studies), green roofs (101), bioretention systems (85), rain gardens (69), swales (49), rainwater harvesting (30), and infiltration trenches (41), among others. This range reflects the flexibility of SWMM in simulating rainfall runoff processes, pipe network hydraulics, and the hydrological response of distributed stormwater controls at the urban catchment scale.

GIS-based modelling approaches constitute the second most frequently used category, applied across 62 studies involving green roofs, 58 involving permeable pavements, 43 involving rain gardens, and 36 involving swales, alongside constructed wetlands (21 studies) and bioswales (16 studies). The strength of GIS-based methods lies in their capacity for spatially explicit analysis, including suitability mapping, priority area identification, and multi-criteria evaluation of candidate sites for distributed stormwater controls. In contrast to SWMM, which simulates dynamic hydrological and hydraulic processes, GIS approaches are predominantly used for spatial planning and screening rather than for event-based hydrological simulation.

The remaining models show considerably narrower application ranges. Statistical-analysis methods appear across green roofs (26), rain gardens (19), permeable pavements (25), and bioretention (24), reflecting the use of regression- and index-based approaches for cross-site comparison. The MIKE model family (MIKE21, MIKE URBAN, MIKE SHE)

is used mainly with green roofs (13), permeable pavements (12), and rain gardens (10). SCS-CN methods appear with green roofs (13), permeable pavements (21), and swales (11). InVEST is largely restricted to green roofs (7), permeable pavements (5), constructed wetlands (4), and rain gardens and swales (3 each), consistent with its focus on ecosystem-service valuation rather than detailed hydrological process modelling. HEC-HMS appears with green roofs (4), permeable pavements (3), and rain gardens (1), while InfoWorks and CityCAT are applied to only a small number of controls each, indicating highly specialised or context-specific applications.

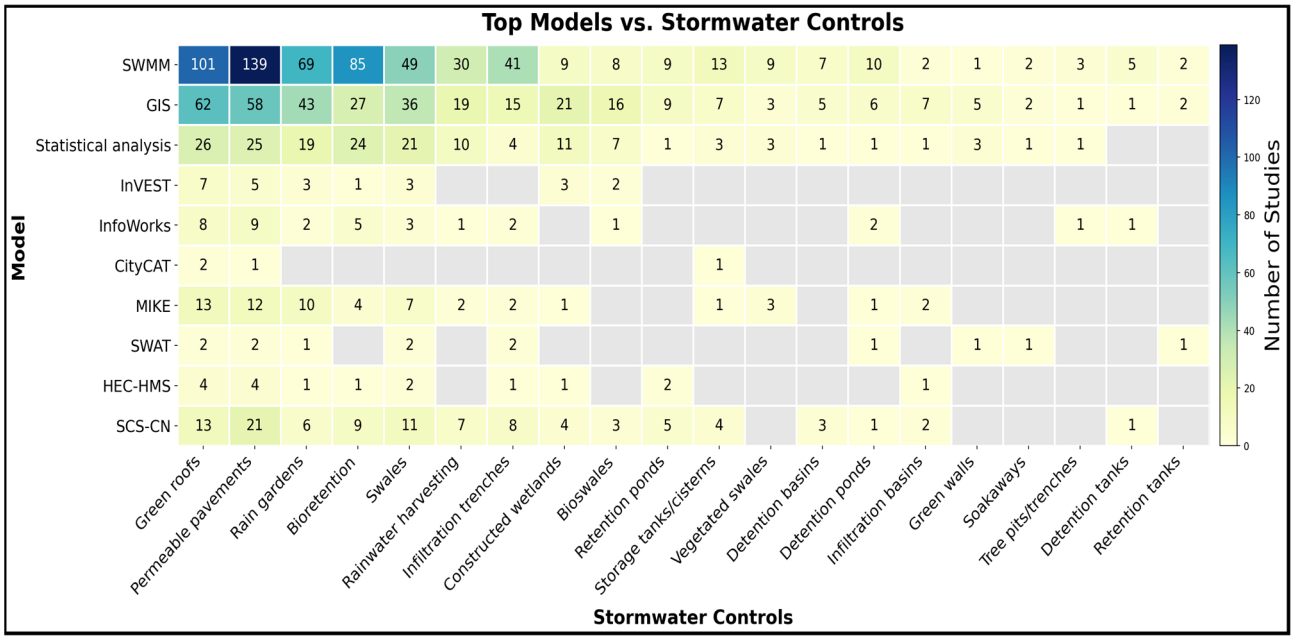


Figure 9. Comparison of modelling tools and applied stormwater controls.

