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Exploring Nature-Based Solutions for Urban River Restoration: Insights from China's Sponge City Programme

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1 ABSTRACT

In cities, river restoration is widely recognised as an essential Nature-based Solution (NbS) that delivers a wide range of benefits. However, rapid urbanisation and economic growth over the past four decades have led to the degradation of Chinese rivers. In response, the Chinese government introduced the Sponge City (SC) concept in 2013 as part of the 'Ecological Civilisation' era. The SC, considered a hybrid NbS, was designed to foster urban resilience, particularly against severe disasters such as floods. The nationwide SC Program (SCP) commenced in 2014. Since then, the number of participating cities has continued to grow. As a result, a large number of Chinese cities have been transitioning from traditional grey infrastructure to green/blue infrastructure with substantial investments, leading to the restoration, redesign and revitalization of urban rivers. Despite these efforts, there is a noticeable lack of research that examines urban river restoration from a multi-beneficial NbS perspective, a current global research trend. To address this research gap, the present study adopted a mixed-methods approach, combining expert interviews with bibliometric analysis, to explore the specific role of urban rivers as an NbS within the SC framework. Our study revealed an increasing scientific interest in urban river restoration beginning in 2013, viewing them as elements of sponge construction. Alongside this, there's a progressively nuanced understanding of rivers as multifunctional NbS. In addition, we identified specific challenges that impede the successful implementation of these NbS in Chinese cities. To overcome these barriers, we formulated a set of recommendations that are in harmony with China's new River Chief System policy and the Ecology Oriented Development (EOD) model. The aim is to enhance the sustainable governance of urban rivers as an NbS in the long term, thus contributing to overall sustainable development in China.

Keywords: social-ecological system, interview analysis, bibliometric analysis, nature-based solution, urban river restoration

2 INTRODUCTION

In 2013, China first proposed the construction of an ecological civilization, which was later incorporated into the country's constitution in 2018. As part of this initiative, the Chinese government introduced the concept of Sponge City (SC) as a scalable NbS in 2012 and launched the nationwide SC Program (SCP) in 2014. SCP aims to develop a holistic urban water management system to adapt to climate change impacts, particularly in response to extreme weather events. This involves replacing traditional grey infrastructure with green/blue infrastructure capable of infiltrating, absorbing and storing excess rainfall during floods, as well as releasing it during droughts. Constructing SC infrastructures includes restoring rivers and floodplains, building artificial wetlands, installing sunken green spaces, rainwater tanks, and green roofs, transforming permeable pavements, and more (Song, 2022).

In 2015, 16 Chinese cities were selected for the first batch of pilot SCP, which expanded to include an additional 14 cities in 2016. The central government covers about 15-20% of the program costs, while the remainder is shared between local governments and the private sector through public-private partnerships (PPP). As of 2018, the fixed subsidy for pilot SC projects amounted to 600 million RMB per year (87.8 million USD) for municipalities, 500 million RMB (73.2 million USD) per year for provincial capitals and 400 million RMB (58.5 million USD) per year for other cities. The development of the SCP in China has been a rapid process; the number of pilot cities reached over 370 in 2018. By 2030, the national goal is anticipated that over 80% of municipal areas will recycle 70% of incident rainfall (Griffiths et al., 2020).

Research on river restoration in China emerged in the late 1990s with the introduction of the concept of „ecological hydraulic engineering" (Dong, 2013). Since 2015, efforts to eliminate black-odorous surface water bodies have significantly improved the water quality of rivers across the country (Cao et al., 2020). Many urban rivers have undergone restoration or rehabilitation under the SCP, attracting considerable investments and serving as integral components of green infrastructure within NbS. The creation of various recreational riverfront parks in densely populated Chinese cities also provides urban green, open spaces and contributes to social well-being. While some research has focused on the role of urban river restoration within the SCP, it has not been thoroughly examined as an integrated NbS. Furthermore, the practical experiences of implementing restoration projects across various Chinese cities remain fragmented among practitioners and have not been in-depth documented or researched by scholars. To bridge this gap, this study endeavours to investigate the following research questions: 1) What is the research trend of studying river restoration within the SC concept? 2) What practical challenges does river restoration face while being implemented in sponge constructions? 3) What is the link between river restoration in China"s SCP and the global advancement of NbS research? The process involves analyzing research trends, identifying practical challenges, discussing findings from an intensive literature review, and providing recommendations for future efforts.

