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Development Trend and Frontier of Stormwater Management (1980–2019): A Bibliometric Overview Based on CiteSpace

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Abstract: The threat of urban floods due to climate change and urbanization has enabled sustained attention to the stormwater management field. Numerous scholars and countries have successively proposed innovative concepts for stormwater management. To grasp the current research focus and status quo and determine the development trend and dynamic direction, this work used CiteSpace, a scientific bibliometric analysis software, to analyze and identify 3080 articles based on the core database of Web of Science from 1980 to 2019. Results show a comprehensive overview of the stormwater management field, including the changes of annual articles with time; the most influential countries, institutions, authors, and articles; and the periodical keywords, highly cited papers, and burst time in the field. A knowledge table in the stormwater management field was obtained, the development context of the field and the research focus of each stage were understood, and the future development trend of the field is inferred. This study aims to provide reference for researchers and practitioners in the stormwater management field.

Keywords: stormwater management; CiteSpace; bibliometric analysis; visualization; urban water cycle

1. Introduction

In the past few decades, the frequency and intensity of extreme weather events (e.g., rainstorms) caused by climate change have continued to increase, floods have become frequent, and water pollution has become increasingly serious [1–6]. These events lead water-related research to obtain increasing attention [7–9]. In a populous metropolis, floods cause serious casualties and economic losses [10]. In 2018, torrential rain in Japan triggered the deadliest flood since 1982, killing 230 people. The August flood in Kerala State in India killed 504 people, affected more than 23 million people, and caused economic losses of 4 billion US dollars [11]. In addition to the extreme precipitation caused by climate change, the increase of urban seepage control area and the defects of drainage system are also common reasons for the increase of flood risk [12,13]. Although climate change and extreme precipitation have yet to be addressed, the resulting increased flood risk can be reduced through stormwater management measures, such as improvement of urban infiltration, drainage systems, and land use [12,14,15]. Hence, urban stormwater management is an important part of a city's sustainable development.

The history of stormwater management can be traced back to 3000 BC. However, the main research purpose at that time was to drain water as soon as possible and cope with flood threats [16–18]. At the beginning of the 19th century, Germany began to build municipal drainage systems in an organized way for the first time to solve the problem of urban environmental pollution. At the beginning of the 20th century, the United States conducted a unified planning of municipal pipe networks to solve the

pollution problem of open channel drainage caused by industrialization. Japan also faced the same problem of urban pollution and promulgated the Old Sewer Law. In the 1940s to 1980s, the United States successively promulgated and revised the Federal Water Control Act, Clean Water Act, and Water Quality Act and gradually proposed the best management practices (BMPs) for stormwater to handle urban water pollution [19–21]. In the 1990s, the Department of Environmental Resources of Prince George's County, United States, first proposed the concept of low-impact development (LID) to solve the stormwater problem by creating an ecological water landscape. Moreover, Australia began to propose water-sensitive urban design (WSUD) [22–24], which conducts water system management by integrating urban planning and design to improve urban sustainability. After entering the 21st century, the United States began to use the concept of green infrastructure (GI) increasingly. Relative to the LID concept, GI emphasizes the comprehensive application of multiple disciplines to explore stormwater management further [25,26]. Meanwhile, many countries, under the influence of the United States, also conducted a series of explorations on sustainable development technologies and methods of water circulation to manage the difficulties of urban stormwater management. Numerous new concepts were developed, showing a trend of hundred flowers blossoming. To maintain a healthy water cycle in the city, the United Kingdom proposed the concept of sustainable urban drainage system (SUDS) [27–29] and set up its working group. At the beginning of the 21st century, the United Kingdom issued the Interim Code of Practice for Sustainable Drainage Systems in which the management methods and achievements of implementing SUDSs in England and Wales were explained. In the same period, New Zealand also issued a guide for low-impact design after nearly 30 years of research and gradually presented a low-impact urban design and development system. Other designs have also been proposed, such as the depression–infiltration ditch system of Germany, the rainwater storage and infiltration plan of Japan, and the sponge city construction of China [30,31]. Emerging concepts have been presented, such as alternative (compensation technologies), stormwater quality improvement equipment, stormwater control measures, and integrated urban water resource management [25,32–34]. These concepts reflect the innovation and design of technological projects in various countries and promote the rationalization of natural and semi-natural measures to manage urban water cycle. Although technological progresses have been made, further advancement is still needed. For example, China is faced with difficult problems in the construction of the emerging "sponge cities". As China occupies a large area of land across latitudes and longitudes, and the climate is diverse, the natural conditions among cities vary a lot. However, the "sponge city method" currently applied to these cities is only a standardized approach, which is replicated mechanically from one city to another. This is not reasonable because measures need to be adjusted to fit local conditions, and this has resulted in doing less with more. In addition to this, there is a shortage of professional and managerial personnel responsible for the design, construction, and maintenance of Sponge City. Still, the imported green infrastructure products and materials do not match the domestic computer software and cannot be installed in due course, which is also a big issue [35,36]. Currently, problem-solving simply by engineering technology is changing to problem-solving by a combination of engineering and non-engineering technologies in the field [37,38]. The concept of sustainable urban water management was promoted by the Swedish Foundation for Strategic Environmental Research in 1999. With its promotion as an example, most of the obstacles faced by many government-funded capacity-building programs in the promotion process are mainly institutionally embedded and systematic and related to law, supervision, finance, the capacity of grass-roots institutions and organizations, and external rules. In a comprehensive view, they are socially institutional rather than technical [39–43]. Meanwhile, an increasing number of scholars in many countries call on the public and nongovernmental actors to participate in stormwater management due to the decentralization trend of flood risk management [44]. Therefore, the combination of technical and social factors is a development trend in the stormwater management field [45–48].

In the past few decades, a large number of papers and scholars have emerged in the stormwater management field, which is developing vigorously. Stormwater management has then started to be

widely applied in many fields, such as environmental science, civil engineering, water resources, urban planning, and meteorological remote sensing. Additional attention is also paid to the realization of ecological value and other benefits of water-receiving areas [49,50]. Currently, although there are a large number of literatures and systematic review articles in the field, there are few studies that analyze the development of the entire stormwater management field from the perspective of literature review. At present, there are some review articles in the field of stormwater management, which can be mainly divided into the following categories. The first category is the review of relevant technologies and concepts in the field of stormwater management. For example, the article by Fletcher, Tim D et al., "SUDS, LID, BMPs, WSUD, and more—The evolution and application of terminology surrounding urban drainage", summarizes the terminology of stormwater management measures worldwide from the perspective of term interpretation, and it documents the history, scope, application, and underlying principles of these terms. However, this article does not provide any summary or prediction to the development of the entire field. The second category is the summary of urban-related stormwater management. For example, "Streams in the urban landscape" by Paul, MJ and Meyer, JL, which explores the impact of urban changes on the streams of the city, is also an overview of a branch of the stormwater management field, but does not cover the development of the entire stormwater management field. The third category includes review articles focusing on the impact of biological and chemical aspects on stormwater management. It is not difficult to see that these review articles are reviews of a certain part of the stormwater management field. In addition, few of these articles combine visualization software with literature review to study the development of stormwater management. Our article aims to study the development of the entire stormwater management field, and to present a clearer and more intuitive research and development process for readers combined with visualization software. For instance, which country and institute are the most active ones and have made outstanding contributions to stormwater management? What will be the research focus and emerging topics of the field in the future? Who are the most influential authors? These studies are helpful in gaining a further comprehensive insight into stormwater management and grasping the major development trend of the field. They can provide the theoretical focus and research frontier of the stormwater management field to researchers and thus become valuable reference. Therefore, to grasp the current research focus and status quo and determine the development trend and dynamic direction from thousands of articles, we must analyze the literature with scientific bibliometric visualization tools to obtain a macro-overview of the research in the current field.