Two patterns are notable. First, the concentration of modelling effort within SWMM is striking: SWMM accounts for non-zero associations across nearly all stormwater control categories, whereas most other models are limited to handful of control types. This reflects both the technical capabilities of SWMM and a degree of path dependency in the field, where familiarity, available tutorials, and prior calibration datasets may reinforce model selection choices. Second, the stormwater controls themselves are unevenly studied: green roofs, permeable pavements, rain gardens, and bioretention collectively dominate the model control matrix, while controls such as constructed wetlands, vegetated swales, retention crates, and French drains receive substantially less modelling attention. This uneven coverage limits the evidence base available for comparative assessment of less studied controls and should be addressed in future research.

3.6. Climate Change Consideration

Climate change is increasingly integrated into urban flood risk assessments using a variety of methodological approaches [46,47]. Many studies apply IPCC-based climate scenarios, particularly RCP4.5 and RCP8.5, while others rely on simplified rainfall intensity increments or synthetic design storms [26,33,34]. Differences in scenario selection, downscaling techniques, and temporal resolution introduce considerable methodological uncertainty. This inconsistency reduces the robustness of cross-study comparison and highlights the need for more harmonised modelling frameworks and transparent scenario justification in future research. Figure 10 presents the geographic distribution of climate scenario applications. The findings highlight that most studies rely on simplified design-based

climate change representations, such as rainfall intensity increase scenarios, rather than formal IPCC pathways. Among IPCC-consistent scenarios, RCP4.5 and RCP8.5 are most frequently adopted, while SSP-based scenarios and global warming level approaches remain limited. A substantial proportion of studies either rely on baseline climatic conditions or do not explicitly define a climate change scenario.

