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Review

Development and Research Regarding Stormwater Runoff Management: Bibliometric Analysis from 2001 to 2021

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Abstract: As a result of climate change and urbanization, human activities are placing increasing pressure on nature, including with regard to urban stormwater runoff; consequently, various concepts related to urban stormwater runoff management have been proposed to tackle this problem in multiple countries. In this study, the latest research and techniques related to stormwater runoff management are reviewed in detail. A bibliometric analysis of proposed stormwater runoff management concepts developed from 2001 to 2021 was conducted based on a screening of 1771 studies obtained from the Web of Science (WoS). Bibliometric analysis is a research method that can be used to quantitatively analyze academic literature. Visualization of the data obtained from the literature using CiteSpace software and subsequent analysis of patent data through S-curve prediction were performed. The United States, China, and Australia were the top three countries from which publications on this issue were sourced. Each country tends to study its own most relevant issues and has a particularly clear understanding of its own research landscape. The development of stormwater runoff management concepts was analyzed using reference emergence analysis. This was followed by keyword clustering and keyword emergence analysis to identify current research hotspots, trends, technological developments, and limitations. The limitations and emerging trends related to current stormwater runoff management concepts are discussed thoroughly, and suggestions for future studies are provided.

Keywords: urban stormwater management; low-impact development (LID); sustainable urban drainage system (SUDS); water-sensitive urban design (WSUD); sponge city

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1. Introduction

Global urbanization and population growth are placing increasing pressure on nature [1]. In conjunction with urban expansion and damage to the natural environment, the varieties of pollutants in runoff are increasing, along with their concentrations, resulting in a significant overall increase in urban water pollution [2]. As global climate change has intensified, frequent urban flooding and droughts have brought increased attention to the management, use, and harvesting of rainwater around the globe [3,4]. The increase in impermeable surfaces due to high rates of urbanization, especially in developed countries with rapid urban growth, has affected ecological environments surrounding major cities [5]. Therefore, methods and concepts for managing urban stormwater runoff have been proposed and developed over the last few decades to address the environmental problems that arise from urbanization and climate change. Approaches to urban stormwater runoff management include low-impact development (LID) in the USA and Canada, sustainable urban drainage systems (SUDSs) in the UK, and water-sensitive urban design in Australia (WSUD) [6,7]. LID focuses on managing stormwater at the source through the use of tailored site-design techniques and green infrastructure practices, such as rain gardens, green buildings, and permeable pavement, to promote infiltration, evaporation, and filtration of runoff. WSUD is a similar approach that emphasizes the use of landscape-based solutions to manage urban water while also considering the social and ecological context of the urban environment in which it is implemented. SUDSs are used in the United Kingdom and are similar to LID, focusing on managing surface water runoff in a sustainable manner while also considering the needs of the community [8,9]. China has grown rapidly over the past decade, which has led to an increase in environmental problems due to urbanization [10]. In 2013, a new type of urban stormwater management was proposed in China known as the "sponge city" approach. Sponge cities are cities that are well-adapted to the environmental and rainwater changes brought about by natural disasters, employing absorption, storage, infiltration, and purification of rainwater followed by release of water stores, with waiting periods between each period of use. This approach is an effective way to improve urban stormwater runoff and manage urban stormwater runoff problems in China [11]. Each of these approaches has unique benefits; however, the original intent and design philosophy of sponge cities are similar to those of other proposed methods [12].

Directions of research on stormwater runoff management vary between countries due to differences in policy and their natural environments. A comparative analysis of stormwater runoff management in the UK and China was previously conducted by Lashford et al. and built upon by Wang et al. They applied these concepts to the development of techniques with the capability of managing pollution caused by water runoff [11,13]. A study published in the *Journal of Environmental Management* in 2021 compared the effectiveness of LID and WSUD practices for the management of stormwater runoff within an urban catchment in Australia [14]. Another study published in the *Journal* by Zeng et al. in 2020 evaluated the sustainability of SUDS practices in the United Kingdom [15]. However, there are few articles summarizing the developmental trends and research hotspots for rainfall runoff management concepts across different periods of time. The aims of this study were to analyze trends and research hotspots in the field through a review of the existing literature, to provide guidance on current research trends and hotspots, and to recommend future studies.

This study provides an overview of the development of stormwater runoff management concepts and associated technologies based on an analysis of literature patents in the field within the WoS and presents trends and research hotspots with regard to these concepts in a clear and simple manner through CiteSpace mapping visualization, which will help researchers quickly access relevant research trends and information. The discussion of the literature using the above methodologies led to the following observations: Countries prefer to study localized stormwater runoff problems and have a clear understanding of their own research directions and problems. Countries and regions with longer histories of research and more publications have closer relationships with other regions in terms of the amount of cooperation. Geographical constraints, technical limitations, and data uncertainty limit the development and dissemination of stormwater runoff management. In the future, multifunctional stormwater runoff design can be used to better address urban issues, and increased interdisciplinary research collaboration can keep the project sustainable

2. Materials and Methods

The data used in this study were collected from the WoS due to the fact that the work in the WoS represents the international research frontier for the relevant scientific fields and much of it has high international impact. Additionally, the WoS has been cited as the primary data source in many recent bibliometric reviews on building structures [16]. The literature search was conducted on 14 July 2022. In the first phase (Figure 1), 1771 articles related to stormwater runoff management concepts were identified. These articles were broken down into the following document types: articles (number = 1651, percentage = 93%), reviews (number = 120, percentage = 6%), conference papers (number = 350, percentage = 16%), other (<100 documents total). Bibliometric analysis and visualization of the information was performed in stage two using the comprehensive data exported from the WoS (fully recorded author information, citations, references, and other textual information).

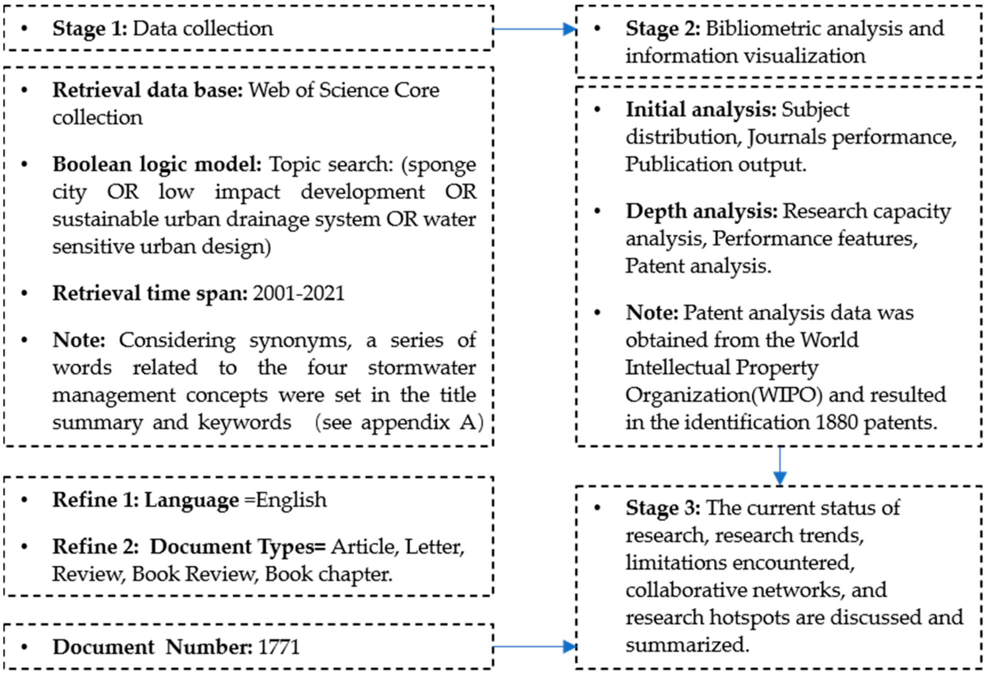


Figure 1. Stages of the bibliometric analysis of urban runoff management (Appendix A).

CiteSpace, a visual analysis tool, was adopted in this study to map multiple knowledge maps and spectrums. Therefore, both research trends and hot topics in the field at large were represented through elements such as node size, network connectivity, and keyword co-occurrence. One of the core functions of CiteSpace is to detect and analyze frontiers in research and knowledge relationships [17]. Therefore, this software allows scientists to determine the extent to which changes are occurring in a field through the global publication distribution, research institution networks, and analysis of co-cited studies.

Furthermore, a specialist database, that of the World Intellectual Property Organization (WIPO), was applied as a data source in this study to analyze and predict the future direction of stormwater runoff technology. The patent analyses provided an understanding of current and future trends, as well as strategic targets for this field [18]. A total of 1880 relevant patents were identified.

A graph known as the s-curve was mainly used for the analysis of patent data. The s-curve is often adopted to describe future prospects and trends in both economies and technologies [19]. In general, technological growth occurs in a cyclical pattern, and the relationship between slow and quick stages of technological development is generally captured by an s-curve. Furthermore, the life cycles of technologies and products can be divided into four phases: the exploration phase (introduction), the growth phase, the maturity phase, and the stagnation phase (saturation) [20]. In this study, a patent trend analysis was performed in Loglet Lab 4 as a means of analyzing and predicting the range of technological developments related to stormwater runoff.

3. Results

3.1. Subject Categories and Their Distribution

The SCI-E and SSCI databases revealed 94 subjects from 1771 reviewed articles, which included agriculture, biology, and energy. These data suggest that the field of stormwater runoff management is interdisciplinary, with the predominant research areas being related to environmental sciences, ecology, and water resources, comprising more than three quarters of all combined categories.

3.2. Journal Performance

Of the 1771 articles that were analyzed, 40% were published in the top ten most recognized journals (Figure 2), with a sudden spike in the number of articles pertaining to "water" after 2015. The majority of journals showed a decline in publications with regard to this topic between 2019 and 2020, which may have been due to the influence of external factors. The journal impact factor (JIF) quartile of a journal indicates the impact of that journal on its field and whether it is considered cutting edge. Of the top 30 journals containing the highest numbers of published articles, 36.7% of the journals were in quartile one. These data suggest that this field is highly influential, and further studies in stormwater runoff management would be valuable.

