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Review

Global Paradigm Shifts in Urban Stormwater Management Optimization: A Bibliometric Analysis

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Abstract: Amidst the growing urgency to mitigate the impacts of anthropogenic climate change, urban flooding stands out as a critical concern, necessitating effective stormwater management strategies. This research presents a bibliometric analysis of the literature on urban stormwater management optimization from 2004 to 2023, with the aim of understanding how the field has responded to these escalating challenges. Aiming to map the evolution and current state of the field, this study employed a methodical approach, using CiteSpace to analyze publication trends, authorship patterns, and geographical distributions, as well as keyword and citation dynamics. The findings reveal a marked increase in research activity after 2014, with significant contributions observed between 2019 and 2022. Key research themes identified include low-impact development, green infrastructure, and stormwater management, with a notable shift towards hybrid grey–green infrastructure solutions that combine traditional and ecological elements. The prevalence of terms such as 'best management practices' and 'Green Roofs' in recent publications indicates a growing emphasis on practical, case-study-based research, particularly in green infrastructure technologies like bioretention cells. These insights underscore the field's movement towards pragmatic, multi-objective optimization frameworks with tangible applications, guiding future research directions in this increasingly complex domain.

Keywords: urban stormwater management; bibliometric analysis; hybrid grey–green infrastructure; low-impact development; multi-objective optimization; green infrastructure

Citation: Wang, M.; Jiang, Z.; Ikram, R.M.A.; Sun, C.; Zhang, M.; Li, J. Global Paradigm Shifts in Urban Stormwater Management Optimization: A Bibliometric Analysis. *Water* **2023**, *15*, 4122. https://doi.org/10.3390/w15234122

Academic Editor: Carmen Teodosiu

Received: 9 October 2023
Revised: 11 November 2023
Accepted: 21 November 2023
Published: 28 November 2023

1. Introduction

In the face of accelerating anthropogenic climate change, its impacts on economic activities, public safety, and ecological resources are becoming increasingly evident [1,2]. A salient ramification of this phenomenon is urban flooding, which, beyond the mere disruption of quotidian life, can inflict considerable economic losses and lead to fatalities in its severest incarnations [3]. Economic losses from flood disasters have risen over the past half-century, exceeding 30 billion USD per year over the past decade [4]. The necessity to develop sustainable and resilient urban drainage frameworks to manage the deluge thus becomes clear [5]. A compendium of urban stormwater management methodologies—sustainable urban drainage systems (SUDSs), low-impact development (LID), best management practices (BMPs), water-sensitive urban design (WSUD), and sponge city programs (SCPs)—has been proactively disseminated and instituted across global urban landscapes [6].

In the realm of urban stormwater management, two strategies emerge as paramount: grey and green infrastructures [7]. Grey infrastructure epitomizes traditional urban constructs such as drainage systems, which are vital for the seamless operation of a modernized economy [8]. In contrast, green infrastructure, despite its inherent robustness in drainage efficiency, is an intricate matrix of natural assets, such as rivers, forests, parks, and green corridors, which, collectively, sustain biodiversity and ecological processes, provide hydrological and bioecological benefits, and, thus, enhance the overall urban livability by safeguarding vital resources [9,10].

Studies suggest that, by combining green and grey infrastructure into a "hybrid" control system, the hybrid grey–green infrastructure (HGGI) can augment the stormwater system's efficacy and resilience [11,12]. Such an amalgamation synergistically melds the drainage prowess of grey infrastructure with the multifunctionality and sustainability inherent to green infrastructure, fostering a harmonious urban equilibrium that holds significant importance for the new design and retrofitting of future urban drainage systems [13–15]. Nevertheless, the quest to optimize HGGI is rife with complexities, requiring meticulous calibrations of both grey and green elements, culminating in intricate multi-objective optimization problems (MOPs) fraught with potentially conflicting sub-goals [16]. Academia has observed a burgeoning interest in this domain, with scholars spearheading innovations in urban stormwater management paradigms [17–19]. These papers have discussed the capabilities of gray infrastructure and the green–gray approach in urban flood control management, the LID–GREI multi-stage planning of urban drainage systems based on land use change, and the comprehensive optimization of the lifecycle cost and system elasticity of gray–green rainwater infrastructure, and the conclusions reached were conducive to the further development of the coupled optimization of gray–green infrastructure. Although much progress has been made, there is still much room for academic expansion.

The field of urban stormwater management has seen significant scholarly attention, focusing on LID, green infrastructure, and water resource management. Despite these efforts, there remains a notable gap in comprehensive, up-to-date reviews that synthesize the full spectrum of urban stormwater management optimization literature. Previous reviews, such as those by Arpita et al. [20] on the optimization and resilience of LID and Xu et al. [21] on meso-level urban stormwater management, have provided valuable insights but have not fully addressed the optimization aspect. Furthermore, Shishegar et al.'s review [22] of optimization methods for stormwater management problems was a step forward; however, the rapid evolution of this field necessitates a current and comprehensive overview that captures the latest developments and methodologies. Traditional literature reviews employ a holistic paradigm, meticulously dissecting extant research's theoretical frameworks, methodologies, and empirical outcomes [23]. Juxtaposed against this is the bibliometric analysis—a more practical, data-driven approach—that exploits statistical algorithms to elucidate inter-textual relationships [24]. Notably, CiteSpace v6.2.—a Java-based knowledge visualization software—has burgeoned as a preeminent tool for this analytical endeavor, and it is adept at discerning the nuanced intricacies of research trends and trajectories [25,26].

Harnessing CiteSpace v6.2 for our bibliometric study, this review aims to address literature gaps on urban stormwater management infrastructure optimization. This study meticulously traverses the academic landscape from 2004 to 2023, striving to elucidate (1) the diachronic trends characterizing urban stormwater management infrastructure research, (2) the pivotal authors, nations, and publications that have indelibly inscribed their scholarly imprints, and (3) the emergent research nexuses poised to dominate future scholarly discourses in this domain.