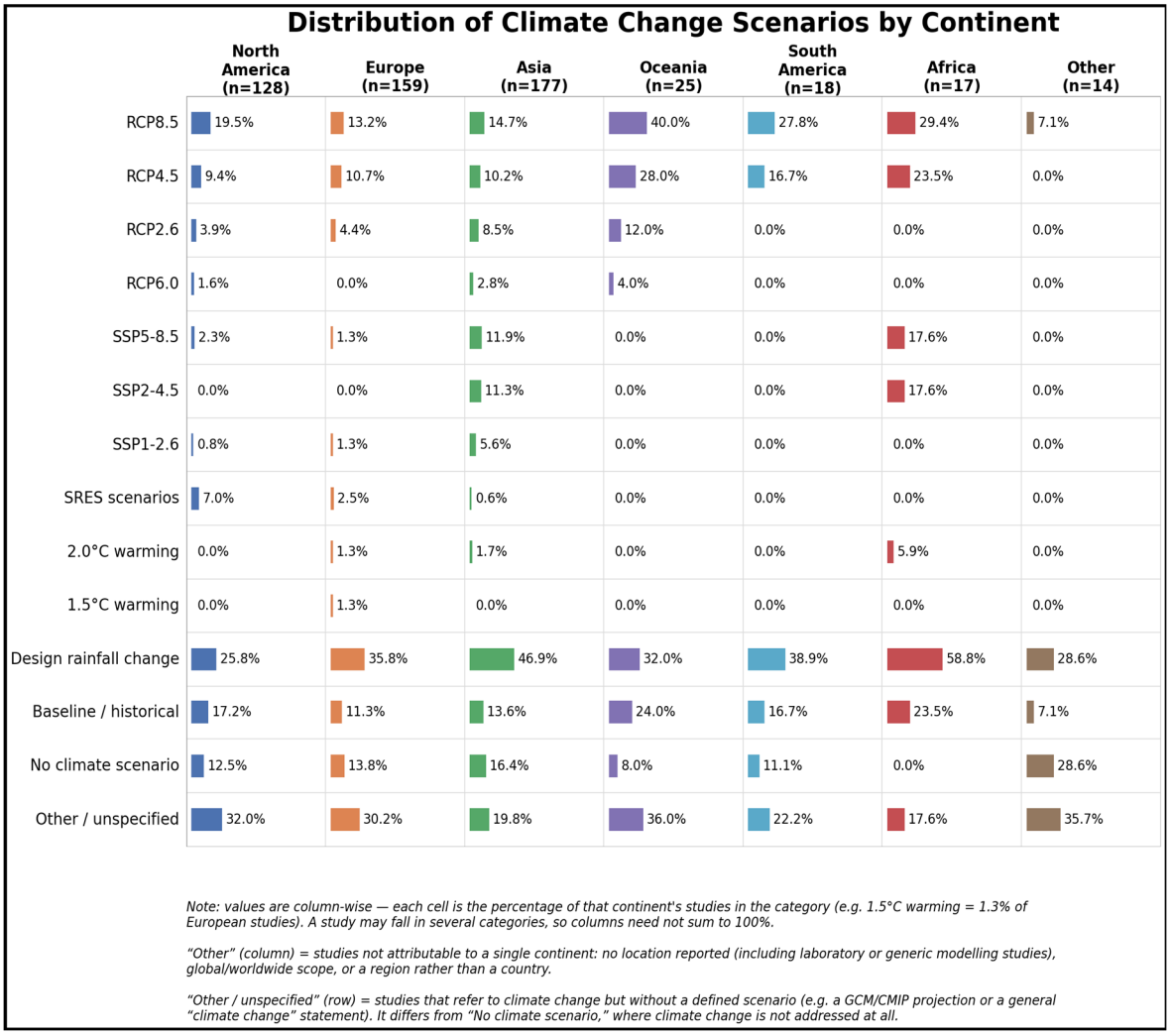


Figure 10. Distribution of climate change scenarios by continent.

This systematic review shows that NBS/BGI are widely studied and are generally effective in reducing urban pluvial flooding impacts. Previous research notes that "there have been numerous investigations on the performance of blue–green infrastructure under moderate rain events", while empirical evidence showed that the retrofitted stormwater system performed successfully during the extreme events [37]. However, the current evidence base is still difficult to compare across cities because studies use different approaches to evaluate performance. For example, some studies assess impacts using total flood volume and average flood duration as system performance indicators, whereas others focus on three main aspects of the water balance, namely, infiltration, runoff, and storage [36,48]. The same issue appears in climate scenario practice. Some studies consider future precipitation intensities based on the RCP8.5, while others use three different scenarios, SSP1-2.6, SSP2-4.5, and SSP5-8.5 [24,36].

Classification of Climate Change Scenario Approaches

To systematically characterise the diversity of climate change representations adopted across the reviewed literature, a three-tier classification framework was developed and applied to all 538 retained studies. This classification distinguishes between: (i) studies employing formal IPCC emission pathway scenarios, (ii) studies that are climate-informed but do not adopt standardised IPCC pathways, and (iii) studies that include no explicit climate change scenario. The classification criteria are defined in Table 4, and the distributional results are presented in Figure 11.

Table 4. Three-tier classification of climate change scenario approaches. Sub-category counts are multi-labelled (a single study may use multiple pathways); subtotals reflect unique studies per tier.

Tier	Category	Sub-Category	*n*	% of 538
Tier 1	Formal IPCC emission pathway scenarios	RCP8.5/SSP5-8.5 (high emission)	120	22.3
		RCP4.5/SSP2-4.5 (moderate emission)	82	15.2
		RCP2.6/SSP1-2.6 (low emission)	42	7.8
		CMIP6 ensemble (multi-scenario)	29	5.4
		CMIP5/CMIP3 ensemble	27	5.0
		Warming levels (1.5 °C/2 °C)	8	1.5
		SRES pathways (A1B, A2)	14	2.6
		RCP6.0	8	1.5
Subtotal (Tier 1)			164	30.5
Tier 2	Climate-informed, non-IPCC approaches	Design storm/IDF-based	144	26.8
		Trend-based (increased intensity/frequency)	70	13.0
		Qualitative/conceptual framing	66	12.3
		Historical/observed data only	43	8.0
Subtotal (Tier 2)			216	40.1
Tier 3	No explicit climate scenario	No identifiable climate representation	158	29.4
Subtotal (Tier 3)			158	29.4
Total			**538**	**100.0**

Note: RCP = Representative Concentration Pathway; SSP = Shared Socioeconomic Pathway; SRES = Special Report on Emission Scenarios; CMIP = Coupled Model Intercomparison Project; IDF = intensity–duration–frequency. Counts derived from the 538-study dataset.

