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Bibliometric analysis of global performance and trends of research on combined sewer overflows (CSOs) from 1990 to 2022

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ABSTRACT

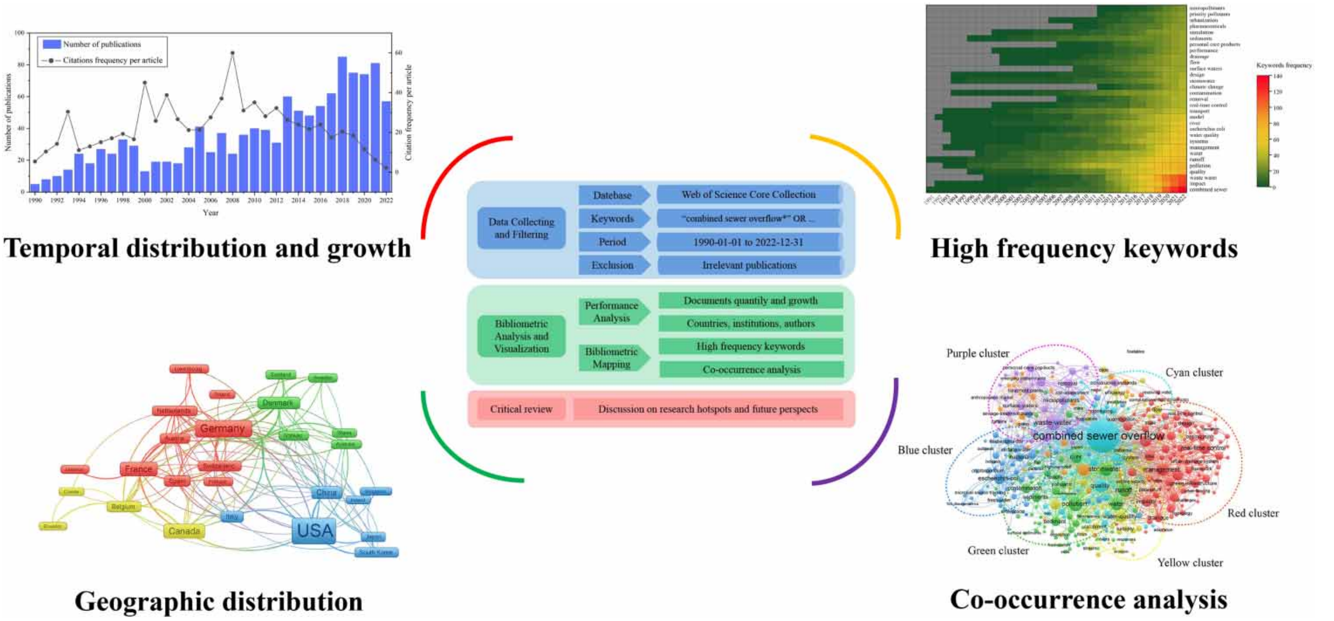
Combined sewer overflows (CSOs) are one of the main sources of pollution in urban water systems and significantly impede the restoration of water body functionalities within urban rivers and lakes. To understand the research and frontier trends of CSOs comprehensively and systematically, a visual statistical analysis of the literature related to CSOs in the Web of Science core database from 1990 to 2022 was conducted using the bibliometric method using HistCite Pro and VOSviewer. The results reveal a total of 1,209 pertinent publications related to CSOs from 1990 to 2022, and the quantity of CSOs-related publications indicated an increasing trend. Investigations of the distribution and fate of typical pollutants in CSOs and their ecological effects on receiving waters and studies on pollution control technologies (source reduction, process control, and end-of-pipe treatment) are the current focus of CSOs research. CSOs pollution control technologies based on source reduction and the monitoring and control of emerging contaminants are at the forefront of scientific investigations on CSOs. This study systematically and comprehensively summarized current research topics and future research directions of CSOs, thus providing a reference for CSOs control and water environment management research.

Key words: bibliometric analysis, combined sewer overflows (CSOs), pipeline, storm runoff, Web of Science Core Collection

HIGHLIGHTS

- Literature on combined sewer overflows is mapped via bibliometrics for the first time.
- A total of 1,209 articles were retrieved from Web of Science and used for analysis.
- The research hotspots can be identified through keyword co-occurrences analysis.
- Research gaps in combined sewer overflows research are successfully identified.
- Technical obstacles and suggestions for further research were studied.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Urban sewer systems can be classified into two main categories: combined sewer system (CSS) and separate sewer system. The CSS is a drainage system that collects domestic sewage, industrial wastewater, and urban runoff in the same channel and transports it to the wastewater treatment plants (WWTPs) (Li *et al.* 2022). Owing to historical circumstances, the majority of cities worldwide still maintain CSS in old urban areas. During periods of rainfall or snowmelt, CSS flow is positively correlated with rainfall intensity. When the flow rate in the pipeline exceeds the discharge capacity of the pipeline system or the treatment capacity of WWTPs, the mixed sewage surplus will be directly discharged into the receiving water body, which is referred to as combined sewer overflows (CSOs) (Brunsch *et al.* 2020). As urbanization intensifies, the current expansion of impermeable surfaces increases the amount of stormwater runoff, causing soil erosion and facilitating the transportation of a significant quantity of pollutants into the urban pipeline network (Baek *et al.* 2015). As urban nonpoint source pollution, CSOs are major contributors to the pollution of urban water environments; thus, the imperative to deal with and manage CSOs pollution has become increasingly pressing.

CSOs are a mixture of sewage and stormwater runoff, which have different properties. In addition, nonpoint source pollution caused by surface runoff scouring the street solid particles and sediments in the pipeline also converge into the CSOs. The diverse pollution sources of CSOs determine the complexity of the CSOs pollution (Peng *et al.* 2017). Controlling CSOs pollution necessitates a thorough understanding of the sources, destinations, discharge regulations, and influencing factors associated with CSOs contaminants. The main contaminants in CSOs include organic matter, nutrients such as nitrogen and phosphorus, suspended matter, heavy metals, pathogenic microorganisms, and other harmful substances (Gooré Bi *et al.* 2015). Furthermore, there is a growing concern about the presence of emerging contaminants (ECs) in CSOs. These ECs such as personal care and pharmaceutical products (PPCPs) (Poopipattana *et al.* 2021), microplastics (MPs)/nanoplastics (Di Nunno *et al.* 2021), antibiotics, and 0 (ARGs) (Eramo *et al.* 2017) are also entering the CSOs through the release of domestic sewage, urban subsurface scouring, and pipeline sediment scouring. CSOs are discontinuous, unstable, and highly polluted, thereby negatively affecting the functions of receiving water bodies, particularly low-flow water bodies, such as rivers (Chen *et al.* 2022). For example, the heavy metals contained in CSOs not only affect the growth and reproduction of aquatic organisms but also transfer and accumulate in aquatic organisms through the food chain, posing a potential risk to human health (Xu *et al.* 2018). Half a century ago, Germany, the USA, Japan, and other countries adopted various technologies to control CSOs through source control, pipeline system management, storage and regulation, and end-of-pipe treatment and developed various corresponding design specifications and standards. The increasingly prominent problem of CSOs and their ecological effects have become the focal points of current research in the field of environmental science.