2. Methodology

In the current scholarly endeavor, the Web of Science constitutes the bedrock database, aggregating an extensive compendium of over 12,000 globally accredited, high-impact scientific journals and serving as an invaluable reservoir for academic intelligence across the globe. Research parameters were rigorously configured to isolate articles indexed within the Science Citation Index Expanded (SCI-Expanded) from 2004 to 2023 and were further refined to solely incorporate manuscripts published in English. To ensure an exhaustive yet focused retrieval of relevant literature, we employed a Boolean search algorithm that was iteratively refined. This involved an initial broad search followed by a detailed analysis of citation patterns and term frequencies in the most influential papers, leading to the selection of targeted search terms such as "urban stormwater management", "stormwater facilities optimization", "Low Impact Development (LID)", and "Green Infrastructure (GI)". These terms were then used in combination to construct a comprehensive search strategy, capturing the multifaceted nature of the field. A strategically formulated Boolean search algorithm was employed: TS = ("urban hydrology" OR "stormwater management" OR "surface runoff" OR "rainfall") AND TS = ("multi-objective" OR "optimization" OR "optimize" OR "optimizing" OR "spatial allocation" OR "decision" OR "resilience") AND TS = ("green-grey infrastructure" OR "grey-green infrastructure" OR "green infrastructure" OR "grey infrastructure" OR "low impact development" OR "nature-based solution" OR "sponge city" OR "water-sensitive urban design"). The retrieval time was July 2023, and disciplines with a low correlation with rainstorm management and hydrology were excluded.

This stringent query matrix initially culled a total of 557 articles, which were subsequently subjected to an assiduous filtration protocol within CiteSpace, thereby eliminating duplicative contributions and zeroing in on pertinent article categories. The ensuing corpus, comprising 524 articles, was subsequently selected for in-depth analysis. In CiteSpace, the K-value was carefully adjusted to manage the visualization of the literature network, ensuring that the most impactful and relevant studies were highlighted while maintaining a clear and focused overview of the field. A schematic representation of the research workflow is depicted in Figure 1. Following a series of scrupulous adjustments that included setting precise thresholds, temporal delineations, pruning strategies, and attribute selections, the dataset was dissected to ascertain emergent publishing patterns, seminal authorships, international scholarly collaborations, keyword co-occurrences, and co-citation networks. This analytical rigor furnishes a robust foundation for prognosticating prospective research vectors within this dynamic academic field.

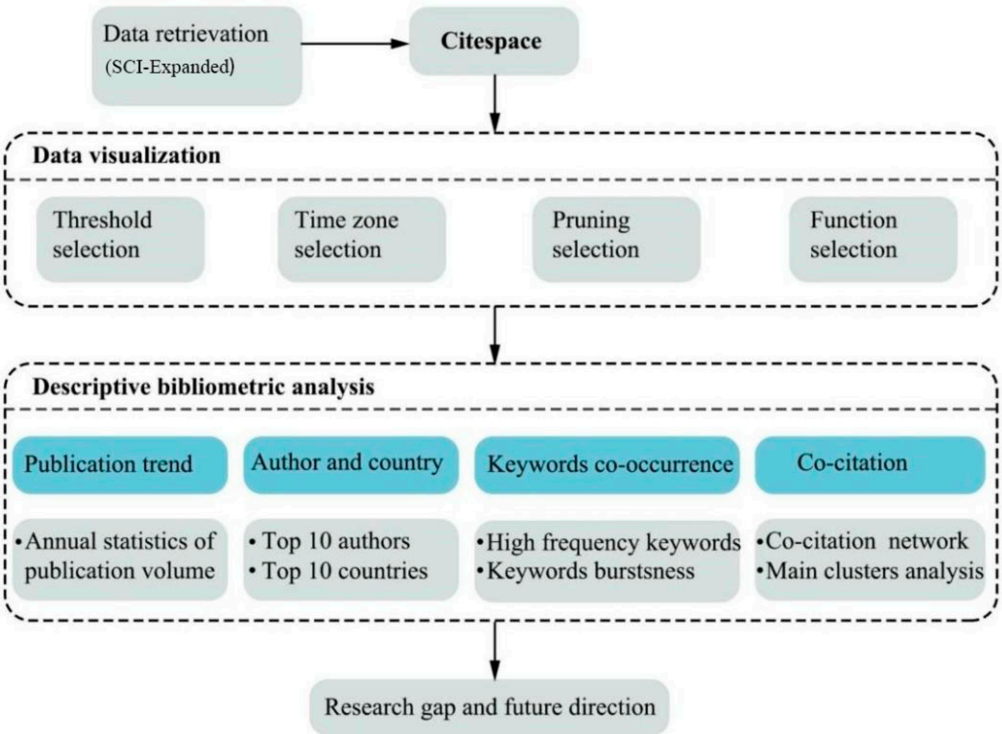

Figure 1. Research stages and description.

3. Results

3.1. Publishing Trend Analysis

Figure 2 delineates the annual evolution of the publication count and citation frequency within the corpus of studies. It is discernible that, before 2004, scholarly contributions about this thematic focus were virtually non-existent. The period from 2004 to 2014 witnessed a subdued scholarly activity, with less than ten papers annually delineating this topic. Post-2014, however, there has been a marked escalation in publication output, as China's introduction of the sponge city concept in 2012 [27] marked a pivotal moment in urban stormwater management. This initiative, aimed at enhancing urban resilience through innovative water management strategies, has significantly influenced the field, leading to rapid development and a notable surge in academic output from China, particularly since 2014. This trend is indicative of the country's growing commitment to addressing urban water management challenges. The temporal span between 2019 and 2022 emerged as the most productive phase of research activity, accounting for a total of 349 papers, which constitutes 66.7% of the entire body of literature. The increasing global focus on extreme weather events and urban flooding has catalyzed scholarly contributions in urban stormwater management. This heightened awareness reflects a broader recognition of the urgent need to optimize urban stormwater systems in response to climate change challenges. Consequently, we observe a steady and growing trend in the volume of research in this area, a trajectory that we anticipate will continue to rise. The year 2022 marked an unprecedented apex in citation frequency, amassing a total of 2862 citations. Conversely, both the publication and citation metrics for 2023 exhibit a declining trend; however, it is crucial to underscore that the data for 2023 are provisional due to its collection up until July of that year, rendering them an incomplete representation of the actual trend.

