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BIORETENTION-BASED STORMWATER MANAGEMENT USING EPA SWMM: BIBLIOMETRIC AND SYSTEMATIC LITERATURE REVIEW WITH IMPLICATIONS FOR TROPICAL REGIONS

Giovanni Ivander[1*]

[1] *Civil Engineering Department, Faculty of Engineering, Al-Azhar University, Medan.*
Corresponding Author's Email: gioivander2@gmail.com
Corresponding Author's Phone Number: 0895392405817

ABSTRACT

Rapid urbanization has increased impervious surfaces, reducing infiltration capacity and intensifying stormwater runoff and flood risks. Bioretention, as a Low Impact Development (LID) approach, has been widely applied for sustainable urban stormwater management. However, the development and applicability of the EPA Storm Water Management Model (SWMM)-based bioretention modeling under tropical climate conditions remain insufficiently synthesized. This study evaluates global research trends, knowledge structures, critical design parameters, and the applicability of SWMM-based bioretention systems in tropical regions through bibliometric analysis and a Systematic Literature Review (SLR) following the PRISMA framework. A Scopus-based search covering 2021–2026 identified 1,067 articles for bibliometric analysis and 22 articles for SLR synthesis. Bibliometric analysis revealed four major research clusters: urban climate adaptation, bioretention performance and stormwater quality, SWMM-based hydrological modeling, and urban drainage integration. Research contributions remain dominated by China, the United States, and Europe, while tropical regions represent only 4.7% of the dataset. The SLR shows that bioretention performance depends strongly on hydrological conditions and design characteristics, with peak flow reductions ranging from 14.3% to 94%. Saturated hydraulic conductivity (Ks) was identified as the key calibration parameter. The study highlights the need for tropical parameter databases, locally validated SWMM models, and integrated hydrological–water quality simulations.

Keywords: bibliometric analysis, bioretention, saturated hydraulic conductivity, SWMM, systematic literature review, tropical stormwater management.

1. INTRODUCTION

Urban flooding in Indonesia has become increasingly frequent as rapid urbanization transforms green spaces into impervious surfaces, reducing natural infiltration capacity and increasing surface runoff that may exceed the capacity of conventional drainage systems [1]. Changes in land cover have an even greater impact on runoff than rainfall variability [2]. On the other hand, the continuously increasing rainfall intensity due to climate change further exacerbates this situation [3].

As an alternative, Nature-Based Solutions (NbS) approaches based on the concept of Low Impact Development (LID), including rain gardens, permeable pavements, green roofs, bioretention, and rainwater harvesting, are increasingly being implemented because they mimic natural hydrological processes. This approach focuses on increasing infiltration and retaining stormwater runoff, unlike conventional drainage systems, which generally only discharge runoff as quickly as possible [4], [5].

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Bioretention systems, a key component of Low Impact Development (LID), have been shown to effectively reduce runoff volume and peak discharge [6] and pollutant loads such as TSS, TP, and TN [7]. The performance of these systems is generally evaluated using EPA SWMM across various designs and climate scenarios [1], [8]. Several studies indicate that bioretention can reduce peak flow by up to 92% under tropical rainfall conditions in Indonesia. In comparison, green infrastructure implementation has been reported to reduce flood volume by up to 98% [1], [3]. However, these results are highly dependent on specific site conditions and design configurations and should not be generalized as representative of overall performance. The effectiveness of bioretention systems is influenced by model calibration and local characteristics, particularly saturated hydraulic conductivity (Ks) [9], [10].

However, most model validation studies have been conducted in temperate regions [11], where rainfall patterns and soil infiltration characteristics differ from those in tropical regions. Consequently, the parameters derived from these studies may not be fully representative of high-intensity tropical rainfall conditions, such as those experienced in Indonesia. Several studies in tropical and equatorial regions have begun to address this gap. For example, standard bioretention designs have shown limited effectiveness in reducing peak discharge under intense tropical rainfall conditions [6], while combinations of bioretention and vegetated swales have demonstrated improved performance in equatorial Malaysia [7]. Nevertheless, the number of studies in these regions remains considerably lower than in temperate areas, and comprehensive reviews integrating research trends, dominant design parameters, and the applicability of SWMM modeling under tropical conditions remain limited.

In Indonesia, SWMM-based bioretention studies remain very limited, with only a few studies specifically examining their design and simulation under tropical rainfall conditions [1], [6]. Similar limitations in Indonesia's contribution to global urban water infrastructure research have also been observed in other related fields with different technical focuses, such as systematic reviews of high-rise building plumbing systems [12], [13]. This indicates that the limited representation of Indonesia in the global literature is not only observed in bioretention research but also reflects a broader challenge in urban water infrastructure studies.

Based on these gaps, this study poses three research questions:

1. What are the trends and knowledge structure of EPA SWMM-based bioretention research in the global literature for the period 2021–2026?
2. What design parameters and modeling approaches are most dominant in bioretention simulations using SWMM?
3. To what extent can existing research findings be applied to tropical regions with high rainfall intensity?

This study aims to synthesize the development of EPA SWMM-based bioretention research through bibliometric analysis and a Systematic Literature Review (SLR) with the following objectives:

1. To identify trends and the knowledge structure of EPA SWMM-based bioretention research for the 2021–2026 period.
2. To analyze the most dominant design parameters and modeling approaches.
3. To evaluate the relevance of global findings to tropical regions with high rainfall intensity.

The novelty of this study lies in its comprehensive synthesis, which integrates research trends, dominant design parameters, and the relevance of SWMM-based bioretention modeling to tropical regions within a single analytical framework based on bibliometrics and SLR. These aspects have largely been discussed separately in previous studies: bibliometric studies generally focus on mapping research trends without evaluating technical aspects, while SWMM-based technical studies rarely examine their position within the global research landscape or their applicability to tropical conditions.

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2. RESEARCH METHOD

The literature search was conducted using the Scopus database through a structured Boolean search strategy applied to the TITLE-ABS-KEY fields. The search was performed on May 9, 2026, and was limited to English-language journal articles in the fields of Engineering, Environmental Science, and Earth and Planetary Sciences, covering publications from 2021 to 2026. The search date was specified because publication records for 2026 were incomplete and may increase as additional articles are indexed.