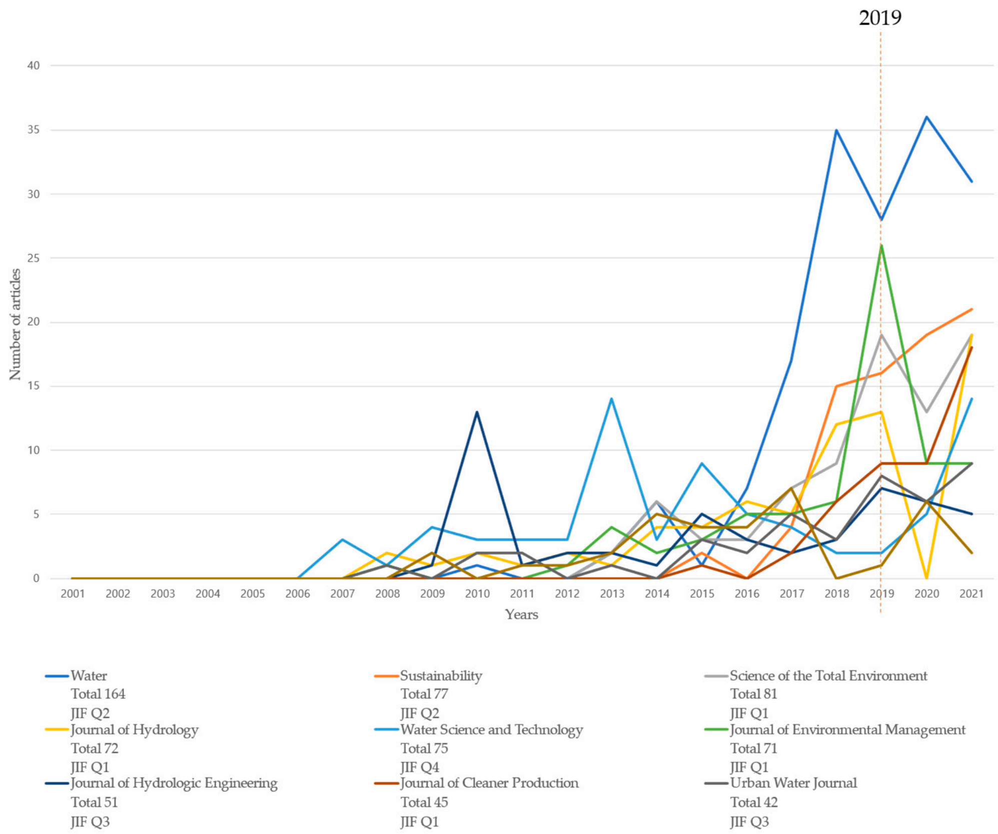


Figure 2. The performance of the top ten most impactful journals.

3.3. Publication Output

Figure 3 shows the trend for annual publications between 2001 and 2021 in this field. Excluding the initial years from 2001 to 2003, the growth rates for publications in this field in 2008, 2013, and 2017 were high at 80%, 103%, and 74%, respectively. These data suggest that potential external interventions, such as government policies or the emergence of new technologies, affected the number of publications. Furthermore, the data show that the number of publications continued to increase after 2016. The growth rate for publications in the field began to slow after 2017; however, the overall trend remained positive. Furthermore, the growth in publications in this field drastically increased between 2020 and 2021, indicating that research efforts in this field have not diminished and can be expected to intensify in the future, partly due to growing environmental concerns.

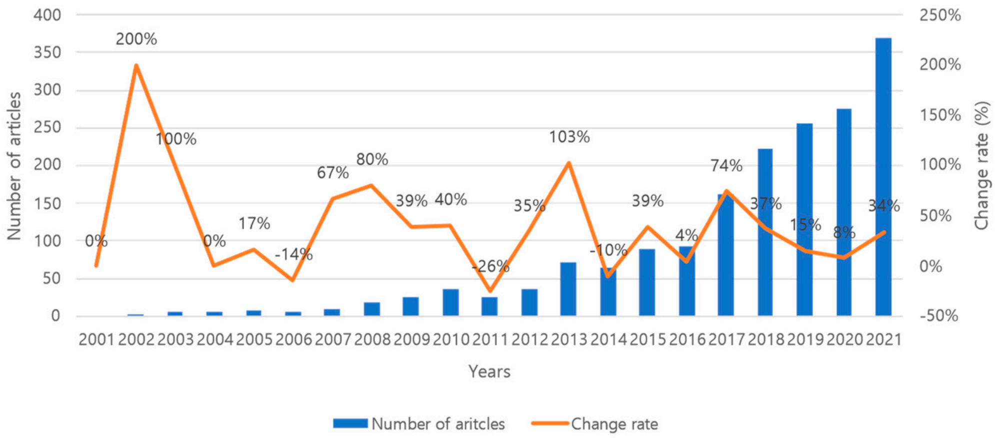


Figure 3. The yearly numbers of articles published from 2001 to 2021.

3.4. Research Capacity Analysis

3.4.1. Country Distribution

Figure 4 shows the global distribution of publications in the field at large, with China taking first place with 35.42%, followed by the USA and Australia with 28.28% and 11.69%, respectively. Countries and territories such as South Korea, Iran, and Europe have also contributed to the development of urban runoff concepts but to a lesser extent than the big three.

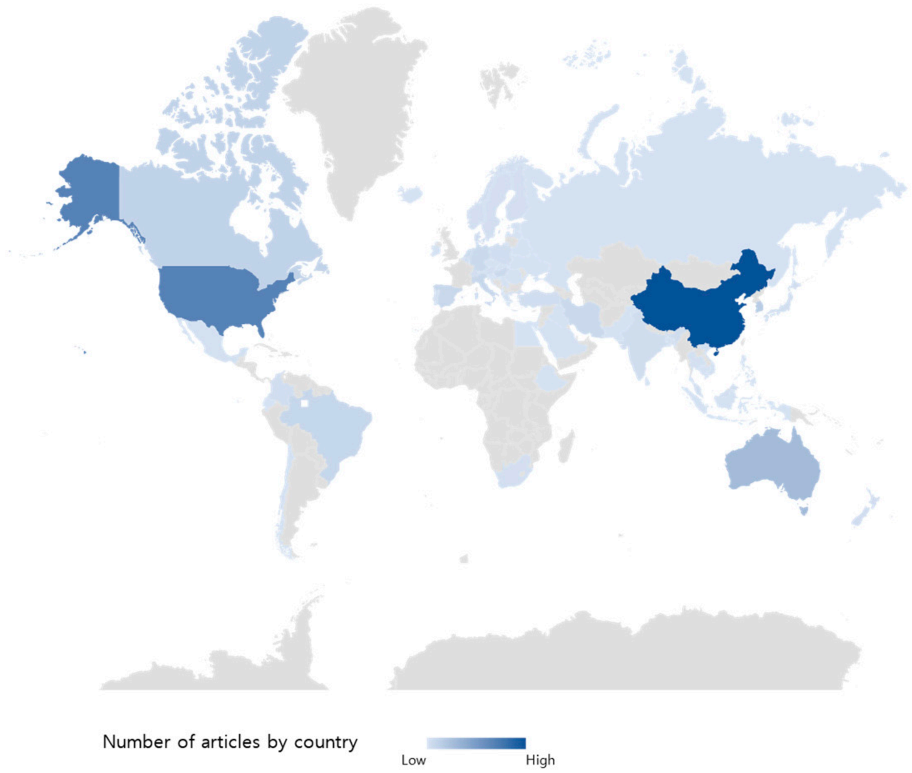


Figure 4. Global geographical distribution of authors' locations.

3.4.2. Global Research Network Trends

Figure 5 demonstrates the collaborative links between countries through a chronogram generated in CiteSpace software. The overall size of the wheel reflects the number of citations, while the wheel color corresponds to the year and the wheel thickness indicates the number of articles published within the corresponding timeframe. A total of 67 countries were involved in research in this field, with approximately 297 lines showing the cooperation between countries and a density score of 0.1343, which refers to the average level of cooperation for urban runoff management. The data show that a longer study period corresponded to a higher number of publications and connections with other countries, indicating a higher degree of cooperation. Conversely, countries with fewer publications tended to have lower levels of cooperation with other countries.

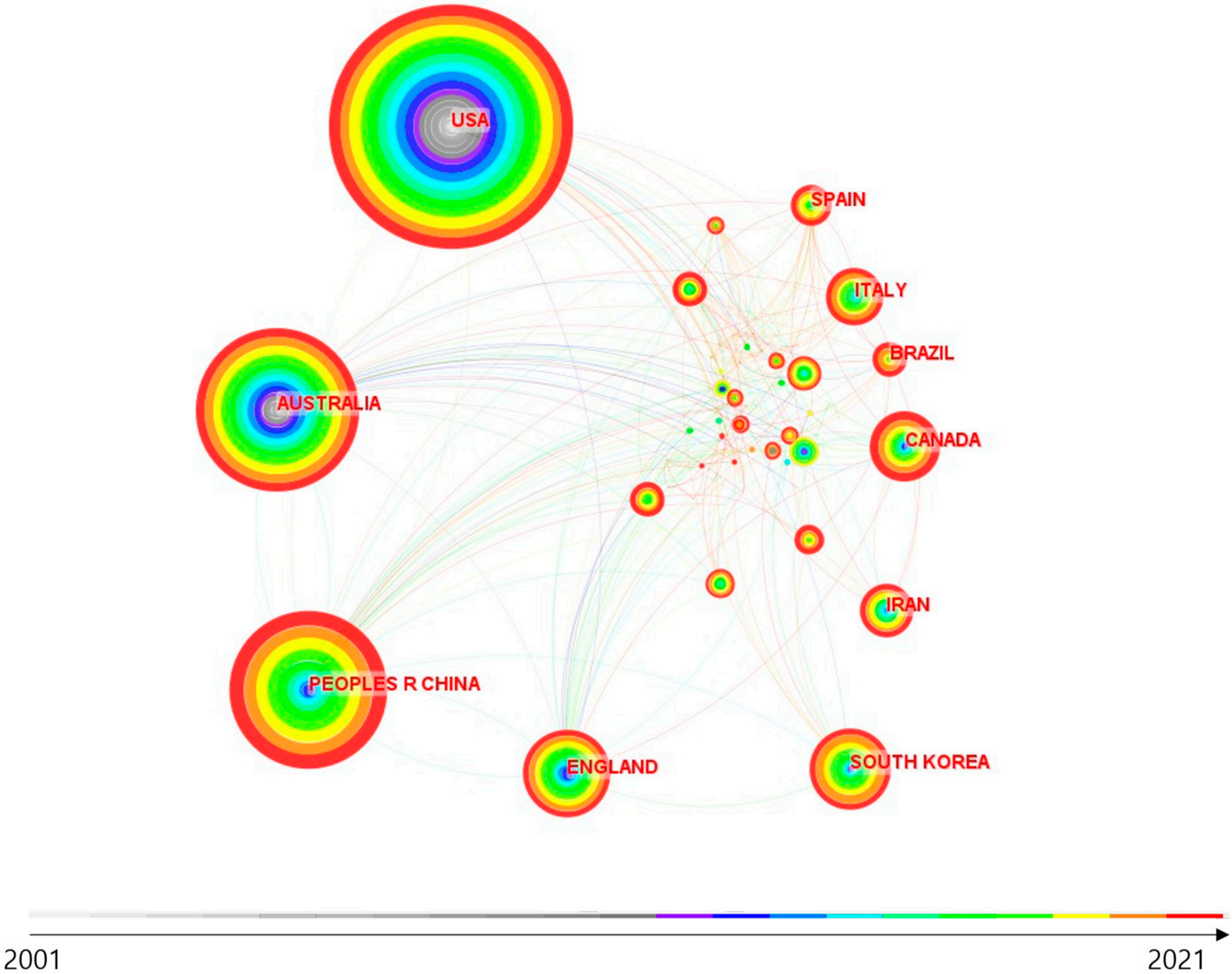


Figure 5. Chronogram cooperation chart for countries employing stormwater runoff management practices.