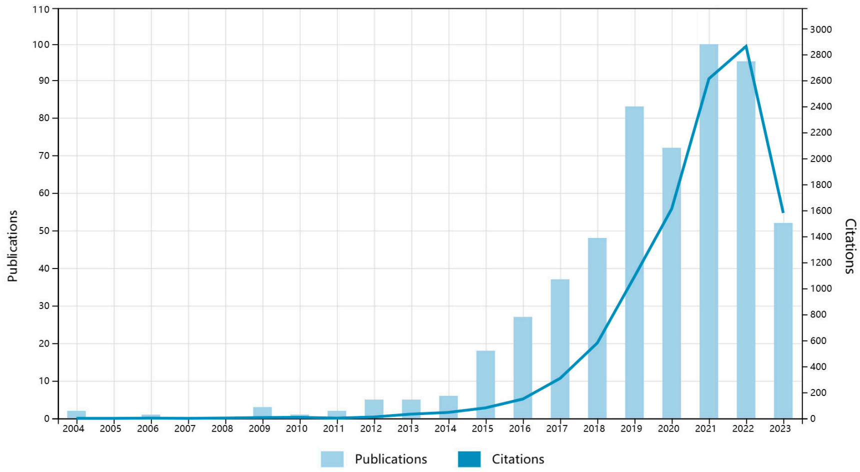

Figure 2. Research on urban stormwater management optimization collected using the WOS database.

3.2. Author and Country Analysis

In CiteSpace, the *g*-index is used to determine the number of nodes (representing articles, authors, or journals, depending on the type of analysis) displayed in a visualization of the network. The scaling factor *k* is a critical parameter that influences this selection by setting a threshold for the g-index. By adjusting *k*, we can control the density of the network, ensuring that only the most relevant and significant nodes are included. The value of $k = 5$ was chosen after a series of trials performed to optimize the balance between a network that is sufficiently comprehensive to represent the field and one that is not overly dense, which could obscure key patterns and relationships. A *k*-value of 5 allowed us to include nodes that represent the most cited and influential literature, providing a clear visualization of the core structure and dynamics of the research landscape in urban stormwater management optimization. The pathfinder algorithm and the pruning of sliced networks were deployed as the designated methods for network optimization. A collaboration network within the finalized dataset comprises 124 authors across 51 nations. Table 1 presents the top ten authors as determined by author co-citation analysis. This method was chosen to identify authors whose work has had a substantial impact on the field, as evidenced by the frequency with which their research is co-cited with others. It provides insights into the key contributors and the thematic connections between their works, offering a more comprehensive view of the intellectual structure of the field. Wang Mo leads the cadre, having published ten articles since 2021; Engel, Bernard A., and Zhang Dongqing share the second and third rankings, each contributing seven publications to the field. The prolificacy of these scholars in the domain of urban stormwater management infrastructure not only underscores their focal commitment to this burgeoning area of inquiry but also highlights their substantial academic contributions.

Table 1. Top ten authors researching urban stormwater management optimization.

Author	Publication Number	The Year the Paper Was First Published
Wang, Mo	10	2021
Engel, Bernard A.	7	2016
Zhang, Dongqing	7	2021
Jia, Haifeng	6	2019
Liu, Yaoze	5	2016
Liu, Ming	5	2022
Wang, Hao	4	2020
Bakhshipour, Amin E.	4	2022
Li, Jiake	4	2021
Tan, Soon Keat	4	2023

Table 2 enumerates the countries that have exhibited preeminent scholarly contributions, with China and the United States manifesting as the most prolific, furnishing 184 and 159 publications, respectively. Their output markedly eclipses that of the third-ranking nation, Australia, which accounts for 48 papers. It is evident that China and the United States are the foremost contributors to urban stormwater management infrastructure optimization. An examination of the principal research themes within these leading nations reveals a mutual focus on the efficacy assessment of LID practices; for instance, a seminal study by Chui et al. [28] scrutinized the cost-effectiveness of specific LID design practices in mitigating significant storm events. Interestingly, according to the database records, although China boasts the highest publication count, the United States and Canada pioneered research in this specialized domain as early as 2004.

Table 2. Top ten countries researching urban stormwater management optimization.

Country	Publication Number	The Year the Paper Was First Published
People's R. China	184	2012
USA	159	2004
Australia	48	2012
United Kingdom	35	2016
Canada	25	2004
Germany	24	2015
Iran	22	2014
Netherlands	17	2015
Singapore	16	2016
Italy	15	2018

Figure 3 delineates the international collaborative network, furnishing invaluable insights into potential partnerships within this specific academic landscape. Within this graphical representation, nodes symbolize the volume of literature contributed by each nation, with node dimensions being directly proportional to the publication count. The thicker the connecting lines between nodes, the more extensive the collaborative endeavors between the respective countries [29]. For example, the purple cluster in Figure 3 illuminates the robust research synergy between the United States and Canada in this realm. This collaboration was already extant before 2010, as evidenced by jointly authored publications.

Figure 3. Map of national cooperation network.

3.3. Keyword Co-Occurrence Analysis

Through the application of keyword co-occurrence analysis on the literature corpus, salient keywords have been identified, thereby elucidating emergent hotspots within the field of recent years. The significance of these keywords is gauged through their betweenness centrality: the use of betweenness centrality in CiteSpace is guided by structural hole theory. The theory was originally developed for social networks. An insightful observation is that connectivity, or lack thereof, can guide us to the most valuable nodes in the network. CiteSpace builds on these theories to detect cross-border potential and new connections in academic publications [30,31]. We have analyzed the keywords with the highest betweenness centrality to understand their role in shaping the research landscape. For instance, keywords such as "Low Impact Development" and "Green Infrastructure" indicate a strong focus on sustainable and eco-friendly approaches in stormwater management. Similarly, the emergence of terms like "Hybrid Grey-Green Infrastructure" reflects the evolving nature of the field, where traditional and innovative practices are being integrated. This analysis not only highlights the current focal points of research but also suggests potential directions for future studies.