3 METHOD

The study adopted a mixed-methods approach, combining expert interviews with bibliometric analysis. Firstly, a bibliometric analysis was employed to identify research trends in river restoration under the SCP, as reflected in both Chinese and English literature. Subsequently, we carried out semi-structured interviews with SCP practitioners to gather information on the practical challenges associated with the design, implementation, and evaluation of restoration projects—challenges that scientific publications do not typically unveil. The bibliometric analysis was conducted using CiteSpace, a Java application for knowledge mapping, to examine scientific publications from 2012 to April 2023, through keyword frequency statistics and clustering. CiteSpace visualises the research structure within a specific domain by creating co-citation networks and keyword clustering (Chen, 2006). The Web of Science (WOS) was selected as the literature search engine, and both the WOS Core Collection (WOSCC) and the Chinese Science Citation Database (CSCD) were used as data sources, for their authoritative journals, publications, research field and time span, as well as for their compatibility with both Chinese and English literature. The CSCD contains Chinese literature with translated titles, authors, keywords and abstracts in English, facilitating a further examination in combination with English literature. We used a search query with the following criteria: TS=„Sponge City" AND TS=„river", DOP=all years (1900-2023), resulting in 333 pieces of literature published between 1999 and 2023. Of these, 210 were from the WOSCC, and 137 were from the CSCD, comprising various publication types such as articles, meetings, reviews, books, and early access. After eliminating duplicates and irrelevant documents, 272 relevant records were obtained, comprising 153 from the WOSCC and 119 from the CSCD. These records, published between 2013 and 2023, were extracted for bibliometric analysis.

In the second step, from 2020 to 2022, we conducted five semi-structured interviews with urban planners and landscape designers actively involved in the SCP. These individuals, based in Beijing, Guangdong, and Sichuan Provinces, provided their firsthand experiences related to specific urban river restoration projects. We thus gained insight into the challenges they encountered in the field through content analysis methods (Downe-Wamboldt, 1992). We then compared the findings from the interviews with the analysis of scientific literature, interpreting them through the lens of NbS. Finally, by synthesizing expert perspectives with the results of the bibliometric analysis, our study offered practical recommendations to bolster the future management of NbS for urban rivers.

4 RESULTS

4.1 Research Trend of River Restoration under SC

4.1.1 General Trend

Out of the total publications analysed, 228 were journal articles, 27 were conference proceedings, 17 were review articles, and 4 were early access publications (Table 1). From 2015 to 2020, there was a consistent growth in the number of publications, with the peak number (58) recorded in 2020, accounting for 21.3% of the total 272 articles. However, starting in 2021, there has been a decline in the number of publications. In 2021, the number of publications dropped to 40 (14.7% of the total), followed by a further decrease to 33 publications (12.1% of the total) in 2022. In 2023 (until April), there were only 3 publications (1.1% of the total), but this number is incomplete as the year is still ongoing.

In summary, the trend shows a growing interest in 'river restoration' and 'SC' research from 2015 to 2020, followed by a decline in the number of publications from 2021 onwards (see Table 1 and Figure 1). The research domains related to 'river restoration' and 'SC' cover a wide range of disciplines, reflecting the interdisciplinary nature of these topics. The Science and Technology domain was the most dominant, with 263 publications (96.7% of the total). Within this domain, the research areas of Environmental Sciences and Ecology (39.3%), Construction and Building Technology (28.3%), Engineering (25%) and Water Resources (22.8%) were the most prominent. The Technology domain, accounting for 55.9% of the total publications, emphasised the importance of technological innovations in fields such as Construction and Building Technology (28.3%), Engineering (25%), Materials Science (2.6%) and Computer Science (2.2%). Life Sciences and Biomedicine involved 112 publications (41.2% of the total), indicating the connection between river restoration, SC construction and the living (primarily aquatic) environment. Research areas in this domain included Environmental Sciences and Ecology (39.3%), Biodiversity Conservation (1.5%), Marine and Freshwater Biology (0.7%) and Public Environmental and Occupational Health (0.7%). The Physical Sciences domain included 92 publications (33.8% of the total), highlighting the relevance of Geology (8.5%), Meteorology and Atmospheric Sciences (2.6%), Oceanography (1.1%) and Physical Geography (1.1%) in understanding the physical processes associated with river restoration. The domains of Arts and Humanities and Social Sciences accounted for 7 publications (2.6% of the total) and 4 publications (1.5% of the total), respectively, indicating relatively less consideration of social and cultural aspects in the literature.

Theme	Results
Year of study	72.1% were published from 2013 to 2020; 27.9% were published from 2021 to 2023
Article type	228 articles, 27 meetings, 17 review articles, 4 early access
Article language	153 in English (WOSCC); 119 in Chinese (CSCD)
Research domains	96.7% Science Technology, 55.9% Technology, 41.2% Life Sciences Biomedicine, 33.8% Physical Sciences, 2.6% Arts Humanities, 1.5% Social Sciences
Research areas (top 10)	39.3% Environmental Sciences Ecology, 28.3% Construction Building Technology, 25.0% Engineering, 22.8% Water Resources, 9.2% Science Technology Other Topics, 8.5% Geology, 4.0% Energy Fuels, 2.6% Architecture, 2.6% Materials Science, 2.6% Meteorology Atmospheric Sciences