Figure 6 represents the academic publishing trends (number of articles) for the top five countries employing stormwater runoff management practices. The United States had the highest share of publications until 2017, with publications declining in 2020 and rising in 2021. All other countries showed a steady increase, with China more than doubling the number of publications from 43 in 2017 to 91 in 2018. A similar upward trend was observed in the UK and Australia, with only South Korea showing a decline in the past year. These data suggest that China has invested significant amounts of money in stormwater runoff management research. These data also show that many other countries and regions have maintained their interest in the field.

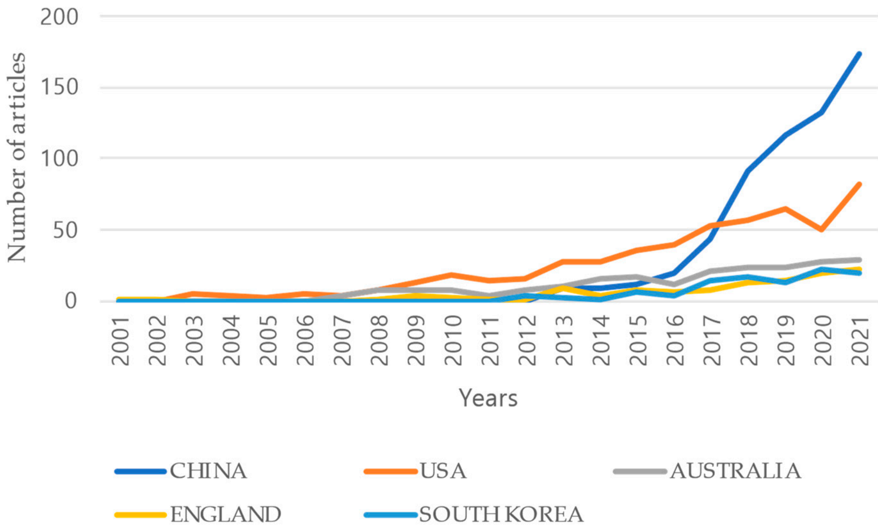


Figure 6. Publishing trends for the top five countries undertaking stormwater runoff management between the years 2001 and 2021.

3.4.3. Analysis of Research Institutions

A network mapping analysis of institutional cooperation identified research institutions at the forefront of research in urban runoff management. There were 236 institutions involved in this area of research (Figure 7) with 372 links and an overall cooperation density of 0.0134, making the density at the institutional level lower than that of international cooperation. Universities accounted for 83.3% of the institutions in the top ten. For example, Monash University in Australia ranked first in terms of the number of articles published and was the first institution to invest in this scientific field in 2007. The institution's top two most cited articles are by Roy, A. (2008) and Coutts, A. (2012), which have 373 and 215 citations, respectively. The study by Roy, A. (2008) summarized seven key barriers to stormwater management, drawing on lessons learned from traditional green infrastructure failures in Australia and the USA, with the aim of slowing the ecological degradation of rivers and proposed solutions to improve river ecology by promoting urban stormwater management [21]. Furthermore, Coutts, A. (2012) proposed to combine water-sensitive and climate-sensitive urban designs to harvest and retain rainwater in the context of an urban landscape in order to reduce urban temperatures and improve human comfort [22]. Table 1 shows the top 20 research institutions with the most publications in the field. China accounted for 55.5% of these institutions; however, it recently entered the field in 2014. The top two most cited articles from Chinese research institutions are by Xia, J. (2017) and Sang, Y. (2016), with 185 and 42 citations, respectively. Xia, J. (2017) studied the urban water issues plaguing China and concluded that the construction of sponge cities in China is confined to low-impact development, demonstrating relatively weak integration with other disciplines, such as urban hydrology and ecological landscaping, and thus requiring improvement [23]. Furthermore, Sang, Y. (2016) also focused on urban flooding and argued that current runoff management approaches have not met expectations. Therefore, urban flooding and its associated problems have not been resolved and require both structural and non-structural measures to improve sponge city construction [24]. It is clear that institutions prefer to focus on problems within their own countries, and Chinese institutions began researching these technologies later than other countries. Articles from China are mainly based around major questions and constructive comments. Australian institutions were the first to begin research in this field and are in a better position to suggest concrete solutions and direct future studies. On the whole, these data suggest that countries have a clear understanding of their research landscapes, as well as the areas they need to develop in the future.

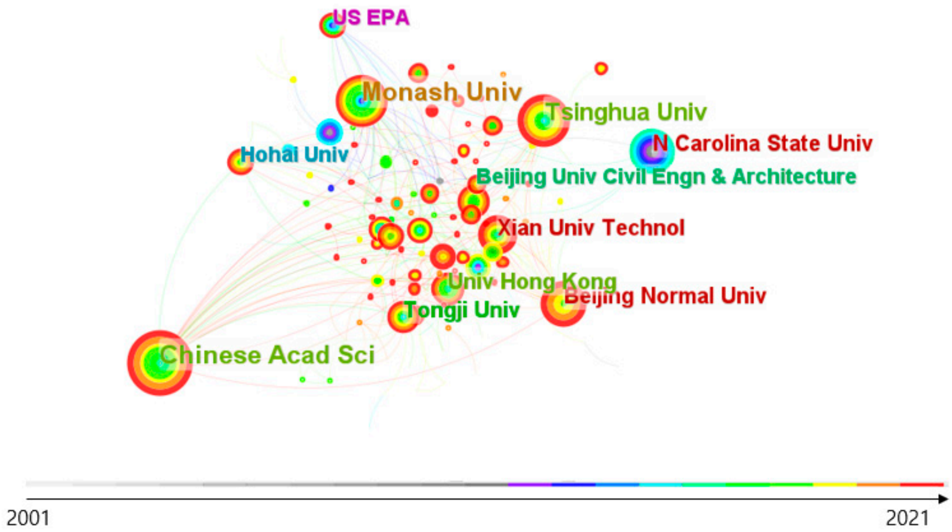


Figure 7. Chronological chart of international research institutions.

Table 1. Top 20 research institutions.

Serial No.	Name of Institution	Year of Debut	Number of Articles
1	Monash University	2007	45
2	Chinese Academy of Sciences	2016	43
3	Tsinghua University	2014	39
4	Beijing Normal University	2018	29
5	Xi'an University of Technology	2016	28
6	North Carolina State University	2009	27
7	Tongji University	2015	26
8	Kongju National University	2012	24
9	University of Hong Kong	2015	24
10	Beijing University of Civil Engineering and Architecture	2013	21
11	Hohai University	2017	21
12	US EPA	2009	21
13	Peking University	2017	20
14	University of Melbourne	2013	20
15	Wuhan University	2017	20
16	Purdue University	2015	17
17	University of South Australia	2009	17
18	China Institute of Water Resources and Hydropower Research	2017	16
19	Texas A&M University	2017	16
20	University of Copenhagen	2012	16

3.4.4. Analysis of Co-Cited Studies

The clustering of co-cited studies reflects the extent of knowledge in a field, which is fundamental to a field's development and overall level of theoretical support, as shown in Figure 8. The "green roof" categories (#0 "green roof" and #2 "extensive green roof") are technical and are included in every runoff management approach. Green roofs include different national and climate characteristics and can have positive effects with regard to runoff, rainwater harvesting, and rainwater quality filtration [25–28]. Category #4, "international practice", refers to the comparison and evaluation of different international standards and technologies for stormwater management. In this work, researchers showed a positive tendency towards proposing new stormwater management practices and suggested more effective solutions and improvements by studying and comparing relevant technologies and management frameworks [29–31]. In the two categories "urban stormwater reclamation" (#6) and "compact growth" (#9), the role of drainage facilities with regard to urban stormwater management is mentioned extensively because sustainable drainage has the potential to improve urban water management and can reduce problems involving road surface runoff and pollutant loads through bioretention facilities and permeable pavement materials [32–34].