Within the CiteSpace interface, the network node type was set to 'keyword' and the temporal slice was calibrated to one year, covering research articles from 2004 to 2023. The threshold was set at k = 15, and the pruning methodology adhered to previously established parameters. The analysis yielded a corpus of 257 articles, as depicted in Figure 4. The dimensions of each node are proportional to the frequency of the corresponding keyword's appearance, and a lavender halo encapsulates nodes with high betweenness centrality, the thickness of which reflects the centrality value. Table 3 enumerates the top 10 keywords based on frequency and betweenness centrality. The results reveal that 'low-impact development' emerges as the most frequently occurring keyword (191 occurrences), followed by 'stormwater management' (178 occurrences) and 'green infrastructure' (166 occurrences). The keyword with the highest betweenness centrality is 'Model' (0.37), indicating that simulation and assessment via modeling could be prevalent research methodologies in this area, with primary models in stormwater management including SWMM, STORM, and MOUSE, among others. For example, Zhang et al. [32] used SWMM to predict the hydrological performance of LID practices in shallow groundwater environments. Additionally, keywords such as 'stormwater management' and 'green infrastructure' rank high in frequency and exhibit substantial betweenness centrality, confirming that both topics are undeniably pivotal issues within the field, regardless of the metric applied.

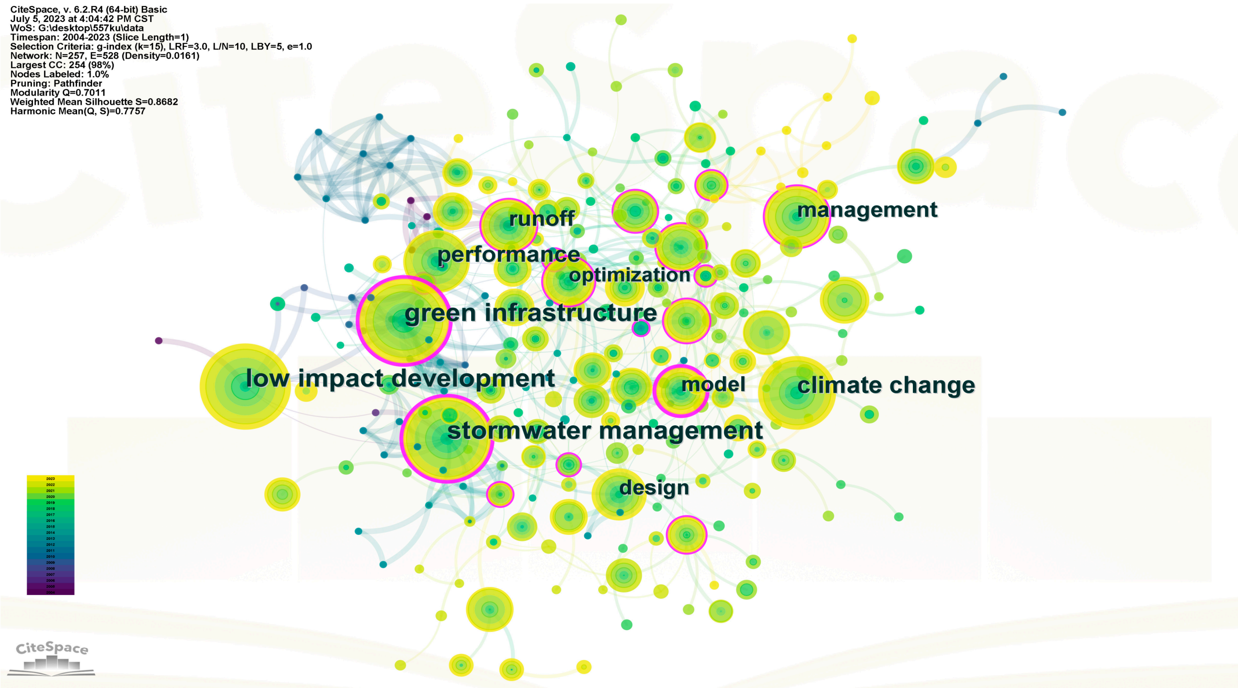

Figure 4. Keyword co-occurrence network diagram.

Table 3. Keyword frequency table (sorted by keyword count or centrality).

	Keywords (Sorted by Keyword Count)	Count	Centrality	Year of First Appearance		Keywords (Sorted by Centrality)	Count	Centrality	Year of First Appearance
1	low-impact development	191	0.05	2004	1	model	67	0.37	2012
2	stormwater management	178	0.33	2004	2	stormwater management	178	0.33	2004
3	green infrastructure	166	0.25	2010	3	green infrastructure	166	0.25	2010
4	climate change	125	0.02	2015	4	best management practices	11	0.18	2009
5	performance	98	0.02	2015	5	benefits	20	0.17	2014
6	management	86	0.11	2016	6	hydrology	18	0.17	2016
7	runoff	78	0.16	2004	7	stormwater runoff	10	0.17	2016
8	model	67	0.37	2012	8	runoff	78	0.16	2004
9	design	64	0.07	2013	9	optimization	59	0.16	2010
10	optimization	59	0.16	2010	10	decision support	12	0.16	2017

3.4. Examination of Top 10 Articles

Table 4 lists the top 10 articles and their main research priorities based on the number of citations on the Web of Science. Bennett et al.'s paper on environmental models has been cited 1034 times, which is the most frequently cited paper in this research database [33]. The paper proposes that environmental modeling requires using and implementing workflows that effectively combine several approaches to use environmental models for management and decision-making. This trend was followed by articles by Gomez-Baggethun and Fletcher [34,35], with 1015 and 864 citations, respectively, which delve into the evolution of urban ecosystem services and urban drainage terminology. Subsequent notable contributions, such as Davis's paper on bioretention facilities, show that bioretention facilities greatly reduce runoff and peak flows and effectively control other pollutants [36]. Fletcher's relevant studies on urban stormwater management and urban hydrology have contributed outstandingly to the comprehensive optimization of urban stormwater management infrastructure [35].

Table 4. Top 10 articles based on global citation.

