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A review of urban rainwater harvesting in China

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ABSTRACT

Over the past 30 years, water security issue in Chinese cities has become increasingly serious, largely due to rapid urbanization, population growth and disproportionate investment in water infrastructure. Urban rainwater harvesting (URWH), a household and community-level rainwater management measure, has been widely used during this period. This study provides a critical review of the policies, methods, technology, construction, implementation and benefits related to URWH in China. We show that URWH in China has gone through three phases over the past 30 years: an initial development phase, a rapid development phase and a sponge city construction phase. URWH research has focused mainly on rainwater harvesting, storage, utilization, management and other technologies, with limited attention to policy and benefit analysis. However, the scale of URWH construction and implementation in China remains small and needs further development. Currently, while URWH assessments cover social, ecological and environmental benefits, the economic benefits need to be further strengthened. The next step in URWH implementation should be to strengthen research and development of policy, legal and design standards. This study provides guidance for the implementation of URWH in Chinese cities and other cities alike in developing countries.

Key words: Chinese cities, rainwater utilization, sponge city, urban rainwater harvesting, urban water management

HIGHLIGHTS

- Urban rainwater harvesting (URWH) in China has been divided into three stages.
- The construction and development of laws and regulations should be emphasized in China in the future.
- The construction of URWH projects in China has been uneven.
- China's URWH construction constitutes government-led investment projects embodying positive social and ecological benefits.

1. INTRODUCTION

Over the past 30 years, Chinese cities have experienced a period of rapid development and construction. Accordingly, China's urbanization rate has increased from 26.41% in 1990 to 63.89% in 2020. However, the urbanization process has been accompanied by increasing urban water problems, and in some cities, water scarcity has severely affected and restricted development (Yang *et al.* 2020; Cai *et al.* 2021; Wang *et al.* 2021a, 2021b, 2021c; Zheng *et al.* 2022). At the Urban High-level Development Forum in 2010, scholars classified China's urban water problems into four categories: water scarcity, urban flooding, water pollution, and damage to water ecology (Liu *et al.* 2017; Zhou *et al.* 2019; Ahmad *et al.* 2020). Stormwater management in urban areas has become a hot topic in urban hydrology research and also plays a key role in solving urban water problems (Jin *et al.* 2014; Moravej *et al.* 2021).

Urban rainwater harvesting (URWH) is an integrated rainwater management measure that collects, stores, treats, uses and discharges rainwater in urban areas (Campisano *et al.* 2017; Zheng *et al.* 2021). Rainwater can be used as a resource to supplement urban water supply and alleviate urban water scarcity (Mankad *et al.* 2013; Zhang *et al.* 2019a, 2019b). Rainwater harvesting and storage can effectively reduce urban surface runoff and alleviate urban flooding (Zhang *et al.* 2012) URWH can increase the retention and penetration of rainwater, reduce the risk of urban flooding, decrease river and lake pollution and improve the environmental and ecological quality of watersheds in urban areas (Campisano *et al.* 2014; Norman *et al.* 2019). URWH is an effective concept and approach to solve comprehensive urban water problems (Zhang *et al.* 2012;

Kaposztasova *et al.* 2014; Campisano *et al.* 2017; Hu *et al.* 2019). For China, the utilization of urban rainwater resources has become very important in the rapid urbanization process.

Urban rainwater utilization in China has a long history, with the construction of ponds to store domestic rainwater recorded as early as the Qin and Han dynasties, and the construction of water cellars in northwest China for several hundred years. However, the research and application of urban rainwater utilization in the real sense began in the 1980s and developed in the 1990s, later than in the United Kingdom, the United States, Australia, Germany and other developed countries (Dai *et al.* 2019). However, the research on rainwater utilization has developed quickly during rapid urbanization (Zhang *et al.* 2020; Wang *et al.* 2021a, 2021b, 2021c). The initial driving factor for URWH development was water scarity in urban areas of China (Song *et al.* 2010). In the 1990s, several cities with severe water shortages began to explore rainwater harvesting and utilization (Sun *et al.* 2001; Zhang *et al.* 2004; Ding *et al.* 2006; Kong 2007). With the organization of the International Conference on Rainwater Harvesting and Utilization in China and the China Urban Rainwater Harvesting and Utilization Conference, the Chinese government began to pay attention to urban rainwater sanitation. The central and local governments issued a series of policies related to urban rainwater utilization (Xu *et al.* 2017), research on URWH methods and technologies has helped to formulate a series of national and local standards to guide the standardized construction and development of urban rainwater management and utilization in China (Cai *et al.* 2021; Wang *et al.* 2021a, 2021b, 2021c). The concept of sponge cities has been proposed in China, and the construction of sponge city pilot projects has been carried out in several cities (Song *et al.* 2018; Dai *et al.* 2019; Liu *et al.* 2020). As an important sponge city measure, URWH has been widely promoted and applied in the 'sponge city' pilot cities (Wei & Chen 2018; Liu *et al.* 2019; Ma *et al.* 2019).

Extensive references cover URWH in China, including many research topics: rainwater utilization and reuse policies, methods and technologies, construction implementation and benefit evaluation. Existing experiences or issues related to these topics will influence URWH development and urban water issues in Chinese cities. Therefore, there is a growing demand for information and guidelines on URWH developments, issues and recommendations in urban areas.

This review summarizes the URWH policy evolution in China, analyzes the methods, technologies, construction and benefits of URWH and puts forward recommendations for the further development of URWH. This review provides a bibliometric analysis of topics related to rainwater harvesting in the relevant literature, covering the timelines of URWH policy development; methods, technologies and construction; and the evaluation of benefit analysis methods.