Table 1: Summary of the filtered 272 literature

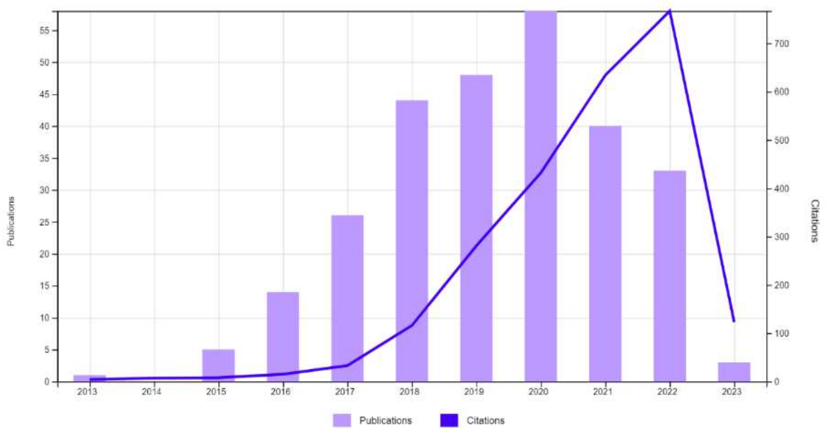

Fig. 1: Number of publications and citations per year from 2013 to 2023

4.1.2 Keyword Co-occurrence Analysis

A knowledge network was constructed based on keyword co-occurrence analysis using the top 36 calculated keywords. This network is visualised in Figure 2, where each node represents a keyword. The most frequently mentioned keyword was „SC“, appearing in 129 articles. Other notable keywords included „climate change“ (24 articles), „low impact development (LID, an approach to land design that uses natural features to manage stormwater runoff)“ (29 articles), „urbanization“ (22 articles), „model“ (14 articles), „impact“ (20 articles), „system“ (19 articles), „stormwater management“ (14 articles), „performance“ (17 articles), „management“ (24 articles), „runoff“ (15 articles), „urban“ (12 articles), „SC construction“ (16 articles), „water quality“ (10 articles), „challenge“ (11 articles), „China“ (11 articles) and „land use“ (9 articles). These keywords suggest that the research focuses on the potential of restoring rivers to address challenges related to climate change, urbanization and stormwater management under the SCP. The prevalence of keywords such as „model“, „impact“, „system“, „performance“, and „management“ indicates an understanding of the functioning, effectiveness and optimization of the river restoration process.

However, there seems to be less emphasis on the watershed perspective, as keywords such as „catchment“ (7 articles) and „river basin“ (6 articles) appeared less frequently (see Figure 2).

During the early stages of the research, particularly around 2015, the primary focus was on understanding the “SC” concept and controlling urban runoff, e.g., “LID”. Between 2017 and 2018, several keywords gained prominence, reflecting a shift towards practical aspects of river restoration. These keywords included „impact“, “SC construction”, “stormwater management”, “performance”, “model” and “land use”. This suggests an emphasis on understanding the real-world implications and practical considerations involved in implementing river restoration projects in SCP. As the field progressed, there was a growing interest in exploring the context of „climate change“ and „urbanization“. Around 2021, the emergence of the keywords „ecosystem service“, „quality“, and „green infrastructure“ was observed, following “management” and “system”, indicating the latest recognition of the regulating, supporting, provisioning, cultural ecosystem services that rivers provide and the aspect of their long-term governance. This shift highlights a deeper understanding of the social-ecological interactions of urban rivers and their potential to deliver multiple benefits as an NbS

Furthermore, the top 6 keywords with the strongest citation bursts (see Figure 3) provide additional insights into the temporal change trends of hot keywords:

- “Ecological restoration” (2016-2019, strength: 1.53) suggests a focus on the improvement of river ecosystems during this period, reflecting an emphasis on restoring the natural state of urban rivers.
- “Water ecology” (2017-2018, strength: 1.84) highlights the ecological dynamics of freshwater systems, indicating a growing interest in the interplay between hydrology and ecology.
- “Urban flooding” (2019-2020, strength: 2.15) emerged as a significant concern, reflecting the need to address flood risks in urban environments, in which river is often considered an infrastructure.
- “Challenge” (2021-2023, strength: 2.27) indicates that researchers are now focusing on identifying the difficulties and obstacles encountered in implementing river restoration initiatives under SCP.
- “Quality” (2021-2023, strength: 1.98) and „Ecosystem Service“ (2021-2023, strength: 1.98) show increasing study numbers in the multi-dimensional outcomes of river restoration, such as improved water quality and the provision of multiple ecosystem services.

The analysis of citation bursts and the temporal change trend reveals a transformation in research focus over time. Initially, the emphasis was on flood risk mitigation, but there has been a subsequent shift towards a more comprehensive understanding of rivers as dynamic social-ecological systems. This shift further addresses the emerging practical challenges in river restoration projects and the need for sustainable management.