With information development and technology improvement, many visualization tools have emerged in recent years, such as VOSviewer, CoPalRed, BibExcel, Sci2, VantagePoint, and CiteSpace [51–53]. These tools can integrate information in the field. However, in CiteSpace, users can directly use the data downloaded from the Web of Science (WOS) database and extract information on the basis of time slices. The co-occurrence network can simultaneously represent time, frequency, and betweenness centrality. Cluster view can mark clusters with phrases extracted from titles, keywords, or abstracts. In comparison with VOSviewer and SCi2, CiteSpace can provide further analysis and complete illustrations, including network betweenness centrality [54,55]. For example, Guo et al. used CiteSpace to analyze the knowledge structure and emerging trends of the literature in the field of smart cities and systematically evaluated the existing research in the field; they performed a comprehensive overview of the field of smart cities, including an overall analysis of the literature, the main fields studied by smart city researchers, the most influential countries (institutions, sources, and authors), and interesting research directions in smart cities [56]. Liang Wang et al. utilized CiteSpace to analyze the relevant research on urban resilience and identified the countries with major contributions in the field, the current research focus, knowledge system clusters, and new trends [57]. Hence, related studies are already underway in similar fields.

Our research focuses on revealing the changes and information dynamics in the field over the time cycle and the data are from WOS. Hence, we use CiteSpace software, scientific bibliometric methods, and information visualization generation systems to conduct a quantitative analysis on the articles

about stormwater management from 1980 to 2019. We analyze the basic conditions of research in the field, including the distribution by time, countries, institutions, and authors as well as the keywords, citations, and research hotspots. We aim to obtain enlightening conclusions, such as the overview, development stage, and future trend of the field [58].

2. Data and Methods

We use CiteSpace 5.3.R4.8.31.2018(Chaomei Chen, Drexel University, Philadelphia, USA), a software that focuses on analyzing the potential knowledge of the discipline. This citation visualization analysis software is generated in the context of the rapid development of scientometrics and data visualization [58]. In addition to basic literature analysis, CiteSpace can also generate literature co-citation networks, clustering networks, keyword citation burst, and so on to determine the internal structure of the field, knowledge base, research hotspots, and research frontiers in different time periods. This study mainly used CiteSpace to analyze the basic situation of the literature, co-citation network, clustering network, and keyword co-occurrence burst [59–61]. Records exported from the WOS database include the basic information of articles, such as author, title, abstract, keyword, citation, publication journal, organization source, publication year, and release number. The data used in this study were obtained from the WOS core database on 23 July 2019 [62]. After data collection, we imported the data into CiteSpace for information visualization construction [58] and analyzed the overall situation of the literature, the co-citation of the literature, the key clusters of keywords, mutation, and burst. The specific data acquisition and analysis processes are as follows.

2.1. Data Acquisition

We used "topic" search and inputted the keyword "stormwater management" in the WOS core database and obtained a total of 3903 documents. The three main types of documents were articles, reviews, and conference papers. As this study is based on noncomprehensive thematic research papers in the field, only 3197 articles were selected after the screening.

2.2. Data Preprocessing

After the screening of the article type is completed, the website will automatically classify the search results according to the discipline category of the paper. We will screen the 3197 papers in the "discipline category" and select articles that are more relevant to the theme of "stormwater management" according to their disciplines. The following are the discipline keywords we screened.

We screened by checking 35 disciplinary keywords, namely, "environmental science(1635)", "water resources(1578)", "engineering environment(872)", "multidisciplinary geosciences(319)", "ecology(287)", "environmental study(165)", "limnology(114)", "green sustainable science and technology(112)", "urban study(106)", "marine freshwater biology(90)", "regional urban planning(87)", "agricultural engineering(85)", "geology(78)", "meteorology and atmospheric sciences(66)", "architecture(43)", "biodiversity protection(37)", "architectural technology(34)", "soil science(29)", "multidisciplinary sciences(28)", "development research(21)", "oceanography(20)", "plant science(17)", "forestry(15)", "entomology(12)", "agronomy(10)", "horticulture(10)", "microbiology(10)", "zoology(7)", "applied microbiology of biotechnology(6)", "fishery(5)", "engineering oceanography(3)", "evolutionary biology(3)", "management(3)", "agricultural multidisciplinary(2)", and "public management(2)". We obtained 3080 articles. (As some of the articles cover multiple disciplines at the same time, the total number of articles in each discipline is greater than 3080).

After the screening, the final database was formed and a total of 3080 articles were included. The earliest article was entitled "Stormwater runoff control: A model ordinance for meeting local water-quality management needs" published by Maloney F.E. et al. in 1980 [63]. (As some journals will be published online in advance, the data includes articles published online in advance in the WOS database as of 23 July 2019).

3. Research Method

3.1. Literature Overview

3.1.1. Distribution of Literature by Stage

To gain a general view of the research on stormwater management, we sliced the WOS data from 1980 to 23 July 2019, annually and compiled them into a line chart, which reflects the rule that the total number of articles (TP) and the influence of annual articles (H) (by using 1 year as a time slice to analyze the co-citation of articles, the number of citations of the articles mostly cited in the year is represented by h, namely, its influence) change with time [35]. Figure 1 presents the drawn line chart. Since the data for 2019 is not enough for the whole year, the 2019 data is excluded when generating the line chart.

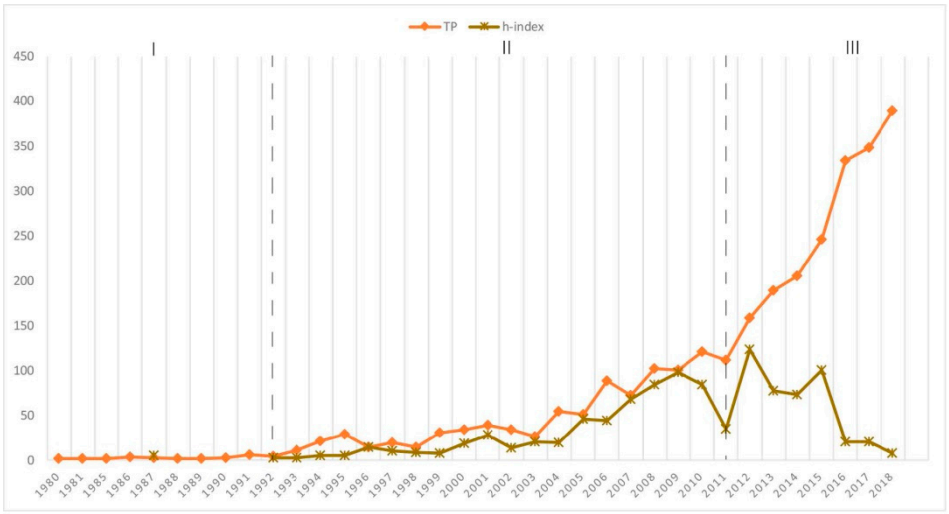


Figure 1. Line chart of TP and H change from 1980 to 2018. (TP value, total number of articles per year; H value, influence of articles per year).