Recently, researchers worldwide have conducted extensive research on pollution characteristics, pollution control technologies, ecological and environmental impacts, management technologies, and policies for CSOs (Table 1). Consequently, the number of research and review articles published related to CSOs has shown notable growth in recent years. These reviews provide an overview of the progress of monitoring (Vicory Jr & Tennant 1994; Weyand 1996), control

Table 1 | The main reviews on CSOs research

Title	Journal	Year	Citations
Urban wet-weather flows	*Water Environment Research*	1997	276
Current and future approaches to wet weather flow management: A review	*Water Environment Research*	2021	156
Combined sewer overflows: A critical review on best practice and innovative solutions to mitigate impacts on environment and human health	*Critical Reviews in Environmental Science and Technology*	2021	119
A review of combined sewer overflows as a source of wastewater-derived emerging contaminants in the environment and their management	*Environmental Science and Pollution Research*	2021	94
Constructed wetlands for combined sewer over flow treatment: A state-of-the-art review	*Science of the Total Environment*	2020	92
Constructed wetlands for treatment of combined sewer overflow in the US: A review of design challenges and application status	*Water*	2014	34
Challenges of combined sewer overflow disinfection by ultraviolet light irradiation	*Critical Reviews in Environmental Science and Technology*	2001	33
Separate and combined sewer systems: a long-term modelling approach	*Water Science and Technology*	2009	28
Performance of ozone as a disinfectant for combined sewer overflow	*Critical Reviews in Environmental Science and Technology*	2001	26
Optimisation potential for a SBR plant based upon integrated modelling for dry and wet weather conditions	*Water Science and Technology*	2009	17
The role of computer modeling in combined sewer overflow abatement planning	*Water Science and Technology*	1992	12
Modelling of biofilters for ammonium reduction in combined sewer overflow	*Water Science and Technology*	2009	12
Influence and modelling of urban runoff on the peak flows in rivers	*Water Science and Technology*	2009	10
Experience with vortex separators for combined sewer overflow control	*Water Science and Technology*	1993	9
The impact of rainwater reuse on CSO emissions	*Water Science and Technology*	1999	8
The influence of system-specific properties on the pollutant discharge of combined sewer systems	*Water Science and Technology*	1993	7
Process design of advanced storage-treatment facilities for CSO control	*Water Science and Technology*	1994	6
Evaluation of the water quality effects of combined sewer overflow (CSO) control measures	*Water Science and Technology*	1993	5
A strategy for monitoring the impacts of combined sewer overflows on the Ohio River	*Water Science and Technology*	1994	5
Smart management of combined sewer overflows: From an ancient technology to artificial intelligence	*Wiley Interdisciplinary Reviews: Water*	2023	4
Reduction of combined sewer overflow quality by application of the coagulation process	*Water Science and Technology*	1993	3
Monitoring runoff conditions in a combined sewer system: Experience and results of ten years' application	*Water Science and Technology*	1996	3
Reducing particle accumulation in sewers for mitigation of combined sewer overflow impacts on urban rivers: A critical review of particles in sewer sediments	*Water Science and Technology*	2024	0
Policies on combined sewer overflows pollution control: A global perspective to inspire China and less developed countries	*Critical Reviews in Environmental Science and Technology*	2023	0
A state-of-the-art review for the prediction of overflow in urban sewer systems	*Journal of Cleaner Production*	2023	0

technology (Weyand *et al.* 1993; Rönner-Holm *et al.* 2009; Tao *et al.* 2014), management technology (Peters & Zitomer 2021; Saddiqi *et al.* 2023), model prediction and evaluation (Roesner & Burgess 1992; Ma *et al.* 2023), disinfection (Wojtenko *et al.* 2001a, 2001b), and policies of CSOs (Wang *et al.* 2023). For example, Rizzo *et al.* (2020) reviewed constructed wetlands as a treatment method for CSOs and evaluated the performance of conventional water quality indicators, the removal of pathogens and ECs, and the effects of design and operating parameters on the overall removal performance of constructed wetlands. Petrie (2021) reviewed the impact of CSOs discharges on the concentrations of ECs in the environment and the treatment strategies for ECs in CSOs. Saddiqi *et al.* (2023) reviewed the application of technologies such as artificial intelligence, geographic information systems (GIS), and remote sensing in the management of CSOs. While these reviews summarized the research progress of various topics in CSOs, they do not offer a comprehensive analysis of the fundamental characteristics and challenges that encompass the research field of CSOs at a macroscopic level.

Bibliometrics is an academic methodology that relies on observable attributes of the studies. It employs statistical and mathematical methods to quantify these characteristics, including the quantitative relationships between the literature and the citations and co-citations, and depicts the current status and development trends of research in a specific field of study (Wang *et al.* 2021c). In contrast to conventional reviews that provide a comprehensive overview of the current state of research, bibliometrics focuses on prospective research directions and emerging trends in the research topic. Bibliometrics is now widely used in various research areas, such as bioretention facilities (Liu *et al.* 2023), sponge cities (Zha *et al.* 2021), stormwater management (Wu *et al.* 2019), and low-impact development (LID) facilities (Islam *et al.* 2021). The application of bibliometrics as an analysis method for CSOs studies has not yet been reported.

Considering the extensive body of literature pertaining to CSOs studies, the application of bibliometric methods to provide visual representations reflects the current status and development of the CSOs studies. In this study, based on bibliometric methods, we used the visual analysis software CiteSpace to review and visualize the current status of the research on CSOs through data mining, quantitative analysis, qualitative evaluation, time series analysis, and cluster statistical analysis. This paper presents a scientometric analysis of studies on CSOs and provides a useful reference for academics, researchers, and policymakers.