2. BIBLIOMETRIC ANALYSIS OF URWH STUDIES IN CHINA

Bibliometric analysis is a scientific and effective approach to literature analysis: a quantitative method to obtain the qualitative characteristics of scientific research by examining science as a knowledge generation system (Wang *et al.* 2021a, 2021b, 2021c). VOSviewer is a software tool for analyzing bibliometric networks, developed by Nees Jan van Eck and Ludo Waltman at Leiden University's Centre for Science and Technology Studies (CWTS). VOSviewer can be used to construct networks of scientific publications, scientific journals, researchers, research organizations, countries, keywords or terms (van Eck & Waltman 2010). Here, we selected keywords and countries to construct an analysis network through VOSviewer (version 1.6.17.0) using the data source Web of Science.

Based on the analysis of high-frequency buzzwords of URWH in the Chinese literature, we selected the following: 'urban rainwater harvesting' OR 'urban rainwater utilization' OR 'urban rainwater management' OR 'urban rainwater harvesting and utilization' as the 'topic'. The 'address', including China, to search the literature on the Web of Science. A total of 1,649 related articles were retrieved from Web of Science. We exported all relevant data from these articles as basic data and then performed bibliometric analysis using VOSviewer software.

Then, we created maps based on the bibliographic data from VOSviewer. The analysis type was 'co-occurrence', and the unit of analysis was 'all keywords'. When the minimum number of occurrences of a keyword was set at 20, the valid items were out to be 100. Figure 1(a) shows the network visualization of the analysis results. Items are represented by their label and, by default, by a circle (Brika *et al.* 2021). The larger the label and circle of an item, the higher the weight of it. The hotspot keywords for China URWH research were rainwater harvesting, rainwater, management, runoff, performance and quality, all of which are highly weighted. The color of an item was determined by the cluster to which the item belonged (van Eck & Waltman 2010). The hotspot keywords for China RWH belonged to four clusters. In the item density visualization, items are represented by their label in a similar way to the network visualization. The higher the number of

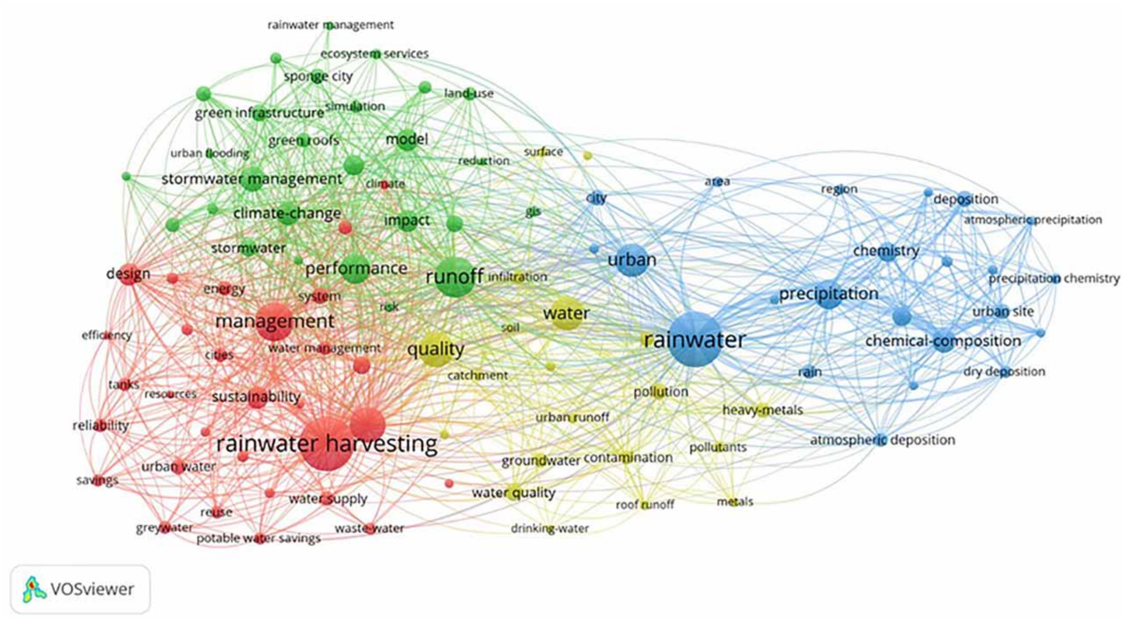

Figure 1 | Bibliometric analysis of RWH: co-occurrence network map of keywords for China.

items in the neighborhood of a point, the higher the weights of the neighboring items, and the bigger size of the circle label. The keywords rainwater harvesting, rainwater, management, runoff and quality have a larger number of items.

3. THE HISTORY OF URWH

3.1. The history of URWH in China

Since 1990, several Chinese cities – including Beijing, Shanghai, Xi'an and Dalian – have conducted research on rainwater harvesting and utilization in urban areas, with the aim of alleviating urban water scarcity (Kong 2007). In the mid-1990s, with the convening of the Chinese Academic Conference on Rainwater Harvesting and Utilization and the International Conference on Rainwater Harvesting and Utilization, research on urban rainwater utilization in China entered a formal development stage. Figure 2 shows the development process and important nodes related to the URWH policy from 1990 to 2021 in China. Through the timeline, the URWH development process in China can be divided into the following three stages over the past 30 years.