As shown in Figure 1, the TP and H values exhibit an upward trend with the change of the year. In the late stage, the TP value fluctuates less and is more stable than the H value, which fluctuates up and down frequently. The specific details thereof can be divided into the following stages:

Initial development stage (1980–1992): The TP value was relatively small with no evident upward trend. Articles in each year were not more than 5. The H value also showed a stable and low trend, indicating that the worldwide research on stormwater management during this period was at the initial stage. Slow development stage (1992–2011): The TP and H values exhibited an overall upward trend but with small fluctuations in some areas. During this period, scholars continuously published new research articles. The number of articles published each year increased from single digits in 1992 to more than 100 articles in 2011. The influence of articles also increased annually. Hence, the stormwater management field continuously developed, the research deepened, and new hotspots were emerging.

Rapid development stage (2011 to present): The TP value line continued to climb steeply, and the number of articles substantially increased from more than 100 articles in 2011 to more than 300 articles in 2018. Thus, the scope of influence of stormwater management continued to expand, researchers continued to emerge, and the field entered a stage of vigorous development. However, the H value fluctuated up and down, which may be related to the lack of influence of published articles. Early articles are often cited more frequently and have a greater influence than newly published articles. The high volatility also proves the rapid development in the stormwater management field.

In general, the stormwater management field is at a vigorous development stage. At present, new research hotspots will emerge continuously and the number of researchers will increase continuously.

3.1.2. Distribution of Literature by Country

We counted the relevant data of the first 30 countries to determine the distribution of stormwater management by country. Table 1 shows the results. The United States ranks first with 1418 articles on stormwater management, accounting for 41.82% of the total number; it has a high centrality and is a pioneer in the field [64]. Australia ranks second with 396 articles and China ranks third with 262 articles, accounting for 11.68% and 7.73% of the total number, respectively. The number of articles published by these top three countries (United States, Australia, and China) accounts for 67.40% of the total articles in the field, indicating that they occupy a dominant research position in the field. Canada ranks fourth with 253 published articles (7.46% of the total number) and has also made significant contributions to the research in the field [65].

Table 1. Top 10 countries/areas with the most published documents.

No.	Country	Counts	Year	Percentage	Sigma
1	USA	1418	1987	41.82%	8.89
2	AUSTRALIA	396	1997	11.68%	1
3	CHINA	262	2008	7.73%	1
4	CANADA	253	1991	7.46%	236.06
5	ENGLAND	118	2000	3.48%	1
6	SOUTH KOREA	115	2005	3.39%	1
7	FRANCE	100	1997	2.95%	1
8	GERMANY	79	1997	2.33%	3.94
9	SWEDEN	64	2001	1.89%	1
10	ITALY	49	2009	1.45%	1

3.1.3. Institutions, Discipline, and Author of the Literature

In addition to the spatial and temporal distribution of literature, we also organized other relevant information about the literature, including quantity summary, active organizations, subject areas to which the literature belongs, active authors, and organizations that often publish the literature, as shown in Table 2.

Table 2. Number of documents, institutions, disciplines, and publications.

Theme	Results
Year of study	(1) 10 (0.3%) documents from 1980 to 1989, (2) 150 (4.8%) documents from 1990 to 1999, (3) 600 (19.4%) documents from 2000 to 2009, and (4) 2320 (75.3%) documents from 2010 to 2019
Category	The top 10 categories are as follows: Environmental sciences and ecology (1803), environmental sciences (1628), water resources (1563), engineering (1357), environmental engineering (865), civil engineering (514), multidisciplinary geosciences (316), geology (316), ecology (279), and marine and freshwater biology (182).
Active authors	(1) The distribution of researchers is scattered. (2) The top 10 authors who published the largest number of articles are as follows: Fletcher TD (57), Hunt WF (45), Deletic A (41), Marsalek J (33), Walsh CJ (29), Viklander M (27), Kim LH (24), Chang NB (23), Stenstrom MK (19), and Goonetilleke A (18).
Active institution	The co-work relationship between institutions is not close. The top 10 institutions are as follows: Monash Univ (116), US EPA (83), Univ Melbourne (72), Univ Maryland (58), Univ Florida (53), N Carolina State Univ (38), Univ Calif Davis (36), Chinese Acad Sci (35), Univ Guelph (34), and Lulea Univ Technol (30).
Journals	Important journals of stormwater management studies include *Water SCIT* (1484), *Water RES* (1266), *JH* (1184), *J EM* (952), *Sci TE* (948), *J AMWRAS* (877), *Environ SCIT* (795), *Water RRES* (765), *Ecol ENG* (752), and *J EE* (740).

After analysis, we obtained the general information of articles in the past 30 years from 1980 to 2019. The quality and quantity of literature in this field are increasing. European and American countries played an important role in the academic study in early years, as shown in the figure. According to statistics, the proportion of articles published from 2010 to 2019 was 75.3%, indicating that the stormwater management field showed a trend of vigorous development at this stage. The field is involved in various disciplines, such as environmental science and biology, water resources, engineering environment, and civil engineering. The authors with outstanding performance in publishing documents are Fletcher TD (57 articles), Hunt WF (45 articles), Deletic A (41 articles), Marsalek J (33 articles), and Walsh CJ (29 articles). Their untiring efforts have contributed to the continuous advancement of stormwater management research. The following organizations or institutions have made significant contributions to the research of the entire field: Monash University (116 articles), U.S. Environmental Protection Agency (83 articles), University of Melbourne (72 articles), University of Maryland (58 articles), and University of Florida (53 articles). However, the cooperation among the organizations is weak and no evident cooperation network is observed. The organizations that often publish periodicals related to stormwater management include Water Science and Technology (1484 papers), Water Research (1266 papers), Journal of Human Resource and Sustainability (1184 papers), Journal of Empirical Medicine (952), and SCI TE (948 papers).

3.2. *Analysis of the Literature Research Focus*

3.2.1. Co-Citation Analysis of Literature

By analyzing highly co-cited articles, we obtained the schematic of literature co-citation, as shown in Figure 2. Co-citation of references refers to the phenomenon that two references are cited by the same document. CiteSpace's literature co-citation analysis function reveals the knowledge structure of a research field by analyzing the clustering and key nodes in the co-citation network [57]. In CiteSpace, each year is set as a time zone, and reference is selected as the cited document for node type. The thresholds of the front, middle, and back time zones are set to 2, 3, and 15; 3, 3, and 20; and 3, 3, and 20, respectively. Pathfinder, pruning the merged network and pruning the sliced networks are selected in pruning, and the first 50 bits of data in each time slice are extracted to generate the visual network views of cited articles [58,66,67]. Figure 2 shows the highly cited articles in the stormwater management field and the relationship network among them. The size of the circle represents the citation frequency, and the lines between the circles represent the cooperative relationship between them. The relationship network is in the form of global concentration and local dispersion. Citespace also ranks the frequently cited papers when generating Figure 2, and Table 3 is what we exported from the ranking. Table 3 shows the relevant information of the 10 most cited citations. They correspond to the big red dots in Figure 2. The combination of image and the table representation enables the researcher to identify relevant information more clearly, such as the influential factors in the field, the title of the article, the name of the publishing institution, the author, the year, and the number of times of citations. It also allows the intuitive display of the amount of citations.

Table 3. Top 10 frequently co-cited documents in stormwater management.