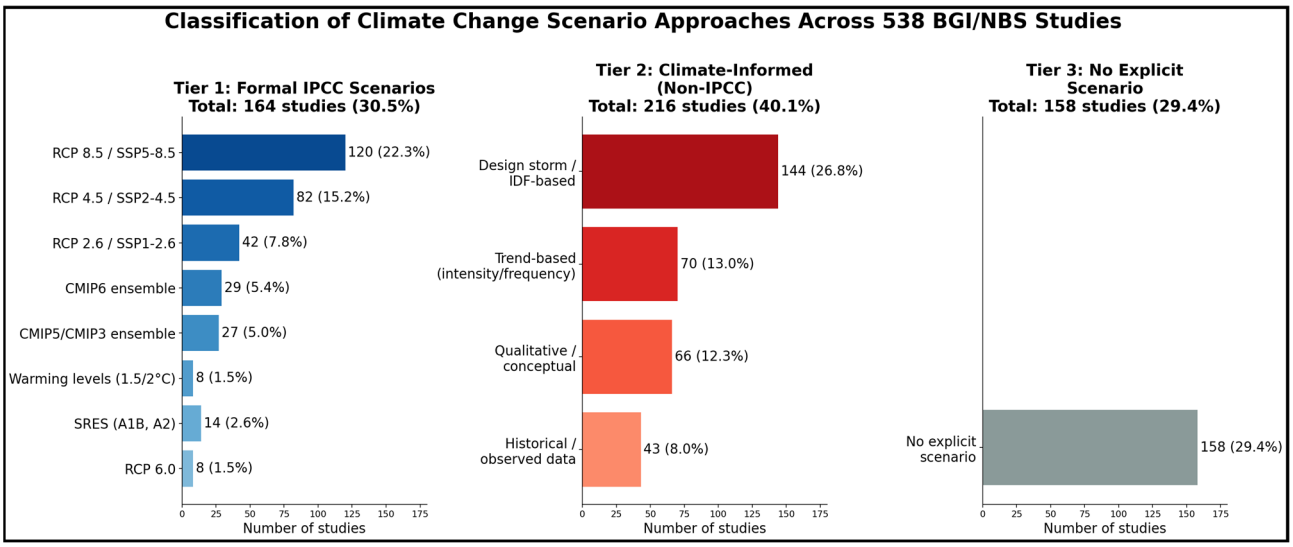


Figure 11. Distribution of climate change scenario approaches across the three tiers and their sub-categories.

Tier 1: Formal IPCC emission pathway scenarios (n = 164; 30.5%). This tier comprises studies that explicitly adopt at least one IPCC-consistent emission pathway, including Representative Concentration Pathways (RCPs), Shared Socioeconomic Pathways (SSPs), or earlier SRES scenarios, and/or employ outputs from CMIP5 or CMIP6 general circulation model ensembles. Within this tier, RCP8.5 and its SSP5-8.5 equivalent dominate (120 studies; 22.3%), followed by RCP4.5/SSP2-4.5 (82 studies; 15.2%) and RCP2.6/SSP1-2.6 (42 studies; 7.8%). CMIP6-based ensemble projections appear in 29 studies (5.4%), while CMIP5/CMIP3 ensemble approaches account for 27 studies (5.0%). Older SRES pathways (A1B, A2) are used in 14 studies (2.6%), global warming level approaches (±1.5 °C or +2 °C) in 8 studies (1.5%) and PCP6.0 in a further 8 studies (1.5%). The dominance of high-emission pathways (RCP 8.5/SSP5-8.5) suggests a tendency in the BGI/NBS literature towards worst-case stress testing rather than balanced multi-scenario assessment. This bias is likely driven by three factors: the engineering convention of designing to worst-case conditions, the wider availability of pre-packaged downscaled datasets for RCP8.5 (e.g., EURO-CORDEX, NARCCAP, NEX-GDDP), and the framing of many studies around 'maximum credible impact' narratives, rather than probabilistic multi-pathway comparison.

Tier 2: Climate informed, non-IPCC approaches (n = 216; 40.1%). This tier includes studies that acknowledge climate change as a driver of altered rainfall regimes or urban hazard exposure, but do not employ a formally defined IPCC emission pathway. The largest sub-category consists of design storm and IDF-based approaches (144 studies; 26.8%), which use return-period analysis or synthetic hyetographs (e.g., Chicago design storm, KOSTRA distributions) to stress-test BGI performance under extreme conditions, effectively treating engineering design standards as climate proxies. Trend-based representations follow (70 studies; 13.0%), in which authors reference increasing rainfall intensity or frequency without specifying a pathway, time horizon, or downscaling method. Qualitative or conceptual framing (66 studies; 12.3%) cites IPCC reports or national adaptation strategies as motivation without modelling, while 43 studies (8.0%) rely exclusively on historical or observed rainfall datasets without future projection.