Table 1. Scopus Database Query

Query	Results
TITLE-ABS-KEY (("bioretention" OR "bioretention cell" OR "rain garden" OR "biofiltration" OR "LID" OR "low impact development" OR "green infrastructure" OR "permeable pavement" OR "swale" OR "SWMM" OR "stormwater management model" OR "EPA SWMM" OR "nature-based solutions" OR "sustainable drainage") AND ("urban flood" OR "urban drainage" OR "stormwater" OR "runoff" OR "flooding" OR "flood control" OR "surface runoff") AND ("evaluation" OR "effectiveness" OR "performance")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (PUBYEAR , 2026) OR LIMIT-TO (PUBYEAR , 2025) OR LIMIT-TO (PUBYEAR , 2024) OR LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021)) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "EART"))	1,067

The search query presented in Table 1 was broadly formulated by including LID-related terms such as permeable pavement, swale, green infrastructure, sustainable drainage, and nature-based solutions to comprehensively map the research landscape of LID and urban stormwater management through bibliometric analysis. However, during the Systematic Literature Review (SLR) phase, article selection was refocused on bioretention studies and EPA SWMM modeling in accordance with the inclusion criteria in Table 2.

The inclusion and exclusion criteria used in this study are presented in Table 2 to ensure that article selection was conducted systematically.

Table 2. Inclusion and Exclusion Criteria

Criteria	Inclusion Criteria	Exclusion Criteria
Document Type	Journal articles	Conference proceedings, review articles, book chapters, and editorial material.
Language	English	Non-English publications
Year of publication	2021–2026	Outside the specified year range
Topic relevance	Bioretention, EPA SWMM, LID, and urban stormwater management	Not relevant to bioretention or runoff modeling
Accessibility	Full text available	Full text not accessible

Literature selection was conducted using the PRISMA flowchart, which consists of the identification, screening, eligibility, and inclusion stages. During the identification stage, 1,067 records were retrieved from Scopus using the Boolean search strategy. Subsequently, 2 duplicate records and 12 inaccessible articles were removed, resulting in 1,053 records undergoing title and abstract screening.

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During the screening stage, 998 articles were excluded for irrelevance. A total of 55 articles were then evaluated during the full-text eligibility stage. Of these, 33 articles were eliminated because they did not meet the inclusion criteria: they did not focus on bioretention (n = 16), did not use EPA SWMM (n = 9), or lacked adequate parameter data or validation (n = 8). Finally, 22 articles were selected for the SLR analysis.

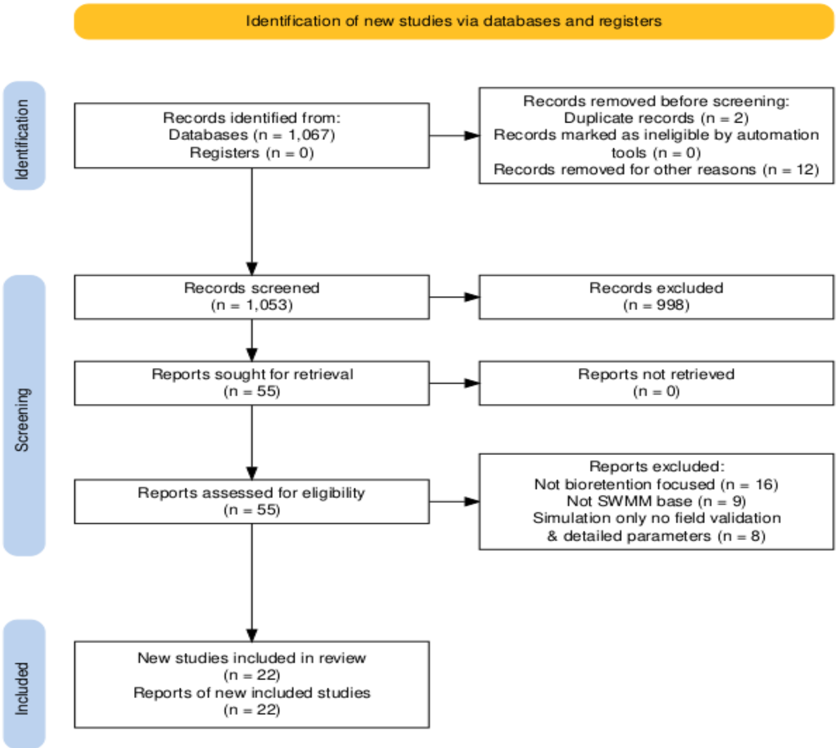

Figure 1. PRISMA Flow Diagram of the Study Selection Process

To evaluate methodological quality and potential bias, the 22 included articles were assessed using an author-developed framework adapted from systematic review quality assessment principles and tailored to SWMM-based modeling studies. Six dimensions were evaluated: research objectives, data and study location, model calibration, validation accuracy, parameter sensitivity, and study limitations. Each dimension was scored from 0 to 2, resulting in a total score of 0 to 12. Articles were classified as having a low (≥9), moderate (6–8), or high risk of bias (<6). The assessment results are presented in Table 3.

Table 3. Quality Assessment and Risk of Bias Classification of Selected Articles

No	Author (Year)	D1	D2	D3	D4	D5	D6	Score	Risk of Bias
1	De-Ville et al. (2025) [10]	2	2	2	2	0	2	10/12	Low
2	Liu et al. (2025) [14]	2	2	2	2	0	2	10/12	Low
3	Ramírez et al. (2025) [15]	2	2	2	2	2	2	12/12	Low
4	Muleta & Knolmar (2025) [3]	2	2	2	2	1	1	10/12	Low
5	Muszyński (2026) [2]	2	2	2	2	2	1	11/12	Low
6	Wicaksono et al. (2025) [1]	2	2	1	0	0	1	6/12	Moderate
7	Adhikari et al. (2026a) [11]	2	2	2	2	0	2	10/12	Low
8	Benoit et al. (2025) [4]	2	2	2	2	0	2	10/12	Low
9	Kuok et al. (2024) [7]	2	2	0	1	0	2	7/12	Moderate
10	Zúñiga-Estrada et al. (2023) [16]	2	2	0	1	0	2	7/12	Moderate
11	Wanitchayapaisit et al. (2026) [9]	2	2	2	2	2	2	12/12	Low
12	Sun et al. (2023) [17]	2	2	1	2	0	2	9/12	Low
13	Daniels & Yeakley (2024) [18]	2	2	2	2	1	2	11/12	Low
14	Muszyński (2024) [19]	2	2	2	2	1	2	11/12	Low
15	Shang et al. (2022) [20]	2	2	1	2	0	2	9/12	Low
16	Lammers et al. (2022) [21]	2	2	1	2	0	2	9/12	Low

