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Rohit Patel and Manoj Kumar

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Review Paper

Urban Flood Assessment Methods and Implications for Resilience Planning: A PRISMA-Based Systematic Review Supported by Bibliometric Analysis

Rohit Patel*, Manoj Kumar

Department of Architecture and Planning, National Institute of Technology Patna-800005, Bihar, India

* Corresponding author: rohitp.pg17.ar@nitp.ac.in

Abstract: Urban flooding has intensified as a result of rapid urbanization, increasing impervious surface coverage, and more frequent extreme rainfall events associated with climate change. This study employs a PRISMA-guided systematic review complemented by bibliometric and thematic analyses to examine recent developments in urban flood research. From 489 records retrieved from the Web of Science Core Collection, 207 peer-reviewed studies were selected following a structured screening process. A study-level coding framework was applied to classify methodological approaches and thematic domains. Hydrological and hydraulic modeling emerged as the most frequently applied methodological category (n = 134), followed by planning and resilience approaches (n = 81), machine learning (n = 54), GIS-based analysis (n = 52), and remote sensing techniques (n = 37). Four major thematic domains were identified: flood modeling and simulation, flood mapping and detection, environmental and climatic drivers, and planning and resilience strategies. The findings indicate a progressive shift from conventional process-based flood simulation toward integrated approaches that combine geospatial technologies, machine learning, and data-driven prediction. Land-use change, urbanization, drainage-system limitations, and climate-related rainfall variability were consistently identified as major drivers of urban flooding. Analysis of corresponding-author affiliations indicates that research leadership is concentrated in China, the United Kingdom, and several European countries, while contributions from many developing regions remain comparatively limited. Although resilience-oriented research has expanded in recent years, most studies evaluate interventions through simulation-based scenarios rather than implemented field applications or policy assessments. Persistent challenges include methodological inconsistency, limited uncertainty quantification, transferability of models across urban contexts, insufficient integration of socio-economic dimensions, and the translation of scientific findings into effective urban flood-management and climate-resilience strategies.

Keywords: Urban Flooding; PRISMA; Systematic Analysis; GIS; Remote Sensing; Hydrological Modeling; Flood Mapping; Climate Change; Urban Resilience

1. INTRODUCTION AND BACKGROUND

1.1. Urban Flooding as a Complex Urban–Climate Challenge

Urban flooding has emerged as a critical manifestation of the interaction between rapid urbanization and intensifying climate variability, posing significant challenges to infrastructure, ecosystems, and human well-being across both developed and developing regions (Gao et al., 2022; C. Li et al., 2024; O'Donnell et al., 2019). Unlike fluvial flooding, urban flooding, particularly pluvial flooding, is primarily driven by high-intensity rainfall exceeding the infiltration and drainage capacity of built environments, leading to rapid surface water accumulation in densely developed areas (Berger et al., 2026; Koko, 2021).

The transformation of permeable landscapes into impervious surfaces is widely recognized as a dominant driver of altered urban hydrology. Increasing imperviousness reduces infiltration, accelerates runoff generation, and shortens hydrological response times, thereby increasing flood peaks and frequency (Owen, 1998; Ro, 2021). These effects are particularly pronounced in rapidly urbanizing regions, where unplanned development, inadequate drainage infrastructure, and informal settlements exacerbate flood vulnerability (Sakib et al., 2023; Y. Zhu et al., 2024). Empirical studies consistently demonstrate that urban expansion and land-use change significantly amplify runoff coefficients and flood susceptibility across metropolitan regions (Al-Zahrani et al., 2017; Liang et al., 2025; Movahedinia et al., 2019; Vamvakeridou-Lyroudia, Chen, Khoury, Gibson, Kostaridis, Stewart, Wood, & Djordjevic S. and Savic, 2020).

Climate change further intensifies these dynamics by increasing the frequency and magnitude of extreme precipitation events. Observational and modeling studies indicate that short-duration, high-intensity rainfall events are becoming more common, overwhelming existing stormwater systems and increasing urban flood risk (Kim & Han, 2020; T. Li et al., 2021; Sim & Kim, 2024; Zheng et al., 2023). This convergence of climatic and anthropogenic drivers positions urban flooding as a systemic socio-ecological challenge rather than an isolated hydrological phenomenon. Beyond physical damage to infrastructure, urban floods disrupt transportation networks, degrade water quality, increase public health risks, and generate substantial economic losses (Cui et al., 2023; Sakib et al., 2023; W. Zhu et al., 2022).

Despite growing recognition of these impacts, the understanding of urban flooding remains fragmented across disciplinary boundaries, with hydrology, remote sensing, urban planning, and climate science often operating in parallel rather than integrated frameworks. This fragmentation limits the ability to develop comprehensive and scalable solutions for urban flood resilience.

1.2. Methodological Evolution in Urban Flood Assessment

The assessment of urban flooding has undergone a significant transformation, evolving from physically based hydrological modeling toward integrated geospatial and data-driven analytical frameworks. Traditional approaches rely heavily on hydrological and hydraulic models, such as SWMM, HEC-RAS, and HEC-HMS, which simulate runoff generation, flow routing, and flood inundation under varying rainfall and land-use conditions (Choo et al., 2021; Son et al., 2023; Swathi et al., 2019). These models provide detailed process-based understanding but are often constrained by data requirements, calibration complexity, and computational intensity.

Advancements in remote sensing and GIS technologies have enabled large-scale monitoring and spatial analysis of urban flooding. Satellite platforms such as Landsat and Sentinel, along with Synthetic Aperture Radar (SAR), provide multi-temporal datasets for mapping flood extent, detecting inundation dynamics, and analyzing land-use change (Han et al., 2021; Kruczkiewicz et al., 2021; Ma et al., 2023; Muro, 2019). SAR-based techniques are particularly valuable due to their ability to penetrate cloud cover, making them suitable for real-time flood detection during extreme weather events. The integration of remote sensing with GIS facilitates spatial overlay analysis, flood susceptibility mapping, and identification of high-risk zones across urban landscapes (Gulshad et al., 2024; Kaur et al., 2025; S. Lee et al., 2018).

More recently, machine learning and deep learning approaches have emerged as powerful tools for flood prediction and susceptibility assessment. Algorithms such as Random Forest, Support Vector Machines, and Artificial Neural Networks are increasingly applied to model complex, non-linear relationships between flooding and its driving variables, including rainfall intensity, topography, land use, and drainage characteristics (Chen et al., 2024; J. Li et al., 2024; Piadeh et al., 2023; Rahmati et al., 2019). These methods often demonstrate higher predictive accuracy and scalability compared to traditional models, although they may lack interpretability and physical grounding.

1.3. Research Gap, Novelty, and Study Objectives

Although the body of literature on urban flooding has expanded rapidly in recent years, several critical gaps remain. First, existing research is highly fragmented across methodological domains, including hydrological modeling, remote sensing analysis, and machine learning-based prediction, with limited efforts to integrate these approaches into a unified analytical framework (Lischeid et al., 2010; Mosavi et al., 2018; Teng, 2020). Second, there is a lack of systematic and quantitative synthesis of the field that combines bibliometric mapping with thematic and methodological analysis. While individual studies provide valuable insights, the absence of comprehensive reviews limits the ability to identify overarching trends, dominant research clusters, and methodological evolution (Cobo et al., 2011; Donthu et al., 2021; Fahimnia et al., 2015).

Third, geographic representation within the literature is uneven, with a strong concentration of studies in regions such as China, India, and the United States, while many rapidly urbanizing areas in Africa and South America remain underrepresented (Dottori et al., 2016; Jongman, 2018; Tellman et al., 2021). Fourth, governance, planning, and policy evaluation appear less represented within the reviewed dataset compared to technical and environmental dimensions. However, this pattern should be interpreted in light of the study's search strategy, which prioritized empirical studies employing geospatial, hydrological, hydraulic, and machine-learning approaches. Consequently, qualitative and governance-oriented resilience research may be underrepresented in the analyzed literature (Rogger et al., 2017; Vamvakeridou-Lyroudia et al., 2020). Finally, the lack of standardized metrics for flood assessment—such as flood depth, inundation extent, and risk indices, hampers quantitative comparison and synthesis across studies (Apel et al., 2009; Jongman et al., 2012; Merz et al., 2010).

In response to these limitations, this study introduces a PRISMA-based systematic review integrated with bibliometric network analysis and thematic synthesis to provide a comprehensive and reproducible assessment of global urban flood research. Unlike conventional reviews that focus on specific methodologies or regional case studies, this study adopts a multi-dimensional analytical framework that combines:

- structured literature screening using WOS Core Collection
- keyword co-occurrence and temporal evolution analysis using bibliometric tools
- thematic classification of methodological, environmental, and planning dimensions
- quantitative comparison of extractable flood-related indicators

The novelty of this study lies in its integrated methodological approach, which bridges quantitative bibliometric mapping with qualitative thematic interpretation and empirical comparison. By synthesizing diverse strands of urban flood research within a unified framework, the study advances understanding of the field's intellectual structure, methodological progression, and emerging research frontiers.

The specific objectives of this study are to:

- analyze global publication trends in urban flood research
- identify dominant research clusters through keyword co-occurrence analysis
- evaluate methodological evolution in flood assessment techniques
- evaluate how findings from technical flood assessment studies contribute to resilience planning and mitigation strategies

Through this comprehensive approach, the study contributes to a deeper understanding of urban flooding as a complex, multi-scalar phenomenon and provides a structured knowledge base to support sustainable urban planning and flood resilience strategies.

2. MATERIALS AND METHODS

This study adopts a mixed-method research design integrating a PRISMA-guided systematic review, bibliometric network analysis, and thematic content synthesis to provide a transparent, reproducible, and quantitatively grounded assessment of global urban flood research. The methodological framework is structured to ensure rigor in literature identification and screening while enabling quantitative mapping of research evolution, thematic clusters, and geographic distribution. By combining systematic review protocols with bibliometric visualization and qualitative synthesis, the study addresses fragmentation in existing urban flood scholarship and enables a multi-dimensional interpretation of the field.

The overall methodological workflow comprises four sequential stages: (1) database search and record identification, (2) PRISMA-based screening and eligibility assessment, (3) bibliometric mapping and statistical trend analysis, and (4) thematic content synthesis (Page et al., 2021a).

2.1. The PRISMA Framework

The PRISMA framework was employed to systematically collect, screen, and analyse articles from the Web of Science (WOS) database. This method ensures transparency and reproducibility, which are vital for academic rigor (Chaudhuri & Kumar, 2022; Fu et al., 2022). The WOS Core Collection was selected as the sole database for this study due to its high-quality indexing standards, rigorous journal selection process, and structured citation metadata, which are essential for reliable bibliometric network construction. WOS is widely adopted in systematic reviews and bibliometric analyses because it ensures consistency in bibliographic records and minimizes duplication across indexed sources. However, it is acknowledged that reliance on a single database may limit coverage compared to multi-database approaches incorporating Scopus or Dimensions. A web search was done on March, 2026, as the initial step. Boolean operators (AND, OR) were applied to refine the results and ensure the selection of pertinent studies. The literature search was conducted using the Topic (TS) field, which includes title, abstract, author keywords, and Keywords Plus, thereby enhancing retrieval sensitivity while maintaining thematic relevance.