Tier 3: No explicit climate change scenario (n = 158; 29.4%). These studies contain no identifiable climate change representation in their scenario field. While many address stormwater management or BGI design, they do not frame their analysis within a climate change context, even qualitatively. This does not necessarily mean that climate change is absent from these papers entirely; rather, it is not operationalised as a scenario variable within their modelling or evaluation framework.

The classification reveals that only 30.5% of reviewed studies employ formal IPCC emission pathway scenarios, while the majority (69.5%) either adopt non-standardised climate-informed approaches or include no explicit climate scenario. This distribution constitutes a significant methodological finding in itself: the field of BGI/NBS urban flood mitigation research has not yet converged on a standardised climate scenario practice. The heterogeneity in scenario selection, combined with differences in downscaling techniques, temporal horizons, and spatial resolution, introduces considerable uncertainty into cross-study comparison and limits the capacity for robust evidence synthesis.

3.7. Emerging Themes and Underrepresented Literatures

While the preceding sections have mapped the dominant modelling tools, stormwater controls, and climate scenario practices, several important and rapidly growing sub-literatures remain underrepresented in the reviewed dataset. Identifying these gaps is essential for guiding future research priorities and ensuring that the evidence base for BGI/NBS implementation keeps pace with evolving challenges.

3.7.1. Sponge City Programme

China's Sponge City Programme represents the largest national-scale BGI implementation initiative globally, encompassing 30 pilot cities since 2015 and generating a substantial body of applied research on permeable pavements, bioretention, rain gardens, and urban wetlands at catchment and city scales [27,49,50]. Although many Chinese case studies appear in the reviewed dataset, they are not systematically examined through the lens of the Sponge City policy framework, which provides unique insights into governance mechanisms, investment models, and performance standards for large-scale BGI deployment. Future reviews should explicitly address this programme as a distinct policy-driven evidence stream.

3.7.2. Machine Learning and AI-Augmented Modelling

The application of machine learning (ML) and artificial intelligence (AI) to urban stormwater management is expanding rapidly, yet these approaches are largely absent from the reviewed literature. Recent advances include deep reinforcement learning for real-time control of distributed stormwater detention systems [51], model predictive control using evolutionary algorithm optimisation for active flood management [52], and logical-base control strategies for adaptive real-time control of distributed BGI systems [38]. Digital twin frameworks that integrate sensor data, ML-based forecasting, and dynamic BGI operation represent an emerging frontier. The limited representation of these methods in the present dataset suggests that the field of BGI/NBS research has not yet fully integrated data-driven approaches, despite their potential to address the computational constraints and uncertainty challenges identified in Section 3.5.

3.7.3. Compound and Cascading Hazards

While the reviewed studies predominantly address pluvial flooding as an isolated hazard, urban flood risk is increasingly understood as a compound phenomenon involving the simultaneous or sequential occurrence of pluvial, fluvial, and coastal flood drivers [53]. The interaction between storm surge, riverine backwater, and intense local rainfall can produce flood impacts that exceed the sum of individual hazards, yet fewer than 5% of the reviewed studies consider such compound events. This gap is particularly critical for coastal cities where sea-level rise may progressively reduce the drainage capacity of BGI/NBS systems. Future research should prioritise multi-hazard simulation frameworks that assess BGI/NBS performance under compound flood scenarios.

3.7.4. Cost–Benefit and Life-Cycle Analysis

Economic evaluation is a critical dimension of BGI/NBS decision-making, yet the reviewed dataset contains very few studies that systematically apply cost–benefit analysis (CBA) or life-cycle assessment (LCA) to BGI/NBS interventions. Ossa-Moreno et al. (2017) [54] demonstrate that the economic case for BGI/NBS depends strongly on the inclusion of co-benefits (e.g., amenity value, carbon sequestration, heat mitigation), while Vineyard et al. (2015) [55] show that life-cycle environmental impacts can vary substantially across different BGI/NBS typologies. The absence of standardised economic metrics limits the ability of planners and decision-makers to compare BGI/NBS with conventional grey infrastructure on a like-for-like basis and should be addressed as a priority in future research.

3.7.5. Environmental Justice and Equitable Distribution

A growing body of literature examines the equitable distribution of BGI/NBS co-benefits across urban populations, with evidence suggesting that socially vulnerable communities often have the least access to green infrastructure and its associated services [56].

While a small number of reviewed studies touch on spatial equity in BGI siting, the broader literature on environmental justice, procedural equity in BGI/NBS governance, and distributional analysis of flood risk reduction benefits remains under-integrated. Given that climate change impacts are disproportionately borne by vulnerable populations, future BGI/NBS research should explicitly incorporate equity metrics alongside hydrological performance indicators.