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No	Author (Year)	D1	D2	D3	D4	D5	D6	Score	Risk of Bias
17	Bond et al. (2021) [22]	2	2	2	2	2	2	12/12	Low
18	De-Ville et al. (2021) [23]	2	2	1	2	1	2	10/12	Low
19	Pan et al. (2022) [24]	2	1	1	1	0	2	7/12	Moderate
20	Al Amin et al. (2025) [6]	2	2	2	2	1	2	11/12	Low
21	Adhikari et al. (2026b) [8]	2	2	2	2	1	2	11/12	Low
22	Boongaling et al. (2024) [25]	2	2	0	0	0	2	6/12	Moderate

The quality assessment results showed that 17 articles were classified as having a low risk of bias, 5 articles as having a moderate risk of bias, and none as having a high risk of bias.

Next, the selected articles were analyzed using a bibliometric approach and a systematic literature review (SLR). Bibliometric analysis was conducted using VOSviewer and Biblioshiny on 1,067 articles to map research trends, knowledge structures, and relationships among keywords. The co-occurrence analysis used the full-counting method with a minimum threshold of 15 keyword occurrences. This threshold was chosen to filter out keywords with low occurrence frequencies, ensuring that the network visualization is more informative, easier to interpret, and focused on dominant research themes.

Subsequently, a descriptive synthesis analysis was conducted on the 22 selected articles to identify research patterns, modeling approaches, and research gaps in EPA SWMM-based bioretention systems. The analysis focused on hydrological performance, SWMM model calibration and validation, the influence of design parameters, and their application in tropical and non-tropical regions.

3. RESULTS AND DISCUSSION

Based on the PRISMA-based literature selection, 1,067 records from Scopus were identified and used as the dataset for bibliometric analysis to map global research trends and knowledge structures. Subsequently, 22 articles that met the inclusion criteria were selected for an in-depth systematic literature review (SLR), focusing on the technical and methodological aspects of EPA SWMM-based bioretention.

3.1. Scientific Publication Trends

Of the total 1,067 records obtained from Scopus (2021–2026), publication trends indicate an overall increasing pattern, from 167 articles in 2021 to 211 articles in 2024, peaking at 258 articles in 2025 (a 54.5% increase compared to 2021). The 2026 data (121 articles as of May 2026) remain incomplete because the indexing period does not yet represent a full publication year. This increase reflects not only quantitative growth but also a shift in research focus from conventional drainage approaches toward more sustainable adaptive systems in response to urbanization and climate change.

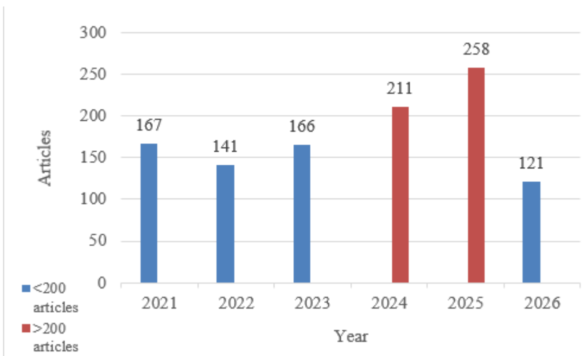

Figure 2. Annual Scientific Production of Bioretention Research (2021–2026)

3.2. Geographic Distribution

The distribution of publications shows a dominance by China (20.5%), followed by the United States (14.6%), the United Kingdom (6.3%), Italy (4.2%), and Australia (3.8%). China's dominance is likely associated with initiatives such as the "Sponge City" policy, which promotes the integration of LID approaches into urban planning. The cumulative contribution of Southeast Asian countries, including Indonesia, Malaysia, Thailand, the Philippines, and Singapore, accounts for only 4.7% of total publications. Although Indonesia contributes several publications within the broader LID and stormwater management dataset, studies specifically focusing on SWMM-based bioretention remain limited. The low contribution from tropical regions is likely influenced by differences in LID policy implementation, limited availability of long-term hydrological datasets for SWMM model calibration, and differences in research capacity and funding availability compared with developed countries. This gap indicates that SWMM-based bioretention research in tropical regions remains concentrated in a limited number of countries and highlights opportunities for broader investigation, considering that tropical rainfall patterns differ from those in temperate regions.

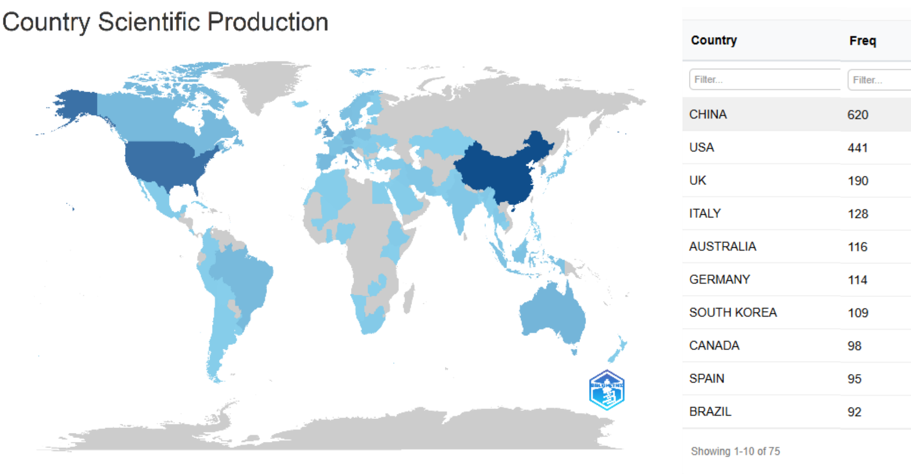

Figure 3. Country Scientific Production

3.3. Leading Journals and Authors

The journal *Water* was identified as the leading publication source, followed by *Sustainability* and the *Journal of Hydrology*. This distribution reflects the interdisciplinary characteristics of bioretention research, where *Water* and the *Journal of Hydrology* mainly contribute to technical aspects, including SWMM modeling, hydrological simulation, and parameter calibration, while *Sustainability* focuses more on green infrastructure and sustainable urban water management perspectives.