The search query was designed to capture urban flood research integrating geospatial, hydrological, and environmental dimensions. The exact search query used was: TS= (("urban flood*" OR "urban flooding" OR "pluvial flood*" OR "urban inundation" OR "surface water flood*" OR "flash flood*") AND ("remote sensing" OR GIS OR geospatial OR satellite OR Landsat OR Sentinel OR "hydrological model*" OR "hydraulic model*" OR SWMM OR "HEC-RAS" OR "HEC-HMS" OR "MIKE FLOOD" OR "flood model*" OR "machine learning" OR "deep learning") AND ("climate change" OR "land use" OR "land cover" OR "impervious surface*" OR drainage OR runoff OR precipitation OR rainfall)).

A structured screening process was then applied using predefined inclusion and exclusion criteria (Table 1). Studies were filtered based on relevance to urban flooding, methodological rigor, and alignment with geospatial or hydrological analysis. To ensure consistency in temporal trend analysis and bibliometric comparison, the review was limited to studies published between January 2016 and December 2025. Although the database search was conducted in March 2026, publications from 2026 were not included in the review dataset because the year was incomplete at the time of data collection. The PRISMA flow diagram was revised to conform to PRISMA 2020 recommendations by reporting exclusion reasons separately at each screening stage. This approach improves transparency and enables reproducibility of the study selection process.

Table 1. Criteria for eligible literature through WOS (excluded if not meeting these criteria).

Category	Inclusion Criteria	Exclusion Criteria
Database	Web of Science Core Collection	Other databases
Document Type	Peer-reviewed journal articles	Reviews, conference papers, editorials, book chapters
Language	English	Non-English publications
Timeframe	Publication Period	January 2016 – December 2025
Topical Scope	Explicit focus on urban flooding, pluvial flooding, or urban inundation	Studies not related to urban flood processes
Methodological Relevance	Use of remote sensing, GIS, hydrological/hydraulic modeling, or machine learning	Purely theoretical or descriptive studies without analytical methods

The criteria outlined in Table 1 were applied to ensure methodological consistency and topical relevance throughout the PRISMA screening process. As shown in Table 1, the inclusion criteria prioritize empirical rigor and methodological relevance, ensuring alignment with the study’s objective of synthesizing urban flood research grounded in geospatial analysis, hydrological modeling, and data-driven approaches. It is important to distinguish between the present study as a systematic review and the exclusion of review articles from the analyzed dataset. The objective of this study is to synthesize primary empirical research rather than secondary syntheses. Inclusion of review papers could result in duplication of findings and overrepresentation of studies that have already been summarized in previous reviews. Therefore, only original research articles containing extractable methodological and quantitative information were retained for analysis.

Conference papers were excluded despite their relevance in urban flood and geospatial research because they often present preliminary findings, limited methodological detail, and less standardized reporting compared to peer-reviewed journal articles. Given the study's emphasis on quantitative comparison, reproducibility, and bibliometric network construction, the inclusion of only full-length journal articles ensures greater consistency, reliability, and comparability across the analyzed dataset.

The PRISMA framework provides a structured four-stage approach, Identification, Screening, Eligibility, and Inclusion—allowing systematic filtering of literature while minimizing selection bias. The detailed flow of records through each stage is illustrated in Figure 1.

The literature search was conducted in the WOS Core Collection database using the predefined search query described earlier in this section. The search yielded 489 journal articles, representing the initial dataset for review. This broad retrieval strategy was designed to capture a comprehensive body of scholarship addressing urban flooding in relation to geospatial techniques, hydrological modeling, and environmental drivers.

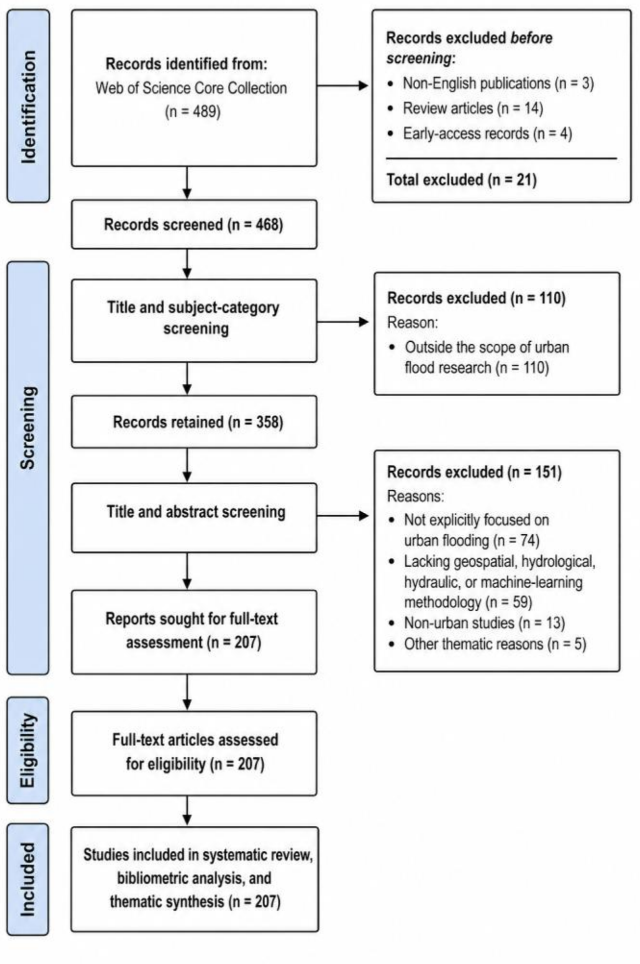

Figure 1. PRISMA framework of the study, Source: PRISMA 2020 (Page et al., 2021b)

During the identification phase, preliminary filtering was applied to remove records that did not meet basic inclusion requirements. During the initial filtering stage, records were excluded according to predefined criteria, including non-English publications (n = 3), review articles (n = 14), and early-access records lacking complete bibliographic information (n = 4), resulting in the exclusion of 21 records in total. After this initial refinement, 468 records progressed to the screening stage.

The screening phase involved a systematic examination of titles, abstracts, and subject categories to assess disciplinary relevance and thematic alignment. Following application of publication-year, language, and document-type filters, 110 records were excluded during title and subject-category screening because they were outside the scope of urban flood research. The remaining 358 records underwent title and abstract screening to assess their relevance to the objectives of this review. During this stage, 151 articles were excluded, including studies not explicitly focused on urban flooding (n = 74), studies lacking geospatial, hydrological, hydraulic, or machine-learning methodologies (n = 59), studies conducted in non-urban settings (n = 13), and records excluded for other reasons, such as insufficient thematic relevance (n = 5). Following this screening process, 207 articles were retained for full-text assessment.

The title and abstract screening process was designed to apply all major eligibility criteria prior to full-text assessment. Consequently, all 207 records that proceeded to full-text review satisfied the predefined inclusion criteria and were retained in the final dataset. Full-text documents were obtained through institutional subscriptions, library services, and publisher repositories whenever available. Importantly, accessibility status was not used as an exclusion criterion. During the eligibility assessment, each article was evaluated against the predefined inclusion criteria: (1) explicit focus on urban flooding, pluvial flooding, or urban inundation; (2) application of geospatial analysis, remote sensing, hydrological or hydraulic modeling, or machine-learning techniques; (3) consideration of environmental or climatic drivers, such as land-use change, runoff, precipitation, or rainfall variability; and (4) empirical investigation within urban or peri-urban settings. Because the major eligibility criteria had already been applied during the title and abstract screening stages, all 207 articles satisfied the inclusion requirements and were retained for the final bibliometric analysis and thematic synthesis.

After comprehensive full-text evaluation, all 207 studies were retained for final analysis. These studies constitute the final dataset used for bibliometric mapping, thematic synthesis, and quantitative interpretation.

The structured progression from 489 initially identified records to 207 included studies, as illustrated in Figure 1, demonstrates the transparency and methodological rigor of the review process. By applying clearly defined criteria at each stage, the study ensures that the final dataset represents a coherent, high-quality, and thematically consistent body of literature on urban flooding.

2.2. Bibliometric Analysis

Bibliometric analysis was conducted to examine the structural characteristics, thematic organization, and temporal evolution of the selected literature. The analysis was performed using VOSviewer (version 1.6.19), which enables visualization of keyword co-occurrence networks and research clusters.

Bibliographic records were exported from WOS in plain text format, including full metadata and cited references. Author keywords were used as the primary analytical unit to represent conceptual focus. Author keywords were selected as the unit of analysis because they provide a direct representation of the conceptual focus of individual studies. The co-occurrence network was constructed using the full-counting method, whereby each occurrence of a keyword contributed equally to the network structure. A minimum occurrence threshold of 1 was applied to retain all author-provided keywords. Initially, 1,075 keywords were identified, of which 1,066 connected keywords were retained in the final network visualization.

It is important to note that bibliometric network analysis provides a descriptive representation of relationships among research themes based on co-occurrence patterns. Such analysis does not establish causal relationships but rather identifies structural tendencies and thematic proximities within the literature. Therefore, interpretations derived from bibliometric outputs should be understood as indicative and are complemented in this study by thematic content analysis and quantitative comparison. The bibliometric procedures described above were designed to provide a reproducible and quantitative foundation for subsequent thematic interpretation. While this section details the analytical workflow, interpretation of network structures, cluster composition, temporal progression, and geographic patterns is presented in the Results section.

2.2.1 Publication Trend Analysis

Annual publication counts were extracted to analyze the growth trajectory of urban flood research over time. The temporal distribution of publications was examined to identify phases of research development, including early exploration, methodological consolidation, and recent expansion. The model was expressed in the form:

$$y = ae^{bx}$$

Where:

- y represents number of publications
- x represents year
- a and b are fitted coefficients

2.2.2 Keyword Co-occurrence Analysis

Keyword co-occurrence analysis was performed to identify dominant research themes and conceptual linkages. A minimum occurrence threshold was applied to include only frequently used keywords, ensuring analytical clarity.

Network visualization was generated using VOSviewer, where:

- node size represents keyword frequency
- link strength indicates co-occurrence relationships
- spatial proximity reflects conceptual similarity

Clusters were identified using modularity-based grouping, revealing major thematic domains such as flood modeling, remote sensing applications, climate impacts, and urban planning.

Overlay visualization was further used to analyze temporal evolution by assigning color gradients based on average publication year. This enables identification of emerging research trends and shifts in thematic focus.

2.2.3 Geographic Distribution Analysis

The geographic distribution of research output was analyzed based on corresponding author affiliations. Each study was assigned to a country and aggregated to identify national contributions and regional patterns. This analysis provides insight into global research concentration, highlighting dominant regions and underrepresented areas in urban flood research. Country-level publication analysis was based on the institutional affiliation of the corresponding author. This approach was used to evaluate publication leadership and research output distribution rather than the geographical location of flood case studies.