No.	Title	Journal	Authors	Year	Citations
1	Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform	*Landscape and Urban Planning*	Matthew J. Burns, Tim D. Fletcher, Christopher J. Walsh, Anthony R. Ladson, Belinda E. Hatt	2012	123
2	Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research	*Water, Air, and Soil Pollution*	Laurent M. Ahiablame, Bernard A. Engel, Indrajeet Chaubey	2012	100
3	SUDS, LID, BMPs, WSUD and more—The evolution and application of terminology surrounding urban drainage	*Urban Water Journal*	Tim D. Fletcher, William Shuster, William F. Hunt, Richard Ashley, David Butler, Scott Arthur	2015	100
4	Bioretention Technology: Overview of Current Practice and Future Needs	*Journal of Environmental Engineering*	Allen P. Davis, William F. Hunt, Robert G. Traver, Michael Clar	2009	98
5	Green roof performance towards management of runoff water quantity and quality: A review	*Ecological Engineering*	Justyna Czemiel Berndtsson	2010	84
6	Impediments and Solutions to Sustainable, Watershed-scale Urban Stormwater Management: Lessons from Australia and the United States	*Environmental Management*	Allison H. Roy, Seth J. Wenger, Tim D. Fletcher, Christopher J. Walsh, Anthony R. Ladson, William D. Shuster, Hale W. Thurston, Rebekah R. Brown	2008	84
7	Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art	*Advances in Water Resources*	T.D. Fletcher, H. Andrieu, P. Hamel	2013	77
8	A watershed-scale design optimization model of BMPs for stormwater	*Environmental Modelling and Software*	Joong Gwang Lee, Ariamalar Selvakumar, Khalid Alvi, John Riverson, Jenny X. Zhen, Leslie Shoemaker, Fu-hsiung Lai	2012	74
9	Impacts of impervious surface on watershed hydrology: A review	*Urban Water Journal*	W. D. Shuster, J. Bonta, H. Thurston, E. Warnemuende, D. R. Smith	2005	73
10	Key issues for sustainable urban stormwater management	*Water Research*	A.E. Barbosa, J.N. Fernandes, L.M. David	2012	70

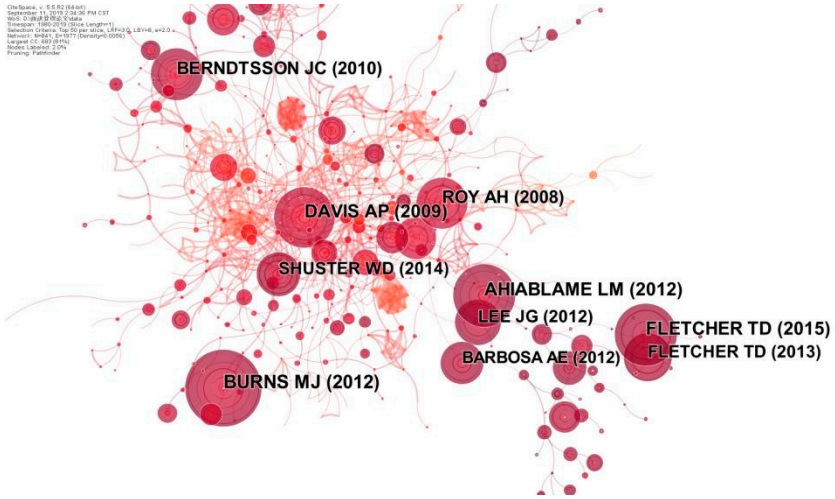


Figure 2. Co-citation of literature.

Among the 10 articles, "Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform" published by Matthew J. Burns et al. in Landscape and Urban Planning in 2012 ranks first in citation frequency. As of 23 July, 2019, this article has been cited 123 times. In this article, a new flow regime management for modern cities is proposed by comparing two conventional urban stormwater management methods [68]. Two articles rank second with a citation frequency of 100. One article is "Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research" published by Laurent M. Ahiablame et al. in Water, Air, and Soil Pollution in 2012. This article proves the helpful use of LID through numerous experiments and provides new insights to researchers [69]. The other article is "SUDS, LID, BMPs, WSUD and more—The evolution and application of terminology surrounding urban drainage" published by Tim D. Fletcher et al. in Urban Water Journal in 2013. This article is a summary classic in the field and explains the history, scope, application, and basic understanding of SUDS, LID, BMPs, WSUD, and other terminologies in detail, greatly facilitating the academic exchanges among regions [33]. The article entitled "Bioretention Technology: Overview of Current Practice and Future Needs" published by Allen P. Davis et al. in the Journal of Environmental Engineering in 2009 ranks third. This article introduces the role of current biological retention technology in controlling and managing water pollutants in a detailed manner and explains the future research direction and needs [70]. In general, the research topics of these four highly cited papers, except for the third one, are the summary of the terminology and all outstanding parts in the stormwater management field. Hence, a large-scale summary research has not yet begun, all research points in the field remain continuously updated, and the existing research results have been widely recognized by emerging researchers.

3.2.2. Citation Burst Analysis

Figure 3 presents a sudden detection analysis of cited articles to explore the literature with significant contributions in the field. We selected 25 citations with the strongest sudden burst in the results and generated Figure 3 on the basis of the burst intensity of citations. The horizontal red bar indicates the duration of the citation burst. References with strong values in the column of intensity values are often important research documents in this field [71].

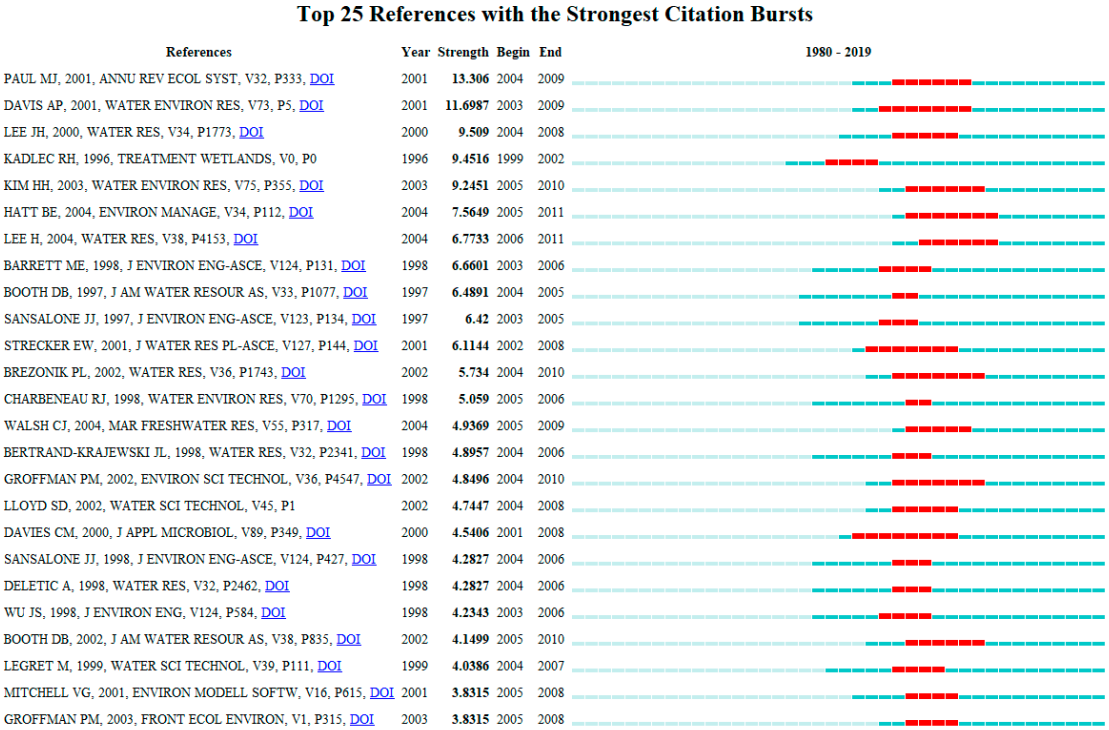


Figure 3. Top 25 citations with strong citation burst.