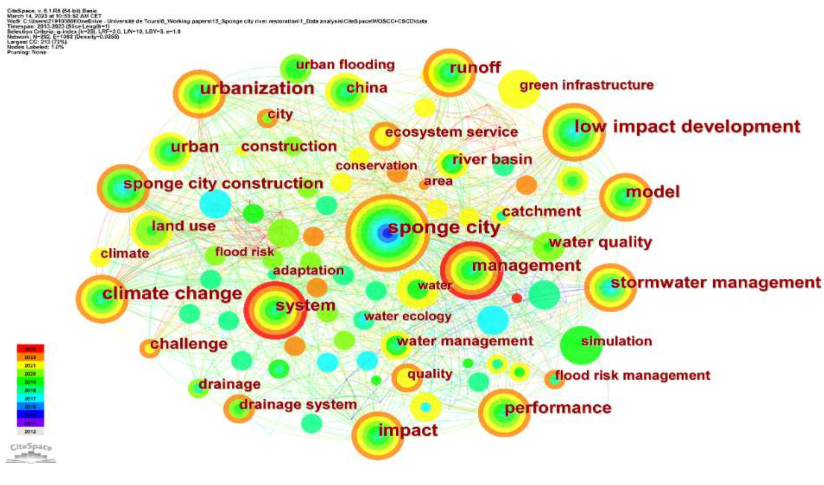

Fig. 2: High-frequency keyword map, based on the frequency and patterns of co-occurring keywords in the literature. The thickness of the rings within each circle reflects the number of papers within a given time frame. The colour of the rings corresponds to the publication time, as indicated by the time bar at the top of the figure. The links between different keywords indicate co-occurrence within the same papers.

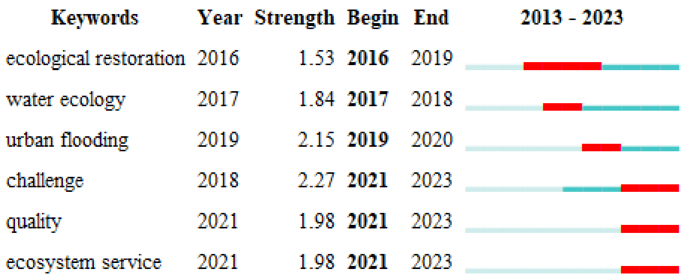

Fig. 3: Top six keywords with the strongest citation bursts.

4.1.3 Cluster Analysis

We applied the log-likelihood ratio (LLR) algorithm to group the keywords which are closely related to one another and identified five distinct research clusters (Figure 4). The cluster modularity Q=0.6009 and weighted mean silhouette S=0.7885 indicate that the cluster structure is significant and effectively delineates the boundaries of research directions within these five clusters. The silhouette value provides a quantitative measure of the coherence and separation of the clusters. Keywords within different clusters are subsequently summarised into specific research themes (Table 2). Specifically, cluster 0 represented urban flooding, cluster 1 focused on SC, cluster 2 dealt with stormwater management, cluster 3 highlighted low-impact development and Cluster 4 addressed flood risk. The overlapping key terms indicate shared research topics, particularly in the domains of hydrology. This can be attributed to the interdisciplinary nature of the field and the need to address different aspects of river restoration simultaneously. Additionally, the citation network structure might have contributed to the overlapping themes, with influential papers shaping multiple clusters. The interconnectedness of the five clusters also suggests that they are part of a larger research framework tackling common objectives.

Cluster 0 (silhouette value=0.70), with an average publication year around 2016 (Figure 5), focused on urban flooding and the application of the Storm Water Management Model (SWMM; e.g., Kong et al., 2017; Luan et al., 2017) in SC. Key terms included „urban flooding“ and „LID practices“. The milestone papers by Xia, Zhang, et al. (2017) and Xia, Shi, et al. (2017) investigated urban water regulations facilitated by SC construction and proposed an integrated approach that combines green infrastructure, such as rivers, lakes and wetlands, with grey infrastructure. Seeing SC as a hybrid NbS, technical guidance was made (Jia et al., 2017), and the combined effectiveness was assessed (Kong et al., 2017). Luo et al. (2021) took the Shenzhen-Shantou Special Cooperation Zone (SSCZ) as a case study, identifying riparian areas as ecological buffer zones with higher flood risks and lower resilience to engineering solutions. They proposed restoring them to act as natural sponge bodies that could effectively mitigate urban floods (Luo et al., 2021).

Cluster 1 (silhouette value=0.81), with research papers published on average around 2016, focused on sponge techniques for sustainable urban development. Key terms included „SC“, „LID“, „total runoff control rate“ and „water system“. Zhang et al. (2016) analysed the SC concept from an urban hydrology perspective and proposed designing flood prevention measures at the river basin level and connecting rivers and lakes to enhance overall drainage capacity. However, Qiao et al. (2020) contended that the SC initiative should not be classified as a LID program since conventional grey infrastructure remains a significant component in its implementation, and there was limited space in compact Chinese cities and an absence of documented efficiency for green infrastructure (Qiao et al., 2020).