2.3 Thematic Content Analysis

To complement the bibliometric mapping, a qualitative thematic content analysis was conducted on the full texts of the 207 selected studies. This approach enables deeper interpretation of methodological approaches, research objectives, and analytical findings beyond keyword-level analysis, thereby providing contextual and conceptual depth to the bibliometric results. The analysis followed an inductive–deductive coding framework. Initially, thematic categories were informed by the bibliometric clusters identified through keyword co-occurrence analysis. Subsequently, an iterative coding process was applied to systematically examine each study and identify recurring patterns, methodological trends, and conceptual linkages. Studies were classified into thematic domains based on their primary research focus and methodological characteristics. The coding framework included categories related to flood modeling and simulation, flood mapping and detection, environmental and climatic drivers, and planning and resilience strategies. Where studies addressed multiple themes, cross-classification was permitted to reflect interdisciplinary integration.

The screening, data extraction, and thematic coding procedures were conducted using a structured review protocol based on predefined inclusion and exclusion criteria. A standardized coding matrix was developed to record key study characteristics, including methodological approach, data sources, spatial scale, environmental variables, validation methods, analytical outputs, and planning implications. The coding framework was iteratively refined during the review process to ensure consistency in thematic classification across the dataset.

During this process, key attributes were extracted from each study, including methodological techniques, data sources and spatial scale, environmental variables, modeling approaches, and policy or planning implications. These attributes were organized into a structured coding matrix to ensure consistency and reduce subjective bias in classification. The bibliometric analysis generated 43 keyword clusters representing detailed and interconnected research topics. Because many clusters were small and conceptually overlapping, an additional thematic synthesis was undertaken. Related clusters were grouped according to their dominant methodological focus, research objectives, and conceptual relationships. This process resulted in four broader thematic domains: (1) flood modeling and simulation, (2) flood mapping and detection, (3) environmental and climatic drivers, and (4) planning and resilience strategies. Each study was assigned to one or more domains depending on its primary analytical focus, allowing for cross-classification where interdisciplinary integration was evident. This combined approach ensures that thematic interpretations are grounded in both quantitative network structure and detailed content analysis of the literature.

2.4 Methodological Rigor and Limitations

Several measures were implemented to ensure methodological rigor and enhance the reliability of the findings. First, a structured PRISMA protocol was adopted to ensure transparency and reproducibility in literature identification and screening. Second, clearly defined inclusion and exclusion criteria were consistently applied to maintain thematic coherence and methodological relevance. Third, keyword normalization procedures were performed to minimize semantic inconsistencies and improve the accuracy of bibliometric network construction. Fourth, established bibliometric tools, specifically VOSviewer, were used to ensure robust and reproducible visualization of keyword co-occurrence patterns. Finally, thematic content analysis was conducted systematically across all selected studies using a standardized coding framework, thereby reducing subjectivity and enhancing analytical consistency.

The screening and coding processes were primarily conducted by one reviewer using predefined criteria and a standardized coding framework. Methodological decisions and thematic classifications were periodically reviewed and discussed among the authors to ensure consistency. However, formal inter-reviewer agreement statistics were not calculated. Consequently, some degree of subjective interpretation may remain, particularly in thematic classification. This limitation should be considered when interpreting the results.

Despite these efforts, several limitations should be acknowledged. The reliance on a single database, namely the WOS Core Collection, may limit the comprehensiveness of the dataset compared to multi-database approaches incorporating sources such as Scopus or Dimensions. Additionally, the use of a structured search query, while improving specificity, may exclude relevant studies that do not explicitly match the selected keywords. The inherent methodological heterogeneity across studies—including differences in data sources, modeling approaches, and reporting formats, limits the potential for direct quantitative comparability. Furthermore, bibliometric analysis provides a descriptive representation of thematic relationships and does not establish causal linkages between research variables. The review dataset was restricted to publications from 2016–2025. Although more recent studies published in 2026 were consulted to provide contextual discussion where relevant, they were not included in the systematic review dataset or bibliometric analyses.

An additional limitation relates to the thematic scope of the search strategy. The search query was designed to prioritize empirical urban flood assessment studies utilizing geospatial, hydrological, hydraulic, remote sensing, and machine-learning methodologies. As a result, studies focused primarily on governance, policy development, community resilience, risk communication, adaptation planning, and other qualitative resilience dimensions may not have been fully captured. Therefore, conclusions regarding the relative representation of planning and governance research should be interpreted cautiously and within the context of the review scope.

Future research can address these limitations by incorporating multi-database search strategies, expanding keyword coverage, and applying meta-analytical techniques where sufficient standardized data are available. Greater integration of socio-economic variables, governance frameworks, and policy evaluation metrics would further enhance the analytical depth and practical relevance of urban flood research.

Given the methodological diversity of the included studies, a formal risk-of-bias assessment tool was not applied. Instead, study quality was considered qualitatively during data extraction and synthesis. Particular attention was given to methodological transparency, model validation procedures, data-source reliability, uncertainty reporting, spatial and temporal resolution of datasets, and reproducibility of analytical workflows. These attributes were considered during thematic interpretation and comparative discussion of findings.

2.5 Study Coding Procedure and Reproducibility

To ensure transparency and reproducibility, all 207 studies included in the final review were systematically coded according to their methodological approaches and thematic focus. Coding was conducted using information extracted from article titles, author keywords, Keywords Plus, and abstracts. These fields were selected because they provide concise descriptions of the study objectives, analytical methods, and research themes.

Two complementary coding schemes were developed. The first focused on methodological classification, consisting of five categories: (1) hydrological/hydraulic modeling, (2) GIS-based analysis, (3) remote sensing, (4) machine learning, and (5) planning and resilience approaches. The second focused on thematic classification, comprising four categories: (1) flood modeling and simulation, (2) flood mapping and detection, (3) environmental and climatic drivers, and (4) planning and resilience strategies.

Because urban flood studies frequently integrate multiple analytical techniques and address more than one research theme, studies were permitted to receive multiple methodological and thematic assignments. Consequently, the reported frequencies represent coding occurrences rather than mutually exclusive study counts. As a result, the sum of methodological or thematic frequencies may exceed the total number of reviewed studies.

Methodological frequencies were calculated by summing the number of studies assigned to each methodological category. Annual methodological trends were derived by aggregating coded studies according to publication year. Thematic distributions were similarly calculated using annual thematic coding frequencies.

To account for multiple thematic assignments, annual thematic percentages were calculated using thematic coding instances rather than individual article counts. The percentage for each thematic category was computed as:

$$P_{t,y} = \frac{N_{t,y}}{\sum N_y} \times 100$$

where $N_{t,y}$ represents the number of coding instances for theme t in year y, and $\sum N_y$ represents the total number of thematic coding instances recorded for that year. This approach ensures that annual thematic percentages sum to 100% while accurately reflecting the multidimensional nature of urban flood research.

To improve reproducibility, all coding decisions were recorded in a study-level coding matrix containing publication year, methodological classifications, and thematic assignments for each article. The study-level coding matrix is provided as Supplementary Material S1.

3. RESULTS

3.1. Publication trends

The temporal distribution of publications on urban flooding demonstrates a clear and sustained growth trajectory, reflecting increasing academic attention and research intensity over the past decade. As illustrated in Figure 2, the annual publication output shows a transition from an initial exploratory phase to a phase of rapid expansion and consolidation.

Publication trend analysis was conducted using only the studies included within the predefined review period (2016–2025). Only 4 studies were published in 2016, followed by an increase to 12 in 2017 and a subsequent decline to 7 in 2018. This phase represents the nascent stage of research development, where urban flood studies were emerging but had not yet achieved consistent scholarly momentum.

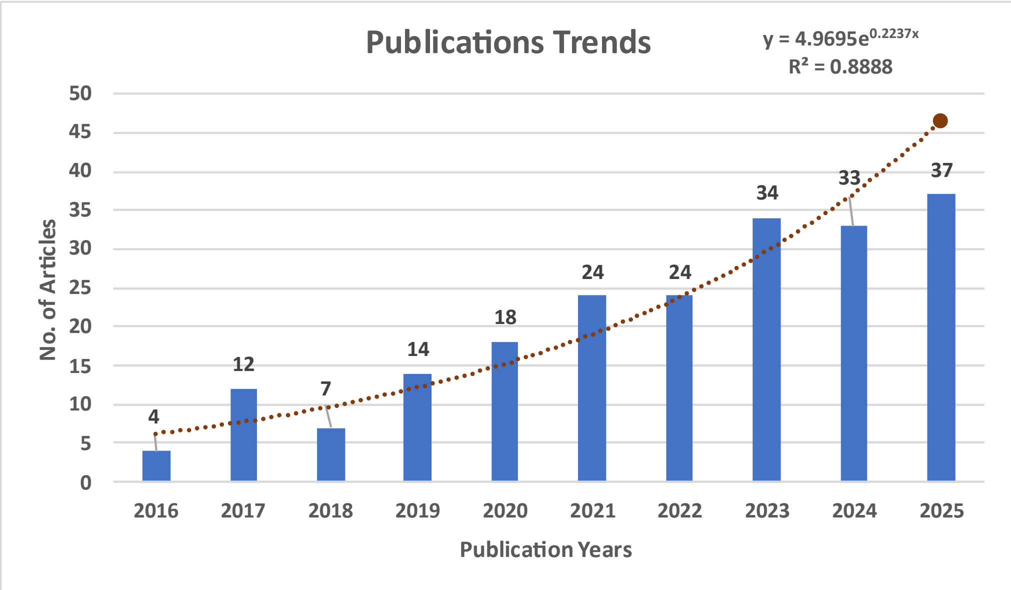

Figure 2. Annual publication trend in the reviewed urban flood literature (2016–2025), showing a consistent increase in research output with an exponential growth pattern (R^2 = 0.8888).

A gradual growth phase is observed between 2019 and 2021, during which publication output increased steadily from 14 studies in 2019 to 18 in 2020, reaching 24 studies in 2021. This period reflects a growing recognition of urban flooding as a critical research area, likely influenced by increased awareness of climate change impacts and advancements in geospatial technologies and hydrological modeling.

From 2022 onward, a pronounced expansion phase is evident. Publication counts remained at 24 in 2022 but increased significantly to 34 in 2023, followed by 33 in 2024 and reaching a peak of 37 publications in 2025. This sharp rise indicates a substantial acceleration in research activity, with more than half of the total publications concentrated in the most recent years. The surge in output corresponds with the increasing integration of machine learning techniques, high-resolution remote sensing data, and climate-driven flood risk assessments within urban environments.

The exponential regression model fitted to the publication data ($y = 4.9695e^{0.2237x}$) demonstrates a strong upward trend, with a high coefficient of determination ($R^2 = 0.8888$), indicating that the growth pattern closely follows an exponential trajectory. This suggests that urban flood research is not only expanding but doing so at an accelerating rate.

Overall, the publication trend reflects a clear evolution from limited early-stage research to a mature and rapidly expanding field. The strong upward trajectory highlights the growing importance of urban flooding as a central topic within urban sustainability, climate resilience, and disaster risk reduction research.