In terms of author productivity, the most active contributors were researchers from China, including Wang J, Li J, and Liu J, which is consistent with China's leading position in publication output associated with the implementation of the "Sponge City" concept. European researchers, such as Viklander, have also contributed significantly to the development of sustainable urban drainage systems (SUDS). Overall, the distribution of authors indicates that bioretention research remains concentrated within several established research groups with strong modeling capabilities and data availability, while contributions from tropical regions remain relatively limited.

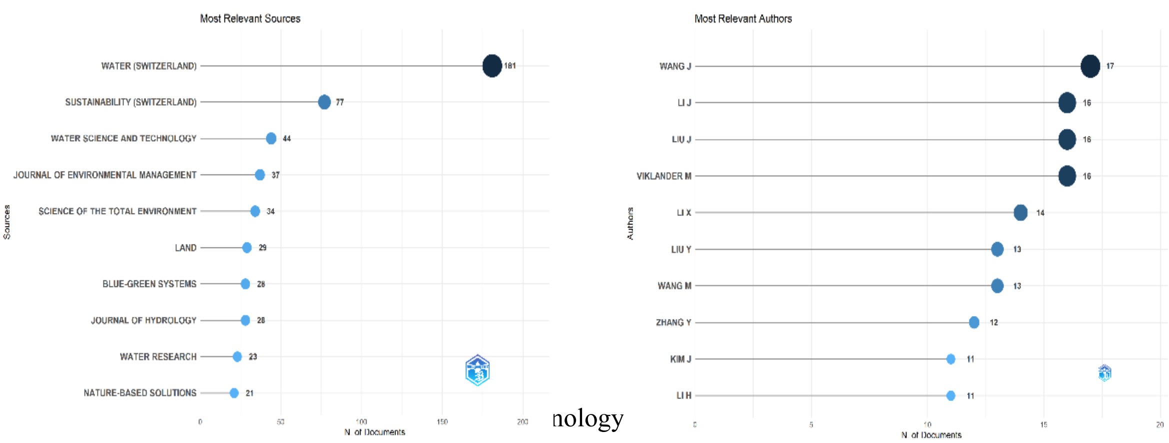

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Figure 4. Most Relevant Sources and Authors

3.4. Keyword Co-occurrence Analysis

The keyword co-occurrence analysis was conducted using a minimum threshold of 15 occurrences. The analysis identified 253 keywords, which were grouped into four main clusters. Table 4 presents the five keywords with the highest occurrence frequencies.

Table 4. Five Keywords with the Highest Frequency of Occurrence

Keyword	Occurrences
runoff	393
stormwater	334
storms	243
water management	242
rain	233

These findings indicate that bioretention research is not only focused on the technical performance of individual systems but is also increasingly integrated with broader urban water management issues, including climate change adaptation, water quality improvement, and hydrological modeling. The four identified clusters are summarized as follows:

1. The "Urban Flood Management and Climate Adaptation" cluster, focusing on climate change, floods, green infrastructure, and flood control.
2. The "Bioretention Performance and Stormwater Quality" cluster, focusing on water quality, pollutant removal, and hydraulic conductivity.
3. The "SWMM-Based Hydrological Modeling" cluster, characterized by runoff, stormwater, infiltration, and hydrological simulation
4. The "Urban Drainage System Integration" cluster, covering sewer networks, combined sewer overflows, and catchment-scale systems.

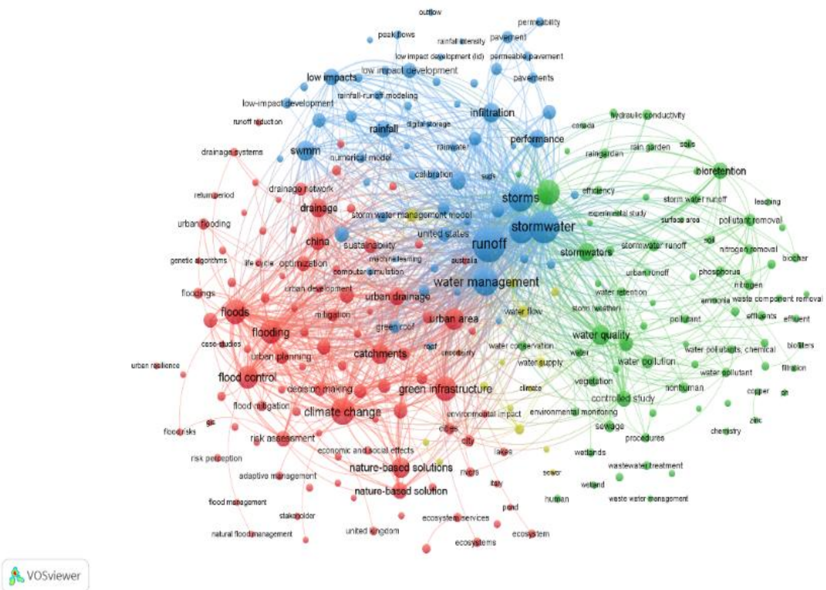

Figure 5. Network Visualization

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The network visualization reveals four interconnected keyword clusters representing the dominant research themes within SWMM-based bioretention studies. A description of each cluster is provided in the following section.

1. Bioretention in Urban Flood Management and Climate Adaptation (Red Cluster)

   This is the largest cluster, indicating that bioretention is increasingly associated with climate change adaptation and urban resilience. The dominant keywords include “climate change” (220 occurrences), “floods,” “green infrastructure,” “flood control,” “urban drainage,” and “nature-based solutions,” showing a shift toward integrating bioretention into broader urban adaptation strategies.

2. Bioretention Performance and Stormwater Quality Treatment (Green Cluster)

   This cluster focuses on bioretention effectiveness in runoff control and water quality improvement, with dominant keywords including “storm sewers” (197 occurrences), “water quality” (128), and “bioretention” (89). Keywords such as hydraulic conductivity, porosity, vegetation, pollutant removal, biochar, and biofiltration indicate research development in media optimization and treatment performance.

3. SWMM-Based Bioretention Modeling and Hydrological Simulation (Blue Cluster)

   This cluster represents SWMM-based bioretention simulation, with “runoff” as the most dominant keyword (393 occurrences), followed by stormwater, infiltration, hydrological modeling, and low-impact development. The presence of machine learning and numerical models indicates emerging integration between physical modeling and data-driven approaches.