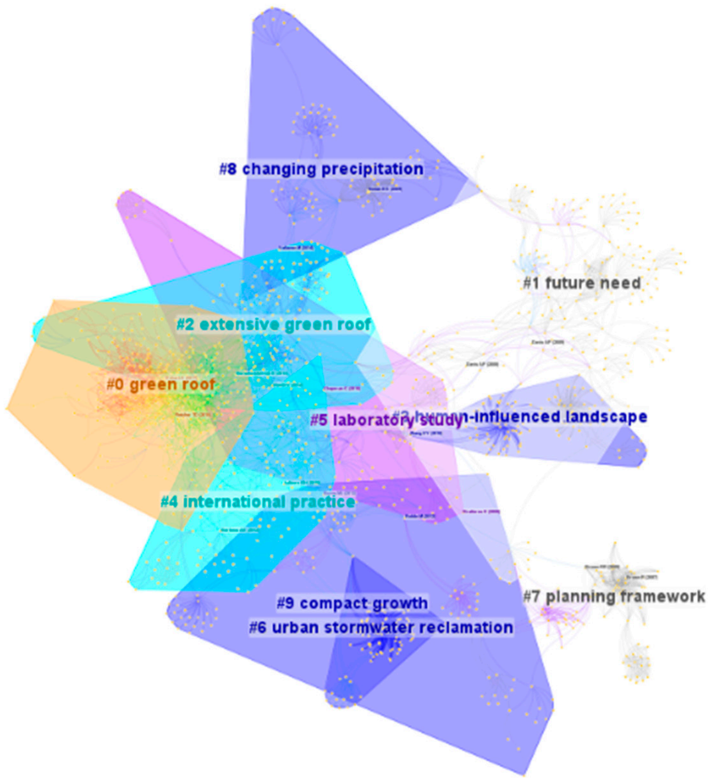
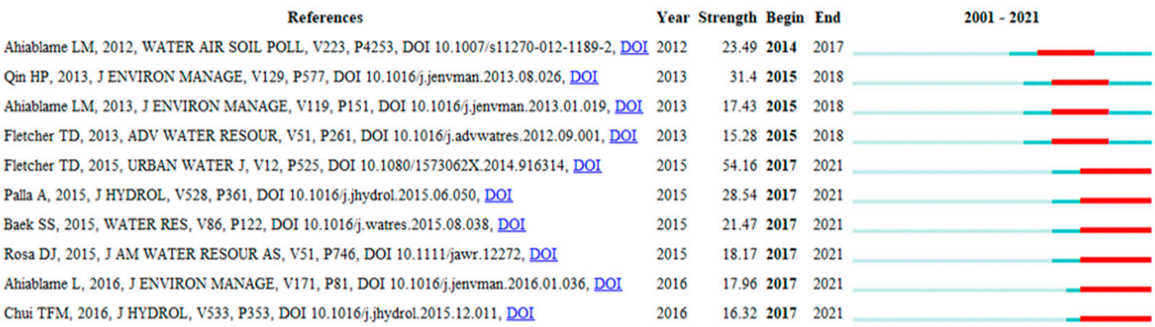


Figure 8. Cluster map for urban rainfall runoff management research.

3.4.5. Reference Emergence Analysis

Citation bursts are sudden increases in citations that occur over a short period of time; they are analyzed to check the range of and trends in the research impacted by the cited studies within a given cycle, as well as to identify influential topics in terms of burst intensity and duration. For this study, burst intensity was analyzed for the top ten publications, with a total of 60 burst items ranked according to intensity, as shown in Figure 9. The color red indicates the burst time period and the color blue indicates the unaffected period. For each stormwater management research area, both emergence intensity and duration were analyzed.



References	Year	Strength	Begin	End	2001 - 2021
Ahiablame LM, 2012, WATER AIR SOIL POLL, V223, P4253, DOI 10.1007/s11270-012-1189-2, DOI	2012	23.49	**2014**	2017	
Qin HP, 2013, J ENVIRON MANAGE, V129, P577, DOI 10.1016/j.jenvman.2013.08.026, DOI	2013	31.4	**2015**	2018	
Ahiablame LM, 2013, J ENVIRON MANAGE, V119, P151, DOI 10.1016/j.jenvman.2013.01.019, DOI	2013	17.43	**2015**	2018	
Fletcher TD, 2013, ADV WATER RESOUR, V51, P261, DOI 10.1016/j.advwatres.2012.09.001, DOI	2013	15.28	**2015**	2018	
Fletcher TD, 2015, URBAN WATER J, V12, P525, DOI 10.1080/1573062X.2014.916314, DOI	2015	54.16	**2017**	2021	
Palla A, 2015, J HYDROL, V528, P361, DOI 10.1016/j.jhydrol.2015.06.050, DOI	2015	28.54	**2017**	2021	
Baek SS, 2015, WATER RES, V86, P122, DOI 10.1016/j.watres.2015.08.038, DOI	2015	21.47	**2017**	2021	
Rosa DJ, 2015, J AM WATER RESOUR AS, V51, P746, DOI 10.1111/jawr.12272, DOI	2015	18.17	**2017**	2021	
Ahiablame L, 2016, J ENVIRON MANAGE, V171, P81, DOI 10.1016/j.jenvman.2016.01.036, DOI	2016	17.96	**2017**	2021	
Chui TFM, 2016, J HYDROL, V533, P353, DOI 10.1016/j.jhydrol.2015.12.011, DOI	2016	16.32	**2017**	2021	

Figure 9. Top ten references with the strongest citation bursts.

In terms of emergence intensity, the most intense article was determined to be the article by Fletcher, T. (2015), which was a study on the evolution and application of urban drainage terminology with an impact period between 2017 and 2021. In summary, the article provides an overview of the development of existing urban stormwater management concepts and describes the evolution of the different terms, as well as their scope of coverage. Furthermore, it also analyzes shortcomings in the field of "uniform terminology" and states that the local development of terminology has an important role to play in advancing the profession and facilitating future communication between different disciplines on the approach to stormwater management [7].

From a time-of-appearance perspective, the earliest cited article was published in 2012, indicating that research on stormwater management began to move from exploration to development. The development period can be divided into two phases: 2014–2017 and 2017–2021. Furthermore, the papers can be divided into two categories. The first category provide favorable evidence regarding the effectiveness of low-impact development practices, demonstrating the effectiveness of the technical facilities that have been completed for flood control, as well as rainwater harvesting and purification, while offering recommendations for future studies [35–37].

The second category of papers attempt to improve the way urban runoff is managed by using simulation models to predict rainfall and runoff and to develop new technologies [35]. This phase of stormwater runoff management research has been proven to be effective, with initial attempts to integrate new technologies and enhance original concepts being largely successful. Five previous studies refer to the development of simulation models to demonstrate the usefulness of low-impact development in extreme climates, such as those with large storm floods, in addition to the evolution of the terminology and applications of urban drainage mentioned above, illustrating the ongoing integration in the field with regard to new technologies and other disciplines [2,38–41].

The development of stormwater runoff management theory can be described as follows. First, a concept is proposed, and then it is clarified and standardized. Further studies demonstrate its feasibility in practice while simultaneously solving problems, optimizing and innovating the technology used for the proposed concept. The final step is to promote the innovations that have been demonstrated through interdisciplinary research cooperation.

3.5. Performance Features

In this section, by combining the Environmental Performance Index (EPI) framework and the concept of stormwater runoff management, trends in research on stormwater runoff management in various environmental performance areas, as well as research hotspots, are examined through keyword timeline analysis and keyword emergence analysis.

As a benchmark index, the EPI framework can be easily adopted by policymakers, environmental scientists, environmental advocates, and the general public [42]. In the context of reducing the impact of environmental stress on human health, as well as enhancing ecosystem vitality and promoting better management of natural resources, the introduction of this performance framework can be an effective way to demonstrate the effect of urban stormwater runoff management on the environment, as well as its effect on the direction of future research.

The EPI framework contains 3 policy objectives and 11 issue categories (Table 2) [43]. Based on this framework, 944 relevant papers were selected from an initial set of 1756 papers, using the concept of stormwater runoff management as a background.

Table 2. Literature screening with the EPI framework.

Policy Objectives	Issue Categories	Article Numbers
Climate	Climate change mitigation	311
Environmental health	Air Quality Waste management Water and sanitation Heavy metals	145
Ecosystem vitality	Biodiversity and habitat Ecosystem services Fisheries Agriculture Acid rain	527

3.5.1. Climate

1. Keyword clustering timeline analysis

The keywords are the primary themes of a written work and can provide clear indications about the topic while serving as summaries of the main subject. They can effectively reflect the areas covered in the literature and, thus, facilitate investigation into the research hotspots and developments in the field, as well as the knowledge background.

The keyword clustering time shows the time span, the evolution of each clustering hotspot, and the relationship between each cluster and the others. The longer the horizontal line is, the greater the time span is, with the cluster coming into existence earlier and lasting longer. The six clusters are plotted in Figure 10. For the climate policy objective, most clusters were closely linked, which indicates a high level of cross-sectional research. The strongest relationships in the study period from 2010 to 2021 were between clusters #0 (source control), #1 (water sensitive urban design), and #2 (bioretention cell), indicating that stormwater runoff management is primarily a response and adaptation to runoff and flooding caused by environmental changes. As can be seen, stormwater runoff management is primarily concerned with responding and adapting to runoff caused by environmental changes, such as flooding.

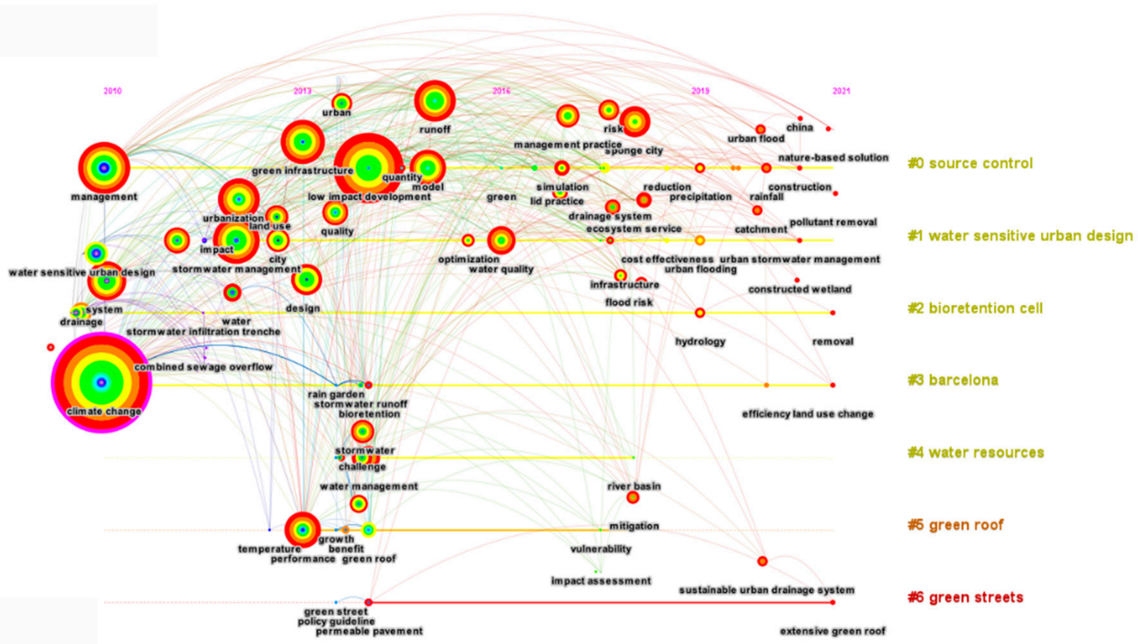


Figure 10. Climate keyword clustering timeline analysis.