Cluster 2 (silhouette value=0.71), with an average publication year around 2018, focused on specific designs and impact evaluation for urban river systems in stormwater management. Key terms included „stormwater management“, „uncertainty“, „rainwater zone“, „design ecology“ and „stormwater quality and quantity“. The article by Zhang et al. (2014) identified the effects of urbanization on the hydrological regime, including the degradation of river ecology, straightening and channelization of rivers and covering or transforming ponds and streams. Booth et al. (2016) and Walsh et al. (2005) further suggested identifying the Urban Stream Syndrome (Wantzen et al., 2019). Liu et al. (2017) explained SC construction guidelines, addressing the protection of natural ecological features, such as wetlands, the maintenance of natural flow regimes of rivers and the reduction of impervious surfaces in river beds. Li et al. (2019) proposed an evaluation system that quantifies the environmental, economic and social benefits of different combinations of LID units for SC construction, incorporating indicators such as water quantity, water quality, landscape and ecological service functions. Using similar methods, Mei et al. (2018) evaluated the cost-effectiveness of GI in urbanised watersheds for flood mitigation under SCP using an SWMM.

Cluster 3 (silhouette value=0.79), with an average publication year around 2018, delved into the role of river restoration in adaptive urban development facing climate change effects. Key terms included „LID“, „town & city planning“, „urban rain island (a phenomenon in which precipitation levels in urban areas are higher than those in the surrounding suburban areas)“, „constant pipe drainage“ and „drainage ratio“. Jiang et al. (2018) examined the root causes of the vulnerability to urban pluvial flooding. Traditional approaches to managing urban rivers, such as channelization and dredging, were insufficient for tackling current challenges (Chan et al., 2018; Wang et al., 2018). Chan et al. (2018) suggested that the SCP offered opportunities to protect rivers and other inland water bodies while dealing with broader environmental issues. More integrated and localised (Nguyen et al., 2019) land-use guidance and assessment tools were recommended (Chan et al., 2018). River“s role in urban heat reduction in the SCP was underlined (Nguyen et al., 2019). Furthermore, developing urban drainage systems needed to consider factors at the watershed scale (Nguyen et al., 2019) and safeguard the watershed's integrity and the health of water resources (Li et al., 2017).

Cluster 4 (silhouette value=0.72), with an average publication year around 2016, emphasised an integrated flood risk management approach that included perspectives from society and decision-making processes. Key terms included „flood risk“, „perceptions of flooding“, „guideline“ and „integrated water management“. Using Wuhan as a case study, Shao et al. (2019) examined the impact of urban impervious surface coverage on hydrological processes and monitored interconnected urban watersheds by calculating impermeability ratios. It also highlighted the absence of integrated decision-support information. With a social survey, Wang et al. (2017) discovered that the public predominantly regarded incomplete drainage systems as the main cause of urban flooding, while impermeable surfaces were considered less significant factors.

By analyzing the characteristics of each cluster, we gain a general understanding of the temporal evolution of research topics related to river restoration and SC. Clusters with an average publication year around 2016 (Cluster 1 and 4) primarily concentrated on hydrological subjects, such as LID, flood risk management, urban runoff and water systems. In a contrasting shift, clusters with an average publication year around 2018 (Cluster 0, 2, and 3) redirected their focus towards more detailed issues, including river design in urban planning, drainage management, climate mitigation and specific case studies such as the SSCZ. Constructed wetlands were also discussed in relation to river restoration, and watershed scales started to receive attention.

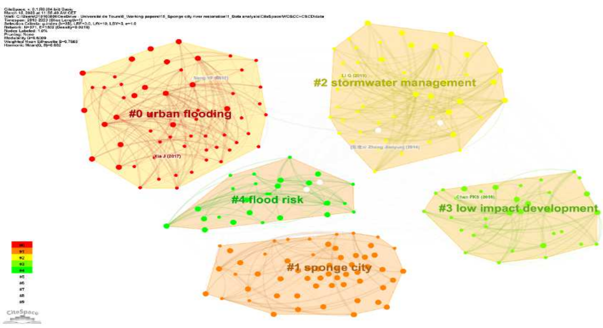

Fig. 4: 5 most significant clusters and the most active citer to each cluster, based on LLR clustering of keywords