3.8. Quality of Evidence Classification

To avoid treating all 538 reviewed studies as equivalent in evidential authority, a three-level quality-of-evidence classification was developed, drawing on the IPCC AR5 guidance on consistent treatment of uncertainties [1], the Collaboration for Environmental Evidence systematic review standards [57], and the adaptation of this approach to NBS evidence synthesis by Sudmeier-Rieux et al. (2021) [58]. Three criteria were selected because they are the dimensions most directly controlling the transferability of the review's findings under future climate conditions. These three criteria were applied in combination rather than individually, reflecting the IPCC convention that high confidence requires convergence of multiple evidence dimensions rather than strength on a single axis alone: (a) model calibration and validation status, (b) climate scenario formality (Tier 1, 2, or 3 as defined in Section Classification of Climate Change Scenario Approaches), and (c) the nature of the assessment approach (empirical field data versus purely simulation-based). Studies were classified into three levels:

- Level A (high confidence): Studies employing a calibrated and validated hydrological model (or empirical field monitoring), using a formal IPCC climate scenario (Tier 1), and reporting quantitative performance indicators with uncertainty or sensitivity analysis. These studies provide the strongest basis for transferable conclusions about BGI/NBS effectiveness under climate change.
- Level B (medium confidence): Studies employing a calibrated simulation model with design storm or trend-based climate input (Tier 2), or studies using formal IPCC scenarios but without documented model calibration. These studies provide useful evidence but with greater transferability limitations.
- Level C (low confidence): Studies using uncalibrated models or qualitative/ conceptual frameworks, with no explicit climate scenario (Tier 3) or only qualitative framing. These studies contribute to understanding research trends and identifying knowledge gaps but provide limited basis for quantitative comparison of BGI/NBS performance.

Applying this classification to the 538 reviewed studies yields the following distribution: Level A (high confidence), approximately 75 studies (13.9%); Level B (medium confidence), approximately 237 studies (44.1%); and Level C (low confidence), approximately 226 studies (42.0%). This distribution reveals that fewer than one in five studies in the current BGI/NBS evidence base meets the highest standard of evidential rigour, combining calibrated modelling, formal climate scenarios, and quantitative performance reporting. The majority (44.1%) occupy a middle ground in which either model validation or climate scenario specification is incomplete. Critically, more than 40.0% of the evidence base provides limited basis for quantitative transferability. This quality gradient should inform how findings are weighted in future meta-analytic syntheses and policy recommendations. Unlike general appraisal tools such as ROBIS, AMSTAR-2, or MMAT, which assess overall review conduct or clinical study designs, this classification was tailored to the specific problem of this review: how reliably a study's evidence transfers to future climate conditions. It is therefore a focused, fit-for-purpose heuristic based on the three criteria above, rather than a general measure of study quality.

4. Discussion, Limitations, and Conclusions

This review shows that nature-based solutions (NBS) and blue–green infrastructure (BGI) are widely studied and reported as beneficial measures for managing urban pluvial flood risk. Across the 538 studies analysed, the reviewed literature broadly reports that interventions such as green roofs, bioretention systems, permeable pavements, and retention features consistently reduce runoff volumes, attenuate peak flows, and enhance storage and infiltration, while delivering co-benefits for urban liveability and ecosystem services, although the magnitude of these effects varies with local context and study design. These findings align with established evidence demonstrating the capacity of decentralised, infiltration-based systems to improve hydrological performance under both extreme events and urbanisation pressures [36,37]. A formal quantitative synthesis of effectiveness was not undertaken, however, because the heterogeneity of reported performance indicators, spatial scales, and climate assumptions precludes valid pooling, a limitation that is itself a central finding of this review and that motivates the call for standardized performance indicators. The evidence base remains geographically skewed towards North America, China, and Europe, constraining transferability to underrepresented regions with differing climatic, socio-economic, and infrastructural contexts.

A central finding is that, while the effectiveness of BGI/NBS is broadly supported, there is limited consistency in how performance is defined and evaluated. The reviewed studies apply diverse and non-standardised indicators, ranging from peak discharge and runoff reduction to inundation depth, flood duration, flooded properties, and broader water balance variables, hindering direct comparison across case studies and climatic settings. This heterogeneity is compounded by divergent modelling approaches, scale of analysis, and treatment of climate change, further limiting the synthesis of generalisable insights.