2. DATA AND METHODS

2.1. Data collection

The existing Web of Science Core Collection (WOSCC) database (Thomson Reuters, USA) contains information regarding scientific content, impact, and collaboration for the most important and influential research literature and is recognized as one of the most comprehensive literature search platforms worldwide (Li *et al.* 2018). The search period for this study was from January 1, 1990, to December 31, 2022, and the search date was June 20, 2023, with 'subject' = 'combined sewer overflow*' or 'combined system overflow*' and 'Document type' = 'article'. The WOSCC database contained 1,208 publications for the period between 1990 and 2022. Keywords with similar meanings were combined into a single keyword, such as 'combined sewer overflow' which stands for 'combined system overflow,' 'combined sewer overflow,' and 'combined sewer overflows (CSOs)'.

2.2. Data analysis

Data from this study were processed and visualized using HistCite Pro, VOSviewer, and Origin 2018 software to summarize the global trends and development direction predictions for CSOs studies included in the WOSCC database for 33 years (from 1990 to 2022). The outputs included the number of publications, countries of publication, countries (regions), institutions, journals, author groups, and keywords.

HistCite Pro is a literature index analysis software that facilitates researchers in rapidly identifying the characteristics of literature (Garfield 2009). VOSviewer is a tool for building and visualizing a network of literature metrics based on citations, co-citations, or co-author relationships (Van Eck & Waltman 2010). The journal impact factor (IF) analysis for the estimation of the impacts of the journals was conducted using the ISI's Journal Citation Report (JCR) (Yang & Zhang 2013).

3. RESULTS

3.1. Temporal distribution of scientific production

The number of academic articles published over time is an indicator of the level of activity in a particular research field, the pace of advancement in related fields and disciplines, and the level of interest exhibited by researchers (Koelmel *et al.* 2015). The statistics of the literature related to CSOs research from 1990 to 2022 are shown in Figure 1. Over the past 33 years, the number of publications increased from 5 in 1990 to 57 in 2022. Based on the observed growth pattern of published journal articles, the published journal articles can be divided into three stages. The first stage (1990–1999), which was the initial research stage for CSOs, had a low annual average of approximately 20 publications and predominantly concentrated on the pollution characteristics of CSOs and their impacts on the water quality of receiving water bodies. The second stage (2000–2012) had an annual average of 29 publications, indicating that research on CSOs slightly increased. Research on CSOs pollution has shifted from organic matter and heavy metals to pathogenic microorganisms and ECs. Additionally, researchers have investigated the efficiency of multiple end-of-pipe treatment techniques in mitigating the impact of CSOs. In the third stage (2013–2022), research on CSOs experienced substantial growth, characterized by an average annual publication rate of approximately 64 articles. Significant advancements in research content and methodologies have led to an abrupt increase in research output. The advancements in computer technology and artificial intelligence have facilitated the simulation of water quality and quantity pertaining to CSOs through models, and these simulations serve as essential tools for the management and regulation of CSOs. Research has begun to focus on the impact of pipeline sediment flushing on CSOs and the mitigation of CSOs pollution through source control methods such as rain gardens and bioretention systems. With the rapid increase in urbanization, scholars worldwide have conducted considerable research on CSOs while attracting more scholars to focus on this field; thus, a steady increase in the number of publications has been observed recently.

3.2. Contributing countries and institution analysis

The WOSCC database retrieved publications on CSOs from 87 countries/regions. Based on the empirical data presented in Table 2, it is apparent that, apart from China and South Korea, the other eight countries of the ten leading countries/regions in terms of publications for the period between 1990 and 2022 were predominantly European and North American regions. This indicates that scholarly research on CSOs was predominantly conducted in economically advanced countries and regions, specifically Europe and the USA. Due to the European Urban Wastewater Treatment Directive and its revision in the European Union (EU), many countries in the EU have researched on the pollution of receiving water bodies caused by CSOs, formulated design regulations and standards for pollution control technology of CSOs, and applied them to production. After long-term development, relative systems have been formed, such as best management practice, LID, and sustainable drainage system. The USA had the highest number of articles (293 articles), followed by Germany and the UK. The USA demonstrated a larger contribution to scientific research in this field, as evidenced by the number of articles

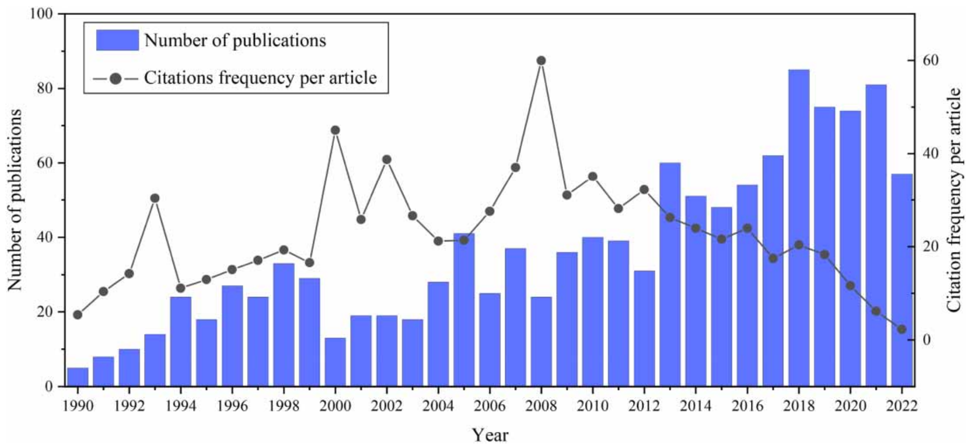


Figure 1 | Quantity of publications on CSOs studies per year from January 1990 to December 2022.