1. 1990–2006: This period marked the initial stage of URWH development in Chinese cities. After the 7th International Rainwater Catchment Systems Association Conference was held in Beijing in 1995, the First National Seminar on Rainwater Utilization was held in Lanzhou, and the Second National Seminar on Rainwater Utilization was held in Xuzhou. Thus, research on URWH policy, theory, and technology had begun in China (Sun *et al.* 2001; Zhao & Niu 2001).
2. 2006–2015: In 2006, the national standard of 'Engineering technical code for rain utilization in building and sub-district' was implemented, marking the beginning of the standardization process of urban rainwater utilization in China (Li *et al.* 2008). During this period, many Chinese cities carried out the construction of rainwater collection and utilization facilities, especially with the 2008 Beijing Olympics as an opportunity (Li *et al.* 2006). URWH in Chinese cities began to develop rapidly (Chao *et al.* 2011; Wang *et al.* 2014). From 2012 to 2014, the Chinese government proposed a new concept for urban development strategy – the 'Sponge City' (Guan *et al.* 2021). The core element of the Sponge City is to achieve reasonable 'infiltration, retention, storage, purification, use and drainage' of rainwater in urban areas (Wang *et al.* 2018). Therefore, URWH is an important integrated engineering measure in sponge city construction (Liu *et al.* 2019; Ma *et al.* 2019).
3. 2015–2021: Starting from 2015, Chinese cities started the pilot construction of sponge cities, and most of the cities have begun to formulate special plans for sponge cities (Chen *et al.* 2020). The Chinese government approved the first batch of 16 pilot cities in 2015 and the second batch of 14 pilot cities in 2016 (Zhou *et al.* 2018). Since then, URWH in China has entered a

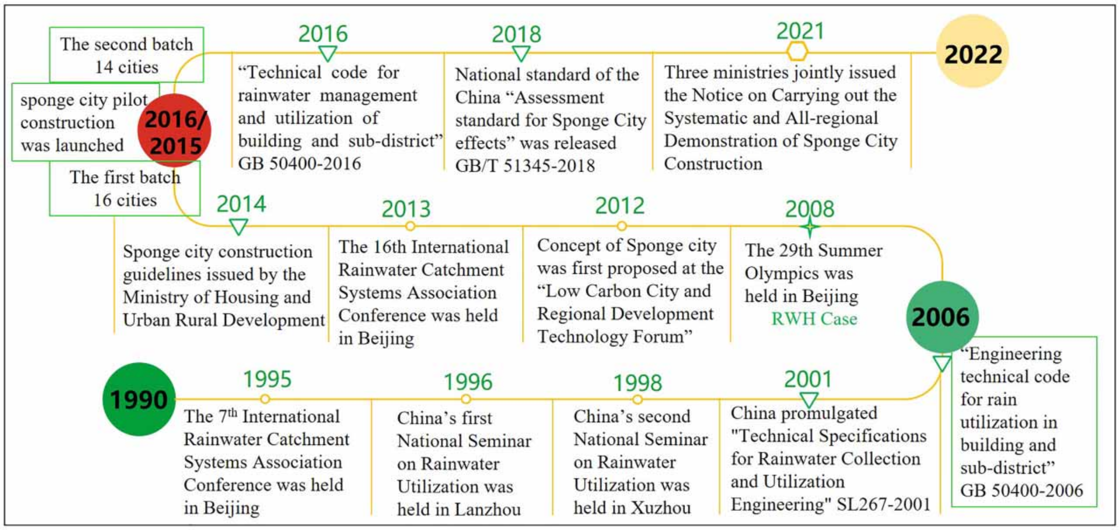

Figure 2 | Policy evolution of URWH in China, 1990–2021.

new stage of development, which is to coexist and merge with the sponge city concept (Dai *et al.* 2019; Wang *et al.* 2019). In 2016, the 'Technical Standards for Stormwater Management of Buildings and Residential Units' was promulgated. In April 2021, the Ministry of Finance, the Ministry of Housing and Urban–Rural Development and the Ministry of Water Resources jointly issued a notice on carrying out the Systematic and All-regional Demonstrations of Sponge City Construction.

In Figure 2, rainwater recycling at the national level in China includes relevant international conferences, national conferences, technical specifications, industry standards, government policy documents and typical application cases. In the past 30 years, the development of Chinese urban rainwater resources under its own demand traction, with domestic and international academic conferences as a starting point, under the lead of national policies and government documents, development of relevant technical specifications, to carry out the construction of rainwater utilization practices, especially in Beijing 2008 Olympic Games as an opportunity to China urban rainwater utilization technology to get fast development. Since 2015, with the implementation of sponge city construction in China, major cities have started the construction practice of rainwater resource utilization measures.

3.2. The history of URWH in Beijing

From the perspective of policy evolution and development for specific cities, many cities have successfully carried out research on URWH since the late 1990s. Beijing was the most prominent representative city in the development and utilization of URWH (Kong 2007). In Beijing, URWH policies cover several aspects, including legal, economy, administration, technology, publicity, and education. An initial development framework has been formed (Wang *et al.* 2014). The economic measures in Beijing include subsidies, fines and relief systems (Zuo *et al.* 2009). We take Beijing as a case study to summarize and analyze the development process of URWH in a specific Chinese city.

Figure 3 shows the development of major URWH-related policies, standards and regulations in Beijing over the past 20 years. After Beijing's government issued the order of 'Beijing Water Conservation Regulations' in 2000, this city successively promulgated and implemented the 'Interim Regulations on Strengthening the Utilization of Rainwater Resources in Land for Construction Projects' and the 'Rainwater Utilization Proposal', and issued the 'Notice on Strengthening Rainwater Utilization Projects of Construction Projects' (Wang *et al.* 2014). In 2009, Beijing released the landmark 'Technical Regulations for Urban Rainwater Utilization Engineering' and 'Regulations for Construction and Acceptance of Permeable Brick Pavements', indicating that Beijing's rainwater collection and utilization policies had entered a standardization process (Zhang *et al.* 2011). In 2013, Beijing compiled the 'Examples Compilation of Beijing Rainwater Utilization Projects'. Beijing became one of the second batches of sponge city pilot cities in 2016 so that URWH began to be widely promoted and get a rapid development. Beijing has become the leader and model of URWH among Chinese cities.