Cluster #0, "source control", included keywords such as "low impact development", "green infrastructure", "management run off", and "model". This cluster was mainly concerned with the prediction of the coping capacity of urban rainwater runoff management facilities when facing possible climate changes in the future. By building a prediction model that can simulate climate change, future urban waterlines, floods, and other problems can be predicted and evaluated. Using these evaluative methods, it has been shown that urban runoff management facilities can have a positive impact on the future of climate change management. Some positive effects of these facilities (including biological retention pool facilities, porous pavement facilities, and others) are that they can effectively reduce surface runoff volume and velocity and the value of the volume capture ratio for annual rainfall can be significantly increased, thus reducing the rate of occurrence of urban floods [44–46]. However, in this cluster, no measures to solve existing climate problems have been proposed.

Cluster #1, "water sensitive urban design", included "rainwater management", "urbanization", "ecosystem service", "urban flooding", and other keywords. It was mentioned in the studies from this cluster that the effective implementation of rainwater management can improve the sustainability of cities and urban water circulation. In addition, rainwater runoff management facilities can help alleviate the effects of climate change on urban environments. The measures mentioned above can be implemented through facilities such as green roofs and rainwater wetlands, which can not only control rainwater runoff but also reduce air pollution and alleviate the effects of climate change [47]. Furthermore, some countries have effectively reduced greenhouse gas emissions resulting from urban water circulation through the optimization of urban water circulation systems, as well as the filtering, storage, and reuse of rainwater made possible by rainwater management facilities [48]. However, these facilities have strict requirements for location, making the implementation of these methods impossible on a large scale.

Cluster #2, "bioretention cell", included keywords such as "system", "water sensitive urban design", "drainage", "hydrology", "strategy", etc. This cluster evaluated and predicted the performance of rainwater runoff management facilities in dealing with rainwater runoff caused by climate change. Runoff management facilities play a significant role in dealing with urban floods caused by smaller storms, but their performance may worsen when faced with the challenge of larger urban floods in the future [49]. The combination of a permeable pavement facility and a detention basin facility is the best arrangement of facilities, providing higher flexibility in the face of major urban floods. However, the flexibility of this combination may be limited depending on the geographical location and the extent of rainwater management facilities [50].

2. Keyword emergence analysis

The emergence of keywords refers to the appearance of terms that are frequently used or closely followed by scholars in a field. It indicates the hotspots and research frontiers in the field and areas that have good research potential, and it can serve as a basis for analyzing development trends.

In total, there were 12 emergent items. The top five were selected, and the top two to three words in terms of intensity were analyzed. As shown in Figure 11, "water sensitive urban design" (WSUD) was not only the most frequent term but also the longest lasting emergent item. This is attributable to the number of measures, many of which are multifunctional, that WSUD offers. These facilities are not only better able to cope with the negative effects of climate change but can also help to address the urban heat island effect and improve the microclimate [51–53].

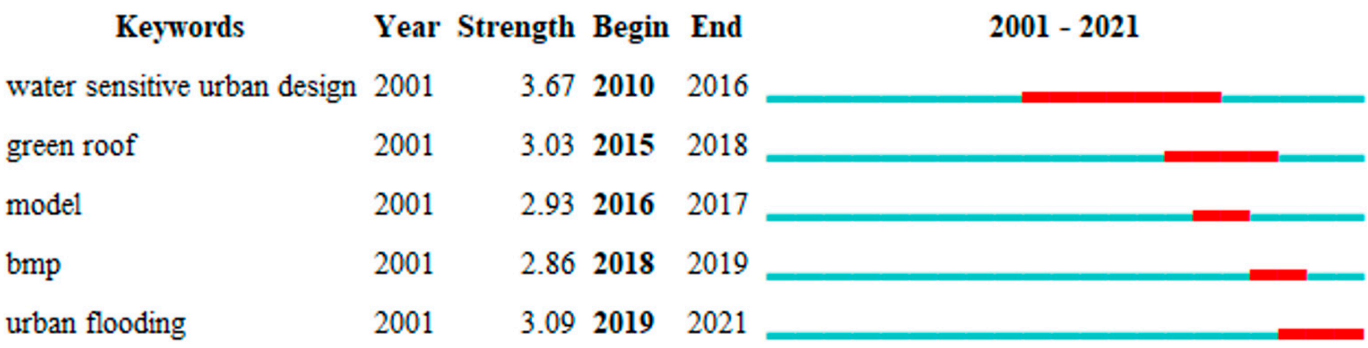


Figure 11. Top five emergent climate keywords.

Green roofs are a kind of popular green infrastructure in highly urbanized areas [54] that have a very good rainwater runoff reduction effect on both inclined and flat impervious roofs [55]. However, the construction of green roof facilities is widely restricted by local environment and climate conditions. Very few green roofs have been implemented in Australia, and their application is still in the developmental stage [56]. However, in other countries during the same period, such as the United States, Germany, and Japan, green roofs have been installed on a large scale with significant results [57]. In addition to environmental factors, there may be difficulties in implementing these facilities on a large scale due to the unavoidable high cost of green roofs, the lack of appropriate regulatory systems among regional agencies, and the lack of local environmental monitoring data [58]. In addition, green roofs can effectively reduce most of the pollutants in rainwater runoff, but material selection and material aging issues should be considered. For example, aging roofs can become a source of metal pollution [59,60].

The most recent keyword was "urban flooding", indicating that it is a frontier research topic in the field of climate research. The problem of urban flooding is becoming increasingly disturbing with the changing climate. It is of particular concern for low-lying cities and has garnered recent attention in several countries [61,62]. In addition, due to the development of rainwater management modeling and monitoring technology, future urban flood problems can be predicted and simulated, and corresponding planning regulations and guidelines can be formulated in order to deal with possible urban flooding problems in the future [63,64]. Rainwater management facilities have performed well in controlling small and medium-sized urban floods, while in the face of serious urban floods, their effect has been limited.

3.5.2. Environmental Health

1. Keyword clustering timeline analysis

Eight clusters were extracted (Figure 12) spanning the period from 2007 to 2021. The field of environmental health has existed longer than the field of climate research. Cluster #1, "polycyclic aromatic hydrocarbons", was most closely associated with clusters #2, "LID", and #4, "sensitivity analysis", and it showed a longer research history.

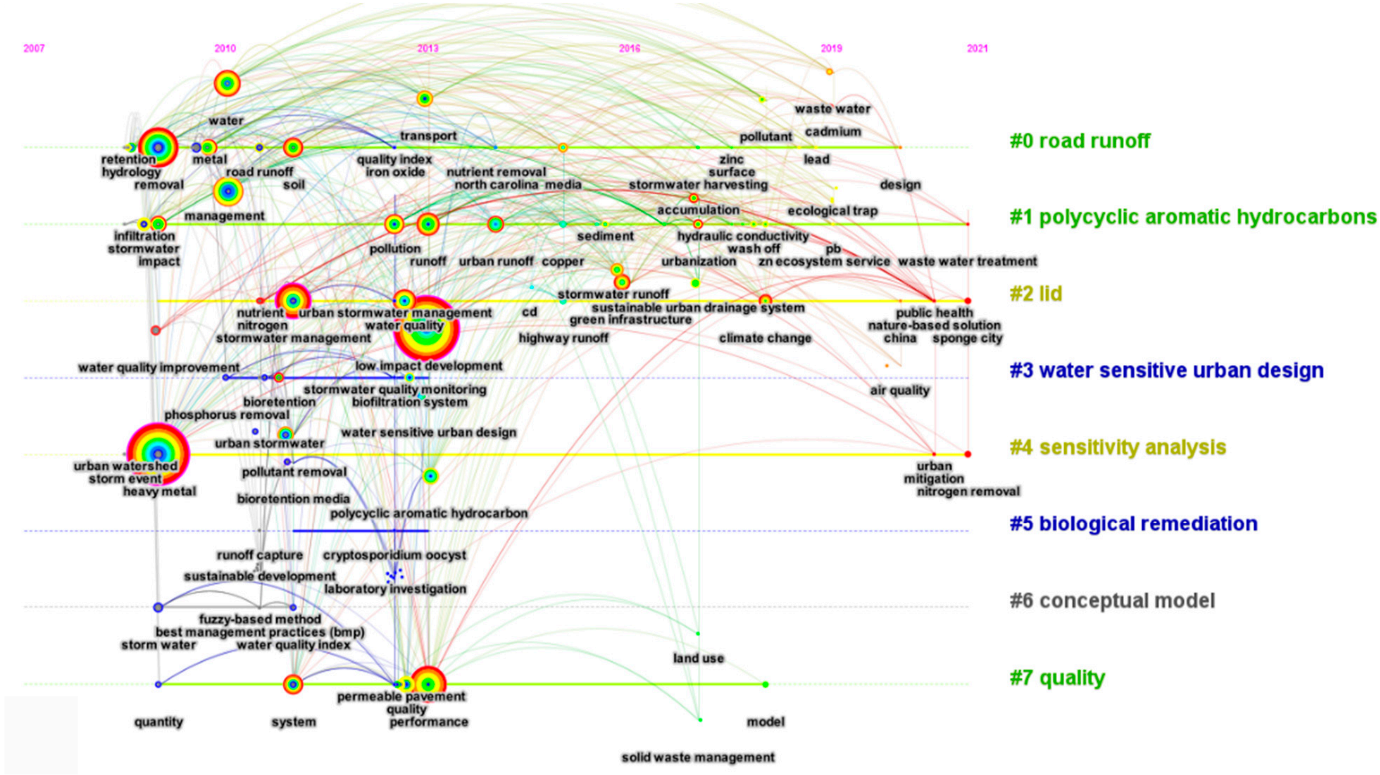


Figure 12. Environmental health keyword clustering timeline analysis.

Cluster #1, "polycyclic aromatic hydrocarbons", included keywords such as "plant", "phytoextraction", "phytoremediation", "land", etc. In this cluster, researchers studied the removal of heavy metals, organic substances, and other pollutants dissolved in rainwater mainly by means of biological interception [65], which improves environmental health. Plants play an important role in filtration, and different plants have different capabilities for removing different pollutants [66]. However, the majority of successful cases come from a small number of specific countries, and there are differences in biological interception systems in different geographical locations, which has caused failures in the installation of rainwater management facilities in other areas [67].