The three-tier classification of climate scenario practices (Section Classification of Climate Change Scenario Approaches) represents a key methodological contribution. The analysis reveals that only 30% of studies employ formal IPCC emission pathway scenarios (Tier 1), while a large proportion (40%) adopt non-standardised, climate-informed approaches (e.g., trend-based intensity assumptions, design storm intensification, or qualitative conceptual framing; Tier 2), and 29% omit explicit climate scenario representation (Tier 3). Consequently, fewer than one-third of the studies can be placed within a coherent, internationally comparable climate risk framework. Within Tier 1, the predominance of high-emission scenarios (RCP8.5/SSP5-8.5; 22% of studies) introduces a systematic bias towards worst-case assessments. While stress-testing under high-emission conditions is valuable for establishing engineering design margins and identifying system failure thresholds, the relative scarcity of analyses under moderate- (RCP4.5/SSP2-4.5; 82 studies) and low- (RCP2.6/SSP1-2.6; 42 studies) emission pathways implies that the evidence base inadequately informs decision-making under the most policy-relevant mitigation scenarios, including those consistent with the Paris Agreement targets. Furthermore, the limited uptake of SSP-based and CMIP6-driven projections (5% of studies) indicates a lag in integrating the latest climate science. Future research should therefore prioritise multi-scenario assessments spanning at least two contrasting emission pathways and multiple time horizons (near-term 2030–2050 and long-term 2070–2100) to enable robust and policy-relevant comparison of BGI performance.

The large proportion of studies in Tier 2 that rely on design storm intensification or return period analysis (27%), while pragmatic and widely used in engineering practice, conflates engineering safety margins with climate projection in ways that are rarely made explicit. A 10–20% intensity increase applied to an IDF curve, for example, may or may not correspond to any specific emission pathway, downscaling method, or temporal horizon, making it difficult to place such results within a coherent climate risk framework or to

compare them with GCM-driven analyses. Similarly, 13% of studies relying on trend-based representations, e.g., statements such as "increasing frequency and intensity of extreme rainfall", without pathway specification provide qualitative motivation but do not enable quantitative cross-study synthesis. To address these limitations, this review advocates for a harmonised reporting protocol requiring explicit documentation of emission scenarios, climate models, downscaling methods, temporal horizons, and baseline reference periods. Such a protocol would substantially improve the comparability and policy relevance of future BGI/NBS flood mitigation research.

It should be noted that the study's inclusion criterion requiring studies to have "considered climate change, extreme rainfall, or future rainfall scenarios" was deliberately formulated as a disjunctive (OR) filter. The intent was not to restrict the review to studies with formal IPCC scenario modelling, but rather to capture the full spectrum of how climate change is operationalised in BGI/NBS research from rigorous GCM-downscaled projections to engineering design storm proxies and qualitative framing. This broad criterion was adopted precisely because the degree and nature of climate scenario integration was itself a key dimension of analysis, and the three-tier classification makes this rationale explicit and transparent. The resulting dataset enables not only the synthesis of hydrological findings but also a critical assessment of the methodological maturity of climate change integration in the field.

The review also highlights the continued dominance of SWMM and related hydrological–hydraulic modelling tools in urban stormwater research, reflecting their wider accessibility, as well as flexibility and capacity to simulate rainfall runoff processes, drainage networks, and stormwater control measures in considerable detail. However, model prevalence should not be conflated with methodological certainty. Significant sources of uncertainty persist in BGI research, including network configuration effects, fine-scale land cover variability, climate uncertainty, and noise in urban flow monitoring data [59]. These uncertainties are further amplified under prolonged or high-intensity rainfall events, where the performance of GI networks is difficult to detect from monitoring records alone. Moreover, performance metrics influence performance, where peak flow reductions are often more detectable than changes in total runoff volume, contributing to divergent findings across studies. When combined with the heterogeneity in climate scenario practices identified in the three-tier classification, these modelling uncertainties substantially limit cross-study comparability and transferability of results.

A further critical insight is that BGI/NBS interventions are not always sufficient as standalone solutions, especially under extreme rainfall conditions. While their effectiveness in attenuating frequent, low-to-moderate events is well established, several studies indicate diminishing performance under high-intensity storms [60]. Emerging evidence increasingly supports hybrid approaches that integrate grey infrastructure and BGI/NBS, demonstrating enhanced robustness and adaptability across a wider range of hydrological conditions. This reinforces a paradigm shift from viewing grey and green infrastructure as substitutes towards recognising them as complementary components within integrated urban drainage systems. More broadly, the field has moved beyond demonstrating whether BGI/NBS can be effective, to addressing the conditions under which they perform optimally, their reliability under uncertainty, and their scalability in real-world contexts. A key limitation of the current evidence base is its strong reliance on modelling, often with limited long-term empirical validation. Model outputs remain sensitive to assumptions regarding soil properties, drainage connectivity, calibration parameters, and rainfall inputs, which constrains generalisability. At the same time, empirical monitoring presents its own challenges, including data noise and difficulties in isolating intervention effects within complex urban systems [59]. Additionally, many studies continue to adopt simplified or

fixed parametrisations and non-standard climate representations, as reflected in the prevalence of Tier 2 scenario practices. While these approaches are pragmatic, they can influence conclusions regarding long-term resilience under changing climatic conditions.