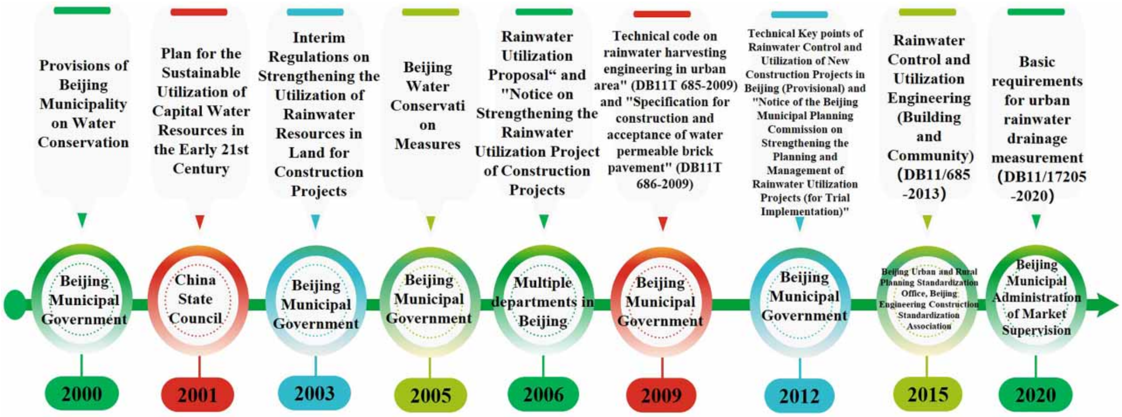

Figure 3 | Key URWH policies in Beijing.

The development of rainwater resources in Beijing is mainly marked by policy issuance and standard formulation. In the past 20 years, the Beijing Municipal government has promulgated a number of policies related to URWH and issued a number of local standards related to urban rainwater control and utilization. Beijing is the most representative city in the utilization of urban rainwater resources in China, and its development process of urban rainwater resources is a model that other Chinese cities should learn from.

4. URWH METHODS (TECHNIQUES) AND CONSTRUCTION

4.1. URWH methods in China

The ways of urban rainwater recycling can be summarized into three categories: rainwater direct utilization technology, rainwater indirect utilization technology and rainwater comprehensive utilization technology (Li *et al.* 2008). Rainwater direct utilization is to directly collect rainwater and reuse it later, the core part of which is the rainwater tank (or reservoir) with the basic function of rainwater storage and treatment (Zhang *et al.* 2010; Chapa *et al.* 2020). Rainwater indirect utilization refers to the use of natural or artificial auxiliary seepage facilities to achieve the purpose of rainwater infiltration (Liu *et al.* 2014). The comprehensive utilization of rainwater is to optimize the combination and integration of various rainwater resources (Yang 2020), which is equivalent to the sum of direct and indirect utilization of rainwater, but its combined benefit is greater than that of a single rainwater resource. Figure 4 shows the classification, collection measures and reuse process of rainwater harvesting. Direct use of rainwater mainly refers to the roof and impervious road surface rainwater collection, storage, treatment and reuse of the use of measures; Indirect utilization of rainwater refers to the rational utilization of natural infiltration facilities or artificial auxiliary infiltration facilities in order to achieve the purpose of rainwater infiltration and replenishment, which can improve water environment and water ecology; The rainwater resource utilization in sponge city or sponge community construction is mainly based on comprehensive utilization.

Based on the investigation and analysis of URWH methods in Chinese cities, a scientific and comprehensive classification of URWH is made based on the characteristics of underlying urban surface types (Yang *et al.* 2010; Hu *et al.* 2012). For different types of underlying surfaces, there are obvious differences in the methods and processes of rainwater harvesting and utilization (Zhang 2005; Ma *et al.* 2019; Zhou *et al.* 2019). According to the land use type of the underlying surface of the city, URWH methods can be classified as roof RWH, hardened ground RWH and green land RWH (Zhang *et al.* 2014a, 2014b). Figure 5 shows the classification of methods and technologies used for URWH for different types of underlying surfaces in Chinese cities.

1. Roof rainwater harvesting method

Roof RWH can be divided into hardened roof RWH and green roof RWH (Hu *et al.* 2012; Chubaka *et al.* 2018). The term 'hardened roof' refers to the traditional impermeable roof, which can intercept rainfall that will be collected in a rainwater tank, rainwater barrel or rainwater pound through a draft tube (Sánchez *et al.* 2015; Dai *et al.* 2019). The rainwater storage