As shown in Figure 3, the earliest burst started in 1999 and the latest burst started in 2005. The strongest citation burst is related to the article entitled "Streams in the urban landscape" published by Paul MJ et al. in the Annual Review of Ecology, Evolution, and Systematics in 2001 [72]. This article focuses on the impact of urbanization on river hydro-geomorphology, river pollution, river ecology, etc. The authors believe that the increase in impervious surface coverage in urban catchments will change the hydro-geomorphology of the rivers, while the pollution from industrial discharge will affect the diversity of river ecosystems. The burst began in 2004 and continued until 2009, indicating that during this period, researchers paid close attention to the water environment problems brought about by urbanization. At the same time, it also implied that similar problems already appeared in the current urbanization, which attracted the attention of researchers. The article with the second strongest citation burst is "Laboratory Study of Biological Retention for Urban Stormwater Management" published by Davis AP et al. in the Water Environment Federation in 2001 [73]. The burst started in 2003 and continued up to 2009. This article analyzes several heavy metals and pollutants in urban rainfall runoff in detail, and its overall findings support the best practice of using biological retention as stormwater management. The article with the third strongest burst is "Characterization of urban stormwater runoff" published by Jun Ho Lee et al. in Water Research in 2000 [74]. The burst started in 2004 and continued up to 2009. This article expounds the relationship between urban rainfall runoff and pollutant concentration. Together with the article with the second strongest burst, this literature demonstrates that researchers in this period paid close attention to the pollution caused by urbanization and actively sought for optimal solutions. From the temporal perspective, the first 25 articles with strong bursts were cited over the period 1999–2011, and each article was not strongly cited for more than 3–7 years. This case occurred because of the research literature update in the field. However, no strong citation is observed in the field in the past 10 years. This result indicates that numerous researchers have jointly proposed stormwater management studies from different angles due to the vigorous development of the field in recent 10 years, leading to rare occurrence of strong citation burst and research results with great influence.

3.2.3. Citation Clustering Analysis

For classifying and summarizing the articles, we use CiteSpace to perform clustering analysis and classify the articles into clusters due to the large number of citations and complicated cross-citation relationship. The automatic clustering label view is based on the default view, which generates knowledge clustering via spectral clustering algorithm and then extracts label words from the relevant citing literature in the citation cluster to represent the corresponding research. Finally, a citation clustering analysis chart is formed, as shown in Figure 4. Each polygonal box represents a cluster with the same theme. The clustering keywords are generated by extracting the high frequency words that appear most frequently in this cluster. When Citespace performs clustering analysis, the computer automatically calculates an S value for each cluster. It is used to measure the network homogeneity. The closer it is to 1, the higher the homogeneity within the cluster is, and the more nodes there are. More nodes indicate that there are not only one or several articles in this cluster. The higher the homogeneity is, the stronger the correlation and aggregation within the cluster are. The S values of the 18 clusters we obtained are close to 1, indicating that the clusters obtained are classified appropriately and have high correlation [58].

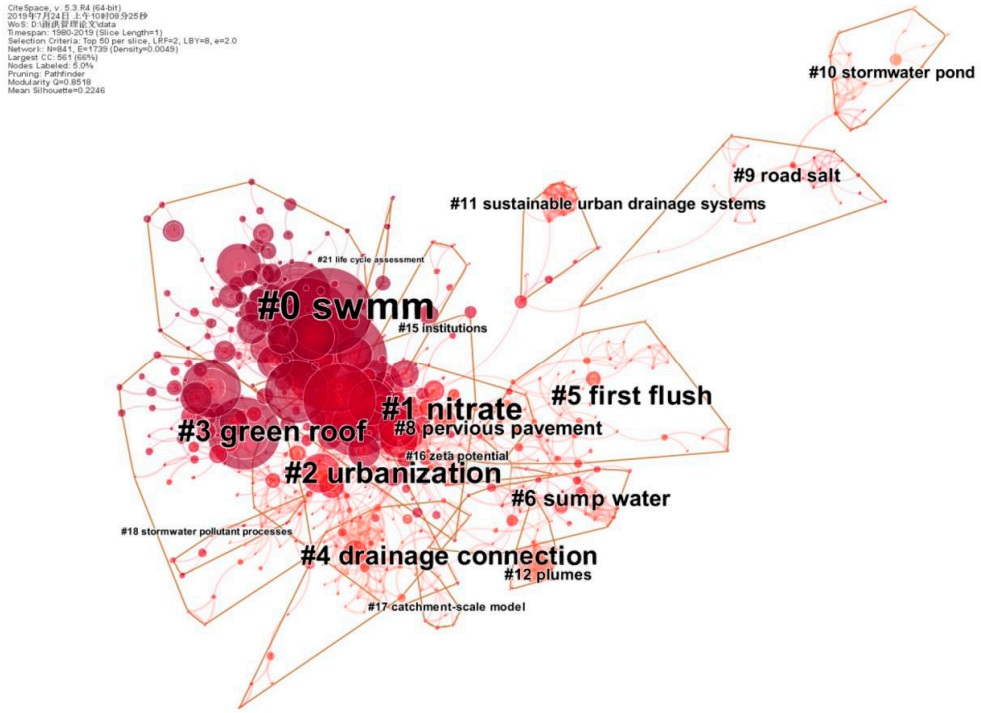


Figure 4. Clustering analysis of articles.

As shown in Figure 4, the theme of the largest literature cluster is stormwater management. A total of 100 articles in the cluster specifically focus on stormwater management with S of 0.881. The high-frequency terms used in this cluster include "cost–benefit assessment", "sensitivity analysis", and "different rainfall conditions".

The theme of the second largest cluster is nitric acid, which is related to water pollution. A total of 66 articles in the cluster have S of 0.739. The high-frequency terms used in this cluster include "rainwater", "heavy metal", "urban rainwater quality", "functional filter media", and "metal." This result shows that the water pollution problem is frequently mentioned in the entire field, and articles and detailed studies on pollutants, especially metal pollution, are also available [75].

The theme of the third largest cluster is urbanization with 60 articles and S of 0.834. The high-frequency terms used in this cluster include "stormwater management", "rainfall runoff", "urban flow syndrome", and "structure of urban pipeline network." The relationship between

urbanization and stormwater management has always been close. The purpose of solving the problems of drainage system, seepage control area, and water pollution during urbanization is one of the main reasons leading to the emergence of stormwater management and the driving force for the development of the field [76].

The theme of the fourth largest cluster is green roof with 60 articles and S of 0.91. The high-frequency terms used in this cluster include "green roof", "modeling study", "design of green roof system", and "key problems." Green roof, also known as vegetation-covered, ecological, or natural roof, is a composite layered structure with specific environmental benefits. They can reconstruct the natural water circulation process and reduce the peak flow rate and pollutant concentration, thus implementing stormwater control [77].

The theme of the fifth largest cluster is drainage connection with 47 articles and S of 0.96. The high-frequency terms used in this cluster include "rainwater drainage system", "rainfall runoff control", "suburbanization", and "wet retention pond." Drainage system is an important part of the urban water circulation system; thus, it is often mentioned [12].