Cluster #2, "LID", included keywords such as "adsorption", "zinc", "copper", "sediment removal", etc. The adsorption of pollutants in water by physical means was the central topic of this cluster, and this is a very important remediation measure in rainwater runoff management facilities [68]. The selection of filter media leads to different effects for different pollutants, and factors such as temperature, humidity, and the flow rate of rainwater runoff can affect the adsorption effect [69]. Therefore, more accurate data sources are needed for the monitoring of local rainwater pollutants, as well as on-site experimental simulation results, prior to the installation of rainwater runoff management facilities.

The keywords included in cluster #4, "sensitivity analysis", were "uncertainty", "rainwater quality", "urban flooding", "hierarchy of hazard control", etc. The research in this cluster mainly discussed how sensitivity analysis and uncertainty analysis can be used to determine the great influence climate change can have on the removal of rainwater pollutants by rainwater runoff management facilities. Due to the limited interception capacities of these facilities, their performance in extreme weather conditions is highly uncertain [70] and can vary depending on geographical location and land-cover distribution [71]. In addition, in the construction of rainwater runoff facilities, the construction of buildings and the transportation of materials can have extremely adverse impacts on the environment [72]. Therefore, prior to the construction of rainwater runoff facilities, there should be extensive early planning, and the benefits should be weighed against the uncertainty regarding the facilities' function and any possible adverse impact on the environment.

2. Keyword emergence analysis

There were five emergent terms in total, all of which were included in the analysis (Figure 13). In general, stormwater management concepts concern the removal of pollutants, such as heavy metals, from urban runoff and have a concentrated time cycle with a short timeframe. The absence of new, emerging terms in the field in recent years suggests that no major new research trends have emerged and that past research directions have continued up to the present. "WSUD" is still the prevalent term. This is due to the multifunctional facilities it offers and the fact that it makes an important contribution to enhancing the inhabitability of cities and improving urban environments through its many amenities [73].

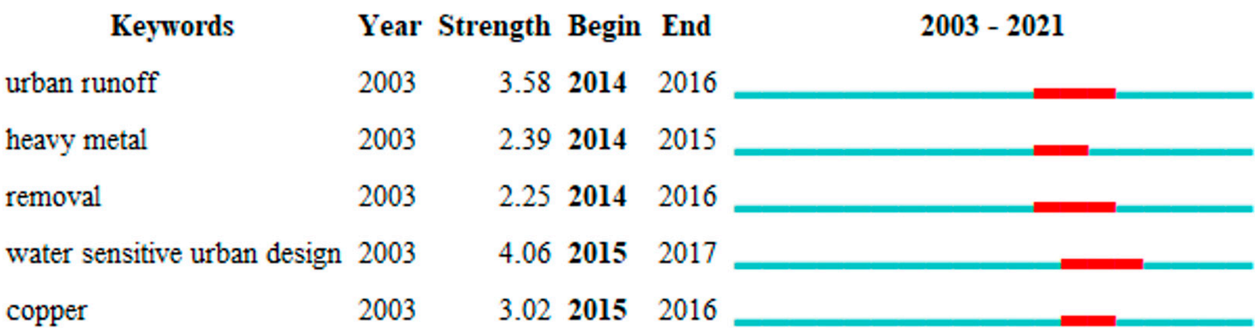


Figure 13. Top five emergent environmental health keywords.

Urban runoff ranked second in the keywords. Any method of rainwater runoff management can be considered an effective measure to reduce urban runoff and improve water quality. With regard to environmental health, many pollutants carried by rainwater runoff are discharged into streams, rivers, and other natural water sources without treatment, causing environmental pollution. It has been proved that runoff management facilities are effective in removing runoff pollutants [74]. However, problems such as the overflow of facilities in cases of heavy rain, the blockage of pipelines after long-term use, and the difficulty in maintaining these facilities are being continuously studied [75,76].

3.5.3. Ecosystem Vitality

1. Keyword clustering timeline analysis

A total of eight clusters were generated and the first five were selected (Figure 14). In these clusters, which span the period from 2004 to 2021, stormwater runoff management concepts have the longest history of study in terms of ecosystem vitality. All studies included have continued to the present day and are closely interlinked. Group #2, the "SWMM model", was the cluster with the longest history of studies being published. The Storm Water Management Model (SWMM) is a software application developed by the University of Florida, USA, which has been widely applied in the analysis of the impact of rainfall on urban runoff. It is helpful in planning how urban drainage systems can be optimized in order to reduce economic losses, such as those caused by urban flooding [77]. This software allows for the effective analysis and assessment of the impact of stormwater runoff management on urban runoff control [78]. More simulation models are currently being applied to rainwater runoff management, including the simulation of pollutants and permeability. However, due to the limitations of pollutants and the lack of concentration data regarding the process of pollutant diffusion, it is impossible to verify the simulation data results. Thus, more systematic data collection and the unification of relevant numerical models could be helpful in improving diffusion and anti-diffusion process related to pollutants [79].

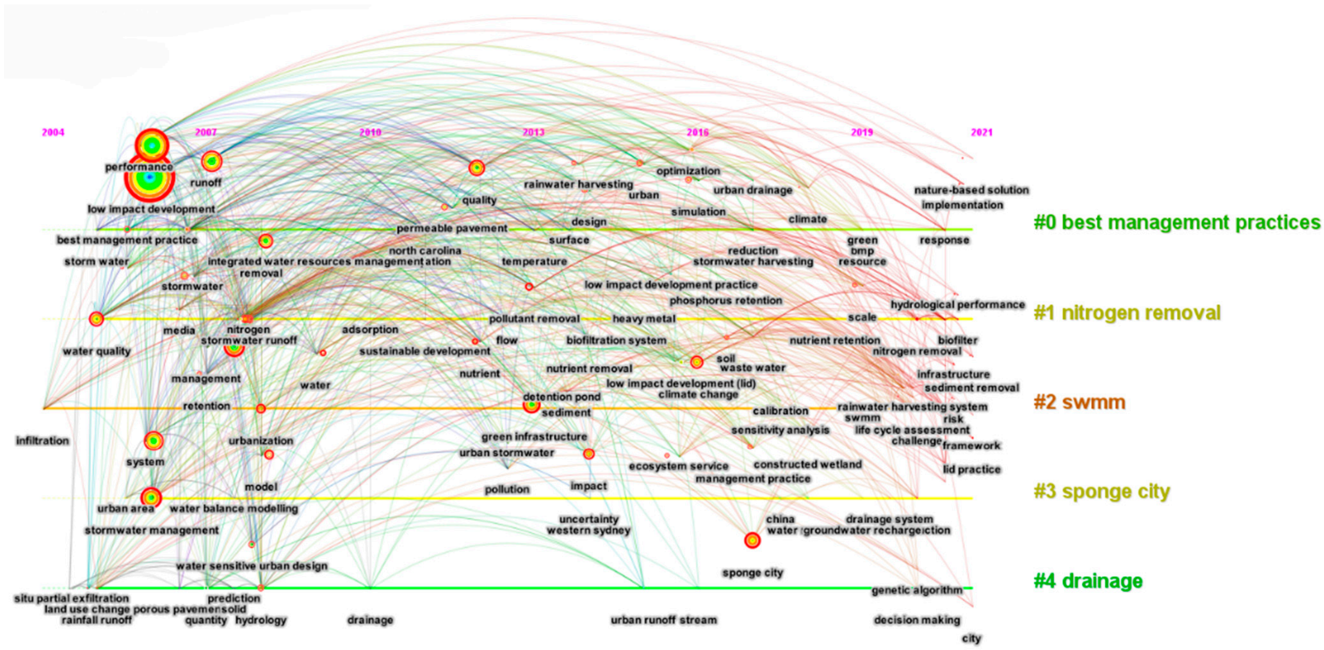


Figure 14. Ecosystem vitality keyword clustering timeline analysis.

Cluster #0, "best management practices", consisted of "low impact development", "performance", "rainwater management", "run off", and other keywords. In this cluster, discussion was mainly focused on urban rainwater runoff management facilities that can provide ecosystem services [80], as well as other benefits in terms of culture, aesthetics, and biodiversity [81]. Although ecosystem services are not the primary function of stormwater management facilities, providing a variety of ecosystem services can increase social acceptability and be conducive to replication.

2. Keyword emergence analysis

There were nine emergent terms in total, and the top five were selected (Figure 15). No new terms have emerged recently, and, therefore, there were no new research trends in the field. The term "best management practice" (BMP) had the longest time span and the greatest strength, and it covered two aspects: industrial wastewater control and municipal wastewater control. Low-impact-development stormwater management measures are referred to as subsets of BMPs and BMP facilities [82]. The combination of LIP and BMP measures can effectively address the complexities of the urban hydrological environment and social factors [83] and provide a more diverse range of ecosystem services.

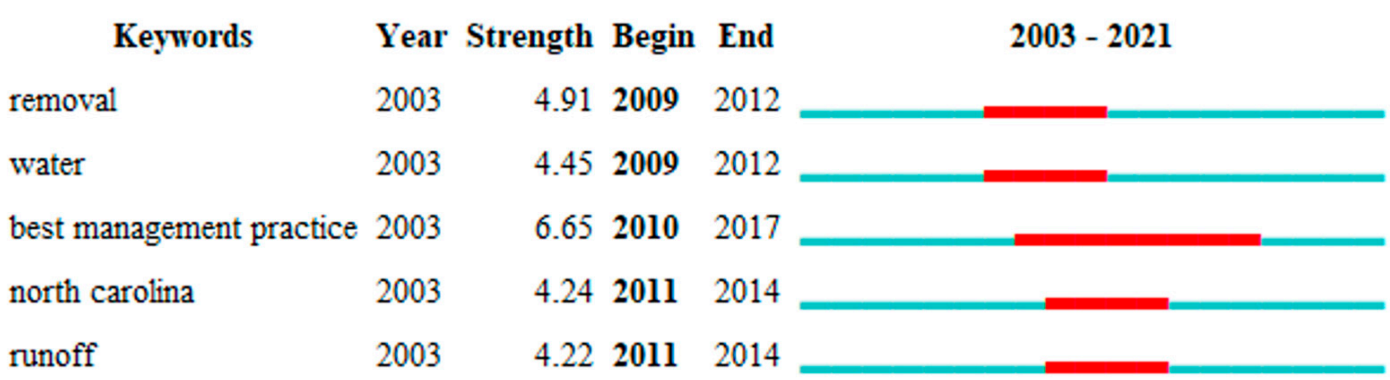


Figure 15. Top five emergent ecosystem vitality keywords.