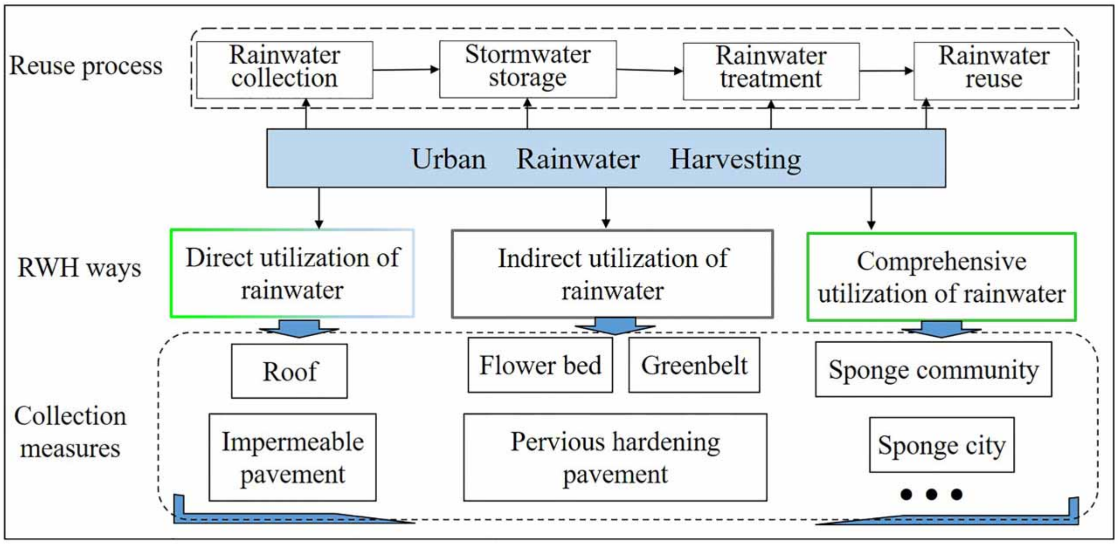

Figure 4 | Urban rainwater harvesting ways' classification.

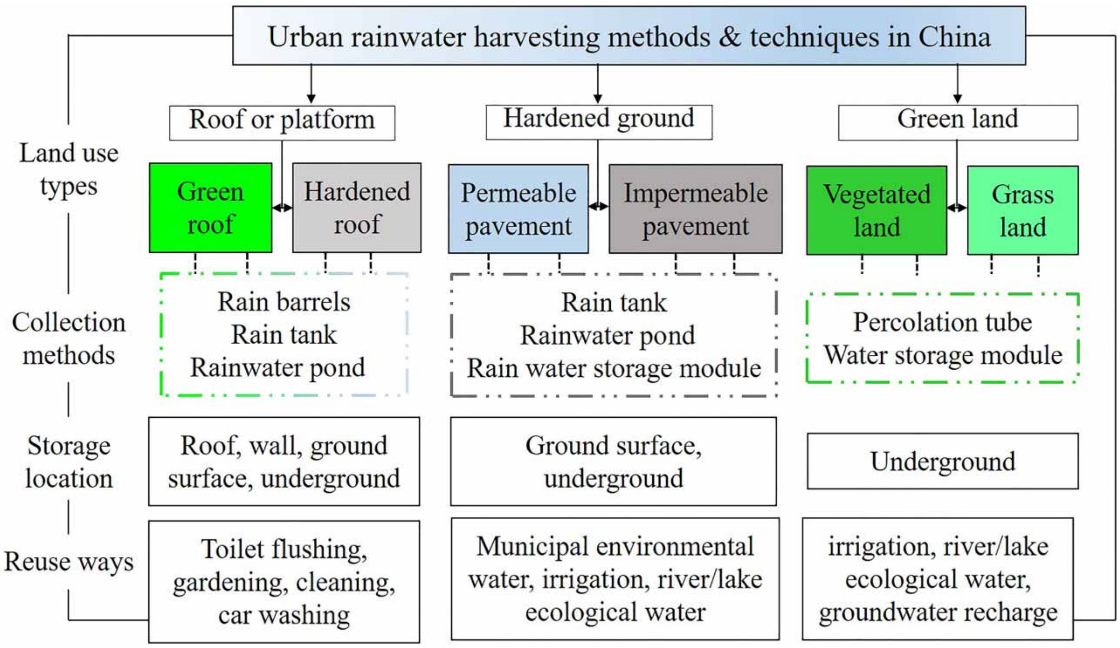

Figure 5 | Classification of methods of rainwater harvesting and utilization.

container can be installed on the roof, wall or other high places, or placed on the surface or underground (Arthur & Wright 2005; Kim *et al.* 2015). Green roofs are also referred to as planted roofs and roof greening (Van Mechelen *et al.* 2015; Abu-Zreig *et al.* 2021). This refers not only to roof planting but also to all kinds of terraces, roofs, balconies, walls, tops of underground garages and overpasses that are above the ground and not connected to the natural soil (Zhang *et al.* 2014a, 2014b; Van Mechelen *et al.* 2015). Green roof RWH absorbs rainwater through vegetation and the root layer, which can then form a micro-water cycle of vegetation–soil–atmosphere, effectively improving the local microclimate (Konopka *et al.* 2021; Zhang *et al.* 2021). Meanwhile, the urban water-storage green roof has a significant effect on the removal of pollutants such as SS, COD, TN and TP in rainwater runoff. After rainfall, rainwater purified by the vegetation rhizosphere is discharged into rainwater harvesting containers through soakaways and rainwater pipes for irrigation of green areas or toilet flushing (Aloisio *et al.* 2016). The rainwater collected from the roof has good water quality, so this rainwater can be used for a variety of purposes (Ahmed *et al.* 2017; Sepehri *et al.* 2018), not only for outdoor uses such as watering and washing cars but also for indoor flushing, washing clothes and cleaning (Norman *et al.* 2019; Zabidi *et al.* 2020; Konopka *et al.* 2021). In Chinese cities, the acceptance of roof rainwater as indoor water is relatively low and is mainly used for flushing. This water is more often used for outdoor vegetation irrigation and car washing (Zhang *et al.* 2014a, 2014b; Hai *et al.* 2019).