3.2. Keyword Co-Occurrence and Temporal Evolution (Overlay Visualization)

To examine the intellectual structure and temporal evolution of urban flood research, a keyword co-occurrence overlay visualization was generated using VOSviewer (version 1.6.19). The network was constructed based on author keywords extracted from the 207 selected studies. Using VOSviewer (version 1.6.19), a keyword co-occurrence network was generated comprising 1,066 connected keyword items organized into 43 clusters, with 10,305 links and a total link strength of 11,460. The association-strength normalization method was applied to ensure proportional representation of keyword relationships, while clustering was performed using the default VOSviewer modularity-based algorithm with a resolution parameter of 1.0 and layout attraction of 2.

The resulting co-occurrence network, presented in Figure 3, reveals a highly interconnected and centralized structure, indicating strong conceptual cohesion within the field. The network is dominated by a core cluster centered around the terms “urban flooding,” “climate change,” “SWMM,” “simulation,” and “city,” which occupy central positions with large node sizes and dense interconnections. This centrality indicates that urban flood research is strongly anchored in modeling-based approaches, particularly those integrating hydrological simulation with climate-related drivers.

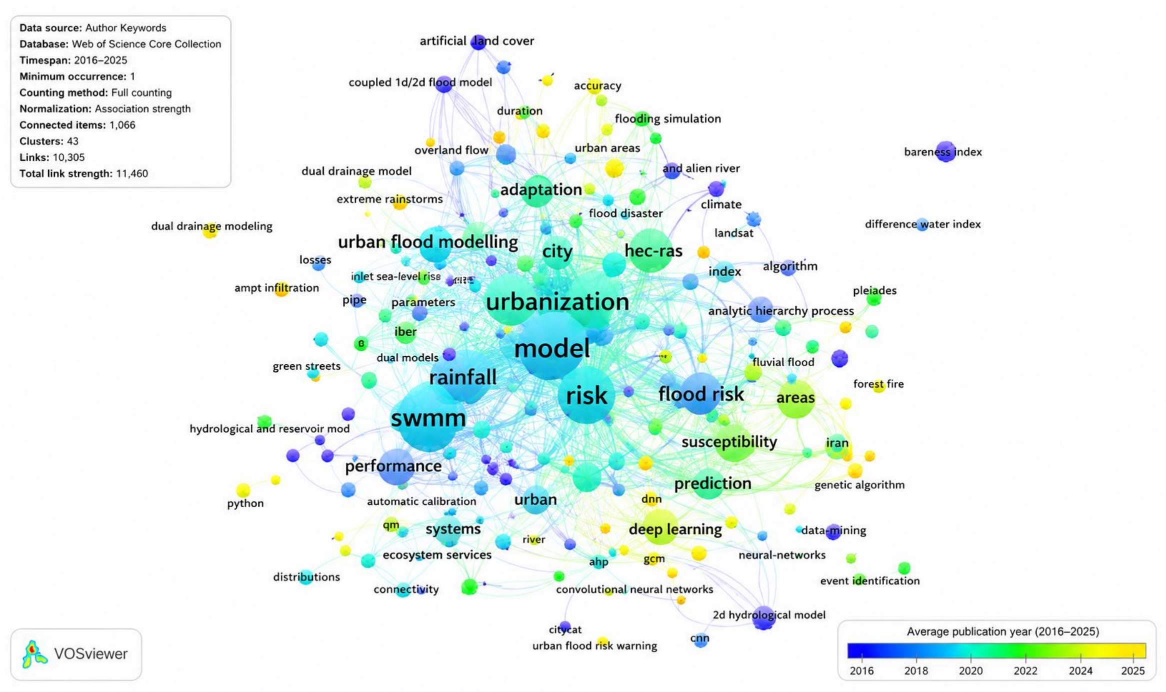

Figure 3. Overlay visualization of the keyword co-occurrence network generated using VOSviewer (version 1.6.19). The network comprises 1,066 connected keyword items organized into 43 clusters, with 10,305 links and a total link strength of 11,460. Node size represents keyword frequency, link strength indicates co-occurrence intensity, and color gradients represent the average publication year (blue = earlier studies; yellow = more recent studies).

A prominent methodological cluster is formed around "SWMM," "simulation," "systems," and "performance," reflecting the widespread application of hydrological and hydraulic modeling frameworks for urban flood analysis. The strong connectivity between these terms and concepts such as "runoff," "inundation," and "surface water" highlights the dominance of process-based simulation in understanding flood dynamics. The presence of terms such as "green roof," "bioretention," and "sponge city" within this cluster further indicates increasing integration of nature-based solutions and sustainable drainage strategies into modeling frameworks.

A second major thematic cluster is associated with machine learning and data-driven approaches, represented by keywords such as "machine learning," "deep learning," "random forest," and "algorithm." These nodes are closely linked with terms such as "susceptibility," "prediction," and "hazard," indicating a growing shift toward predictive analytics and flood risk mapping. The emergence of deep learning as a relatively recent keyword (yellow tones in the overlay) suggests increasing adoption of advanced computational techniques for handling complex, non-linear flood processes.

Environmental and climatic drivers form another important thematic domain within the network. Keywords such as "climate change," "extreme rainfall," "precipitation," "land use," and "impervious surface" are strongly interconnected with urban flood terms, reflecting the critical role of both climatic variability and land-use transformation in influencing flood dynamics. The central positioning of "climate change" underscores its role as a key linking concept between physical processes and broader environmental impacts. The network also highlights a distinct cluster related to flood impacts and risk assessment, including terms such as "flood hazard," "flood risk management," "impacts," and "vulnerability." These keywords are moderately connected to the core modeling cluster, suggesting that while impact assessment is an important component of the literature, it remains somewhat secondary to methodological and simulation-focused research.

From a temporal perspective, the overlay visualization reveals a clear evolution in research focus. Earlier studies (represented in blue tones, approximately 2020–2021) are primarily concentrated on traditional hydrological modeling approaches, including SWMM-based simulation, runoff estimation, and GIS-based flood mapping. The mid-phase (2021–2022) shows increasing integration of environmental variables and spatial analysis, with greater emphasis on land use, climate interactions, and flood hazard assessment. More recent studies (2023–2025), represented by yellow tones, demonstrate a significant shift toward machine learning, deep learning, and data-driven modeling approaches, as well as increased attention to scenario simulation, real-time systems, and resilience-oriented planning strategies. The appearance of keywords such as "deep learning," "scenario simulation," and "sustainable urban planning" indicates a transition from descriptive and process-based analysis toward predictive, adaptive, and decision-support frameworks. Additionally, the presence of geographically specific terms such as "China," "Oregon," and "Vancouver" reflects the continued reliance on case-study-based research, although these nodes remain peripheral compared to the central methodological clusters.

Overall, the keyword co-occurrence network reveals three key structural characteristics: (1) strong centralization around hydrological modeling and simulation approaches, (2) increasing integration of climate and environmental drivers, and (3) a recent and rapidly growing emphasis on machine learning and predictive analytics. Despite this evolution, governance- and policy-oriented keywords remain relatively peripheral, indicating that translation of technical findings into planning and policy frameworks remains underdeveloped.

The overlay visualization thus demonstrates that urban flood research has evolved from model-centric and process-based analysis toward a more integrated, data-driven, and sustainability-oriented research paradigm. However, the continued dominance of technical methodologies suggests that future research should strengthen the linkage between analytical outputs and practical urban planning and governance strategies.

3.3. Analysis of country distribution

The distribution of publications based on corresponding-author affiliations provides insight into the global distribution of research leadership and publication output in urban flood studies. Based on the 207 articles included in this review, the results indicate a highly uneven distribution of publication activity across countries, with a substantial concentration of research output among a relatively small number of nations.

As shown in Figure 4, China (People's Republic of China) is the most prolific contributor, accounting for 80 publications. This contribution substantially exceeds that of all other countries and reflects China's prominent role in urban flood research. The high publication output may be associated with rapid urbanization, increasing exposure to flood hazards, extensive investment in flood-risk management, and growing research capacity in geospatial technologies, hydrological modeling, and smart-city initiatives.

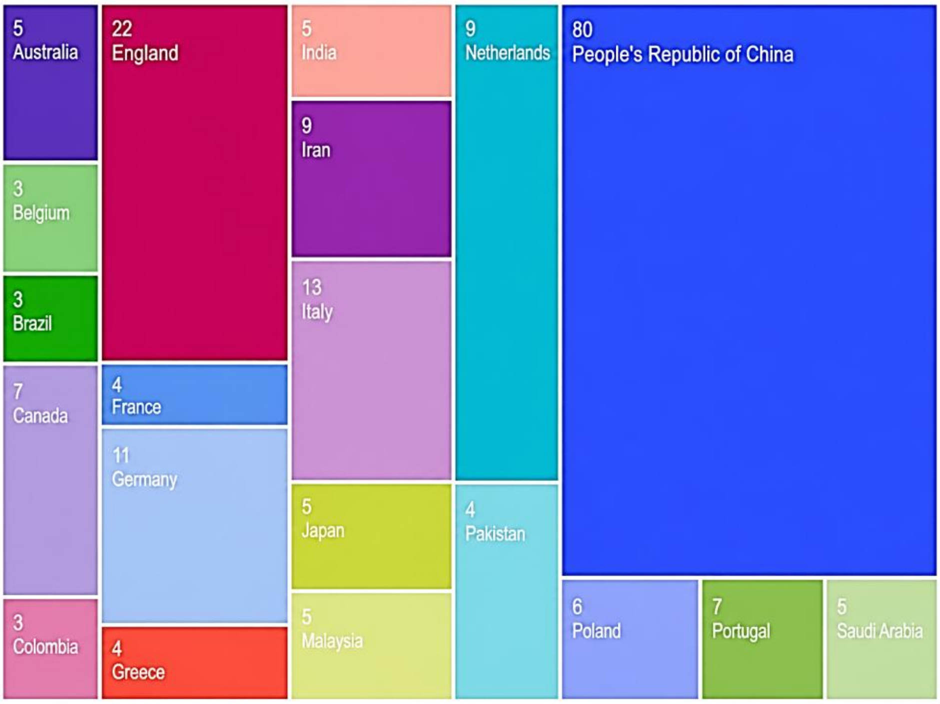

Figure 4. Distribution of publications based on corresponding-author affiliations among the reviewed studies.

The United Kingdom represents the second-largest contributor with 22 publications, followed by Italy (13 publications) and Germany (11 publications). Additional notable contributors include the Netherlands and Iran, with nine publications each, demonstrating active engagement in urban flood research and water-management studies. Canada and Portugal each contributed seven publications, while Poland accounted for six publications. Australia, India, Japan, Malaysia, and Saudi Arabia each contributed five publications, indicating consistent participation in the field. Other countries, including France, Greece, and Pakistan (four publications each), as well as Belgium, Brazil, and Colombia (three publications each), contributed smaller but notable shares of the reviewed literature.

The treemap visualization highlights the concentration of publication output among a limited number of countries, particularly China. It should be noted that these results reflect the institutional affiliations of corresponding authors and therefore represent patterns of research leadership and publication activity rather than the geographic distribution of urban flood case studies. Consequently, publication output should not be interpreted as a direct measure of where urban flood research has been conducted geographically.