Reference	Type	Citations	Main Content
Bennett et al. [33]	Article	1034	This paper proposes that environmental modeling requires the use and implementation of workflows that combine several approaches to use environmental models effectively for management and decision-making.
Gomez-Baggethun et al. [34]	Article	1015	This paper discusses the various ways in which urban ecosystem services enhance urban resilience and quality of life. It identifies a range of possible economic costs and the socio-cultural impacts of the loss of urban ecosystem services, as well as knowledge gaps and challenges for the ecosystem services research agenda in urban areas.
Fletcher et al. [35]	Review	864	The history, scope, application, and basic principles of urban drainage terminology are documented, and recommendations are made for clearly communicating these principles.
Davis et al. [36]	Article	620	It is pointed out that bioretention facilities significantly reduce runoff and peak flow and can effectively control other pollutants, but there are still many design problems in practice.
Fletcher et al. [35]	Article	570	It describes the significant progress made in urban stormwater management toward restoring a more natural water balance and points out that urban hydrology still faces many significant challenges.
Kabisch et al. [37]	Article	563	The various scenarios in which nature-based solutions are relevant to climate mitigation and adaptation in urban areas are explored, and indicators and related knowledge gaps are identified for assessing the effectiveness of nature-based solutions.
Ahiablame at al. [38]	Review	538	This paper emphasizes the evidence of the beneficial use of LID practice in literature, discusses how to represent LID practice in hydrological/water quality models, and proposes the direction of future research.
Gunawardena et al. [39]	Article	528	A meta-analysis of how green and blue spaces affect urban canopy and boundary layer temperature was conducted to mitigate the adverse effects of urban heat islands and enhance climate adaptation ability.
Demuzere et al. [40]	Article	511	The contribution of green spaces to climate change mitigation and adaptation services is explored, and avenues for further research on the role of green urban infrastructure in different types of urban, climatic, and social contexts are identified.
Meerow et al. [41]	Article	468	The green infrastructure spatial planning (GISP) model was introduced to provide an inclusive and replicable approach to planning future green infrastructure.

In the scientific discourse surrounding LID and GI, there has been a growing emphasis on the adoption of these transformative approaches to address the complex challenges posed by urban stormwater management, which are exacerbated by accelerating urbanization and the multifaceted impacts of climate change. Of the ten most important papers, two were academic review papers: in one, Fletcher et al. [35] explored the evolving vocabulary of urban drainage, expressing concern about its diverse and occasionally confusing nature. They advocate persuasive and clear communication among professionals, emphasizing the indispensability of such clarity in avoiding misunderstandings, especially given the nuances of local contexts and the need to shape the evolution of terminology. The other was a study on LID by Ahiablame et al. [38], which emphasized the evidence of the beneficial use of LID practice in the literature, discussed how to represent LID practice in hydrological and water quality models, and proposed the future research direction of LID. Their reviews shed light on the interconnectedness of these practices with environmental and socio-economic aspects of water, demonstrate available strategies and optimization tools, and shed light on existing research gaps.

In the empirical study, Gunawardena et al. [39] conducted a meta-analysis on the main ways that urban greening and blue space affect the temperature of the urban canopy and boundary layer so as to reduce the adverse impact of an urban heat island and enhance the urban climate adaptation ability, which belongs to the research on blue–green infrastructure. Demuzere et al. [40] explored the contribution of green space to climate change mitigation and adaptation services. They identified avenues for further research on the role of green urban infrastructure in different types of urban, climatic, and social contexts, identifying the indispensable role of green infrastructure in urban stormwater management. Meerow et al. [41] introduced the green infrastructure spatial planning (GISP) model to provide an inclusive and replicable approach to planning future green infrastructure. These academic contributions collectively advocate for an integrated, holistic, and systematic approach to urban stormwater management that integrates green and green infrastructure and considers future uncertainties brought about by climate change and urban sprawl.

3.5. Cluster Analysis

Co-citation analysis is an illustrative instrument used to gauge the significance or popularity of published works [42]. The outcome of such an analysis is a network composed of nodes and edges [43]. The primary objective of co-citation analysis is to measure the frequency with which cited articles concomitantly appear in other scholarly works [44]. This analytic approach offers a comprehensive methodology for scrutinizing the internal structural dynamics of a research domain. The similarity between fields or concepts depends on the co-citation frequency between two articles [45].

Figure 5 is a cluster view generated based on co-citation, accentuating the structural characteristics between clusters and spotlighting key nodes and critical connections [46]. A node represents each article, the size of which grows in proportion to the number of times the article has been cited. The graph displays only the top ten clusters, using numbered color-coded labels as cluster tags derived from post-keyword clustering. CiteSpace offers three distinct algorithms for cluster label extraction, namely, latent semantic indexing (LSI), log-likelihood ratio (LLR), and mutual information (MI). The LSI algorithm was opted for because LSI-produced cluster labels are more congruent with the actual research scenarios. A detailed interpretation of the top three largest clusters—in terms of the number of articles—is conducted based on the extracted cluster labels, as outlined in Table 5. This aims to elucidate the focal points and internal correlations within these clusters.