Table 2 | Number of publications on CSOs by top 10 countries/regions from January 1990 to December 2022

Country	Articles						
	No.	%	SCP	MCP	MCP_Ratio	Total citation frequency	Citation frequency per article
USA	293	24.25	263	30	10.24	8,251	28.16
Germany	121	10.02	93	28	23.14	2,405	19.88
UK	111	9.19	90	21	18.92	2,175	19.59
Canada	99	8.20	75	24	24.24	1,938	19.58
France	84	6.95	57	27	32.14	1,892	22.52
China	68	5.63	48	20	29.41	1,212	17.82
Denmark	58	4.80	42	16	27.59	956	16.48
Italy	48	3.97	31	17	35.42	876	18.25
Spain	36	2.98	25	11	30.56	827	22.97
South Korea	35	2.90	27	8	22.86	725	20.71

SCP: intra-country cooperation index, MCP: intercountry cooperation index.

published by the USA (2.42 times and 2.64 times higher than that by Germany and the UK, respectively). Moreover, the total citation frequency (refers to the cumulative number of times a paper has been cited by other academic articles) of publications in the USA was 8,251, with an average citation frequency per article of 28.16. This observation indicates that the USA allocated more resources and effort to scientific research, resulting in more productive scientific research outcomes. The other top 10 countries/regions, in descending order, are as follows: the USA (293, 24.25%), Germany (121, 10.02%), the UK (111, 9.19%), Canada (99, 8.20%), France (84, 6.95%), China (68, 5.63%), Denmark (58, 4.80%), Italy (48, 3.97%), Spain (36, 2.98%), and South Korea (35, 2.90%). The number of lines connecting different countries/regions indicates the extent of collaboration between them. Collaborative publications between countries/regions were visualized using the VOSviewer software (Figure 2). The size of each node in the figure represents the total number of international collaborative publications of countries/regions, where larger nodes indicate that the country/region's research has more publications on CSOs, and the width of the connecting lines indicates the frequency of collaboration between different countries/regions. As demonstrated by the information presented in Figure 2, the USA had frequent exchanges and cooperation with other countries pertaining to CSOs, and there was a higher prevalence of collaborative endeavors between European and North American countries/regions, whereas Asian countries/regions exhibited comparatively fewer academic connections with other countries/regions.

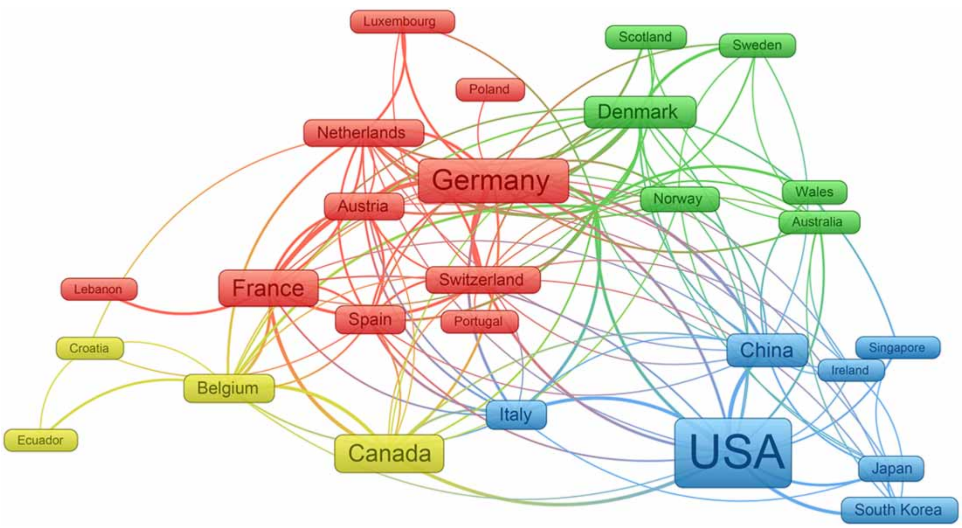


Figure 2 | Collaboration network among countries/regions on CSOs research from January 1990 to December 2022.

An analysis of the main academic institutions conducting CSOs studies provided an accessible summary of these institutions (García-García & Rodríguez-Salvador 2020). There were 1,332 institutions with 1,209 publications. The research institutions that had the most publications on CSOs over the last 33 years are listed in Table 3. Among the top 10 research institutions, the most productive institutions in terms of the number of publications were the Technical University of Denmark with 35 publications, which accounted for 2.90% of the total publications, followed by the Tongji University (28 publications, 2.32%), and the University of Sheffield (28 publications, 2.32%). The average citation frequency of Swiss Federal Institute for Environmental Science and Technology (EAWAG) from Switzerland exceeded 40, indicating that the research of the institution was recognized and gained attention from scholars in the field and that they had strong research overall. Based on the mapping of the research institution cooperation network relationships (Figure 3), the Technical University of Denmark had the largest node in the network and the most connected lines with other research institutions, indicating that it had frequent cooperation and communication with other research institutions. Additionally, 9 of the top 10 research institutions were from developed countries (except Tongji University), such as the USA and the EU, which systematically carried out studies related to CSS and CSOs controls in the early stages, resulting in significant achievements.

3.3. Journals

An analysis of journals publishing CSOs research can provide quick and accurate access to current authoritative journals on CSOs research. The JCR IF is a recognized means of characterization in academia, with a higher IF indicating a greater

Table 3 | Institutions contributing to publications on CSOs from January 1990 to December 2022

		Articles			
Institution	**Country**	**No.**	**%**	**Total citation frequency**	**Citation frequency per article**
Technical University of Denmark	Denmark	35	2.90	735	21
Tongji University	China	28	2.32	333	11.89
The University of Sheffield	UK	28	2.32	424	15.14
University of Innsbruck	Austria	23	1.90	346	15.04
University of Lyon	France	23	1.90	225	9.78
Environment Canada	Canada	21	1.74	362	17.24
University of Illinois	USA	21	1.74	428	20.38
US EPA	USA	20	1.66	589	29.45
Delft University of Technology	Denmark	18	1.49	206	11.44
EAWAG	Switzerland	17	1.41	750	44.12

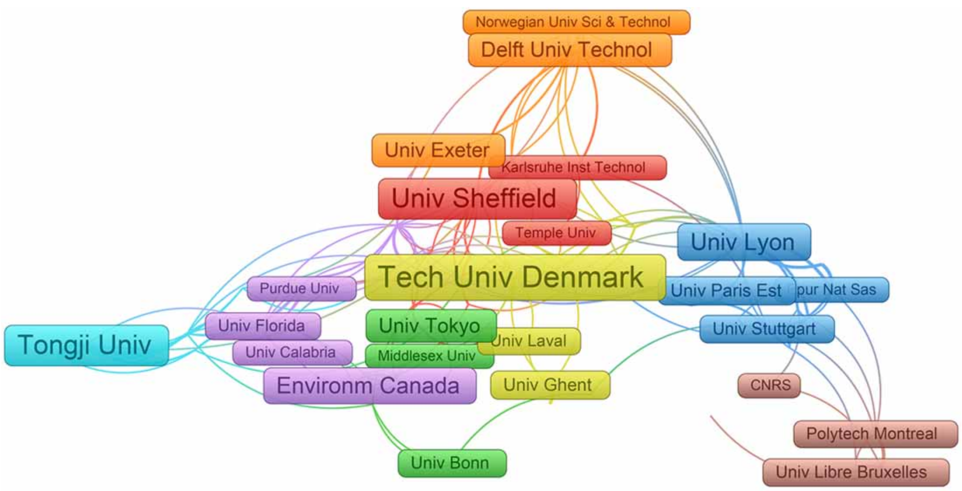


Figure 3 | Collaboration network among institutions on CSOs research from January 1990 to June 2022.

influence of the journal and a higher citation rate of its articles (Pérez-Hornero *et al.* 2013). Based on the results of the bibliometric analysis, CSOs studies published from 1990 to 2022 were distributed among 244 different journals, with *Water Science and Technology* having the most publications (269, 22.25%), followed by *Science of the Total Environment* (87, 7.20%), and *Water Research* (62, 5.13%). The top 10 journals, ranked by the number of publications, had a total of 617 publications, accounting for 51.03% of the total journals on CSOs (Table 4).