2. Hardened ground rainwater harvesting

Hardened ground RWH is divided into permeable pavement hardened ground RWH and impervious hardened ground RWH (Hou & Zhang 2014; Zhou *et al.* 2021). For permeable hardened pavements, rainwater passes through the permeable hardened layer mainly through infiltration and enters the rainwater collection device under the pavement, and this rainwater is used after purification (Qin *et al.* 2019; Zhou *et al.* 2021). The impervious ground intercepts rainfall and collects rainwater through scattered perforated strainers (Roy & Shuster 2009; Dams *et al.* 2013). The pavement can be all types of urban ground such as squares, parking lots, sidewalks and motor vehicle lanes (Liu *et al.* 2015; Elqattan & Elryies 2021). The main storage containers for such rainwater include rainwater tanks, rainwater ponds and other rainwater storage modules (Mahmoud *et al.* 2014). Usually, these rainwater storage containers are placed below the ground. Rainwater collected from urban ground is mainly used for municipal environmental water and irrigation of greenbelts (Chakraborti *et al.* 2017; Gado & El-Agha 2020). In Chinese cities, rainwater collected from the ground is mainly used for road sprinkling, vegetation irrigation and ecological water replenishment for rivers and lakes (Luo & Wang 2018; Zhang *et al.* 2019a, 2019b).

3. Green land rainwater harvesting

Green land RWH includes rainwater gardens, rainstorm gardens, sunken green spaces, constructed wetlands and other green and low-impact development infrastructure (Zhang 2005; Kong 2007; Wang *et al.* 2019). Greenland rainwater collection and utilization methods intercept rainwater mainly through vegetation, absorb and purify it through vegetation rhizosphere, and surface runoff flows into water bodies such as ponds and pools or human-constructed wetlands (Song *et al.* 2018; Wei & Chen 2018; Wang *et al.* 2019; Liu *et al.* 2020). Rainwater collected from urban green space is mainly used as urban ecological and environmental water (Weichselbraun *et al.* 2014; Wiesner *et al.* 2016). In Chinese cities, rainwater is mainly used for vegetation irrigation, groundwater recharge and ecological recharge of rivers and lakes (Yu *et al.* 2011; Zhang & Chui 2019).

Table 1 shows the implementation cases of various URWH methods or measures in Chinese cities, taking Beijing as an example. The selected cases are representative of Beijing's rainwater harvesting and utilization measures. The scale of implementation, the volume of rainwater available, the rainwater utilization method and other parameters are shown in Table 1.

4.2. URWH construction in China

The average annual rainfall in Beijing is 585 mm, which is unevenly distributed throughout the year; the majority of rainfall occurs from June to August (Zhou *et al.* 2020). Beijing's per capita water resources are below 150 m^3/year, substantially less than the standard value (1000 m^3/year) marking severe water shortage in cities according to the United Nations. Therefore, Beijing is a city with severe water shortages (Jia *et al.* 2017). Beijing has been exploring and implementing urban rainwater resource policies since the 1990s (Zuo *et al.* 2009; Zhang *et al.* 2011). Presently, URWH implementation in Beijing is at the forefront of Chinese cities (Xu *et al.* 2017). Therefore, we choose Beijing as an exemplary city to summarize and analyze the construction and implementation of URWH in Chinese cities.

In 2000, the Beijing Municipal Water Resources Bureau and the University of Essen of Germany jointly initiated a rainwater utilization project, marking the initiation of URWH construction in Beijing (Zhang *et al.* 2011). In 2004, the number of rainwater utilization projects in Beijing stood at 38, with a catchment area of 7.45 km^2 and a rainwater utilization volume of 920,000 m^3. By the end of 2006, Beijing had completed 60 rainwater utilization projects within the urban area, distributed in schools, parks, government agencies and residential communities (Li *et al.* 2008). The utilization volume of rainwater then exceeded 20 million m^3. In 2007, more than 300 rainwater utilization projects were newly built in Beijing. By the end of 2010, there were nearly 700 rainwater utilization projects in Beijing, with a rainwater utilization volume of more than 40 million m^3 (Li *et al.* 2015).

Table 1 | Implementation cases of URWH methods in Beijing

RWH method	Project name	Water collecting area (m^2)	RWH capacity (m^3)	RWH technique	Water Use
Hardened roof RWH	Water Cube (Zuo *et al.* 2009)	29,000	10,500	Scattered collection and centralized processing	Vegetation irrigation, Landscape water, Toilet flushing
Green roof RWH	Tianxiu Garden Community (Chiu 2012)	23,900	5,600	Centralized collection and centralized processing	Vegetation irrigation, Landscape water
Permeable pavement RWH	Bird's Nest Square (Liu *et al.* 2015)	220,000	67,000	Scattered collection and centralized processing	Vegetation irrigation, Landscape water, Toilet flushing, Washing of parking lots, runways and roads
Impermeable pavement RWH	Lotus Bridge Reservoir (Wang *et al.* 2021a, 2021b, 2021c)	136,000	12,000	Scattered collection and centralized processing	Vegetation irrigation, River supplement water
Green land RWH	Olympic Sunken Garden (Li *et al.* 2017a, 2017b)	45,000	26,325	Scattered collection and scattered processing	Landscape water, Ecological water

Since 2012, the Beijing Municipal Water Affairs Bureau has tracked the number of urban rainwater utilization projects, comprehensive rainwater utilization capacity and comprehensive utilization of rainwater, annually. Figure 6 shows the construction and development of rainwater collection and utilization projects in Beijing from 2012 to 2021, of which the data are obtained from the Beijing Municipal Water Affairs Statistical Yearbook (2012–2021). Rainwater harvesting capacity refers to the amount of rainwater collected by Beijing URWH projects in a given year under a given rainfall condition. The results show that in the past few years, the number of URWH projects in Beijing has increased rapidly. The number of URWH projects in 2021 increased by 56.22% compared to 2012 and the rainwater harvesting capacity increased by 57.20% from 2021 to 2012. The utilization volume of rainwater resources in Beijing amounts to nearly 50 million m^3. The actual amount of rainwater use is less than the rainwater harvesting capacity in most years except for 2012 and 2013. This was because the statistical caliber of actual rainwater utilization volume in Beijing has been adjusted since 2014. In both 2012 and 2013, the reduced runoff volume in areas with rainwater reclamation measures was all considered as rainwater utilization volume. However, since 2014, only the rainwater collected within the collection facility was considered as the actual rainwater utilization volume. The current situation of URWH in Beijing is that collected rainwater is mainly used for vegetation irrigation. It can be shown that the actual volume of rainwater utilization is related to factors such as rainfall, rainwater collection capacity and rainwater reuse times. If the rainfall is insufficient and the amount of rainwater used is higher than the preset target, the actual amount of rainwater used will exceed the preset rainwater harvesting capacity. The specific relationship is more complex and requires more data for analysis and future research.