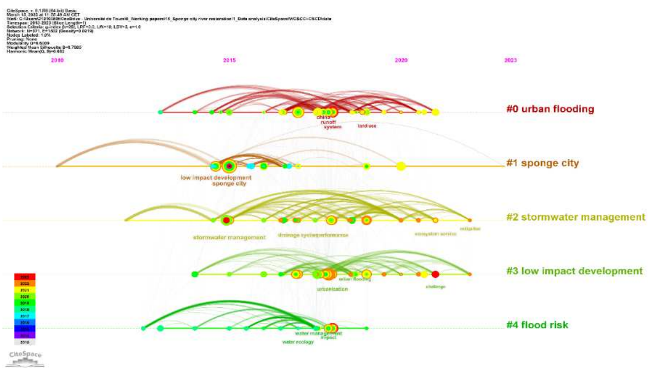

Fig. 5. Timeline of five clusters

Cluster ID	Size	Sihouette Value	Average year	Top terms (LLR, p-value)
0	59	0.703	2018	urban flooding (4.32, 0.05); SWMM (4.32, 0.05); Shenzhen-Shantou special cooperation zone (3.77, 0.1); LID practices (3.77, 0.1)
1	58	0.808	2016	SC (16.17, 1.0E-4); LID (5.91, 0.05); total runoff control rate (5.75, 0.05); water system (5.75, 0.05)
2	50	0.709	2018	stormwater management (4.27, 0.05); uncertainty (4.2, 0.05); rainwater zone (4.2, 0.05); design ecology (4.2, 0.05); stormwater quality and quantity (4.2, 0.05)
3	33	0.788	2018	LID (4.6, 0.05); town & city planning (4.26, 0.05); urban rain island (4.26, 0.05); constant pipe drainage (4.26, 0.05); drainage ratio (4.26, 0.05)
4	27	0.724	2016	flood risk (6.02, 0.05); perceptions of flooding (4.81, 0.05); guideline (4.81, 0.05); integrated water management (4.81, 0.05)

Table 2: Summary of cluster size, silhouette value, average year and top terms of each cluster

4.2 Practical Challenges

4.2.1 Knowledge Gaps and Spatial Inequality

The bibliometric analysis indicated that the subjects related to ecological restoration had gained prominence since 2016 in scientific research. However, the findings from the interviews revealed a gap in practical knowledge, with conventional methods such as river channelization and dredging still being widely implemented in river restoration efforts, despite their inadequacy in addressing complex water management issues (Chan et al., 2018; Wang et al., 2018). Many river restoration projects simply dredged the river channel—removing sediments and debris from the riverbed—to tackle issues with black and odorous water bodies. This method is often implemented by the local Water Resource Bureaus, reflecting their engineering-centric tradition and lack of ecological knowledge, as river dredging can harm the ecosystems by disrupting aquatic life and destroying natural filtration layers that are essential for maintaining potable water reserves.

Furthermore, the interview analysis highlighted the challenge of convincing local government officials to allocate space for floodable riparian areas in cities, which would benefit biodiversity instead of building higher concrete embankments. This process can be time-consuming due to the knowledge gap among government officials regarding river-floodplain systems. An example is the „river restoration“ project in Dali, Yunnan Province, China, in 2020. Despite its aim to control mudslides, the project resulted in the devastation of the natural riverbed and riverbank through the encasement of 18 small rivers in concrete. Although the project faced public criticism and had eventually been interrupted due to media pressure, these rivers in Dali remain channelised.

This phenomenon also presented a spatial inequality among Chinese cities. Practitioners widely believed that river restoration efforts under SC construction had made more progress in China's first and second-tier cities, primarily located in the eastern and southeastern coastal regions. These cities, such as Shenzhen, have superior economic performance and a higher standard of living, as evidenced in the case study by Luo et al. (2021). Conversely, third-tier cities, particularly those in less developed provinces such as Yunnan in the southwest, experienced more frequent channelization of rivers. These cities, with smaller populations and lower economic output, often rely on traditional engineering approaches to SC construction. This spatial inequality is also attributed to the knowledge gap and institutional path dependency of local governments.

4.2.2 Inadequate Evaluation of River Health and Failed PPP Models

River health assessment within the context of the SCP has not been a primary focus of scientific research. Rather, most scientific tools have been geared towards appraising the cost-effectiveness of green infrastructure, as evidenced by Mei et al. (2018). Similarly, investigations such as Li et al. (2019) have mainly focused on the various benefits of combinations of LID units rather than examining rivers in isolation. Regrettably, despite the pressing need for it, a proper evaluation of the health of rivers after restoration has yet to be established. China established standards for surface water environmental quality in 2002; however, the absence of biological indicators renders the current physical and chemical measuring methods insufficient for comprehensively assessing river ecosystem health (Cao & Wantzen, 2023).

In a groundbreaking move, the Chinese Ministry of Water Resources released the „River Health Evaluation Guide" in 2020, which united multiple performance indicators, including water quantity, quality and biology (such as invertebrates, fish and aquatic plants), as well as social service functions, to assess the overall health of river systems. This initiative was widely propagated to governments at all levels across the nation. Additionally, beginning in 2019, the notion of ecological flow was instituted into policy. The Yangtze River Commission has, therefore, established ecological flow targets for important rivers and lakes, and instituted an ecological flow rule platform to ensure those rivers do not dry up during droughts. However, urban streams are rarely addressed. The financial burden of conducting regular river health assessments has hindered progress; applying the „River Health Evaluation Guide" is not yet standard practice under the SCP.