"Removal" was the second ranking keyword in terms of frequency. Rainwater runoff management facilities can significantly reduce concentrations of urban runoff pollutants, with the treatment process being carried out using chemical, biological, and physical means, including sedimentation, filtration, adsorption, reduction, plant absorption, and microbial biomass assimilation [82]. A single removal method cannot solve all of the problems faced, and a combination of multiple means can be more effective in achieving the removal of pollutants than any single method. In addition, the combination of treatment methods should be adjusted according to the requirements of the particular location, making the promotion of standardized methods less applicable.

3.6. Patent Analysis

Compared to article analysis, patents can often better reflect the results of actual technical applications. For this paper, patent records for stormwater runoff technologies were extracted for the period from 2001 to 2021 using the World Intellectual Property Organization's database. Technological development follows a pattern—namely, precursors–invention–development–maturity, which is known as the S-shaped growth pattern [69,84]. A total of 1880 patents were found covering 520 items in the International Patent Classification (IPC) database. Employing the IPC codes for the top 20, this article classified the top patents into four fields for further S-curve analysis. These were "Drainage", "Collection", "Treatment", and "Testing and Simulation" (Table 3).

Table 3. Top 20 keywords in classified patents.

Class	IPC Index	Keywords	Number of Patents
Drainage	E03F1/00	Draining off of sewage or storm water	209
	E03F5/04	Drainage wells	126
	E03F3/04	Drainage accessories	65
	E03F3/02	Piping system arrangement	44
	E04D13/08	Roof drainage fitting	40
	E03F5/00	Sewerage structures	36
	E04D13/00	Roof drainage facilities	24
	E01C11/22	Gutters and curbs	87
Collection	E03F5/10	Sewage collection	176
	E03B3/02	Rainwater collection	103
	A01G9/02	Planter, flower box, or tree bed water collection	41
Treatment	C02F3/32	Plant filtration	91
	C02F9/14	Biofiltration	102
	C02F1/00	Wastewater and water treatment	57
	C02F1/28	Adsorption	41
	C02F3/34	Microbial filtration	38
	E03F5/06	Filtration structure	37
	C02F101/16	Filtered nitrogen	34
	E03F5/14	Solid–liquid separation	171
Runoff prediction and modelling	G06Q50/26	Runoff simulation and detection	53

3.6.1. Drainage

The patents for drainage were divided into three categories: road drainage fittings and facilities; drainage structures and plans; and roof drainage fittings and facilities. As is shown in Figure 16, generally speaking, this field is at an intermediate to late stage in its development, with both road drainage and other drainage structures having been in precursor (emerging) periods for a long time and roof drainage entering the invention stage early on. Urban road drainage is very complex and is not just a single discipline but rather involves many aspects [85]. Its complexity has resulted in a long period of exploration.

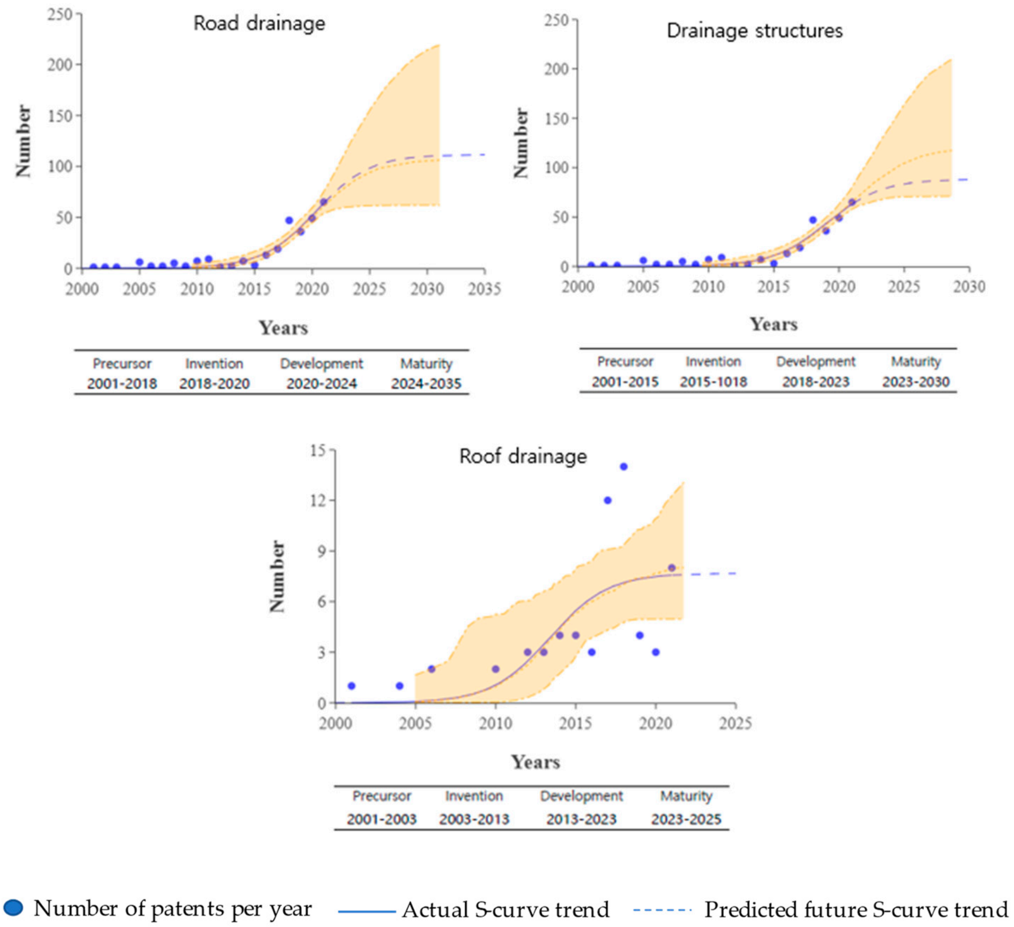


Figure 16. S-curves for drainage in patents.

3.6.2. Collection

Collection patents fell into two categories, wastewater collection technology and rainwater collection technology (Figure 17), with wastewater collection technology being at an advanced stage of development and rainwater collection at the beginning stage of development, demonstrating a long maturity cycle. Rainwater harvesting is considered to be a part of a rainwater harvesting system and includes collection, storage, and use of rainwater [46]. At present, rainwater harvesting techniques include not only collection but also consideration of later use in order to ensure safety [86].

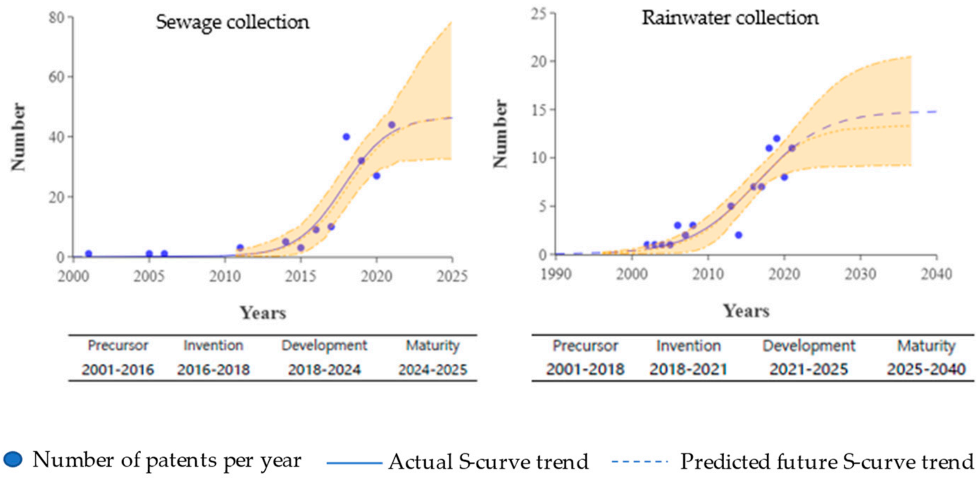


Figure 17. S-curves for collection in patents.

3.6.3. Treatment

Treatment patents were divided into three categories (Figure 18): sedimentation, adsorption, and biofiltration. Sedimentation is in the early stages of development, while adsorption and biofiltration technologies are in the early stages of maturity. The periods of development for these two technologies were also periods of growth in the literature on these technologies, and there was a positive correlation between the two technologies. In the context of stormwater runoff management, there has been a drive to use natural means to remove harmful substances and suspended solids from stormwater. The development of biofiltration systems, which combine technologies from a variety of fields, is constantly advancing [87].

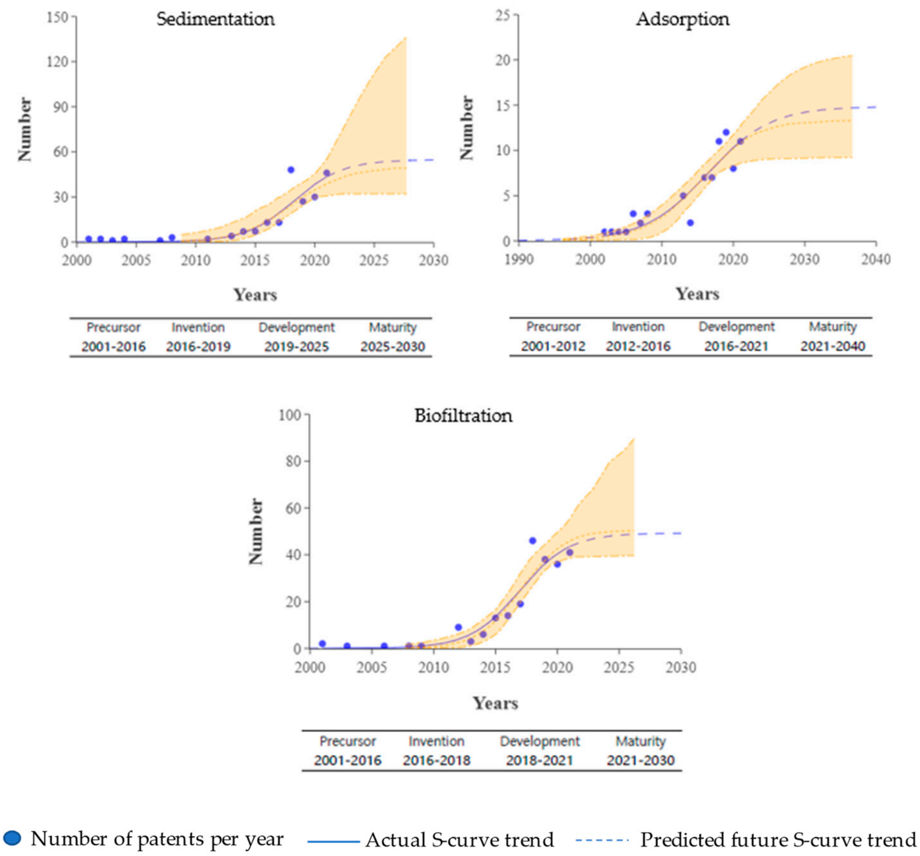


Figure 18. S-curves for treatment in patents.