From the statistical data, it can be seen that the project number, comprehensive utilization capacity and comprehensive utilization of rainwater resources in Beijing have not changed significantly since 2017. In the past five years, the annual rainfall in Beijing has changed significantly, but the utilization of rainwater has not changed significantly. The main reason may be that the construction of rainwater resources in Beijing has not made significant progress and changes in recent years, and the utilization demand of rainwater in Beijing has not changed significantly.

The data investigation and data collection show that no cities in southern China have carried out systematic and large-scale construction of rainwater resources, and no official reports on rainwater collection and utilization have been found like Beijing. In order to understand the construction and development of rainwater resources in other cities in China, the literature analysis was carried out as follows: The construction of the 2008 Beijing Olympic Games venues was a typical RWH case in Chinese cities, and the 2012 Shanghai World Expo also adopted a large number of rainwater recycling measures (Li *et al.* 2021). After 2015, with the implementation of sponge city construction in China, urban rainwater harvesting measures, as comprehensive sponge measures, have been widely applied to the construction of sponge communities, sponge parks or sponge roads (Zhang *et al.* 2017; Li *et al.* 2022). The practice of rainwater utilization in Nanjing City shows that 55% of

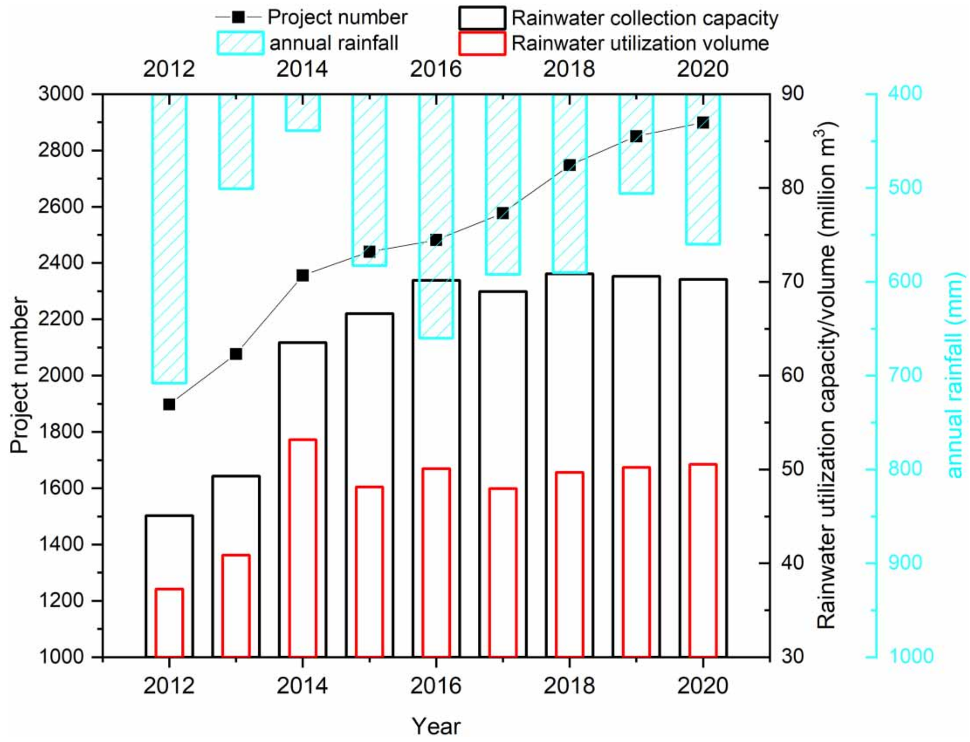

Figure 6 | URWH project construction in Beijing from 2012 to 2021.

the roof with rainwater collection boxes can reduce 15–58% of the surface runoff under different rainfall conditions (Zhang *et al.* 2012). The case study of rainwater collection and utilization in residential communities in Shanghai shows that when the life cycle of rainwater recycling system is 15 years, the return on investment time is 8.26 years, furthermore, rainwater utilization can improve the sustainability of cities. Guangzhou, Wuhan, Beijing and Harbin were selected as the representatives of four cities with different climate regions to evaluate the water-saving potential and economy of the rainwater resource system (Chen *et al.* 2022). The results show that Guangzhou has the largest water-saving potential and the highest return on investment (Chen & Zhang 2021).

5. URWH BENEFITS

URWH brings economic, social, ecological and environmental benefits (Christian Amos *et al.* 2016; Zhang *et al.* 2020). From the perspective of economic benefits, URWH can save on the costs of alternative water resource treatment and transportation, and it can also save the costs of rainwater discharge and treatment (Dallman *et al.* 2021). In the long run, it can also save on the costs of urban water transportation projects and inter-basin water transfer projects, along with reducing energy consumption caused by water supply and drainage (Zuo *et al.* 2010). The indirect method of URWH economic benefits evaluation is mainly based on the amount of rainwater that can be collected and used (Christian Amos *et al.* 2016). The methods for evaluating the amount of rainwater available in cities are the empirical method and the runoff coefficient method (Zuo *et al.* 2009, 2010). The direct evaluation method for economic benefits adopts the cost–benefit analysis method for Chinese cities (Fan & Matsumoto 2019).