Practitioners from the private sector also shed light on the dearth of a well-defined business strategy for the PPP model in SC funding (Wang et al., 2017), notwithstanding the endorsement of it by the central government. In recent years, private companies are gradually distancing themselves from investing in SCP due to the lack of immediate financial benefits. Local government investments and debt issuances become the only funding sources for current SC construction. The obstacles associated with the PPP model confirm those identified in prior research on obstacles to the Chinese PPP model, notably cost overruns, time overruns and wrong expected return (Bashar et al., 2021).

4.2.3 Fragmented River Management and Deficient River Basin Perspective

River restoration projects posed a challenge, which was not frequently mentioned in scientific papers but extensively observed in reality, on the collaboration and coordination between diverse departments involved in river management in Chinese cities. China follows a sectoral river management structure, where each department is only answerable for its tasks: The Environment and Ecology Bureau oversees water quality, the Water Resource Bureau looks after flood protection, the Planning and Natural Resources Bureau is responsible for land use and the Forestry and Parks Bureau is in charge of riparian vegetation, with little horizontal connections among them (Shen, 2021). This setup led to conflicts during the river restoration, with each department prioritizing its duties without any cooperation (Cao & Wantzen, 2023). Nevertheless, our interviews also confirmed the effectiveness of the newly introduced national policy in 2018, known as the River Chief System, as a crucial role in resolving inter-departmental conflicts and creating a shared vision for river management (Li et al., 2020; Wang & Chen, 2019). Integrated river basin management was also found to be a distant goal in China as the coordination mechanism at the basin level remains weak. Despite the existence of six river basin committees, including the Yangtze River Committee and the Yellow River Committee, they are still subordinate to the Ministry of Water Resources, leaving them with limited coordinative powers among the upstream and downstream provinces (Cao & Vazhayil, 2023). Administrative boundaries serve as the province and city's jurisdictional limit in managing rivers, with little motivation for co-managing transboundary rivers between administrative regions. This finding, in alignment with the bibliometric analysis, underscored the missing river basin perspective in current river restoration.

4.2.4 Limited Public Awareness and Participation

The final challenge lay in the public's limited awareness of rivers and restricted public participation in the river management process. The public sometimes failed to view the river as a 'sponge' entity, lacking an understanding of the river"s flood mitigation capacity. This finding was in line with the social survey results of Wang et al. (2017). Conversely, the public's expectations of SCP were found to be excessively idealistic, with many erroneously believing that it could entirely resolve urban flooding issues. When the Zhengzhou flood disaster struck in July 2021, the public thus criticised the Zhengzhou government"s sizable investment in SC construction, which still resulted in huge flood damage, leading to scepticism about the SC concept nationwide. However, as an NbS, SC needs time to demonstrate its effectiveness, and mitigating floods from intense rainfall events often requires hybrid measures (Vojinovic et al., 2021). As a relatively new policy, the application of SC in China is still underway. Lastly, due to the limited public participation in China's current river management scheme, many river restoration projects do not include societal stakeholders in decision-making. Public engagement is not only under-discussed in scientific studies, as revealed by the bibliometric analysis, but also overlooked by practitioners in SC design. On a positive note, the RCS has created opportunities for public involvement; despite being limited, the public can supervise RCs" work, thereby raising their awareness of urban rivers (Cao & Wantzen, 2023).

5 DISCUSSION

Implementing on a national scale, SCP is a mainstream effort by the Chinese government to implement NbS with hybrid solutions, supported by continuous government investment. Similar to sustainable drainage systems (SuDS) and LID, the SC concept is developing with Chinese characteristics during rapid urbanization (Griffiths et al., 2020; Lashford et al., 2019). Urban rivers, often reflecting the historical water city design in ancient Chinese dynasties (Liu et al., 2015), are critical to managing flood risks under the SCP (Xia, Shi et al., 2017) and restored by SC construction (Wang et al., 2016). As revealed by keywords' temporal analysis (see Figure 3), a growing scientific understanding has shifted river restoration focus from solely hydrological control to a more holistic approach incorporating social-ecological consideration (Zhao et al., 2019) and microclimate effects (Jiang et al., 2018), such as heat island reduction (Wang et al., 2018). This shift emphasises the sustained benefits of urban river restoration, in accordance with the cross-sectoral multifunctionality of NbS for sustainable urban development (Nesshöver et al., 2017).