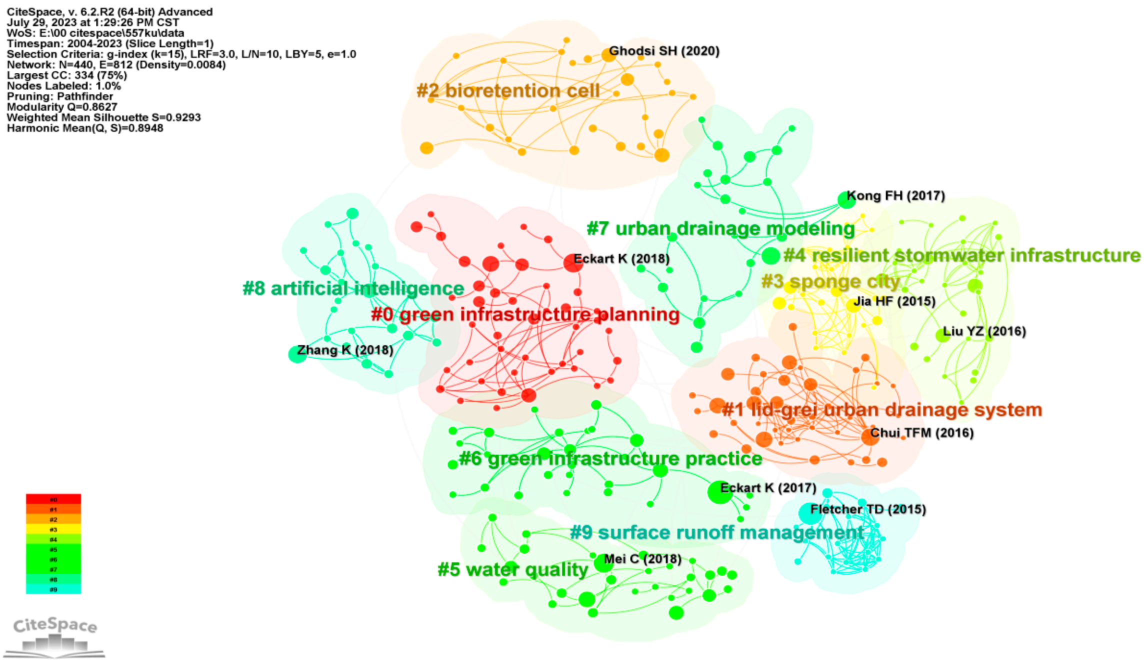

Figure 5. Co-citation clustering network diagram [28,32,47–54].

Table 5. Clustering table.

Cluster	Amount	Clustering Label (LSI)
1	63	green infrastructure planning; urban stormwater management; using green infrastructure; systematic bibliometric review; catchment scale丨sponge city; urban stormwater management; green infrastructure; green-grey infrastructure; current gap
2	55	using green infrastructure; multi-stage planning; land-use change; deep uncertainty application; flood management丨LID–GREI urban drainage system; shared socio-economic pathway; assessing hydrological performance; resilience assessment; decision-making framework
3	48	case study; bioretention cell; cost-based greedy strategy; adaptive socio-hydrology; situating green infrastructure丨regulating urban surface runoff; nature-based solution; alternative selection; small urban catchment; different investment period

(1) Cluster 1: Green Infrastructure Planning

Cluster 1 features the most articles among all clusters, with a total of 63 papers. According to the LSI algorithm, high-frequency keywords extracted from the titles include "green infrastructure planning", "urban stormwater management", "using green infrastructure", "systematic bibliometric review", and "catchment scale", among others. The primary focus of this research cluster is on green infrastructure planning in relation to urban stormwater.

Out of the 63 studies, 21 papers (33.3%) concentrate on optimizing stormwater management, 15 articles (23.8%) evaluate hydrological performance and ecological benefits, and 9 papers (14.2%) provide an overview of low-impact development (LID) practices. Additionally, eight articles (12.6%) mainly focus on hydrological modeling.

Within these 21 optimization-focused studies, eight explore multi-objective optimization methods for stormwater facilities, some of which employ the stormwater management model (SWMM) and genetic algorithms for optimization. The nine review papers in this cluster predominantly discuss LID's performance, spatial distribution, optimization, and resilience. This includes the most cited paper in the cluster, a review of the performance and implementation of low-impact development by Eckart et al. [53].

Overall, this cluster revolves around the core topic of green infrastructure planning. It explores optimization methods for urban stormwater management and assesses the hydrological performance of green infrastructure, helping to clarify future directions for green infrastructure planning.

(2) Cluster 2: Hybrid Grey–Green Infrastructure

Cluster 2 ranks as the second largest cluster, encompassing 55 papers. The primary keywords in the titles of the papers in this cluster include "LID-GREI urban drainage system", "shared socio-economic pathway", "assessing hydrological performance", "resilience assessment", and "decision-making framework". This cluster mainly focuses on various types of drainage facilities like grey–green, blue–green–grey, and blue–green, aiming to evaluate and optimize their designs.

Among the top 10 most-cited articles in this cluster, five papers primarily explore coupled drainage infrastructure. Alves et al. [11] assess the combined benefits of green–blue–grey infrastructure for sustainable urban flood risk management. Bakhshipour et al. [55] delved into the design of mixed decentralized green–blue–grey urban drainage systems. In addition, three studies focused mainly on green infrastructure, and the remaining two concentrated on LID.

This cluster contains five review papers that primarily discuss the mechanisms and applied research progress of green infrastructure practices in stormwater management [56], as well as the terminology, research, and future outlook of stormwater management [57]. Articles in this cluster also consider urban planning and drainage under the impacts of climate change [58]. In a more recent study, Wang et al. [59] assessed the hydrological performance of integrated gray–green infrastructure based on a shared socio-economic path. This can provide a new perspective to evaluate the hydrological performance of high, built-up urban catchments in response to climate change.

The distinct difference between this cluster and the previous one lies in its greater emphasis on the coupled optimization of various types of drainage infrastructure rather than solely focusing on the planning and design of green infrastructure.

(3) Cluster 3: Bioretention Cell

Cluster 3 includes a total of 48 papers, with key clustering terms such as "case study", "bioretention cell", "cost-based greedy strategy", "adaptive socio-hydrology", and "situating green infrastructure". While the primary focus of this cluster remains on green infrastructure, it zeroes in on specific facilities like bioretention cells and green roofs. It applies green infrastructure research to case studies.

Out of the 48 papers, six focus intensively on bioretention cells, including a review of the application of bioretention technology in urban stormwater treatment [60]. Nine papers carry out specific case studies, such as the work by Liu et al. [54], which used the Trec Creek watershed in Indiana as a case study to explore the optimal selection and layout of green infrastructure to mitigate the impacts of land-use changes and climate change on hydrology and water quality.

The cluster includes six review papers that primarily cover the evolution of urban drainage terminology [35] and the effectiveness of best management practices in improving hydrology and water quality [61]. Beyond the cluster's main focus, one study also explores the hydrological performance of green roofs [62]. This cluster is unique in its detailed approach to specific types of green infrastructure, particularly in bioretention cells, and its application of research findings to real-world case studies. In recent years, scholars have studied the long-term performance of biological retention systems in storm runoff management under climate change and lifecycle conditions, which is helpful in improving the decision support system of LID planning and urban stormwater management infrastructure [63].