To further examine global research collaboration, a country co-authorship network was constructed based on author affiliations and is presented in Figure 5. The network reveals extensive international collaboration within the urban flood research community. China, the United States, and England occupy central positions in the network, indicating strong collaborative relationships with researchers from multiple countries. Among these, China appears as the most prominent node, reflecting both high publication output and extensive international connectivity. The United States and England similarly function as major collaboration hubs linking multiple regional research clusters.

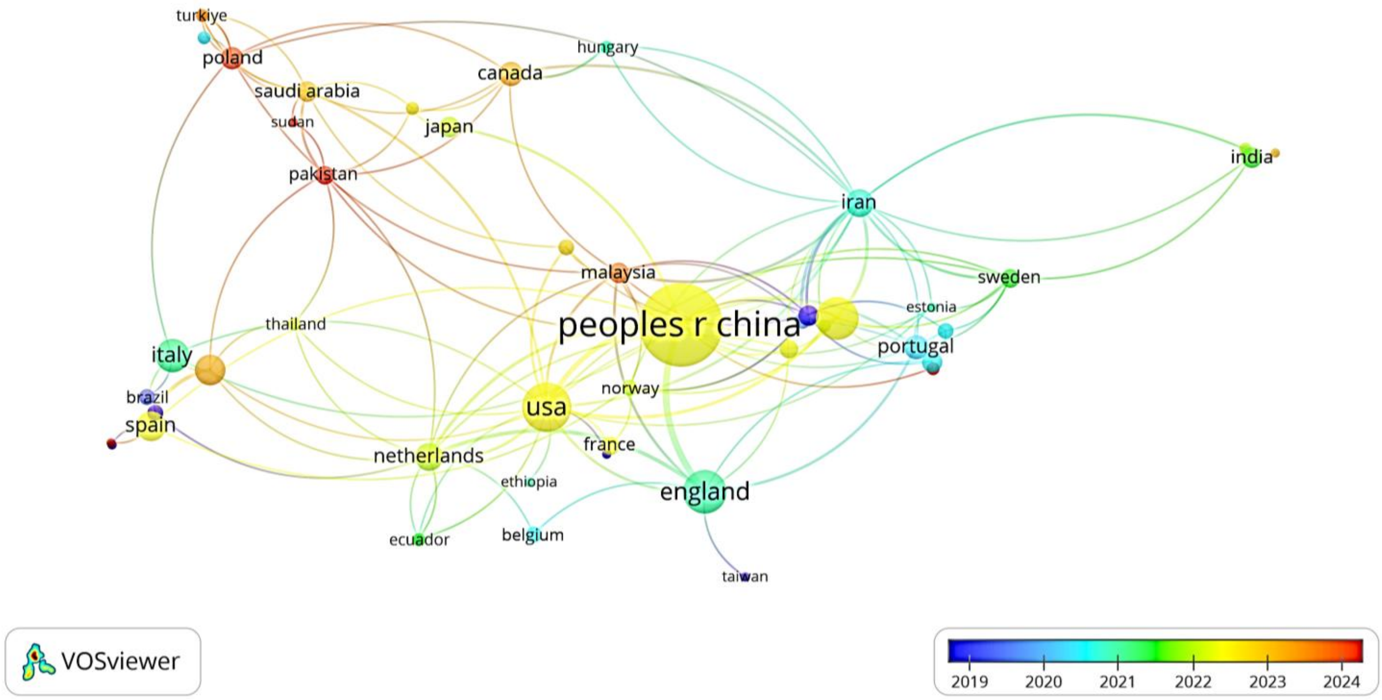

Figure 5. International co-authorship network based on author affiliations within the reviewed urban flood literature. Node size represents publication output by affiliated countries, while link strength indicates the intensity of collaborative relationships between countries.

The network structure demonstrates a high degree of international interconnectedness within urban flood research. Countries such as Iran, Portugal, Sweden, and Malaysia act as important bridging nodes that facilitate knowledge exchange across different regions. In contrast, several countries occupy peripheral positions within the network, suggesting lower levels of international collaboration and reduced integration into global research partnerships.

The overlay visualization also reveals temporal changes in publication activity and collaboration patterns. Earlier contributions (blue tones) are more strongly associated with countries such as the United States and several European nations, whereas more recent contributions (yellow tones) indicate increasing publication activity from countries including China, India, and several Middle Eastern nations. This trend reflects the growing international importance of urban flood research, particularly in rapidly urbanizing regions facing increasing climate-related flood risks.

Overall, the authorship and collaboration analysis reveals three key patterns. First, publication output is highly concentrated, with China emerging as the dominant contributor in terms of corresponding-author affiliations. Second, European countries, particularly the United Kingdom, Germany, Italy, and the Netherlands, continue to play significant roles in advancing urban flood research. Third, international collaboration networks are increasingly diverse, with growing participation from emerging research communities in Asia and the Middle East. However, because this analysis is based on author affiliations rather than study locations, the results should be interpreted as indicators of research leadership and collaboration rather than the geographic distribution of urban flood case studies. Future reviews incorporating systematic extraction of study locations could provide additional insight into the spatial coverage of urban flood research worldwide.

3.4. Thematic Content Analysis

The thematic content analysis of 207 selected studies reveals a highly structured yet evolving research landscape in urban flood studies, characterized by strong methodological convergence and increasing interdisciplinary integration. Building upon the bibliometric clustering (Figure 3), the analysis identifies four dominant thematic domains: (1) flood modeling and simulation, (2) flood mapping and detection, (3) environmental and climatic drivers, and (4) planning, mitigation, and resilience strategies. These domains collectively represent the core intellectual architecture of urban flood research, while also highlighting critical imbalances between technical advancement and applied implementation.

The thematic classification reflects both structural patterns observed in the bibliometric network (Figure 3) and empirical evidence extracted from Supplementary Material. Together, these domains illustrate the multidimensional architecture of contemporary urban flood research.

3.4.1. Flood Modeling and Simulation

Flood modeling and simulation constitute the largest thematic domain within the dataset, representing a substantial proportion of the analyzed studies. As shown in Table 2, this domain is characterized by the extensive use of hydrological and hydraulic models, including SWMM, HEC-RAS, and coupled 1D–2D modeling approaches. This domain is characterized by extensive use of physically based hydrological and hydraulic models, along with increasing adoption of hybrid and data-driven approaches.

A significant number of studies employ SWMM-based modeling frameworks for simulating urban runoff, drainage performance, and flood dynamics (Bai et al., 2019; J. Lee, 2012; Tanim et al., 2024; Xiao et al., 2019; Xie et al., 2020). These models are frequently used to assess system behavior under varying rainfall intensities and land-use conditions. In addition, HEC-RAS and coupled 1D–2D models are widely applied to simulate flood propagation and surface–subsurface interactions (Mihu-Pintilie et al., 2019; Sanudo et al., 2020; Varra et al., 2025).

Several studies within the reviewed dataset incorporate high-resolution spatial data, including DEMs and urban micro-topography, to improve simulation accuracy (Halder, Kumar, Deepak, Kumar, et al., 2025; Y. Li, 2020; Zhang, 2023). Similar trends have also been reported in recent literature published after the review period (e.g., Rathod et al., 2026). Multi-source data integration, including rainfall records, land-use datasets, and drainage network information, is commonly reported. Data-driven approaches are increasingly integrated into modeling workflows. Machine learning and deep learning models are applied for flood prediction, scenario simulation, and susceptibility analysis (Ciampi, 2021; Craninx et al., 2021; Taromideh et al., 2022). These approaches are often used either as standalone predictive tools or in combination with physically based models.

Hybrid frameworks combining simulation models with machine learning are also observed (Jamali et al., 2018). These approaches aim to reduce computational complexity while maintaining predictive performance.

Overall, this domain is characterized by:

- strong emphasis on process-based simulation
- increasing integration of data-driven techniques

- frequent use of scenario-based analysis.

3.4.2. Flood Mapping and Detection

Flood mapping and detection represent a major research domain focused on spatial identification and classification of flood-prone areas. This domain is primarily supported by GIS-based analysis, remote sensing data, and machine learning algorithms.

A large number of studies apply GIS-based multi-criteria decision-making (MCDA) methods to generate flood susceptibility maps (Ahmad et al., 2024; Andreadis et al., 2022; Nkonu et al., 2023). These approaches typically integrate variables such as elevation, slope, drainage density, and land use.

Remote sensing plays a significant role in flood mapping. Studies utilize satellite imagery (e.g., Landsat, Sentinel) and LiDAR-derived elevation data to improve spatial resolution and mapping accuracy (Meng et al., 2019; Natkaniec & Godyn, 2024). These datasets are used for both pre-event susceptibility mapping and post-event flood extent analysis.

Machine learning techniques are widely applied for flood prediction and classification. Algorithms such as Random Forest, decision trees, and hybrid models are used to improve predictive accuracy (Darabi et al., 2019; Rafiei-Sardooi et al., 2021; Yuan et al., 2024). Deep learning approaches are also employed for spatial pattern recognition and flood susceptibility modeling (W. Li et al., 2022).

This domain shows:

- strong reliance on spatial datasets
- increasing use of AI-based classification
- integration of multi-variable spatial analysis.

3.4.3 Environmental and Climatic Drivers

A substantial portion of the studies focuses on environmental and climatic factors influencing urban flooding. These studies analyze the role of land-use change, rainfall variability, and urbanization in shaping flood dynamics. Land-use change and urban expansion are frequently identified as major contributors to increased flood risk. Several studies report that increasing impervious surface coverage leads to higher runoff generation and reduced infiltration (Moniruzzaman et al., 2021; Yao et al., 2016). Spatial analysis of land-use patterns is commonly integrated into flood modeling frameworks.

Rainfall intensity and variability are key climatic drivers incorporated into flood analysis. Studies include rainfall data in simulation models and susceptibility assessments to evaluate flood response under different scenarios (Hassan et al., 2017; Sperotto et al., 2016). Additional environmental variables such as slope, soil type, drainage characteristics, and topography are frequently included in analysis (Hussein et al., 2025; Taromideh et al., 2022; Wu et al., 2019). These variables are used in both statistical and machine learning models.

This domain is characterized by:

- integration of climate and land-use variables
- use of multi-factor analysis
- application in both modeling and mapping studies.

Figure 6 presents the conceptual structure of urban flood research, illustrating the interconnections among four primary thematic domains: flood modeling and simulation, flood mapping and detection, environmental and climatic drivers, and planning and resilience strategies.