In general, the citation clustering shows that the research topics of the field remain related to water pollution, urbanization, and drainage system. Clusters with themes of "green floor", "sump water", and "first flush" have prominent performance and may become major research topics in the future.

3.3. Keyword Analysis

3.3.1. Keyword Connection Network

The keyword co-occurrence analysis function in CiteSpace can analyze the Descriptors (DE) and Identifiers (ID) fields in the document and generate the network view. The generation method is the same as that of the cited literature, but "keyword" is selected in the node type selection. We used such method to obtain the keyword co-occurrence network. On the basis of this network, we summarized keywords to grasp the research frontier that is constantly developing in the field. As shown in Figure 5, the size of the cross corresponding to the keywords in the figure is proportional to the co-occurrence frequency of the keywords, and the lines between the crosses represent the mutual relationship between the keywords. Table 4 lists the top 50 keywords with the highest frequency.

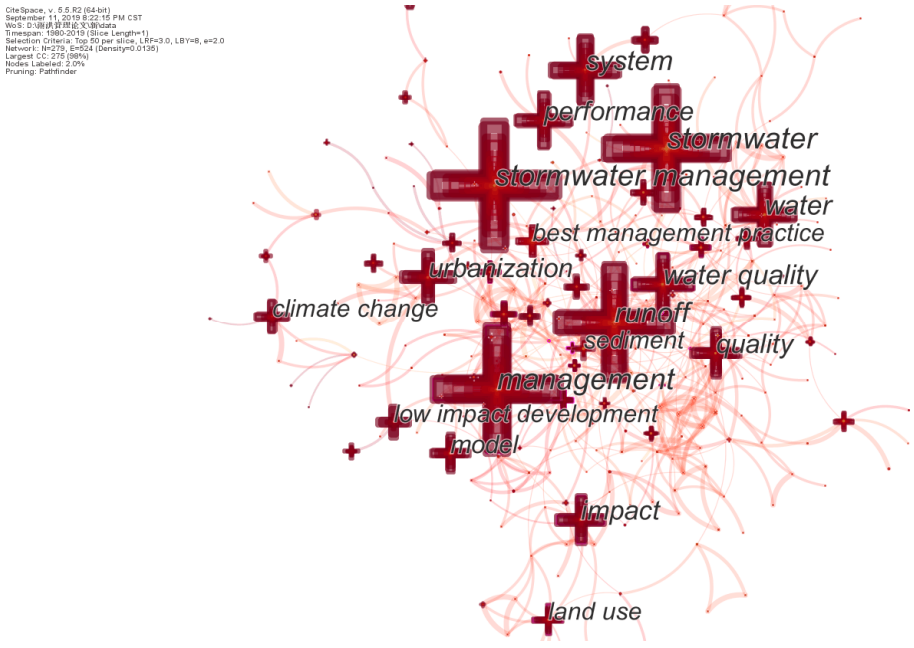


Figure 5. Keyword co-occurrence diagram.

Table 4. Top 50 keywords with their frequencies in stormwater management.

No.	Keywords	Frequency	No.	Keywords	Frequency
1	stormwater management	632	26	design	138
2	stormwater	608	27	removal	138
3	management	571	28	hydrology	129
4	runoff	542	29	phosphorus	125
5	water quality	335	30	catchment	119
6	system	327	31	nitrogen	119
7	water	325	32	retention	113
8	performance	285	33	green roof	111
9	quality	277	34	urban stormwater	105
10	urbanization	267	35	nutrient	101
11	impact	250	36	urban runoff	89
12	model	222	37	stream	88
13	best management practice	191	38	management practice	83
14	low-impact development	184	39	drainage	82
15	climate change	178	40	Stormwater management	82
16	sediment	173	41	area	76
17	land use	170	42	optimization	73
18	stormwater runoff	162	43	constructed wetland	71
19	heavy metal	159	44	city	68
20	bioretention	152	45	flow	66
21	infiltration	146	46	United States	66
22	pollution	143	47	stormwater management	60
23	green infrastructure	141	48	simulation	60
24	urban	140	49	metal	60
25	soil	140	50	restoration	57

On the basis of Figure 5 and Table 4, we preliminarily classified and sorted the 50 keywords as follows:

The first category of keywords, such as "stormwater management (632 occurrences in all articles)", "rainwater (608)", "runoff (542)", "water quality (335)", "infiltration (146)", "hydrology (129)", and "catchment (119 occurrences)", is related to the water environment. These terms are in line with the research priorities in the field. The second category of keywords, such as "urbanization (267)", "climate change (178)", "land use (170)", "urban rainstorm (105)" and "drainage (82 times)", is related to cities. The reason is that the effects of urbanization lead researchers to pay attention to the importance of stormwater management. Solving the stormwater problem during urbanization is the original intention of the field; it runs through the entire research process and is an important part of the research. The third category of keywords, such as "best stormwater management practices (191)", "low-impact development (184)", "green infrastructure (141)", "green roof (111)", and "artificial wetland (71)", is related to terminologies of the field. These terms are stormwater management concepts in the field. They are the optimization schemes proposed by various countries to solve the problem of rainwater management and have exerted influence in the world. The fourth category of keywords, such as "heavy metals (159)", "pollution (146)", "phosphorus (125)", and "metal (49)", is related to water pollution. This category shows that improvement of water pollution has always been a continuous concern in the field [78–80]. The fifth category of keywords includes other relevant terms, such as "management (571)", "removal (138)", and "retention (113). The research of these topics minimally significant.

The clustering shows that the research focus in the field includes urbanization, climate change, land use, and water pollution in addition to specific stormwater management measures, which is in line with the previous conclusions.

3.3.2. Time Zone Chart Analysis of Keywords

The co-occurrence chart of keywords only shows the frequency of keywords and cannot be efficiently combined with the time relationship. Thus, we have drawn the following time zone chart

of keywords. The time zone chart focuses on delineating the relationship between clusters and the historical span of a certain cluster keyword. CiteSpace initially clusters the default view and assigns appropriate labels to each cluster. Then, each node is set at the corresponding position to generate the timeline view on the basis of the cluster to which the node belongs (the vertical axis of coordinates) and the published time (the horizontal axis of coordinates) [81,82]. As the nodes of the same cluster are arranged on the same horizontal line on the basis of time sequence, the documents in each cluster are like strings on a timeline, showing the historical achievements of the cluster. In Figure 6, the horizontal axis represents time, and the vertical axis on the right represents the name of the keyword cluster. We can see the time of occurrence of keywords in different clusters and their relationship through the horizontal analysis. The larger the cross of keywords is, the higher the occurrence frequency of the keywords will be, indicating that such keywords are the hotspots in this period.