3.6.4. Runoff Prediction and Modeling

Runoff prediction and modeling technology is the latest of these patented technologies and is still in the invention phase (Figure 19), with significant potential for future development. Modeling techniques can make cities more resilient and better able to predict and cope with extreme weather and urban flooding in the future [40].

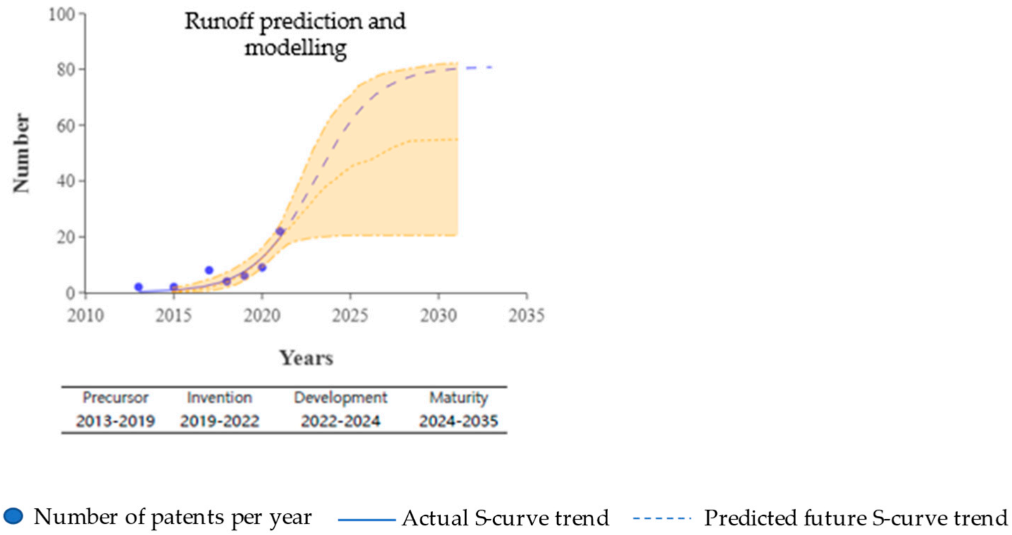


Figure 19. S-curve for runoff prediction and modeling in patents.

4. Discussion

4.1. Constraints on Development

Geographic constraints. There is wide variability between one geographic area and another due to local climate factors, other environmental factors, and localized urban runoff problems [50,69], and these factors can have a great impact on the effectiveness of stormwater runoff facilities [67,69,82]. In addition, the construction of stormwater runoff facilities itself has many constraints regarding site selection, including financial investment, local policies, and land area [58]. In summary, fixed models and concepts are difficult to replicate on a large scale in different regions.

Technological limitations arise mainly from the fact that technological developments related to stormwater runoff management facilities are at an advanced stage of development or even fully mature, but there are still uncertainties as to the performance of the facilities in the face of extreme weather. In Figures 13 and 15, the word "removal" is highlighted, indicating that the removal of pollutants from rainwater has figured prominently in the development of stormwater runoff management, with chemical and biological pollutants being of particular importance [88,89], the main filtration methods for them being adsorption and biofiltration. From a technological perspective (Figure 18), the growth period in the development of adsorption and biofiltration has come to an end. However, when the runoff velocity exceeds the threshold, problems such as the pollution caused by effluent overflow and limited interception capacity remain [70,75]. In addition, there is still much room for progress in the sustainable reuse of materials, cost control, and research and development regarding new materials and systems [87,90].

Uncertainty of data. The scarcity of front-end data can affect the proper planning of stormwater runoff facilities, which can produce secondary pollution, as well as affect the utility of the facilities [69,72]. Since the post-simulation data cannot be verified [79], there are questions about the authenticity of the final results, as well as the sustainability at later stages.

4.2. Future Development Trends

The trend for stormwater runoff management will tend toward multifunctional designs. Versatile stormwater runoff management facilities can more effectively address multi-disciplinary urban issues compared to single-method facilities. In order to cope with the changing climate and urban development, approaches to urban stormwater runoff management should face and solve more problems, not only limited to the stormwater runoff aspect but also involving more fields. The most prominent of these multifunctional approaches is the WSUD approach (Figures 11 and 13), which is implemented through both structural and non-structural measures [91]. WSUD has established a complete evaluation platform incorporating multiple disciplines in order to evaluate space feasibility through various approaches, such as modeling, reviews, and planning simulations, making it possible to build WSUD facilities in the most suitable place [92]. In addition, multiple targets that are originally processed separately are integrated for unified processing in order to achieve several side functions while simultaneously realizing the main functions. Strict evaluation methods and multifunctionality not only reduce expenses but also greatly improve practicality [93]. The above approaches have put forward new methods for the improvement of runoff rainwater management facilities that have previously failed to achieve the desired effect [24]. Functions have been improved through the combination of stormwater runoff management facilities and other facilities. Stormwater runoff management itself offers an improvement over previously existing urban planning methods [35] and can effectively solve multiple problems when used in combination with traditional grey infrastructure, drainage systems, and green infrastructure [94–97]. For example, the combination of LID and BMP (Figure 16) facilities can more effectively solve multiple complex problems [84]. This combination is bidirectional and can not only improve the functionality of stormwater runoff management but can also contribute to the repair of the original facilities [98]. The mutual combination of functions also merits further evaluation, as the situation is more complex than a simple combining of two methods but rather requires the consideration of various factors in order to maximize the beneficial effects [99]. Efficient synergistic effects can be produced through the correct combination of facilities [100]. Increased interdisciplinary research collaboration can maintain the sustainability of the project. In recent years, integrated models for addressing environmental issues have been developed and applied extensively to urban water management practices [101]. As research in each direction continues, the uncertainty in model predictions can be reduced [102,103]. For example, one of the hot research topics in recent years, "urban flooding" (Figure 12), not only relies on the integrated simulation of models but also requires a large amount of rainfall data and extensive data acquisition [104]. The application and acquisition of these data are closely related to the development of smart cities, collection and analysis using big data networks, the development of new sensors, and various other new technologies. In the digital age, with the maturity of the concept of and technology for stormwater runoff management, there is great value in the maintenance and updating of facilities in the later stages of the development of these technologies [58–60,76]. With cutting-edge technologies, more effective early planning for and prediction of future economic and social benefits can be achieved [81].

5. Conclusions

A review and analysis of 1756 English-language articles published from 2001 to 2021 in the WoS databases were conducted. The results of this study show that the literature on urban stormwater runoff management concepts has grown rapidly over the last 20 years. This indicates that research in this field is expanding and developing rapidly, generating a great deal of interest from academia and industry. This suggests that issues involved in the field of stormwater runoff management are becoming increasingly important and require more research in order to understand and address them in depth. Furthermore, the fast growth of the literature may reflect the innovative and forward-looking nature of the research within this field, as well as the wide recognition from and interest of researchers.

According to the distribution of publications and articles by country and institute, China, the United States, and Australia have produced the most publications in this field. However, as the research period has extended and more articles have been published, greater cooperation with other countries has occurred, which may indicate that the research in this field has reached a certain level of maturity and scale and that international cooperation has become more important in order to promote development and innovation. International cooperation can provide researchers with more research resources and expertise, increasing the depth and comprehensiveness of the research.

Reference emergence analysis showed that the development of stormwater runoff management concepts has evolved from theoretical formulation toward the current need to promote innovation and application through interdisciplinary research collaboration, which indicates that the problems in this field have become increasingly complex, thus requiring cooperation and communication between various disciplines. This provides more opportunities for collaboration and innovation among researchers from various disciplines and promotes the interdisciplinary development of academic research.

As can be seen from Sections 3.5 and 3.6 on performance features and patent analysis, the implementation of stormwater runoff management has undoubtedly improved the urban environment. The development of technologies such as green roofs, permeable pavements, adsorption and sedimentation techniques, and simulation and prediction has brought benefits to the urban climate environment, improving urban flood control and urban water quality, but deficiencies remain. "Urban flooding" is a current research hotspot, and the "sponge city" concept has significant advantages in the field of urban flood control. The advantages of the WSUD concept include its favoring of the establishment of multifunctional stormwater runoff facilities, which is in line with the future development direction for this research.

In the future of stormwater runoff management, it will be necessary to solve the problem of limited promotion due to geographical problems and the bottleneck in the development of practical technology. The collection and detection of urban data are critical to future development, and advanced technological tools, such as artificial intelligence, big data, cloud computing, and the Internet of Things, should be used in order to achieve digitalized smart cities. Multifunctionality and sustainability are the primary development directions for stormwater runoff management. The popularity of multifunctional stormwater runoff facilities, as well as greater consideration of the future sustainability of and concept planning for these facilities, can facilitate further development in this field.

In this study, we mainly searched for papers in English and, therefore, papers in other languages were not included, but this does not negate the fact that research in this area has been carried out in non-English-speaking regions; in recent years, there has been an increase in research in the Middle East and the Arab region in the field of stormwater runoff. Therefore, this paper has some limitations in terms of research orientation, and in subsequent research, the scope of the multilingual paper search can be expanded in order to better summarize and examine current hot topics and research trends.

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

Appendix A

"Sponge city" or "sponge cities" or "low impact development" or "low impact development(lid)" or "low-impact development" or "low-impact development(lid)" or "water sensitive urban design" or "water-sensitive urban design" or "water sensitive urban design(wsud)" or "water-sensitive urban design(wsud)" or "sustainable urban drainage systems" or "sustainable urban drainage".

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