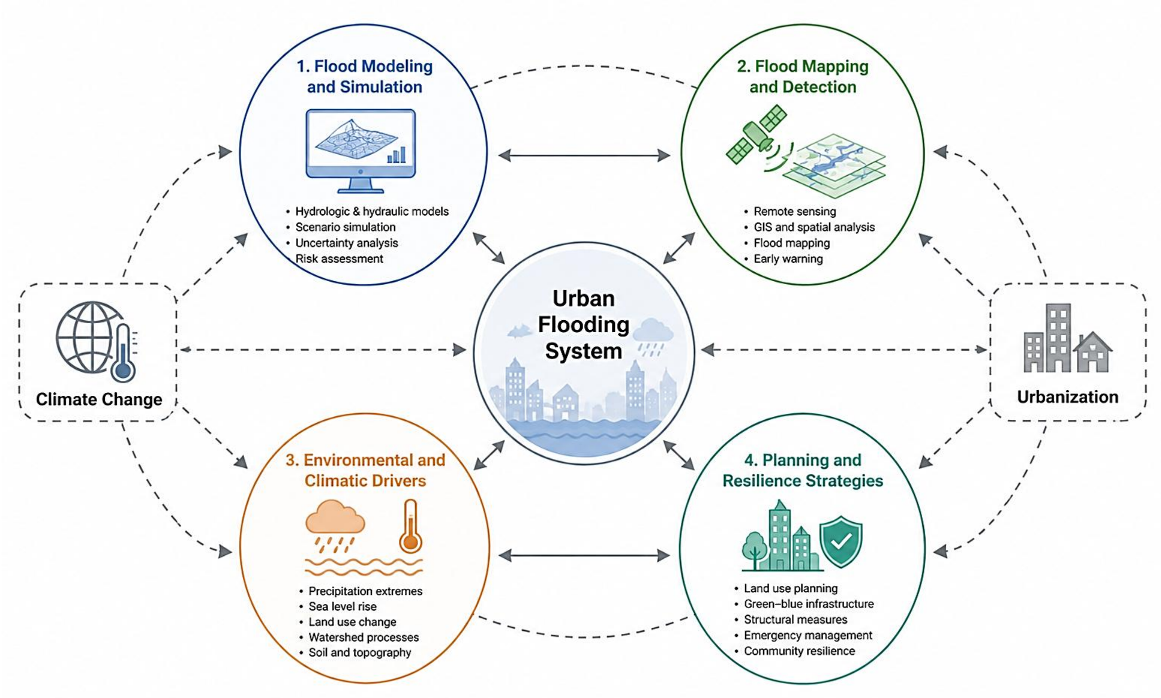

Figure 6. Conceptual framework of urban flood research illustrating interactions among four major domains: modeling and simulation, mapping and detection, environmental drivers, and planning and resilience strategies.

The central node, "Urban Flooding System," represents the integrated nature of flood processes, while bidirectional arrows indicate strong interactions among domains. For instance, modeling studies frequently incorporate environmental variables such as rainfall and land use (Halder et al., 2026; Moniruzzaman et al., 2021), while mapping approaches rely on outputs from hydrological simulations to improve spatial accuracy (Gigovic et al., 2017; Kanwal et al., 2026; Kittipongvises et al., 2020). The figure also highlights external drivers—climate change and urbanization, which influence all domains simultaneously, reinforcing their role as overarching factors in urban flood dynamics.

The domain-specific components further illustrate methodological diversity. Flood modeling includes hydrological and hydraulic simulations (Halder, Kumar, Deepak, Mandal, et al., 2025; Sanudo et al., 2020; Sweta Rupapara et al., 2025), while flood mapping integrates GIS and remote sensing techniques for spatial analysis (Mihu-Pintilie et al., 2019). Notably, several studies apply combined approaches, such as integrating GIS with remote sensing data or coupling simulation models with spatial analysis tools, indicating methodological overlap across domains (Darabi et al., 2019; Halder & Kumar, 2025). Environmental drivers incorporate precipitation, land-use change, and topographic variables, which are frequently embedded within both modeling and mapping workflows. Planning and resilience strategies, although less represented, are linked to simulation outputs and environmental assessments, particularly in studies evaluating low-impact development (LID) and sustainable drainage systems (SuDS) performance

(Bai et al., 2019; Guptha et al., 2021; Kumar & Shukla, 2022). Overall, Figure 6 demonstrates that urban flood research operates as an interconnected system rather than isolated thematic areas.

3.4.4 Planning and Resilience Strategies

The planning and resilience domain encompasses studies focused on flood mitigation measures, sustainable drainage infrastructure, urban adaptation strategies, and resilience-oriented planning frameworks. Compared with hydrological modeling and flood simulation studies, this domain remains less methodologically intensive but has gained increasing attention in recent years as urban areas seek long-term solutions to escalating flood risks.

Several studies evaluated Low-Impact Development (LID) practices and Sustainable Urban Drainage Systems (SuDS) using simulation-based modeling frameworks. These investigations generally reported reductions in runoff volumes, peak discharge, and inundation extent under alternative design scenarios (Bersabe & Jun, 2025; Ramos & Besharat, 2021). Simulation-based assessment remains the dominant evaluation approach within this domain, reflecting the practical challenges associated with long-term monitoring of implemented interventions. Green infrastructure measures, including permeable pavements, retention systems, bio-retention facilities, and other nature-based solutions, have also been examined for their effectiveness in mitigating urban flood impacts (Maragno et al., 2018). Several studies further assessed infrastructure performance under future climate-change scenarios, highlighting the importance of adaptive planning strategies in rapidly urbanizing environments (Guptha et al., 2022). In addition, resilience-oriented research increasingly incorporates decision-support systems, integrated planning frameworks, and urban resilience assessment tools to support flood-risk management and policy development (Vamvakeridou-Lyroudia, Chen, Khoury, Gibson, Kostaridis, Stewart, Wood, & Djordjevic S. and Savic, 2020).

However, it is important to distinguish between simulated performance and demonstrated implementation outcomes. Most studies within this domain evaluate intervention effectiveness through scenario-based modeling rather than field observations or post-implementation monitoring. Consequently, reported reductions in runoff and flood impacts should be interpreted as projected performance rather than direct evidence of operational effectiveness.

Figure 7 presents the distribution and temporal evolution of methodological approaches and thematic domains across the 207 reviewed studies. Panel A summarizes methodological frequencies identified through the coding framework. Hydrological and hydraulic modeling represents the most frequently applied methodological category (n = 134), followed by planning and resilience approaches (n = 81), machine learning (n = 54), GIS-based analysis (n = 52), and remote-sensing techniques (n = 37). Because studies were permitted to receive multiple methodological classifications, these values represent method-usage frequencies rather than mutually exclusive study counts. For example, GIS-based analyses are frequently integrated with remote-sensing datasets for flood mapping (Mihu-Pintilie et al., 2019), while machine-learning approaches are often combined with GIS-derived predictors for susceptibility assessment and spatial prediction (Darabi et al., 2019; Lei et al., 2021). Similarly, hydrological and hydraulic models are commonly coupled with geospatial techniques to enhance the spatial representation of flood processes (Jamali et al., 2018; Wang et al., 2018).

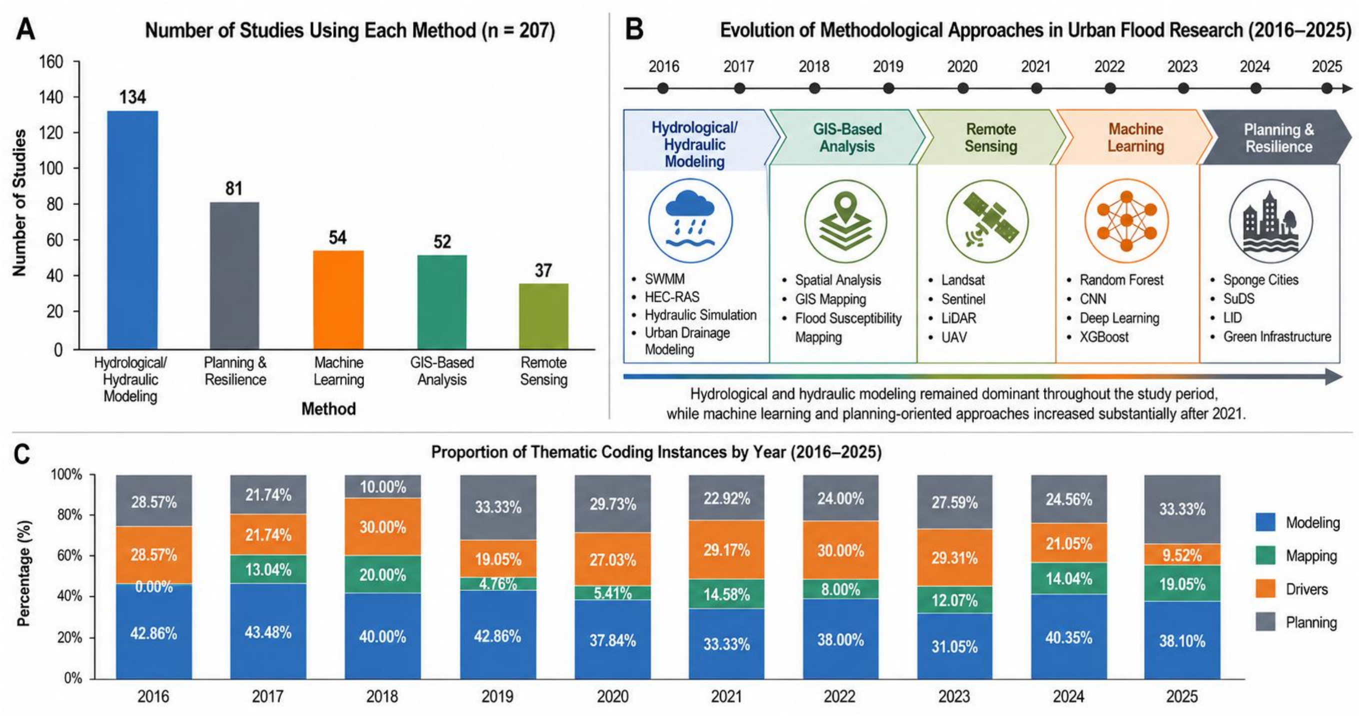

Figure 7. Distribution and evolution of methodological approaches in urban flood research, showing the relative contribution of modeling, geospatial analysis, machine learning, and planning-based studies.

Panel B illustrates the evolution of methodological approaches throughout the review period (2016–2025). Hydrological and hydraulic modeling remained the dominant analytical framework across all years, while GIS-based analysis, remote sensing, machine learning, and planning-oriented approaches exhibited increasing adoption, particularly after 2021. The growing integration of data-driven methods reflects increasing availability of geospatial data, computational resources, and advanced analytical techniques for urban flood assessment.

Panel C presents annual thematic distributions calculated using thematic coding instances rather than exclusive article counts, allowing studies to contribute to multiple thematic domains. Flood modeling and simulation remained the dominant theme throughout the review period, accounting for 140 coding instances across the dataset. Planning and resilience strategies emerged as the second most represented theme (100 coding instances), followed by environmental and climatic drivers (88 coding instances) and flood mapping and detection (46 coding instances). The results indicate that while process-based modeling continues to underpin urban flood research, increasing attention is being directed toward resilience planning, environmental drivers, and integrated flood-management strategies.

Table 2 summarizes the thematic classification and methodological characteristics of the reviewed studies. Collectively, the evidence highlights the growing methodological diversity of urban flood research while emphasizing the continued importance of physically based modeling frameworks as the foundation of flood-risk assessment.