The journal *Water Research* had the highest total citation frequency, with values reaching 3,432, and a citation frequency per article of 55.35, ranking second among the top 10 journals. The number of articles published in *Environmental Science & Technology* was 23; however, the average number of citations per article was 69.17, and its $IF_{2023} = 11.4$, the second-highest journal in terms of the number of articles published, indicating that research published in this journal gained attention and readership from fellow scientists. Based on the 2023 JCR, six journals: *Science of the Total Environment*, *Water Research*, *Journal of Hydrology*, *Journal of Environmental Management*, *Water Environment Research*, and *Environmental Science & Technology*, were classified under the Q1 category, and the remaining four journals with IFs ranging from 2.7 to 5.8 were placed in the Q2 and Q3 categories in the citation report.

3.4. Keyword analysis

Keyword analysis is a rapid and effective way to understand the full text and content of an article. By analyzing the frequency of keywords, one can effectively discern and highlight research hotspots and changes related to CSOs (Xu & Feng 2021). A total of 3,059 keywords were identified from the retrieved literature. Further analysis was conducted on high-frequency keywords, focusing on 30 keywords with the highest frequencies, as shown in Figure 4 and Table 5. The color shades in the squares of the figure indicate the frequencies of each keyword appeared per year (gray represents null values). Keywords such as 'combined sewer overflow,' 'runoff,' 'stormwater,' 'management,' 'personal care products,' 'sediments,' 'pharmaceuticals,' and 'micropollutants' were found to occur more frequently, indicating that research on CSOs in recent years has mainly focused on CSOs management strategies, pipeline sediments, and control of ECs.

VOSviewer software was employed to conduct an in-depth investigation of keyword co-occurrence analysis. The size of the nodes in the resulting network diagram indicates the frequency of occurrence of each keyword. A total of 383 keywords appeared more than five times in the literature, according to the statistical results of keyword network co-occurrence mapping (Figure 5). Based on the size of the node and the node position near the center, keywords related to CSOs were divided into seven clusters: cyan, yellow, blue, purple, red, green, and orange.

The cyan cluster mainly included the following keywords: 'combined sewer overflow,' 'water quality,' 'nitrogen,' 'phosphorus,' and 'monitoring'. The yellow cluster mainly included 'turbidity,' 'dissolved oxygen,' and 'organic matter,' which represent the pollution characteristics of CSOs. The composition and distribution of contaminants in CSOs are always of primary concern. The main contaminants commonly detected in CSOs include suspended particulate matter, organic matter, heavy metals, nitrogen, and phosphorus (Yu *et al.* 2018). These contaminants are considered the primary control targets of the CSOs. As a primary contaminant in CSOs, particulate matter is an important carrier of contaminants, including

Table 4 | Top 10 most productive journals on CSOs research from January 1990 to December 2022

Journal	Articles	% of 1,209	IF_{2023}	JCR partition	Total citation frequency	Citation frequency per article
Water Science and Technology	269	22.25	2.7	Q3	3,220	11.97
Science of the Total Environment	87	7.20	9.8	Q1	2,693	30.95
Water Research	62	5.13	12.8	Q1	3,432	55.35
Water	47	3.89	3.4	Q2	437	9.30
Journal of Hydrology	31	2.56	6.4	Q1	1,178	38.00
Journal of Environmental Management	28	2.32	8.7	Q1	498	17.79
Water Environment Research	27	2.23	3.1	Q1	323	11.96
Urban Water Journal	26	2.15	2.7	Q3	385	14.81
Environmental Science & Technology	23	1.90	11.4	Q1	1,591	69.17
Environmental Science and Pollution Research	17	1.41	5.8	Q2	258	15.18