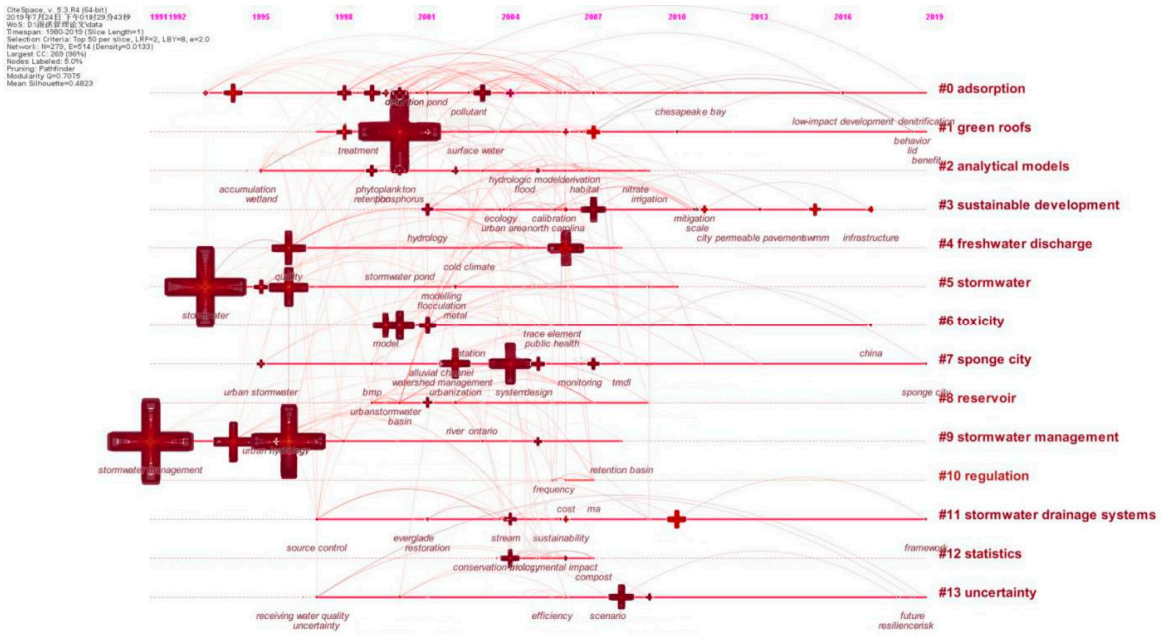


Figure 6. Time zone chart of keywords.

Figure 6 shows a total of 13 timelines. High-frequency keywords appeared mostly before 2007. The clusters in which they appear are as follows: "#2 green roof", "#5 stormwater", and "#9 stormwater management." Cluster "#9 stormwater management" appeared at the earliest time, and the timeline expired around 2008. Cluster "#5 stormwater" appeared only later than cluster 9, but the timeline expired around 2010. This result shows that although the keywords related to two clusters, such as "stormwater management", "management", and "urbanization", have great influence, appeared early, and been frequently mentioned in the early days, their popularity has declined recently [83]. The timeline of cluster "#1 green roof", which has high-frequency keywords, has been running to this day. Hence, research related to green roof is ongoing and still popular. The timelines of clusters "#0 adsorption", "#7 sponge city", "#11 stormwater drainage systems", and "#13 uncertainty" have also been running to this day. Thus, research related to these clusters still needs development. The cluster "#0 adsorption" rose around 2000. Although no high-frequency keywords were observed in the timeline, the cluster ran through the entire research period. The keywords in the cluster are "pollutant", "detention pond", and "low-impact development identification", indicating that water pollution-related research has been ongoing since the emergence of stormwater management.

In addition to the abovementioned clusters with high-frequency keywords, two clusters are also interesting: "#10 regulation" and "#12 statistics." Both clusters rose in a short period of time and then abruptly stopped developing. The cluster "# 10 regulation", wherein the keywords are "frequency" and

"retention basin", started bursting around 2006 but did not appear again after only 1 year. Similarly, the cluster "#12 statistics", wherein the keywords include "mental impact" and "conservation biology", emerged in 2004 but did not appear until around 2007. Hence, the research behind the two clusters may have short-term burst, which will soon end.

3.3.3. Keyword Burst

In addition to the time zone chart of keywords, keyword burst detection can also imply the focus of research on bursts. Therefore, we generated a burst detection diagram of keywords and obtained the top 25 keywords with strong burst. Figure 7 shows their sequence sorted by time wherein the red long bar indicates the start to end time of the burst.

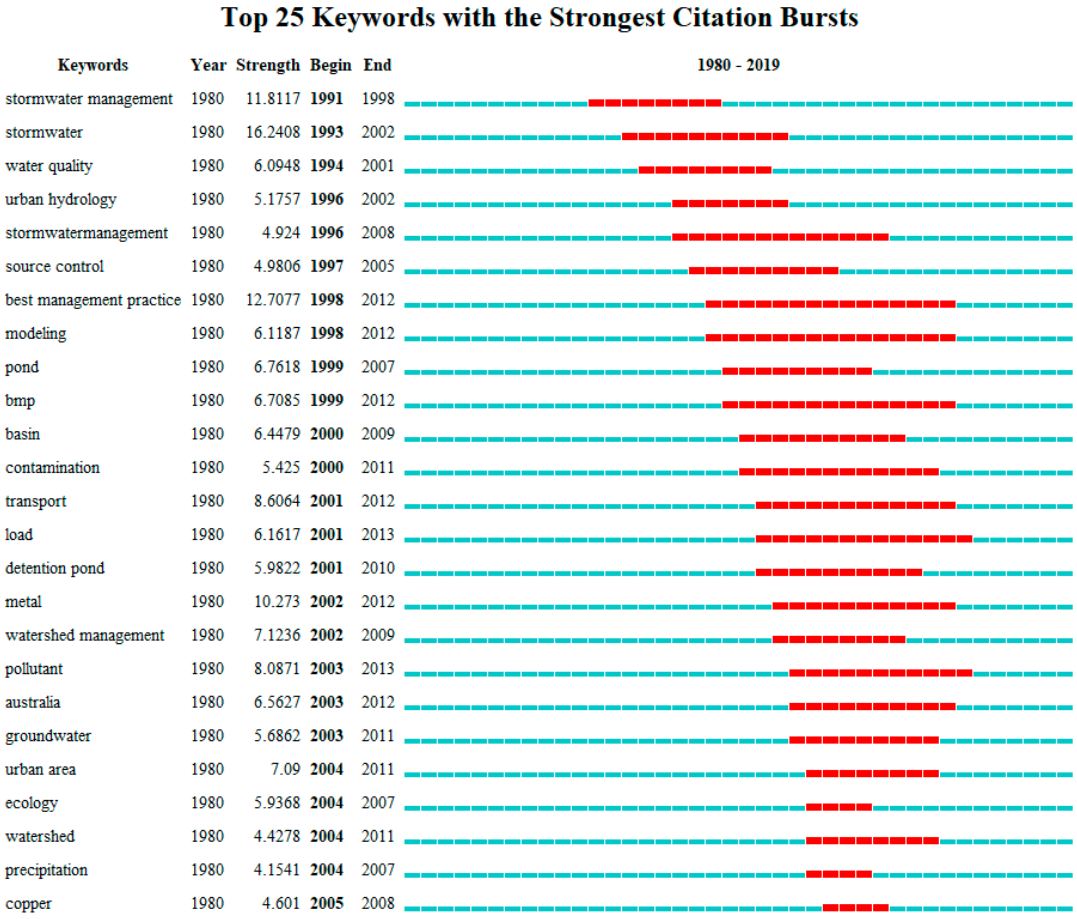


Figure 7. Time sequence of keywords.

Figure 7 shows the top 25 keywords with the strongest burst from 1980 to 2019. The keyword with the earliest burst is "stormwater management" (started in 1991); the keyword with the latest burst is "copper" (started in 2005). The keyword with the longest burst duration is "modeling" (from 1998 to 2012); the keyword with the shortest burst duration is "copper" (from 2005 to 2008). The top 10 keywords with the strongest burst are "stormwater", "best management practice", "stormwater management", "metal", "transport", "pollutant", "watershed management", "urban area", "pond", and "BMP." These terms are all sudden research hotspots. They are related to the research directions of best management, water pollution, and urbanization. Throughout the entire development history, the research keywords of the field since 1991 have gradually changed from water quality, stormwater management, source control, BMPs, and other classical concepts to basin, pollutant, transport, metal, watershed management, ecology, watershed, precipitation, and copper. Correlations among the

keywords are minimal and the burst duration shows an overall trend of continuously shortening, indicating that the research topics change fast, and many research branches are in vigorous development.