Table 2. Thematic Classification and Methodological Characteristics

Theme	Sub-methods	Data Sources	Key Variables	Output Type	Scale	Strength	Limitation	Representative Studies

Modeling	SWMM, HEC-RAS, 1D–2D, CNN	rainfall, DEM, drainage	runoff, depth	simulation maps	local–city	high accuracy	data intensive	(Barreiro et al., 2023; Sanudo et al., 2020; Sun et al., 2022; Wei et al., 2025)
Mapping	GIS, RS, ML	satellite, LiDAR	slope, land use	susceptibility maps	regional	spatial coverage	uncertainty	(Ahmad et al., 2024; Darabi et al., 2019; Gigovic et al., 2017; Natkaniec & Godyn, 2024; Nkonu et al., 2023)
Drivers	statistical, RS	climate, LULC	rainfall, impervious	correlation, prediction	multi-scale	integrated view	variability	(Bakhrel et al., 2025; Moniruzzaman et al., 2021; Xu, 2006)
Planning	LID, SuDS	urban data	infrastructure	scenario results	local	sustainability	limited validation	(Ferrans et al., 2023; Guptha et al., 2022; Jemberie & Melesse, 2021; J. Lee, 2012; Luan et al., 2017; Qin et al., 2025)

The combined presentation of Panels A–C demonstrates a temporal shift in methodological emphasis, with increasing representation of GIS-based, remote sensing, and machine learning approaches, alongside continued use of hydrological modeling. The figure also shows frequent co-application of methods, including combinations of GIS, remote sensing, and machine learning within individual studies (Dufitimana et al., 2025; Rafiei-Sardooi et al., 2021). Although many studies reported substantial reductions in runoff and flood impacts under simulated scenarios, these results should be interpreted as projected performance rather than evidence of successful implementation unless supported by field observations, monitoring data, or policy evaluations.

3.4.5. Critical Evaluation of Methodological Approaches

Hydrological and Hydraulic Models

Hydrological and hydraulic models, particularly SWMM and HEC-RAS, remain the most frequently applied approaches in urban flood research. Their widespread use reflects their ability to simulate runoff generation, drainage-system performance, and flood inundation processes under different hydrological conditions. However, the reliability of model outputs depends heavily on calibration procedures, validation datasets, and input-data quality. Several studies reported calibration against observed flow, water-level, or inundation data, while others relied primarily on parameter values adopted from previous studies. Differences in drainage-network representation, digital elevation model (DEM) resolution, and rainfall inputs can substantially influence model performance. Consequently, model prevalence should not be interpreted as evidence of superior predictive capability.

Machine-Learning Approaches

Machine-learning methods have become increasingly prominent in recent years, particularly for flood susceptibility mapping, classification, and prediction. Commonly reported performance metrics include accuracy, precision, recall, F1-score, area under the receiver operating characteristic curve (AUC), root mean square error (RMSE), and coefficient of determination (R^2). Although many studies reported strong predictive performance, model accuracy is strongly influenced by training-data quality, feature selection, class imbalance, and validation strategy. Furthermore, relatively few studies explicitly discussed spatial or temporal data leakage, which may lead to optimistic performance estimates when training and testing datasets are not fully independent.

GIS and Remote-Sensing Approaches

GIS and remote-sensing techniques provide efficient tools for flood mapping, hazard assessment, and susceptibility analysis. Their effectiveness depends largely on the quality, spatial resolution, and temporal availability of input datasets, including satellite imagery, LiDAR products, and digital elevation models. While these approaches offer broad spatial coverage and cost-effective analysis, uncertainties associated with classification accuracy, image resolution, and terrain representation are not consistently evaluated across studies.

Transferability and Uncertainty

A recurring challenge across the reviewed literature is the transferability of models between cities with different climatic, topographic, and infrastructural characteristics. Models calibrated for one urban environment may not perform similarly when applied elsewhere. In addition, uncertainty and sensitivity analyses remain inconsistently reported, limiting the ability to assess the robustness of model predictions under changing environmental conditions. Greater emphasis on uncertainty quantification and independent validation would improve confidence in future urban flood assessments.

Planning and Resilience Strategies

Studies addressing resilience interventions primarily evaluated measures such as Low-Impact Development (LID), Sustainable Urban Drainage Systems (SuDS), sponge-city concepts, and green infrastructure through scenario-based simulations. These studies frequently reported reductions in runoff volume, peak discharge, or inundation extent. However, simulation-based performance should not be interpreted as evidence of implemented resilience success. Comparatively few studies assessed long-term field performance, operational effectiveness, stakeholder acceptance, or policy implementation outcomes. Consequently, the current evidence base is stronger for projected intervention performance than for empirically verified resilience outcomes.

Table 3. Critical Evaluation of Major Methodological Approaches in Urban Flood Research.

Methodological Category	Typical Validation Approach	Common Performance Metrics	Strengths	Key Limitations
Hydrological/Hydraulic Models (SWMM, HEC-RAS)	Calibration against observed runoff, water levels, or flood extent	NSE, RMSE, R^2, flood extent agreement	Physically based representation of flood processes	Sensitive to calibration, drainage data quality, and DEM resolution
GIS-Based Analysis	Comparison with observed flood locations and historical events	Mapping accuracy, spatial agreement	Strong spatial representation and visualization	Dependent on input data quality and spatial resolution
Remote Sensing	Validation against field observations	Classification accuracy, Kappa	Large spatial coverage and rapid	Image resolution and classification

Methodological Category	Typical Validation Approach	Common Performance Metrics	Strengths	Key Limitations
	or reference imagery	coefficient	assessment	uncertainty
Machine Learning	Train-test validation, cross-validation	Accuracy, Precision, Recall, F1-score, AUC, RMSE, R^2	Strong predictive capability and pattern recognition	Risk of overfitting, transferability limitations, potential data leakage
Planning and Resilience Approaches	Scenario-based simulations, limited field evaluation	Runoff reduction, flood-volume reduction, resilience indicators	Supports adaptation planning and decision-making	Limited evidence from implemented interventions and long-term monitoring

3.5 Temporal Shift in Research Emphasis

The temporal analysis of the 207 reviewed studies reveals a progressive diversification of methodological approaches and research priorities between 2016 and 2025. As illustrated in Figure 7, urban flood research evolved from a strong reliance on physically based hydrological and hydraulic modeling toward increasingly integrated approaches that combine geospatial technologies, machine learning, environmental analysis, and resilience-oriented planning.

During the early period (2016–2018), research activity was dominated by flood modeling and simulation. Hydrological and hydraulic approaches focused primarily on rainfall–runoff processes, drainage-system performance, flood-depth estimation, and inundation modeling using physically based simulation frameworks (Hassan et al., 2017; Li et al., 2019). Consistent with this emphasis, flood modeling and simulation accounted for approximately 40–43% of thematic coding instances during these years (Figure 7C), reflecting the central role of process-based understanding in urban flood research.

From 2019 onward, the literature increasingly incorporated GIS-based spatial analysis and remote-sensing techniques to support flood mapping, susceptibility assessment, and spatial visualization (Gigovic et al., 2017; Mihu-Pintilie et al., 2019). This transition was accompanied by growing integration between hydrological modeling and geospatial analysis, enabling improved representation of spatial heterogeneity and urban flood dynamics. Although flood mapping and detection remained a smaller thematic component than modeling, its relative contribution increased over time, particularly after 2021.

The most notable methodological expansion occurred during the later period (2021–2025), characterized by rapid growth in machine-learning and deep-learning applications. These approaches were increasingly employed for flood susceptibility mapping, classification, forecasting, and real-time prediction (Darabi et al., 2019; Lei et al., 2021; Guo et al., 2022). As shown in Figure 7B, machine learning emerged as a major methodological component of urban flood research, complementing rather than replacing conventional hydrological and hydraulic models. Many recent studies adopted hybrid frameworks that integrate machine-learning algorithms with GIS, remote sensing, or physically based models to improve predictive performance and computational efficiency.

Research attention also expanded toward environmental and climatic drivers of urban flooding. Studies increasingly investigated the influence of rainfall variability, climate change, urbanization, land-use change, and impervious-surface expansion on flood occurrence and severity (Moniruzzaman et al., 2021; Sperotto et al., 2016). Environmental and climatic drivers consistently represented a substantial thematic component throughout the review period, accounting for approximately 21–30% of annual thematic coding instances in most years.

Planning and resilience-oriented research demonstrated steady growth over time and became increasingly prominent in the later years of the review period. The proportion of planning and resilience studies increased from approximately 22–29% during the early and middle stages of the review period to 33.33% in 2025 (Figure 7C). Studies in this domain primarily evaluated adaptation measures such as LID practices, SuDS, green infrastructure, and sponge-city concepts using simulation-based approaches (Bai et al., 2019; Guptha et al., 2021). Nevertheless, relatively few studies assessed long-term implementation outcomes or policy effectiveness, highlighting an important research gap between modeled performance and real-world application.

Overall, the temporal evolution of urban flood research is characterized not by the replacement of one methodology with another, but by increasing methodological integration. Hydrological and hydraulic modeling remains the dominant analytical foundation, while GIS, remote sensing, machine learning, and resilience-oriented planning are increasingly incorporated to address the growing complexity of urban flood challenges. This convergence of physical, spatial, computational, and planning perspectives reflects the multidisciplinary nature of contemporary urban flood research and supports more comprehensive approaches to flood-risk assessment and management.

Figure 8 presents a conceptual synthesis of the temporal evolution of urban flood research, demonstrating a sequential progression of dominant methodological approaches from 2016 to 2025. The figure shows that early-stage studies were primarily centered on hydrological and hydraulic modeling, focusing on rainfall–runoff processes and simulation-based analysis. This was followed by increased integration of GIS and remote sensing techniques, enabling spatial mapping, land-use classification, and change detection.