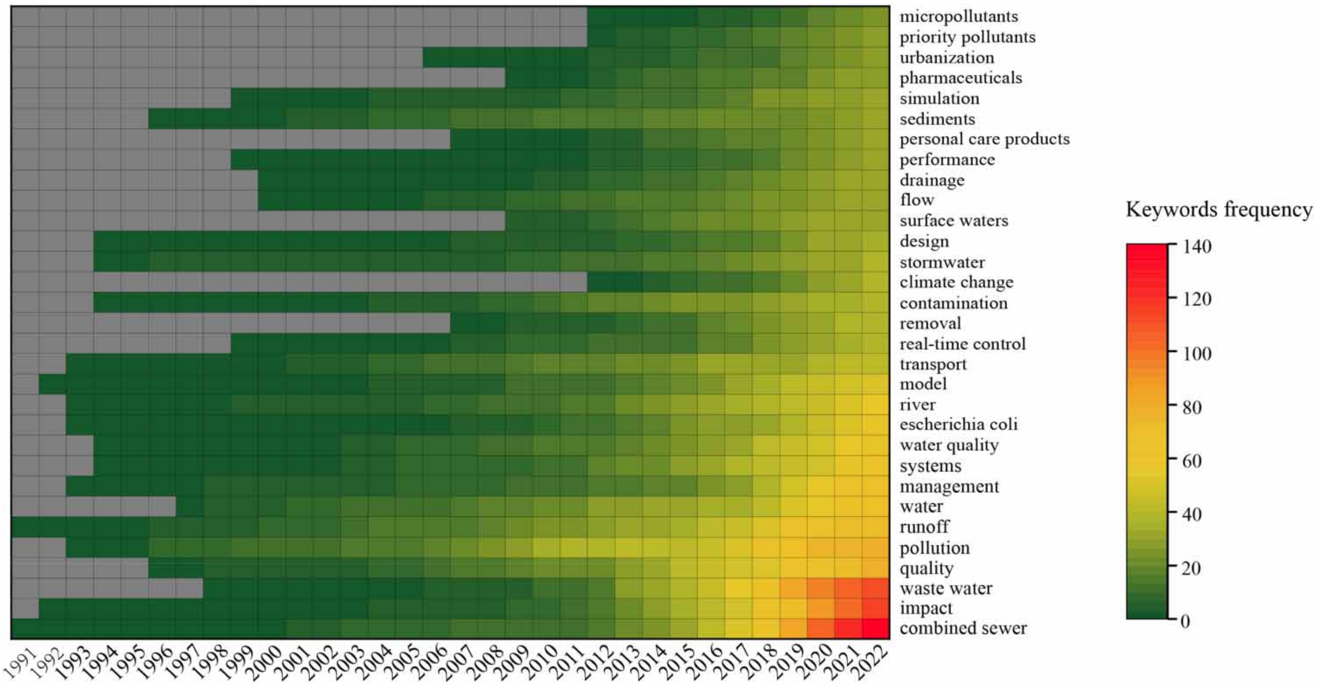


Figure 4 | High-frequency keywords of studies related to CSOs from January 1990 to December 2022.

Table 5 | The main keywords in different keyword clusters

Clusters	Keywords
Purple cluster	Waste water; contaminants; micropollutants; pharmaceuticals; personal care products; emerging contaminants; risk assessment; removal; sewage treatment plants; constructed wetlands
Cyan cluster	Combined sewer overflow; water quality; nitrogen; phosphorus; monitoring
Red cluster	Management; model; real-time control; low impact development; green infrastructure; urban drainage system; receiving water; urban flooding
Yellow cluster	Turbidity; dissolved oxygen; organic matter; erosion; deposition; behavior
Green cluster	Stormwater; runoff; sediment; pollution; toxicity; emissions;
Blue cluster	*Escherichia coli*; bacteria; microbial source tracking; enteric viruses; 16 s ribosomal-rna; outbreak; indicator

chemical oxygen demand (COD), nutrients, organic matter, and heavy metals. It plays an important role in the water quality of CSOs and the chemical reaction of dissolved contaminants. Additionally, the presence of highly concentrated organic contaminants in CSOs necessitates a substantial amount of dissolved oxygen during the degradation process, which causes hypoxia in the water body when it exceeds the oxygen-enriched capacity of the water body and affects the normal survival of aquatic plants and animals, consequently affecting the aquatic ecology and resulting in the formation of black and odorous water bodies (Zhu *et al.* 2021). Oxidation-rich CSOs are rich in nitrogen and phosphorus, which promote the growth and reproduction of algal organisms, resulting in a brownish-green coloration of the water body and the formation of water bloom (Li *et al.* 2021).

The characteristics of different contaminants in CSOs significantly vary among countries owing to variations in precipitation characteristics, geographic conditions, intensity of human activities, and design parameters of drainage pipelines. With the increasing amount of fundamental data, it is essential to enhance the application of data models such as the

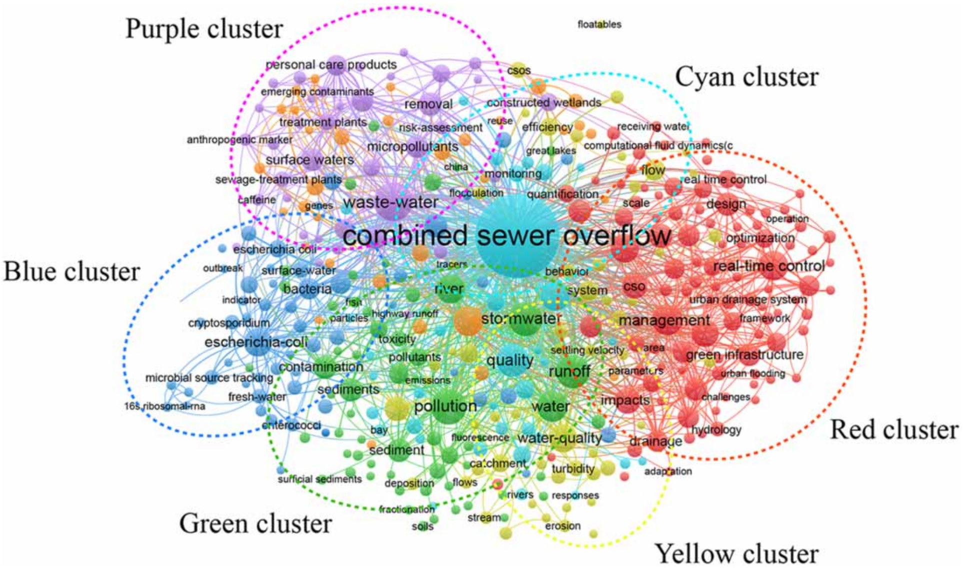


Figure 5 | Map network visualization of keywords related to CSOs from January 1990 to December 2022.

environmental fluid dynamics code (Saharia *et al.* 2019), hydrodynamic models (Kouyi *et al.* 2011), and artificial intelligence models (El Ghazouli *et al.* 2022) to efficiently simulate water quality in CSOs and quantitatively evaluate ecological risks in receiving water ecosystems.

The blue cluster primarily included the following keywords: '*Escherichia coli*,' 'bacteria,' 'microbial source tracking,' and 'enteric viruses,' which represent microbial contamination in CSOs. The primary source of microbial contamination in CSOs can be attributed to the deposition of precipitation on impermeable surfaces, such as roofs, and the presence of human feces, wildlife excrement (e.g., avian species), and domestic animal waste (particularly from canines). Of the total volume of CSOs, 5% contributes to over 99% of the pathogen load discharged into the receiving water. Pathogenic microorganisms constantly reproduce and spread using water as a medium, and can cause human intestinal diseases, respiratory diseases, myocarditis, meningitis, and other infectious diseases via fecal-oral and aerosol transmission. Pathogenic microorganisms in runoff and CSOs have become major sources of microbial contamination in surface water in urban areas (Sterk *et al.* 2016). Microbial source tracking (MST) is a highly efficient tool for identifying the source of pathogens in CSOs. Zeki *et al.* (2021) identified the main sources of microorganisms in estuaries through the detection of fecal-indicator bacteria and human-associated *Bacteroides* and found that rainfall had a moderately positive correlation with all MST indicators, indicating that CSOs are one of the main sources of microbial contamination in estuaries.