A principal limitation identified in this review is the fragmentation of climate scenario practices, evidenced by the three-tier classification. Hence, any comparative synthesis of BGI effectiveness under future climate conditions must be interpreted against this structural constraint. A second limitation concerns gaps in evidence scope. Despite the increasing importance of compound and cascading hazards in urban flood risk, fewer than 5% of studies explicitly address such conditions. Furthermore, the literature is overwhelmingly dominated by plot- or parcel-scale analyses, with only ~1% of studies explicitly operating at catchment scale, which is the scale most relevant for strategic urban flood management. This skewed emphasis limits understanding of system-wider hydrological behaviour and scalability of BGI/NBS interventions. A third limitation relates to transferability and validation. The geographical concentration of studies in North America, China, and Europe restricts applicability of findings to other climatic and institutional contexts. Comparative assessment of green, grey, and hybrid systems remains uneven, despite growing evidence that integrated strategies outperform stand-alone BGI/NBS under severe conditions. Moreover, the predominance of simulation-based analyses, often with limited long-term empirical validation, constrains confidence in generalising findings beyond specific modelling assumptions and local conditions.

Regarding the methodology of this review itself, several points warrant transparency. The data extraction was primarily performed by the lead reviewer; to verify reproducibility, a random subset of 125 articles were independently re-coded by a second reviewer, yielding Cohen's $\kappa = 0.76$–0.95 across all six extraction dimensions (Section 2.5), confirming substantial to near-perfect agreement. While the automated keyword-based screening was validated through confusion-matrix assessment (Section 2.4), the multi-dimensional coding of hazard type, stormwater control, model, indicator, and climate scenario across 538 papers introduces inherent subjectivity, particularly in boundary cases where studies use hybrid or ambiguous approaches. To address the risk of treating all studies as equivalent in evidential authority, a three-level quality-of-evidence classification (high/medium/low) was applied based on model calibration status, climate scenario formality, and assessment approach (Section 3.8). The resulting distribution, with approximately one in eight studies (~12%) achieving Level A (high confidence), provides a structured basis for weighting evidence in future meta-analytic syntheses and policy recommendations. It is acknowledged that this quality classification is simplified relative to formal instruments such as ROBIS or AMSTAR-2; however, it represents a meaningful advance over zero-weighting approaches that are common in mapping reviews of this scale.

Despite these limitations, the review provides a comprehensive synthesis of 538 studies, clarifying patterns in hazard focus, intervention types, modelling approaches, performance indicators, and climate scenario practices. The review reveals that urban pluvial flooding is the dominant hazard addressed in the literature, that green and infiltration-based measures are the most frequently studied controls, and that SWMM remains the most widely used model. Critically, the three-tier classification reveals that the field is still characterised by deep methodological fragmentation in climate change representation, with a systematic bias towards high-emission stress-testing and a large body of work operating outside formal IPCC scenario frameworks. This is an important finding because it explains why the literature, although extensive, is still difficult to compare in a systematic and transferable way, and it provides a concrete diagnostic for where harmonisation efforts should be directed.

In conclusion, NBS and BGI are critical components of climate-resilient urban flood management, but their effectiveness is strongly shaped by context, modelling choices,

and implementation conditions. Advancing the field requires: (i) multi-scenario analyses spanning contrasting emission pathways with transparent reporting of downscaling methods and baselines; (ii) increased use of the GCM-driven projections over simplified design storm proxies; (iii) standardised performance indicators to enable direct cross-study comparison; and (iv) expanded empirical validation, particularly at catchment scale, in underrepresented regions, and under compound/extreme conditions. Such advances are essential to support robust, scalable, and policy-relevant implementation of BGI/NBS under increasingly uncertain climate conditions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su182110994/s1, Table S1: Peer-reviewed literature used within the analysis (N = 538); Table S2: Per-study classifications of the 538 included studies; Table S3: PRISMA 2020 checklist.

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