However, the successful implementation of NbS in urban settings faces many barriers (Ershad Sarabi et al., 2019). By combining the results of interviews with practitioners and bibliometric analysis, we have identified several challenges in urban river restoration within China's SCP. The identified knowledge gap confirms the need to enhance the cognitive capacities of local policymakers to integrate NbS into daily planning practices and associated governance (Wamsler et al., 2020). In terms of flood management, there is still a prevalence of engineering mindsets (Qiao et al., 2018) and prioritization of quantifiable objectives within short time frames (Qiao et al., 2020) in river restoration projects. This phenomenon manifests as spatial inequality in Chinese cities, where less-developed regions often struggle to overcome path dependency in organizational decision-making to adopt NbS, compared to their more-developed counterparts (Davies & Lafortezza, 2019).

Although aquatic ecology has been increasingly emphasised in the literature, in practice, ecological considerations are not always prioritised in river restoration under the SCP. In Chinese cities, the restoration of urban rivers is predominantly achieved through site-specific landscape design (Qi et al., 2021); selected river sites are strategically transformed to maximise their functions for human use, overwhelmingly serving as riparian public parks (Liu et al., 2019). This approach underlines the high recreational values of rivers (Durán Vian et al., 2021; Zingraff-Hamed et al., 2018), but the integrity of the river ecosystem, such as supporting biodiversity, is often not a priority and lacks proper monitoring and evaluation. In the long term, this may lead to potential trade-offs among the ecosystem services that NbS provide (Seddon et al., 2020).

This study also addresses the common barriers to NbS uptake concerning inadequate financial resources and uncertainty regarding the implementation process and effectiveness (Ershad Sarabi et al., 2019). While many studies have proved the role of private sector involvement in ensuring the financial viability of the SCP, our interviews revealed that the PPP model faces difficulties in the operation and maintenance of water projects (Liang, 2018). This might necessitate a change in the measurement technique of the cost-effectiveness of NbS compared to engineered alternatives, particularly in terms of valuing their significance in addressing societal challenges (Dick et al., 2019). In 2020, China's central government introduced the Ecology Oriented Development (EOD) model intending to address the critical issues of inadequate funding sources for ecological engineering projects and convert environmental benefits into economic gains (Wang & Han, 2022). The first list of pilot projects, launched nationwide in 2021, has extensively encouraged the PPP (Ministry of Ecology and Environment, 2021). This EOD model may offer fresh opportunities for refining the PPP in the context of river restoration in Chinese cities.

Employing NbS extends beyond a technical issue and presents a new governance challenge. In China, persistent obstacles arise from institutional fragmentation in river management (Cao & Wantzen, 2023; Ershad Sarabi et al., 2019). Moreover, while effective communication, involvement, and feedback are crucial for public participation in NbS (Ferreira et al., 2020), these elements are notably lacking in the river restoration under SCP (Dai et al., 2018). The limited representation of social science and governance research in this field also confirms this gap. Designing collaborative governance for NbS (Malekpour et al., 2021) that actively involves stakeholders and the wider society aids in understanding the complexity of urban rivers as social-ecological systems (Wantzen et al., 2016, 2019; Zingraff-Hamed et al., 2021). This is particularly important for restoring the social connectivity of rivers (Kondolf & Pinto, 2017; Wantzen, 2022). China's RCS plays a pivotal role in this respect by assigning stewardship to Civil RCs, who often include NGOs, experts, and local communities. These groups are involved in preserving the environmental quality of

ISBN 978-3-9504945-2-5. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER, H. R. KAUFMANN – Ljubljana, Slovenia

rivers and providing feedback on the work of the official RCs. This cooperative model (dual RCS) should be effectively implemented across all types of urban river restoration projects in China (Cao & Wantzen, 2023).

6 CONCLUSION

In summary, the steady increase in scientific publications on river restoration under SCP from 2012 signalled a persistent interest in promoting NbS as a critical component of sustainable development in China, with restoring urban rivers serving as a multifaced NbS example for generating both environmental and social benefits. The bibliometric analysis highlighted the interdisciplinary nature of these combined topics and a research trend evolving from primarily managing flood risk towards an integrated focus on aspects such as ecology, urban planning, climate change adaptation, and methodology of modelling and evaluation. However, while there was a strong emphasis on engineering-led river restoration approaches, both the current research agenda and practical application displayed an absence of the social science field. Insights from SCP practitioners identified firsthand challenges in implementing river restoration projects under the SCP, including knowledge gaps, spatial inequality, a deficient evaluation of river health, unsuccessful PPP models, fragmented river management, and limited public participation. These issues conformed to the existing obstacles to NbS adoption and mainstreaming, particularly the limited acknowledgment of local policymakers, insufficient funding resources, potential ecosystem service trade-offs, institutional path dependency, insufficient cost-effectiveness evaluation, and collaborative governance. In China, the RCS policy fostered cross-departmental cooperation and opportunities for public involvement in protecting the river environment. Moreover, the newly established EOD model could potentially revive PPP models at a local level for investing in comprehensive river restoration. Consequently, future research and projects should pursue a more expansive, trans-disciplinary view, considering urban rivers as social-ecological systems and encouraging stakeholder and societal involvement in the long-term management of NbS.

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