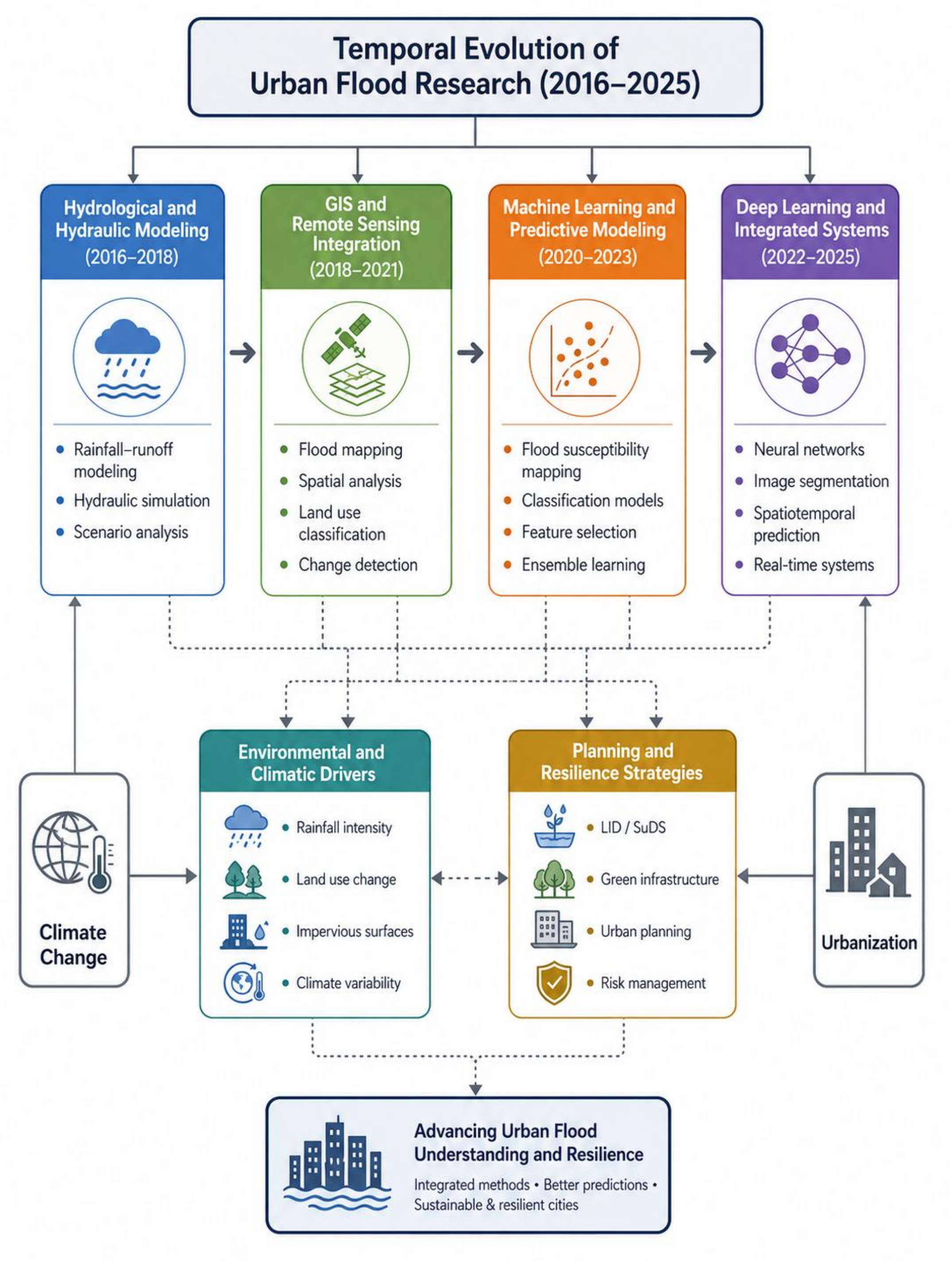

Figure 8. Conceptual framework of the temporal evolution of urban flood research (2016–2025), showing the transition from hydrological modeling to GIS/remote sensing, and toward machine learning and deep learning, with integration of environmental drivers and resilience strategies under climate change and urbanization.

More recent studies show a growing emphasis on machine learning and deep learning methods, particularly for flood susceptibility mapping, classification, and spatiotemporal prediction. In addition to methodological progression, the figure highlights the continuous influence of environmental and climatic drivers, including rainfall intensity, land-use change, and impervious surfaces, which are incorporated across all stages. Planning and resilience strategies, such as LID, green infrastructure, and risk management, are also shown to be linked with multiple methodological domains. The overall structure of the figure indicates increasing methodological integration over time, with multiple approaches being applied within individual studies.

4. DISCUSSION

The findings of this study demonstrate a clear evolution in urban flood research, marked by a transition from traditional process-based modeling toward integrated, data-driven, and spatially explicit approaches. While hydrological and hydraulic models remain fundamental for understanding flood dynamics, their relative dominance has declined with the increasing adoption of GIS, remote sensing, and machine learning techniques. Similar transitions have been reported in recent literature, where advances in geospatial technologies and computational capacity have enabled more comprehensive analysis of urban flood systems (Guo et al., 2022; Lei et al., 2021; (Kumar, Maurya, Mandal, Mir, et al., 2025). As shown in Figure 7, this shift is not a replacement of traditional methods but rather an expansion toward hybrid frameworks that combine physical and data-driven approaches.

A key outcome of this study is the identification of methodological convergence across research domains. Increasingly, studies integrate multiple techniques, such as combining GIS and remote sensing for spatial analysis or embedding machine learning models within hydrological simulation frameworks. This trend reflects the inherent complexity of urban flooding, which cannot be adequately addressed through single-method approaches. Previous studies have similarly emphasized the need for integrated modeling frameworks that capture both physical processes and data-driven patterns (Jamali et al., 2018; Wang et al., 2018). The conceptual synthesis in Figure 8 further illustrates how these methodological domains are interconnected, with environmental drivers and planning strategies acting as cross-cutting components.

Differences in validation procedures, uncertainty assessment, and reporting standards across studies represent an important source of heterogeneity within the reviewed literature. Consequently, conclusions regarding methodological effectiveness should be interpreted as indicative patterns rather than definitive evidence of methodological superiority.

Another important finding is the growing incorporation of environmental and climatic drivers, including rainfall intensity, land-use change, and impervious surface expansion. This aligns with broader research highlighting the role of urbanization and climate variability in amplifying flood risk (Moniruzzaman et al., 2021; Sperotto et al., 2016). The integration of these variables into both modeling and mapping approaches reflects a shift toward system-level understanding, where urban flooding is viewed as the outcome of interacting natural and anthropogenic processes. However, despite this progress, inconsistencies remain in how these variables are quantified and integrated across studies, limiting comparability.

Despite methodological advancements, planning and resilience-oriented studies appear less represented within the reviewed dataset. However, this observation should be interpreted cautiously because the search strategy prioritized technically oriented urban flood assessment literature. Consequently, governance, policy, and community-based resilience studies may not be fully represented in the analyzed corpus. While technical approaches dominate, relatively few studies translate these findings into actionable planning strategies. Existing work on low-impact development (LID) and sustainable drainage systems (SuDS) demonstrates potential for flood mitigation (Bai et al., 2019; Guptha et al., 2021), yet these approaches are often evaluated in controlled or simulation-based contexts. Similar concerns have been raised in the literature regarding the disconnect between technical modeling and policy implementation (Vamvakeridou-Lyroudia et al., 2019). As shown in Figure 7C, this domain remains the least represented, indicating a need for stronger integration between science and practice.

Furthermore, the geographical concentration of studies in specific regions highlights issues of spatial bias and limited generalizability. Consistent with previous bibliometric analyses, research is heavily concentrated in countries such as China, the United States, and parts of Europe, while rapidly urbanizing regions in Africa and South America receive comparatively less attention. This imbalance may hinder the development of globally applicable flood management strategies, particularly given regional differences in infrastructure, climate, and governance systems. The widespread use of a methodological approach should not be interpreted as evidence of methodological superiority, as reported performance is strongly influenced by validation procedures, data quality, uncertainty treatment, and contextual applicability.

Overall, the results suggest that urban flood research is evolving toward increasingly interdisciplinary and integrative frameworks, as illustrated in Figure 8, but challenges remain in standardization, practical application, and global representation.

4.1. Implications for Research and Practice

The findings of this study have several important implications for both research and practical applications. First, the observed shift toward integrated methodologies suggests that future research should prioritize multi-method frameworks that combine hydrological modeling, geospatial analysis, and machine learning. Such approaches can leverage the strengths of individual methods while addressing their limitations, particularly in complex urban environments.

Second, the increasing role of spatial data highlights the importance of high-resolution and multi-source datasets, including satellite imagery, LiDAR, and real-time sensor data. Improving data accessibility and interoperability will be critical for advancing urban flood research and enabling more accurate and scalable analyses.

From a practical perspective, the results emphasize the need to translate technical findings into decision-support tools that can be used by urban planners and policymakers. While many studies provide detailed simulations or predictive models, their applicability in real-world contexts remains limited. Bridging this gap requires the development of user-friendly tools, standardized indicators, and frameworks that align with planning processes and stakeholder needs.

4.2. Policy Translation and Governance Challenges

A critical challenge identified in this study is the limited integration of research outcomes into policy and governance frameworks. Although significant advances have been made in modeling and prediction, their translation into actionable policies remains constrained. This issue is widely acknowledged in the literature, where gaps between scientific knowledge and policy implementation are often attributed to institutional, technical, and communication barriers (Vamvakeridou-Lyroudia et al., 2019; Kumar, Maurya, Mandal, Halder, et al., 2025).

One key limitation is the lack of standardized metrics and evaluation frameworks, which makes it difficult for policymakers to compare results across studies and apply them in decision-making contexts. Additionally, many studies focus on technical optimization without considering governance structures, stakeholder engagement, or socio-economic factors. This limits their relevance for integrated urban planning.

Another challenge is the fragmentation of responsibilities across different sectors, such as water management, urban planning, and disaster risk reduction. Effective urban flood management requires coordinated approaches that integrate these domains, yet such coordination is often lacking. The findings of this study suggest that future research should place greater emphasis on interdisciplinary collaboration and policy-oriented frameworks to enhance implementation.

4.3. Future Research Directions

Based on the identified gaps and trends, several directions for future research can be proposed. First, there is a need to develop hybrid modeling frameworks that combine physically based models with machine learning techniques, enabling both interpretability and predictive accuracy. Such approaches can address current limitations related to data dependency and model generalization.

Second, future studies should focus on standardization of methodologies and metrics, particularly for flood hazard assessment, risk quantification, and model validation. Establishing common frameworks will improve comparability and facilitate meta-analysis across studies.

Third, expanding research into underrepresented regions, particularly in Africa and South America, is essential for improving the global relevance of urban flood research. This includes incorporating local data, context-specific variables, and regionally appropriate modeling approaches.

Finally, there is a need to strengthen the integration of social, economic, and governance dimensions within urban flood research. Moving beyond purely technical analysis toward interdisciplinary frameworks will be critical for addressing real-world challenges and supporting sustainable urban development.

5. CONCLUSION

This study provides a comprehensive synthesis of urban flood research through a PRISMA-guided systematic review, bibliometric analysis, and thematic evaluation of 207 peer-reviewed studies published between 2016 and 2025. The findings demonstrate that urban flood research has evolved into an increasingly interdisciplinary field that integrates hydrological and hydraulic modeling, geospatial technologies, machine learning, and resilience-oriented planning approaches.

Hydrological and hydraulic modeling remains the most frequently applied methodological approach, although growing use of GIS, remote sensing, and machine-learning techniques reflects a shift toward integrated and data-driven flood assessment frameworks. Four major thematic domains were identified:

flood modeling and simulation, flood mapping and detection, environmental and climatic drivers, and planning and resilience strategies. While resilience-related research has expanded in recent years, much of the evidence remains based on simulation scenarios rather than implemented interventions and long-term performance evaluation.

The review also highlights persistent challenges, including methodological inconsistencies, limited uncertainty assessment, variable data quality, and difficulties in transferring models across different urban contexts. In addition, publication output remains concentrated among a relatively small number of countries based on author affiliations, emphasizing the need for broader international participation and collaboration.

Overall, future advances in urban flood research will depend on improved methodological transparency, stronger validation and uncertainty analysis, greater integration of socio-economic and governance dimensions, and closer linkage between scientific research, urban planning, and climate-resilience policy. Such efforts will be essential for supporting effective and sustainable flood-risk management in rapidly urbanizing environments.

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