4. Summary of Stormwater Management

In conjunction with the time-phased division in Figure 1, we integrated the basic information of the field to intuitively present the basic overview of stormwater management. Table 5 presents the results.

As shown in Table 5, we divided the entire field into three stages on the basis of line chart 1 and explained the specific information of each stage, including the total number of articles, the most active countries and institutions, the articles with the largest influences (most citations), the top five authors with largest influences (i.e., the authors who published articles with most citations), and top 20 keywords. The combination of our research and time phase enables readers to have a comprehensive understanding of the knowledge framework and development process in the stormwater management field during the period of rapid development at present.

Initial development stage (1980–1992): This stage was the initial development stage of stormwater management, with only 22 articles. The most influential countries in this period were USA and Canada. The paper with the most citations was "Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs" published by Thomas R. Schueler in 1987 [83]. The top four authors were Roesner L.A., Huber W.C., Schueler T., and Oberts G.L. After keyword search, only one keyword, that is, stormwater management, was obtained. We did not obtain data on the top three institutions due to the lack of data and the fact that most of the articles are published in the name of individuals. The overall development at this stage was still in its infancy.

Slow development stage (1992–2011): The total number of articles about stormwater management at this stage reached 970, and Australia entered into the matrix of the most influential countries in addition to the USA and Canada. The top three universities were Monash University, the University of Florida, and the University of California, Los Angeles. The paper with the most citations was "Streams in the urban landscape" published by Paul M.J. et al. in the Annual Review of Ecology, Evolution, and Systematics in 2001 [72]. The top five authors were USEPA, Marsalek J, Sansalone J.J., Davis Allen P., and Novotny Vladimir. Notable emerging keywords included runoff, water quality, management, best management practice, sediment, urbanization, infiltration, pollution, phosphorus, heavy metal, and soil. As observed, the research was continuously developing, and the research focuses were mainly on water pollution, water management, BMPs, and urbanization. The research at this stage, compared with the previous stage, had begun to deepen continuously, and new hotspots were emerging continuously.

Rapid development stage (2011 to present): The number of articles at this stage showed a rapid growth. As of 23 July 2019, 2088 articles were published in the WOS core database. The most influential countries changed from the USA, Canada, and Australia at the previous stage to the USA, Australia, and China. Monash University still occupied the first position among the research institutions, whereas the second and third places were taken by Melbourne University and USEPA. The paper with the most citations was "Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform" published by Matthew J. Burns et al. in Landscape and Urban Planning in 2012 [68]. The top five authors were Davis Allen P, Dietz Michael E, Walsh Christopher J, Fletcher Tim D, and Rossman L.A. Notable emerging keywords included climate change, low-impact development, land use, green infrastructure, bioretention, and design. The overall research direction in the field is further specific, with the emergence of fast-growing emerging countries and additional detailed emerging keywords. Thus, research points are emerging continuously in the field at this stage, and many branch studies have entered the blooming stage.

Table 5. Review stage in stormwater management.

	Initial Stage of Development (1980–1992)	**Slow Development Stage (1993–2011)**	**Rapid Development Stage (2012–2019)**
Number of articles	22	970	2088
Top 3 of the most active countries	1. USA 2. Canada	1. USA 2. Australia 3. Canada	1. USA 2. Australia 3. China
Top 3 of the most active institutions		1. Monash Univ 2. Univ Florida 3. Univ Calif Los Angeles	1. Monash Univ 2. Univ Melbourne 3. USEPA
Most influential literature	Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs	Streams in the urban landscape	Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform
Top 5 of the most influential authors	1. Roesner LA 2. Huber WC 3. Schueler T 4. Oberts GL	1. USEPA 2. Marsalek J. 3. Sansalone J.J 4. Davis Allen P. 5. Novotny Vladimir	1. Davis Allen P. 2. Dietz Michael E. 3. Walsh Christopher J. 4. Fletcher Tim D. 5. Rossman L.A.
Top 20 keywords	Stormwater management	1. Stormwater 2. Stormwater management 3. Runoff 4.Water equality 5. Management 6. Best management practice 7. Water 8. Sediment 9. Urbanization 10. System 11. Infiltration 12. Quality 13. Pollution 14. Phosphorus 15. Heavy metal 16. Model 17. Soil 18. Urban 19. Urban runoff 20. Impact	1. Management 2. Stormwater management 3. Stormwater 4. Runoff 5. System 6. Performance 7. Water 8. Water quality 9. Quality 10. Impact 11. Urbanization 12. Model 13. Climate change 14. Low-impact development 15. Land use 16. Green infrastructure 17. Bioretention 18. Stormwater runoff 19. Design 20. Removal

5. Conclusions

Stormwater management is a field under rapid development. Over the past few decades, countries have made unremitting efforts to solve stormwater management problems. In this study, CiteSpace data visualization analysis software is used to analyze the articles on stormwater management in the WOS core database from 1980 to 2019 (as of 23 July 2019). The conclusions are as follows:

(1) Forming the existing knowledge table in the stormwater management field on the basis of the time stage:

As shown in Table 5, table information statistics are conducted in accordance with the research results to form a knowledge table of the stormwater management field. New researchers and readers can obtain basic information of the field on the basis of the table and determine the number of articles, countries, institutions, highly cited documents, influential authors, and keywords at different development stages of the field, providing valuable information and reference for new research.

(2) Revealing the development stages of stormwater management:

The development of the entire field is divided into three stages: initial, slow, and rapid. Currently, the field is at the rapid development stage. The articles published during this period account for 75.3% of the total number of articles. The articles published annually are rapidly increasing and new researchers continuously emerge. The research keywords of the field since 1991 have gradually changed from water quality, stormwater management, source control, best management practices, and other classical concepts to land, pollutant, transport, metal, watershed management, ecology, watershed, precipitation, and copper. Correlations among the keywords are minimal. The burst interval does not last long, and the burst duration shows an overall trend of continuously shortening. Thus, the field enters into the rapid development stage at present, the research topics change fast, new hotspots emerge continuously, and many research branches are in vigorous development.

(3) Predicting the future development direction of stormwater management:

We determine in the research on keyword burst and cluster that various keyword clusters, such as "adsorption", "sponge city", "stormwater drainage systems", and "uncertainty", have been running throughout the time axis since their emergence. Hence, the research related to these clusters still needs development. For instance, the studies on sponge city, water pollution control, green roof, and source control will continue for a period of time in the future.

On the basis of the development status of the stormwater management field, we can infer that the research on the entire field and on internal branches will develop vigorously, expand, and deepen in the future.

(4) Others

Statistics show that the United States played an important role in the research of the field in its early years, and then various countries successively conducted research on stormwater management suitable for them, showing a multi-direction development trend of the field. However, no strong cooperation is observed between institutions and authors. Therefore, the strengthening cooperation among countries, regions, and organizations may bring new development of the stormwater management field.

Finally, although CiteSpace is used to perform a visual quantitative analysis of information in the field, this research can only be regarded as a preliminary work due to the vigorous development of the stormwater management field. As the WOS core database is only used as the foundation, limitations still exist. Future researchers should conduct increasingly in-depth relevant analysis on the basis of data update.

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