Furthermore, the presence of ARGs significantly contributes to increased pathogenicity resulting from microbial contamination. ARGs can be transferred between various microorganisms through horizontal gene transfer, thereby increasing the risk of water ecosystem contamination by pathogenic microorganisms (Cheng *et al.* 2020). Pathogenic microbial contamination has always been a challenging issue in surface water management, and CSOs lack sufficient attention as important sources of microbial contamination in surface water. The continuous development of molecular biology technologies, such as polymerase chain reaction, quantitative polymerase chain reaction, gene chips, and high-throughput detection technology based on second-generation sequencing technology, can facilitate better monitoring of the microbial contamination of CSOs and control them through corresponding strategies.

The purple cluster mainly included the following keywords: 'wastewater,' 'contaminants,' 'micropollutants,' 'pharmaceuticals,' 'personal care products,' 'emerging contaminants,' and 'risk assessment,' which represent the ECs in CSOs. Urban atmospheric and surface contaminants in the urban environment and on the ground surface are flushed, carried by runoff, and discharged into receiving water bodies through pipelines and CSOs. These ECs enter the environment and biomagnify through the food chain, posing larger risks to ecosystems and human health (Diepens & Koelmans 2018). In addition to conventional contaminants such as particulate matter, nitrogen, phosphorus, grease, and heavy metals, ECs include PPCPs (Hawkins *et al.* 2023), and MPs (Zhou *et al.* 2023). Unlike conventional contaminants, the hazardous characteristics of

ECs are relatively hidden, and their impacts on human health and ecosystems are often chronic. Their long-term accumulation affects the growth, reproduction, and heredity of aquatic organisms and plants and seriously threatens human health through the enrichment of the food chain. Therefore, it is imperative to strengthen the detection and identification of ECs in CSOs and determine the appropriate EC control. In addition, there is a need to deepen the understanding of the migration and transformation mechanisms of ECs in pipeline systems and CSOs and elucidate the migration and transformation law of ECs in pipeline networks and their interaction mechanisms with the transformation of conventional contaminants (COD, nitrogen, and phosphorus). Further development of efficient adsorption and advanced oxidation technologies is essential for the removal and control of ECs from CSOs.

The red cluster mainly included the following keywords: 'management,' 'model,' 'real-time control,' 'low impact development,' and 'green infrastructure,' which represent the source reduction of CSOs pollution. Due to the harmful effects of CSOs on urban water environments, researchers have proposed three technological routes (source reduction, process control, and end-of-pipe treatment) for controlling CSOs pollution. These approaches involve source reduction, process control, and end-of-pipe treatment methods (Quaranta *et al.* 2022). During the rainy season, the main cause of CSOs is excess rainwater exceeding the interception capacity of the main pipeline; thus, it flows into the CSS. LID facilities, such as green roofs, concave herbaceous fields, and grassed swales can effectively facilitate the infiltration and absorption of rainwater, thereby reducing the amount of water entering the pipeline network. Additionally, filtration and interception methods, including the application of rain gardens, penetrating pavements, and bioretention facilities, can be applied to effectively reduce and remove the contaminants carried by runoff (Fu *et al.* 2019). In addition to the reconstruction of separate drainage systems, process control in CSOs management can be effectively achieved by increasing the interception ratio of the pipeline system and the number of storage ponds to transport the highly polluted stored mixed sewage through the pipeline network to the WWTPs for treatment.

The implementation of a real-time control system enables optimal utilization of the storage capacity in the pipe network, providing a more cost-efficient and efficient solution to solve the challenges of CSOs and waterlogging. The structure of the distributed optimal control system encompasses a real-time control mechanism for drainage systems, employing multiple agents that exchange information and make decisions based on local data. This distributed optimal control minimizes the data load on individual agents, effectively mitigating the high computational burden encountered in centralized control systems. Zhao *et al.* (2022) developed a distributed optimal control approach for regulating multipoint control units in urban sewer systems. For instance, in a sewer network located in Chaohu City, China, consisting of five pumping stations and 18 associated sewage or stormwater pumps, the total nitrogen (TN) loading released into the receiving waters could be maximally reduced by 37.6% through optimal control. Implementing suitable end-of-pipe measures by the contamination characteristics and hazards associated with CSOs is crucial for managing and mitigating CSOs pollution.

Furthermore, it is imperative to enhance national policy intervention, legal and regulatory mandates, and top-level planning and management strategies to enhance the management of CSOs and mitigate their adverse effects (Chen *et al.* 2019). With the development of sensor, measurement, communication, and computing technologies, data collection has become less challenging, paving the way for the establishment of intelligent monitoring networks and data infrastructures. By implementing technologies such as artificial intelligence, GIS, and remote sensing, it is possible to effectively manage runoff and CSOs, assess the degree of pollution and potential impacts of CSOs, and provide references and support for the construction of infrastructures adapted to climate change and urbanization (Saddiqi *et al.* 2023).

The green cluster mainly included the following keywords: 'stormwater,' 'runoff,' 'sediment,' and 'pollution,' which represent the study of pipeline sediments. Pipeline sediments are a significant source of CSOs contamination (Wang *et al.* 2021a). Studies have shown that pipeline sediments contribute between 30 and 80% of the pollution load in receiving water bodies during rainstorms. Specifically, the contribution of pipeline sediments to the TN content of the receiving water bodies ranges from 20.9 to 44.6%, whereas their contribution to the total phosphorus content ranges from 35.7 to 47.3% (Li *et al.* 2022). Pipeline sediments are also an important source of numerous ECs. Zhang *et al.* found that pipeline sediments are a major source of ARGs contamination in CSOs based on the 'tidal' flushing characteristics of CSOs contamination (Zhang *et al.* 2022). Urban pipelines are commonly silted with sediments, especially in CSS, which are easier to deposit during the dry season (Hua *et al.* 2022). The presence of sediments in pipelines can block pipelines, reduce drainage flow, induce pipeline corrosion, overload the drainage system, and cause premature overflow of the CSS. Additionally, sediments emit hazardous gases, such as hydrogen sulfide and methane. Therefore, the transportation of pipeline sediments during rainfall events is a significant contributor to environmental pollution (Chen *et al.* 2022).