4. Bioretention in Urban Hydrological and Sewer Network Systems (Yellow Cluster)

   This smallest cluster consists of 15 keywords, dominated by simulation (69 occurrences), city/cities (46), water flow (46), catchment area (35), sewer network (28), and combined sewer overflows (17). The cluster highlights the integration of bioretention into urban drainage systems at the catchment scale, which remains an emerging research area.

3.5. VOSviewer Visualization and Biblioshiny Analysis

Overlay visualization analysis indicates a shift in research focus toward emerging topics. Keywords such as “bioretention,” “hydraulic conductivity,” and “biochar” show recent growth during 2024–2025, reflecting increasing interest in filter media characteristics and substrate modification. Meanwhile, “nature-based solutions,” “climate change,” and “green infrastructure” represent growing research themes related to sustainable urban stormwater management. In contrast, “permeable pavements,” “low-impact development,” and “infiltration” are established topics that form the foundation of LID research.

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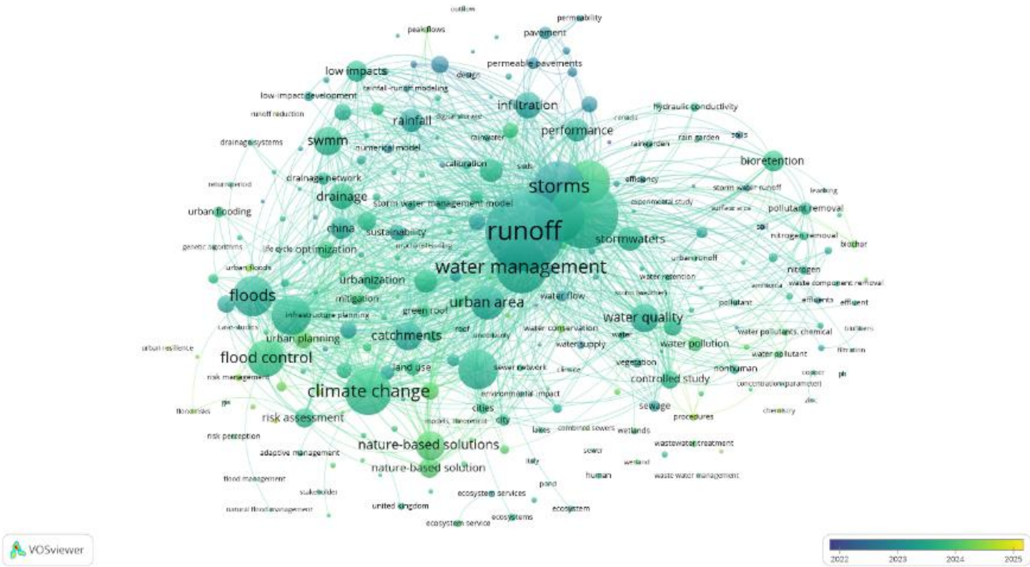

Figure 6. Overlay Visualization

The density visualization confirms that "runoff," "storms," and "water management" are the dominant themes within the SWMM-based bioretention research network. Conversely, topics such as biochar, machine learning, and hydraulic conductivity show lower density, indicating emerging research directions.

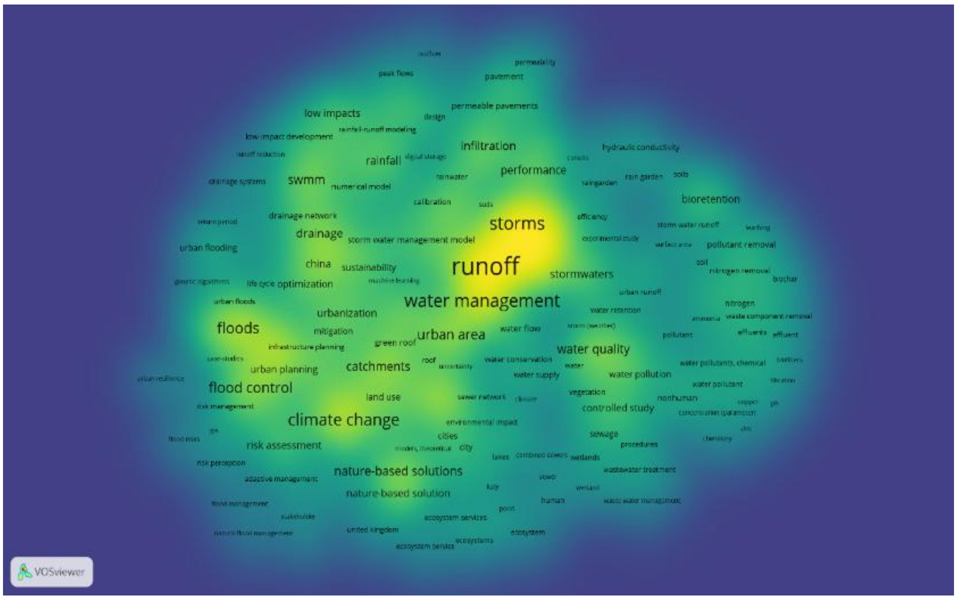

Figure 7. Density Visualization

The thematic structure identified through VOSviewer was further validated using Biblioshiny, which revealed three consistent themes: green infrastructure, SWMM-based modeling, and bioretention and water quality. The agreement between both analyses confirms the stability of the identified knowledge structure in global SWMM-based bioretention research.

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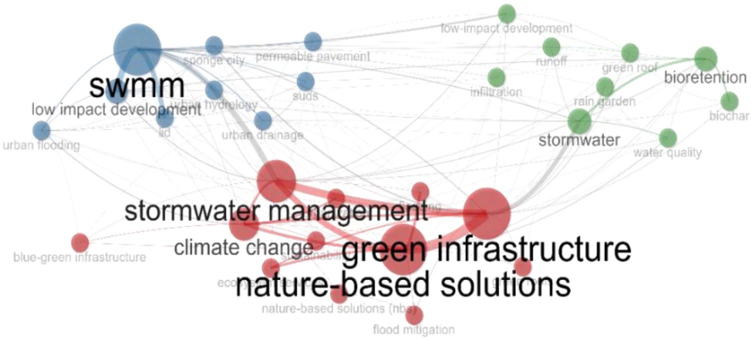

Figure 8. Results of Network Visualization Using Biblioshiny

3.6. Research Gaps

Based on the synthesis of bibliometric analysis, keyword co-occurrence analysis, thematic mapping, and systematic literature review findings, three major research gaps were identified in SWMM-based bioretention studies.