3.6. Keywords with the Strongest Citation Bursts

In addition to cluster analysis, CiteSpace's burstiness feature ranks highlighted keywords based on their burst intensity, indicating the importance of these research directions [64]. Figure 6, under the condition of γ = 0.7, displays 10 keywords along with their intensity, burst starting time, and ending time. The keywords with the top ten burst intensities are best management practices, design, watershed management, and model. We first selected the keywords that have emerged the longest and are also the strongest, along with the latest keywords, for analysis.

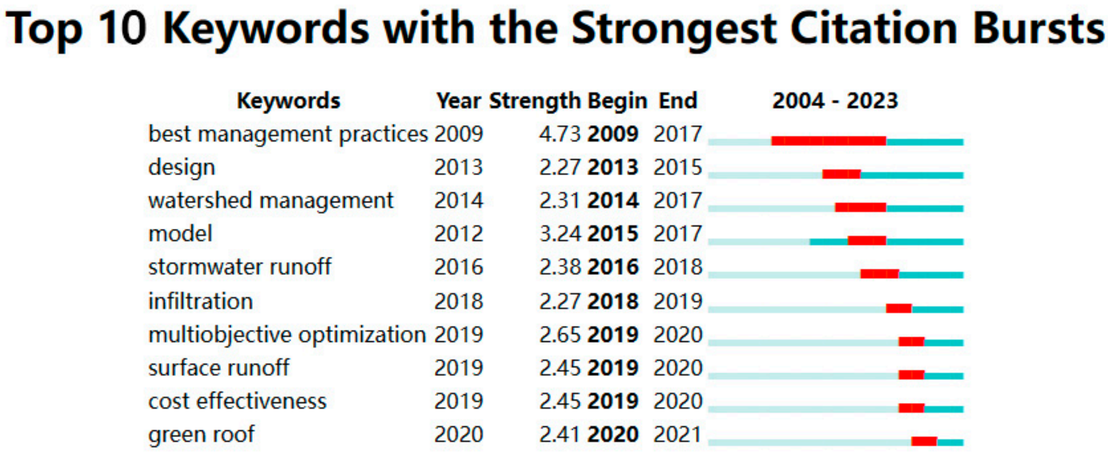

Figure 6. Top 10 keywords with the strongest citation bursts.

The keyword with the highest intensity and most prolonged duration is "Best Management Practices (BMP)", indicating its consistent prominence as a frontier hot topic from 2009 to 2017. BMP is not merely a conveyance of technical details or concepts; over time, it has created a "brand" that helps attract politicians, policymakers, and society at large [35]. Therefore, terminologies like BMP or WSUD have crafted successful or cautious images. As a practical method of stormwater management, its position cannot be shaken.

Since 2020, "green roofs" have emerged as the newest keyword, garnering significant attention and highlighting the promise of green roofs as a cutting-edge green building approach. They have considerable potential in increasing urban albedo and mitigating the urban heat island effect [65], offering benefits in winter heating reduction as well as in summer cooling [66]. This can make communities healthier and more aesthetically attractive. Urban planners, designers, and ecologists need to focus on urban green space strategies and explicitly protect social and ecological sustainability [67].

In addition, it is evident that recent years have seen a focus on design and modeling in this field. Their enhancement began in 2013 to 2015, and people will pay more attention to practical research in the future; moreover, there will be a lot of room for development in modeling.

4. Discussion

4.1. Relation between Research Intensity and the Origin of Terminology

In this research, articles were first retrieved from the Web of Science core collection database, and their publication years and citation trends were generated to showcase these papers' emergence and growth rate. A series of analyses, including author, country, keyword, and co-citation analyses, were then performed using CiteSpace.

An intriguing discussion arises from the country analysis: why do China and the United States far outpace other countries in academic contributions to this field? We speculate that, first, the United States, being the origin of key related concepts like LID, BMP, and stormwater control measures (SCMs) [35], and one of the world's most economically advanced countries, would naturally focus on optimizing urban stormwater management to minimize economic losses from extreme rainfall. On the other hand, China, as the world's largest developing country [68], has issued several policies since 2012 aimed at improving urban drainage systems and strongly advocating for the construction of "sponge cities", thereby making significant contributions to the field [69–71]. The measurement of the supply and demand and spatial allocation of sponge facilities in the construction of sponge cities is of great importance, and scholars have proposed a framework that can be used to achieve a balance between "supply" and "demand" for more participation, which will promote the balanced development of sponge cities [72].

Following closely behind are Australia, the originator of water-sensitive urban design (WSUD), and the United Kingdom, the originator of sustainable urban drainage systems (SUDSs); both countries are world leaders in stormwater management. While there is not a single example of a water-sensitive city in the world, some cities, such as in Australia and Singapore, are leading the way in the unique and different attributes of water-sensitive approaches [73]. This suggests an inseparable link between a country's research intensity and the origin of urban drainage terminology. Observing the historical development of urban stormwater management, it is clear that topical foci shift over time; however, some endure.

4.2. Artificial Intelligence: Emerging Research Method

In the co-citation analysis, three clusters were identified for a detailed description. The LSI algorithm was used for each cluster to extract keywords to identify research sub-themes. Analyzing the latent themes within each cluster and considering the keywords can provide recommendations for future research. Cluster 1 mainly focuses on green infrastructure, while Cluster 2 discusses grey–green infrastructure, blue–green–grey infrastructure, or blue–green infrastructure. The results of the analysis indicate that research topics under these two clusters are at the forefront of current research. Grey–green coupling, blue–green–grey coupling, and various other coupling systems, which are significant components of urban drainage systems, will be the focus of future research. Compared to Cluster 1, Cluster 3 emphasizes specific LID practices like bioretention and green roofs. Thus, Cluster 3 can be seen as a more detailed, particular subset of Cluster 1.