Researchers have conducted in-depth studies on the structure and properties of pipeline sediments and numerous tests to explore the scour characteristics of pipeline sediments under different hydraulic conditions. Various data analyses have been conducted to predict the migration process of sediments under different conditions (Liu *et al.* 2021; Zhang *et al.* 2023). However, most recent studies have focused on the role of runoff and its initial scour on CSOs, whereas few studies have been conducted on the mode and degree of contribution of pipeline network sediments in CSOs. When the CSOs occur, a large amount of dissolved organic matter (DOM) will be transported into water bodies, which affects water eutrophication and ecosystem health. Therefore, determining the source contribution of DOM is of great importance to improve water pollution (Liao *et al.* 2021) provided a method to describe the mode and degree of contribution of pipeline network sediments to CSOs using the degradation potential index and the end member mixing model. Therefore, it is important to explore the contribution patterns of pipeline sediments to CSOs pollution to control it and the health of the urban water environment.

The orange cluster mainly included the following keywords: 'CSO treatment,' 'disinfection,' and 'coagulation,' which represent the control and treatment of CSOs. Since CSOs result from the mixture of dry season sewage, rainfall runoff, and sediment washed out from the pipeline, it has the characteristics of discontinuous, explosive and random pollution, and its short-term impact on the drainage system is stronger. Therefore, it is of great significance to take appropriate treatment measures to reduce CSOs pollution. The end-of-pipe treatment is the purification of pollutants at the end of the pipeline system to reduce the load of pollutants discharged into the receiving water, which is the most effective, most thorough, and fastest treatment to CSOs pollution.

The end-of-pipe treatment of CSOs primarily consists of ecological and technological measures. Ecological measures mainly refer to constructed wetland technology, which can reduce the speed of water flow, filter a variety of pollutants. However, due to the spatial constraint, it faces significant challenges in the engineering implementation. Technical measures include mechanical methods (e.g., cyclone separation, thin layer separation, sand filtration, and grille separation) and physicochemical methods (e.g., adsorption, coagulation, flocculation, and disinfection) (Masi *et al.* 2023). Cyclone separation is the most commonly used CSOs pollution control owing to its small footprint and low construction costs. Coagulation and sedimentation technologies are widely used to treat the pollution caused by CSOs. However, the dosages of chemicals in the coagulation and precipitation processes pose a challenge and can easily cause secondary pollution during rainstorms. To address this problem and enhance the pollution removal efficiency, researchers have proposed magnetic coagulation technology to control CSOs pollution. Furthermore, to reduce the microbial contamination of CSOs, typical disinfection methods are used, including chlorine, ozone, and ultraviolet disinfection (Crocetti *et al.* 2021).

Constructed wetlands are an end-of-pipe treatment that efficiently controls CSOs pollution. They have less construction investment, low operation cost, strong ability to handle pollution load. They can also be combined with the landscape in urban construction, which not only beautifies the urban environment but also regulate rainwater flooding and improve the ecological environment, which has a good prospect for development (Wang *et al.* 2021b). At present, research related to end-of-pipe treatment focuses on the simultaneous removal of suspended solids, nitrogen, phosphorus, organic pollutants, and microorganisms, while there is a lack of research on the removal of ECs. At the same time, the impact of treated effluent on the ecological restoration of receiving water bodies should be considered.

4. CONCLUSIONS AND PERSPECTIVE

This study analyzed 1,209 articles retrieved from the WOSCC database between 1990 and 2022 in terms of the number of articles, countries/institutions, institutions, and journals based on bibliometrics and using the citation analysis software HistCite Pro and web visualization software VOSviewer. Keywords were used to determine research hotspots and developmental trends on CSOs. Based on the results of the analysis, the most important conclusions are as follows:

(1) In terms of the number of published articles, there was an increasing global emphasis on CSOs research. The three most important research institutions were the Technical University of Denmark, the Tongji University, and the University of Sheffield. The USA has the highest number of publications related to CSOs, followed by Germany and the UK. Studies in this field were mainly published in journals such as *Water Science and Technology*, *Science of the Total Environment*, and *Water Research*. Using the VOSviewer software to analyze keywords, it was found that CSOs pollution sources, characteristics, risk assessment, and control measures are the current main research directions on CSOs. Pollution control measures for CSOs based on source control and ECs in CSOs are potential research topics.

(2) The control of CSOs must be scientifically designed and planned. According to the technical guidelines and standards that can be implemented, the technical and economic analysis methods should be established to optimize the implementation plan and guide the control system design of CSOs. Formulate medium and long-term targets and plans for pollution control of CSOs in different cities, apply new concepts and methods of stormwater management, actively develop efficient control technologies and equipment, apply green infrastructure and gray infrastructure to reduce investment and improve control efficiency, and continuously monitor and evaluate the implementation effect. Optimize the operation and management, and finally solve the pollution problem of urban CSOs. The USA is one of the early pioneers in systematically implementing CSOs pollution control worldwide. The legal and policy system construction, basic research, and engineering practice of CSOs pollution control have been carried out for decades. Approximately 3.2 billion m^3 of CSOs is discharged annually in the USA. Based on the 2000 estimate by the U. S. Environmental Protection Agency (EPA), at least $50.6 billion investment would be required to achieve 85% control of the CSOs, accounting for 27.9% of the total investment demand for drainage facilities in the USA. After decades of treatment, the pollution control of CSOs in the USA has achieved obvious results on the whole. For example, according to the statistics of 2014, 54% of the annual CSOs of seven states in the Great Lakes region have been controlled. However, CSOs pollution is still a problem that has not been completely solved in the USA, and the development level of different regions is also quite different. Many cities are still implementing more economical and efficient pollution control through various methods such as promoting green infrastructure (GI) and formulating long-term plans.
(3) The design and construction of urban CSOs control systems require consideration of various factors, including real-time rainfall data, the configuration of pipeline networks, the population size, the scale of sewage treatment facilities, and the deposition of subsurface and pipeline networks. Furthermore, the composition of CSOs systems is highly intricate because it encompasses a range of technical measures, such as source control, pipeline network management, storage process control, and end-of-pipe control measures. Therefore, the accurate assessment of CSOs control systems is the basis for the correct understanding of CSOs in CSS and reasonable selection of the scale of CSOs pollution control measures. With the emergence of the concept of a 'smart city,' the application of computer models (e.g., artificial intelligence models) can provide substantial assistance in the planning, optimization, operation, and evaluation of CSOs control systems. The aforementioned strategy enables efficient planning, optimization, operation, and evaluation of CSOs control systems, thereby indicating a future direction for the design and construction of urban CSOs control systems.

AUTHOR CONTRIBUTIONS

Chen Shen contributed to the conceptualization and participated in writing the original draft and reviewed and edited the manuscript. Qingbang Yang contributed to the methodology and participated in writing the original draft; Zhonghong Li contributed to the methodology and software development, and visualized the preparation of the work.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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