1. First, most SWMM model validation studies have been conducted in temperate and developed regions, including the UK and Canada [10], [22], while tropical studies remain in the minority, for example, in Indonesia and Malaysia [1], [7]. This imbalance indicates that commonly used design parameters and modeling assumptions in SWMM literature are still largely based on non-tropical hydrological characteristics.
2. Second, design parameters, particularly Ks and infiltration characteristics, are still largely derived from non-tropical climate conditions, such as the Ks calibration in the UK [10]. The increase in Nash-Sutcliffe Efficiency (NSE) from 0.25 to 0.70 following field-data-based calibration underscores the risk of bias when using default parameters without local calibration [11]. Studies specifically examining Ks under tropical conditions remain rare, as seen in the study from Thailand [9].
3. Third, the integration of hydrological and water quality simulations within a single SWMM framework at the city or multi-site scale in tropical regions remains very limited. Water quality studies in tropical regions, such as the comparison of bioretention and swales in Malaysia [7], have so far only covered a single-site scale with short data periods. The multifunctional role of bioretention cannot yet be comprehensively optimized through current numerical modeling, particularly in a tropical context.

3.7. Results of the Systematic Literature Review

This systematic literature review focuses on bioretention modeling, including bioretention cells, rain gardens, and biofiltration systems, within the Low Impact Development (LID) framework using SWMM-based approaches. Literature was retrieved from the Scopus database using a structured search strategy combining keywords related to bioretention, LID, SWMM, and urban stormwater management, with a publication range of 2021–2026. Of the 1,067 initial articles, 22 were selected as final studies through a screening process of titles, abstracts, and full texts based on their relevance to the research focus. The complete characteristics of these 22 studies, including location, methods, key parameters, main findings, and limitations, are presented in Table 5.

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Table 5. Synthesis Results of the 22 Selected Articles

No	Author (Year)	Location	Method	Key Parameters	Key Findings	Limitations
1	De-Ville et al. (2025), [10]	UK	Laboratory column experiment; evaluation of percolation models	Hydraulic conductivity (Ks)	Ks varies widely; crucial for calibration	Laboratory scale
2	Liu et al. (2025), [14]	China	SWMM spatial scenarios	Spatial BC configuration	Decentralization improves runoff efficiency	Single-catchment simulation
3	Ramírez et al. (2025), [15]	USA	SWMM + infiltration test	Swale media infiltration rate	Higher Ks improves swale performance	Small-scale test
4	Muleta & Knolmar (2025), [3]	Ethiopia	SWMM + CMIP6 climate	CMIP6/SSP climate scenarios	Flood reduction 86–98%	One sub-catchment
5	Muszyński (2026), [2]	Poland	SWMM historical-projected	Land cover changes 1940–2060	Coverage of 3–4% offsets urbanization	Depends on historical maps
6	Wicaksono et al. (2025), [1]	Indonesia	SWMM 5.2	Percentage of bioretention coverage	Peak reduction of up to 92%	Single case study
7	Adhikari et al. (2026a), [11]	Sweden	SWMM + field validation	Outflow discharge from the underdrain	Reliable model after calibration	Only 4 locations
8	Benoit et al. (2025), [4]	Canada	PCSWMM	A combination of green infrastructure scenarios	Effective; requires a combination of LID	Extreme climate scenarios are based on projections and have not yet been validated under future real-world conditions
9	Kuok et al. (2024), [7]	Malaysia	SWMM	Comparison of bioretention vs. swale	Bioretention is more effective than swales	1-month rainfall data
10	Zúñiga-Estrada et al. (2023), [16]	Mexico	SWMM + monitoring	First-flush water quality	Effectively reduces first-flush pollutants	Single-area coverage
11	Wanitchayapaisit et al. (2026), [9]	Thailand	SWMM + Ks test	Local hydraulic conductivity	Local parameters improve accuracy	Limited availability of tropical Ks data
12	Sun et al. (2023), [17]	USA	Long-term SWMM	Pre-development hydrological indicators	Simulating pre-development hydrology	Hypothetical BC, not yet actual
13	Daniels & Yeakley (2024), [18]	USA	Continuous SWMM	Rain garden coverage percentage	Effective at the suburban scale	One suburban catchment
14	Muszyński (2024), [19]	Poland	SWMM event-based	Design rainfall duration	Peak reduction of up to 94%	Event-based model only
15	Shang et al. (2022), [20]	China	SWMM multi-LID	Combination of LID types	Effective rainfall return period <10 years	Only return periods <10 years
16	Lammers et al. (2022), [21]	USA	Regional SWMM	BC size & climate conditions	Performance is influenced by climate and size	SWMM lumped model, minimal evaluation of cold/snowy conditions
17	Bond et al. (2021), [22]	Canada	SWMM calibration	Conductivity & seepage rate	Most sensitive parameters identified	One pilot project
18	De-Ville et al. (2021), [23]	UK	SWMM	Type of recycled media	Recycled media remains viable	Laboratory evaluation

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No	Author (Year)	Location	Method	Key Parameters	Key Findings	Limitations
19	Pan et al. (2022), [24]	China	SWMM + VADOSE/W	Long-term groundwater balance	Increasing groundwater recharge	One toll road infrastructure
20	Al Amin et al. (2025), [6]	Indonesia	SWMM + experiments	Hydraulic conductivity (Ks)	Optimal coverage 10–20%	Laboratory experiments
21	Adhikari et al. (2026b), [8]	Sweden	SWMM optimization	Combination of design parameters	Optimal design to reduce overflow	Synthetic design rainfall (Chicago), does not represent the long-term climate
22	Boongaling et al. (2024), [25]	Philippines	PCSWMM	LID scenarios by land use	LID implementation improves runoff reduction performance	Performance drops sharply during heavy rainfall

Based on the synthesis in Table 5, SWMM-based bioretention studies have been conducted under diverse hydrological conditions, modeling approaches, and design parameters. However, these studies remain fragmented, and the influence of climatic characteristics on bioretention performance has not been systematically compared. Therefore, a further synthesis was conducted by grouping studies into tropical, non-tropical, and unidentified climate categories to compare bioretention performance across regions.