Apart from these three clusters, other major clusters, such as sponge cities, resilient stormwater infrastructure, water quality, green infrastructure practices, urban drainage models, artificial intelligence, and surface runoff management, have also emerged from the filtering results. These clusters effectively encapsulate the major sub-themes in current urban stormwater management optimization. Among them, artificial intelligence (AI) has recently emerged as a management method with features of autonomy, adaptability, and robust learning capabilities [74]. AI is increasingly popular in solving various optimization problems and has been widely applied in multiple domains [75].

Yang et al. [76] proposed a machine learning method to learn the hydrological response of sustainable urban drainage systems. El Ghazouli et al. [77] proposed a novel model based on neural networks for predicting flows, a stormwater management model (SWMM) for water conveyance, and a genetic algorithm for optimizing sewer system operations and defining optimal control strategies. These can effectively reduce combined sewer overflows. Wang et al. [78] utilized the proximal policy optimization (PPO) algorithm to formulate control strategies for mid-sized stormwater systems, significantly mitigating flooding during major storm events. This method demonstrated good convergence and stability, achieving robust out-of-sample performance. Liu used the Levenberg–Marquardt backpropagation training algorithm to successfully train recurrent neural networks for flash flood forecasting [79]. Technological breakthroughs and methodological advancements are increasingly important factors in stormwater management infrastructure research [80]. To stay up-to-date, advanced technologies should be employed to modernize and make urban stormwater management more intelligent.

4.3. Prognostications and Constraints

The trajectory of salient and incipient research trends within the literature corpus is discerned through the diachronic analysis of keywords. Burstiness analysis corroborates that "Best Management Practices" (BMPs) emerge as a predominant keyword, ostensibly owing to its capacity to galvanize key stakeholders, including political dignitaries, policy architects, and the broader societal constituency. Nonetheless, with the temporal evolution of research landscapes, BMP has been relegated from its erstwhile status as a vanguard term to one that increasingly aligns with eco-centric paradigms [81]. This metamorphosis concurs with more extensive paradigmatic shifts across interdisciplinary domains, marked by a transition towards holistic and ecologically nuanced methodologies that prioritize ecosystemic considerations in planning and strategic governance. Whereas "Urban Stormwater Management" manifests as the most contemporaneously resonant keyword, "Sponge City" retains its preeminence as the cynosure in the thematic panorama. This underscores that, in the context of climate change and rapid urbanization, scholarly and practical paradigms in urban hydrological management are perpetually evolving, necessitating sustained attention to both urban stormwater governance and the cultivation of sponge cities.

Concurrently, the study acknowledges several limitations: the intricate interdependencies among prevalent keywords remain insufficiently elucidated, and no systematic effort has been directed toward the disambiguation or deduplication of synonymous terminologies. Moreover, given the heterogeneity of methodologies available for cluster label extraction in CiteSpace, the findings of this study should be construed as a heuristic representation of an optimal experimental configuration; moreover, alternative taxonomies, emergent through divergent clustering algorithms, warrant further scholarly scrutiny. While the study engenders some innovative insights, it is still incipient in its theoretical robustness, mandating subsequent in-depth investigations to further the nascent field of urban stormwater management infrastructure.

5. Conclusions

This study uses a multi-pronged analysis model to conduct a detailed bibliometric analysis of the academic discourse on urban stormwater management infrastructure. This academic effort reveals the diachronic evolution, key focus, and trends of this expanding field of study.

A discernible intensification in investigative activities became palpable post-2014, with the temporal span from 2019 to 2022 manifesting as exceptionally fecund. Geopolitically, the predominance of China and the United States in the scholastic yield becomes evident; yet, the ubiquity of international collaborations underscores the transnational necessity. Preeminent scholars such as Wang Mo, Engel, Bernard A., and Zhang, Dongqing have furnished seminal contributions, particularly in the realm of optimizing and appraising the effectiveness of LID practices.

Co-occurrence and co-citation analyses illuminate core thematic constructs like "Low Impact Development", "Green Infrastructure", and "Stormwater Management" as being quintessential to the intellectual discourse. Additionally, the frequency of citation to lexical entities such as "Best Management Practices" and "Green Roofs" predicts their importance. Heterogeneous yet interrelated clusters within the co-citation network elucidate concentrations of scholarly activity in areas such as green infrastructure planning, hybrid drainage systems, and bioretention cells.

A compelling insight gleaned is the scholastic pivot toward integrated paradigms featuring multi-objective optimization frameworks for stormwater management. Lexemes including 'Model' and 'Design' manifest in elevated betweenness centrality metrics, indicating an augmented gravitas accorded to simulation and evaluative methodologies. Concomitantly, further emphasis is placed on practical applications to achieve stormwater runoff quality and quantity management through an increased focus on case studies and specific green infrastructure technologies such as bioretention cells [82].

In summation, the urban stormwater management infrastructure field constitutes a dynamically evolving landscape marked by an intricate tapestry of research imperatives. Amid escalating global urbanization and climatic vicissitudes, the quest for productive stormwater management becomes a societal mandate of pressing import. The revelations afforded by this bibliometric exploration serve as an intellectual compass, orienting both scholarly and policy-oriented trajectories toward integrative and productive solutions for the conundrum of urban stormwater management.

Author Contributions: Conceptualization, M.W.; methodology, M.W. and Z.J.; software, Z.J. and C.S. validation, J.L.; formal analysis, M.W., R.M.A.I., C.S. and M.Z.; investigation, Z.J.; resources, M.W., M.Z. and J.L.; data curation, Z.J.; writing—original draft preparation, M.W. and Z.J.; visualization, Z.J.; supervision, M.W., R.M.A.I. and M.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Guangdong Province, China [grant number 2023A1515030158], the Science and Technology Program of Guangzhou, China [grant number 202201010431], and Guangzhou University (RC2023008).

Data Availability Statement: The study did not report any publicly archived datasets.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AI, artificial intelligence; BMPs, best management practices; GI, green infrastructure; HGGI, hybrid grey–green infrastructure; LID, low-impact development; LSI, latent semantic indexing; MOPs, multi-objective optimization problems; PPO, proximal policy optimization; SCI-Expanded, Science Citation Index Expanded; SCMs, stormwater control measures; SCPs, sponge city programs; SUDSs, sustainable urban drainage systems; SWMM, stormwater management model; WSUD, water-sensitive urban design.

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