Table 6. Comparison of Bioretention Performance Based on Climate

Aspect	Tropical Studies (n = 5)	Non-Tropical Studies (n = 15)	Other Climate Regions (n = 2)
Related Studies	Wicaksono [1], Al Amin [6], Kuok [7], Wanitchayapaisit [9], Boongaling [25]	De-Ville [10], [23]; Liu [14]; Ramírez [15]; Muszyński [2], [19]; Adhikari [8], [11]; Benoit [4]; Sun [17]; Daniels & Yeakley [18]; Shang [20]; Lammers [21]; Bond [22]; Pan [24]	Muleta & Knolmar, Ethiopia [3]; Zúñiga-Estrada, Mexico [16]
Peak flow reduction	80–92% [1]; 22.98–24.71% [7]	14.3–94% depending on simulation approach and rainfall scenario [18], [19]	NSE model 0.58–0.75 in CMIP6 scenarios [3]
Saturated hydraulic conductivity (Ks)	63.3–325.6 mm/h based on direct measurements in the Al Amin study [6]	101 mm/h in laboratory-engineered media (De-Ville [10], [23]); 349–631 mm/h from field measurements at four bioretention systems (Adhikari [11])	Not specifically addressed
Response to extreme rainfall/climate change	Volume reduction decreased from 2.1–11.2% (2-year return period rainfall) to 1.4–6.8% (50-year return period rainfall) [6]	Benoit: Individual BGI systems offset 20–118% of the increase in flood volume due to climate change, while a combination of BGI systems achieved 162–167% [4]. Sun: Peak discharge reduction decreased significantly for rainfall with a return period >1 year [17]	Not yet discussed
Bioretention coverage of the catchment	Al Amin recommends 10–20% [6]; Kuok evaluated up to 39.7% (combination of bioretention and swales) [7]	Muszyński shows that 3–4% coverage can offset the impacts of urbanization and climate change through 2060 [2]	Tested up to a maximum coverage of 30% [3]
Scale and methods	Predominantly conducted at single-site or laboratory scales [1], [6], [9]	Lammers showed that volume reduction is more effective at the sub-basin scale, while peak discharge reduction is more effective at the watershed scale [21]	Field studies at a single location, CMIP6 projections [3], [16]
Water quality	Kuok reported reductions of 20.09% for TSS, 19.75% for TP, and 12.26% for TN [7]	Quantitative water quality assessments remain very limited	Zúñiga-Estrada reported removal efficiencies of >95% for phosphate and lead, while nitrate had an efficiency of approximately 31% [16]

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Table 6 shows that most studies are still dominated by non-tropical regions, while studies in tropical regions are relatively limited. This comparison provides an overview of variations in bioretention characteristics and performance across climatic conditions, serving as a basis for further synthesis.

3.8. General Performance of Bioretention in SWMM Modeling

A synthesis of 22 articles indicates that bioretention generally reduces peak runoff discharge, although the reported effectiveness varies widely (14.3–94%) [18], [19]. An examination of the two studies that provided this range shows that the lowest reduction (14.3%) was obtained from a continuous simulation with 223 rainfall events on a suburban scale [18], while the highest reduction (94%) came from a calibrated single-event model [19]. This considerable variability indicates that bioretention effectiveness is not fixed but depends on local hydrological characteristics, rainfall intensity, and system design parameters. Therefore, within the SWMM framework, bioretention should be understood as a context-dependent system.

Among all model parameters, saturated hydraulic conductivity (Ks) is the variable that most significantly influences simulation performance. The use of Ks values based on field measurements has been shown to improve model accuracy compared to default values [9], [10], while improvements in NSE following observation-based calibration underscore the importance of incorporating local parameters to improve SWMM reliability [11]. Findings from other LID systems also indicate that increasing infiltration capacity through the hydraulic characteristics of the medium contributes to improved hydrological performance [16]

A bioretention coverage of 10–20% of the sub-catchment area has demonstrated effective performance under extreme rainfall conditions [6], while a smaller coverage (±3–4%) is still capable of offsetting the impacts of urbanization under normal conditions [2]. The relationship between application area and runoff reduction is also evident in scenarios with 5%, 10%, and 20% sub-catchment coverage, which result in peak discharge reductions of 80%, 88%, and 92%, respectively [1]. However, there is no universal design configuration because the system's response is highly dependent on rainfall characteristics and the physical conditions of the catchment area.

3.9. Effectiveness in Various Hydrological and Climatic Contexts

Bioretention performance is highly sensitive to changes in rainfall intensity. Increased rainfall intensity can reduce system effectiveness due to increased runoff and overflow frequency [21], particularly in areas with extreme rainfall events that exceed design capacity [25]. Nevertheless, combinations of different LID types have demonstrated effectiveness under rainfall events with certain return periods, particularly those below 10 years [11].

In addition to rainfall characteristics, the effectiveness of bioretention is also influenced by the scale of implementation and system configuration. At the watershed scale, runoff reduction tends to be greater than at the sub-basin scale due to the cumulative effect of hydrograph changes [21]. Decentralized configurations with series flow patterns have also demonstrated better performance than centralized systems with equivalent areas [14]. Thus, the benefits of bioretention do not depend solely on peak flow reduction capacity but also include increased groundwater recharge [24] and the ability to restore hydrological characteristics to near pre-development conditions [17].

These variations in response are also evident in the context of climate change, where the effectiveness of bioretention is influenced by the severity of future hydrological scenarios. Flood reduction of 86–98% can still be achieved under some moderate CMIP6/SSP scenarios, but decreases under more extreme scenarios [3]. This indicates that the use of green infrastructure alone has limitations in addressing the increasing intensity of extreme rainfall, making a combination of various stormwater management strategies even more necessary [4].

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3.10. Critical Design Parameters and SWMM Model Sensitivity

The performance of bioretention in SWMM is highly influenced by several sensitive design parameters, including saturated hydraulic conductivity (Ks), filter media depth, ponding depth, storage connection, and conductivity slope. Small variations in these parameters can result in significant differences in model output, particularly in the volume reduction and peak flow reduction indicators.

Conductivity slope and seepage rate are the most sensitive parameters in the SWMM calibration process [22]. Meanwhile, the implementation of a storage connection significantly improves runoff reduction efficiency and reduces overflow frequency [11]. Simultaneous optimization of design parameter combinations has also been shown to further reduce overflow frequency [8]. In terms of materials, recycled media have also been shown to remain suitable for use as bioretention filter media without significantly reducing their hydrological performance [23], opening up opportunities for more sustainable applications in terms of material selection. These findings indicate the presence of design trade-offs, where there is no universal optimal configuration; rather, the design must be tailored to the control objectives and local hydrological characteristics.

3.11. Water Quality Performance

In addition to its hydrological functions, bioretention also contributes to improving urban stormwater quality by removing total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN), particularly during the first flush, which typically has higher pollutant concentrations [7], [16]. The effectiveness of this removal is influenced by the system's initial conditions, such as the antecedent dry period, rainfall intensity, and filter media characteristics. Quantitatively, Kuok et al. reported TSS removal of 20.09%, TP removal of 19.75%, and TN removal of 12.26% in a tropical study in Malaysia [7], while Zúñiga-Estrada et al. demonstrated removal efficiencies of over 95% for phosphate and lead, but only about 31% for nitrate in a study in Mexico [16]. These differing patterns indicate that pollutant removal mechanisms are influenced by contaminant characteristics and system configuration, in addition to hydrological factors.

Integrating bioretention with a vegetated swale also results in higher pollutant removal efficiencies compared with a single-system application [7]. These findings reinforce the role of bioretention as a multifunctional element in Low Impact Development (LID) systems, not only for controlling runoff but also for improving water quality.

However, the aspect of water quality remains a relatively under-explored area in the reviewed literature. Only two of the 22 studies quantitatively evaluated water quality performance [7], [16], and neither of these studies integrated water quality analysis with peak discharge or runoff volume evaluations within a single SWMM modeling framework. This highlights the need to develop bioretention modeling approaches capable of simultaneously evaluating hydrological performance and water quality within an integrated framework.

3.12. Research Implications and Recommendations

The findings of this study indicate that the successful application of EPA SWMM-based bioretention in tropical regions is highly dependent on the use of design parameters calibrated based on local conditions, particularly saturated hydraulic conductivity (Ks). Therefore, future research should focus on developing a database of tropical hydrological parameters, integrating hydrological and water quality simulations within a single SWMM framework, and evaluating bioretention performance under various long-term climate change scenarios. From an implementation perspective, bioretention should be applied as part of an integrated Low Impact Development (LID) strategy tailored to the hydrological characteristics of each watershed to ensure optimal stormwater management performance.

3.13. Research Limitations

This study has several limitations.

1. The reliance on a single database, namely Scopus, may have resulted in the exclusion of relevant publications indexed in other databases, potentially affecting the comprehensiveness of the literature search.
2. The restriction to the 2021–2026 period allows this study to focus on recent developments; however, it may exclude several fundamental studies that contributed to the early development of the bioretention concept.
3. This study does not involve primary data collection or independent model simulations; therefore, the findings rely entirely on the quality and limitations of the secondary studies analyzed.

3.14. Research Question Findings

1. RQ1. What are the trends and knowledge structure of EPA SWMM-based bioretention in the global literature for the 2021–2026 period?

   A bibliometric analysis of 1,067 Scopus-indexed articles indicates that research on EPA SWMM-based bioretention has shown a continuous increasing trend during the 2021–2026 period. Scientific publications remain dominated by China, the United States, and European countries, while contributions from tropical regions remain relatively limited. A keyword analysis identified four main thematic clusters reflecting research developments in the areas of urban climate adaptation, SWMM modeling, bioretention performance and water quality, and the integration of bioretention into urban drainage systems. Additionally, recent research is beginning to focus on topics such as hydraulic conductivity, biochar, and machine learning.

2. RQ2. Which design parameters and modeling approaches are most influential in bioretention simulations using SWMM?

   The synthesis results indicate that saturated hydraulic conductivity (Ks) is the most influential parameter affecting SWMM model calibration accuracy. A bioretention coverage of approximately 10–20% of the sub-catchment area, combined with a decentralized configuration featuring a series flow pattern, has demonstrated improved hydrological performance in several studies. Variations in performance observed across various studies indicate that the effectiveness of bioretention is highly influenced by hydrological conditions and design characteristics at each site.

3. RQ3. To what extent can existing research findings be applied to tropical climates with high rainfall intensity?

   Most of the analyzed studies were conducted in temperate regions; therefore, the design parameters and modeling approaches reported in the literature cannot be directly transferred to tropical regions without calibration using local conditions. Furthermore, research from tropical countries remains relatively scarce, and the integration of hydrological and water quality simulations within the SWMM framework for tropical urban areas is still very limited. These conditions indicate that the development of more representative models for tropical regions remains a priority for future research.

4. CONCLUSION

This study examines the development of EPA SWMM-based bioretention within the Low Impact Development (LID) framework through a bibliometric analysis and Systematic Literature Review (SLR) of 1,067 Scopus publications from 2021 to 2026, with 22 articles selected as the basis for the main analysis. Publication trends show a significant increase during the 2024–2025 period, reflecting growing global attention to the application of nature-based solutions in urban stormwater management. Geographically, research remains concentrated in China, the United States, and European countries, whereas tropical regions, particularly Southeast Asia, remain underrepresented.

Bibliometric analysis confirms four main thematic clusters: urban climate adaptation, SWMM modeling, bioretention performance and water quality, and the integration of bioretention into urban drainage systems and sewer networks. Three structural gaps were consistently identified: the dominance of studies on non-tropical climates; the limited availability of design parameters based on local tropical

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conditions; and the suboptimal integration of hydrological and water quality simulations within the SWMM framework.

The SLR results indicate that bioretention performance in SWMM is highly context-dependent, with peak flow reduction ranging from 14.3% to 94%. Saturated hydraulic conductivity (Ks) proved to be the most sensitive parameter in model calibration, while decentralized configurations with series flow patterns were more effective than centralized systems. From a water quality perspective, bioretention contributes significantly to the reduction of TSS, TP, and TN, although the integration of hydrological and water quality modeling has not yet been fully optimized.

Overall, bioretention proved to be a key component in SWMM-based LID systems; however, its effectiveness is highly dependent on local parameterization, climatic conditions, and the system's spatial configuration. The development of a database of local tropical parameters, the integration of hydrological and water quality models, and scenario-based studies on climate change represent important directions for future research.

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