Chinese cities have promoted URWH social benefits to urban residents in terms of using rainwater resources, along with enhancing awareness of water conservation (Chai *et al.* 2019). Construction of China's sponge cities focuses on policy publicity and citizen participation (Zhang *et al.* 2018). In the process of participation, citizens gradually realize the severe situation of water scarcity in Chinese cities, which promotes social recognition and the development of URWH (Hai *et al.* 2017). URWH construction in Chinese sponge cities can effectively reduce surface rainfall-runoff peak and volume of rainfall in stormwater management areas, effectively reduce and mitigate the risk of urban flooding and protect the lives and properties of urban residents, with yielding significant social benefits (Hai *et al.* 2019).

In terms of ecological and environmental benefits, URWH projects, such as green roofs, rainwater gardens, permeable pavements and constructed wetlands, not only utilize rainwater but also infiltrate it into the soil (Jóźwik 2020), which contributes to a vegetation–soil–atmosphere water cycle model that can effectively improve the microclimate and mitigate the heat island effect in urban areas (Novo *et al.* 2013). Therefore, URWH can effectively improve the water environment and water ecological quality in urban areas in China.

Table 2 shows several calculation methods for rainwater collection/utilization volume and benefits analysis of URWH projects in China. These methods are applicable mainly to URWH projects based on underlying surface types in Chinese cities (Sun *et al.* 2001; Li *et al.* 2011). The estimation method of rainwater collection volume is the runoff coefficient method. The main methods of economic benefit evaluation are cost–benefit analysis and rainwater utilization benefit index analysis. There are also comprehensive analysis methods of economic, social and environmental/ecological benefits based on the vague set and AHP (Analytic Hierarchy Process) model (Zuo *et al.* 2009). These methods are suitable for the estimation of rainwater

Table 2 | Calculation methods for rainwater utilization estimation and benefit analysis for URWH in China

Order	Evaluation target	Calculation method	Spatial scale	Temporal scale	Remarks
①	Rainwater volume (Huang *et al.* 2007)	$W = F \times P \times r$	City/region	Year/ month/ Specific rainfall	W is regional rainwater utilization volume, F is the regional area, P is precipitation, r is combined runoff coefficient
②	Rainwater volume (Ma *et al.* 2019)	$W = H \times A \times \alpha \times \beta \times \varphi$	Plot/ underlying surface type	Year/ month/ Specific rainfall	W is rainwater utilization volume, A is plot/surface area, H is precipitation, φ is combined runoff coefficient, α is abandon flow coefficient, β is seasonal reduction factor
③	Rainwater volume (Yu *et al.* 2007)	$Q_S = Q_1 + Q_2 + Q_3$ $Q_1 = \sum_{i=1}^{m} (R_i - R_k) \times S_1$ $Q_2 = \sum_{i=1}^{m} (R_i - r_a) \times S_2$	City/region	Year/month	Q_S is potential urban rainwater harvesting, Q_1 is the amount of rainwater generated by impervious underlying surface, Q_2 is the amount of rainwater resources generated by green space, Q_3 is the amount of rainwater in the water area
④	Rainwater use efficiency (Zhu *et al.* 2017)	$E_i = P_i \times S_i$	City/country	Year	E_i is urban rainwater utilization efficiency index, P_i is rainwater utilization potential index, S_i is the weight of water scarcity of city
⑤	Cost–Benefit Analysis (Zuo *et al.* 2009; Chao *et al.* 2011)	$\alpha = \frac{E}{P}$ $E = B \times \frac{(1+i)^n - 1}{i(1+i)^n}$ $P = I + C \times \frac{(1+i)^n - 1}{i(1+i)^n}$	City/region	Year	α is the benefit–cost ratio, E is total benefits value of RWH systems, P is cost value of RWH projects, B is total benefit of URWH projects in one year, C is annual operating costs of stormwater utilization projects, I is fixed gross investment of URWH, n is the design life of URWH
⑥	Comprehensive benefit evaluation of based on Vague set (Jiang *et al.* 2014)	$V_i = W_i \otimes R_i$	Region	Year	R_i is an evaluation matrix of a vague set of economic, social and ecological benefits, which is determined by the AHP, $\otimes$ is the operation symbol of the vague set, W_i is weight vector corresponding to indexes.
⑦	Comprehensive benefits based on the AHP model (Sun *et al.* 2001; Li *et al.* 2017a, 2017b)	$C = SUM[E(x),\ S(x), R(x)]$	City/region	Year	$E(x)$ is economic benefits, $S(x)$ is social benefits, $R(x)$ is environment benefits

amount, analysis of economic benefits and analysis and evaluation of comprehensive benefits for URWH (Chao *et al.* 2011; Zhu *et al.* 2017). Furthermore, these methods are applicable urban and regional scales and usually monthly or annual time scales.

Method ① is mainly used to estimate the rainwater availability of a city or region. It can be assessed for specific rainfall events, or for monthly or annual rainwater availability. In method ②, the discard coefficient and seasonality coefficient are added on the basis of ①, and the use condition and range are the same as ①. Method 3 is to divide the different land use types to evaluate and calculate the rainwater available use, which is applicable to urban or regional scale, mainly calculating the rainwater available use at the monthly or annual scale. Method ④ is used to calculate the efficiency of rainwater use in a city, which is usually calculated in terms of years. Method ⑤ is used for the cost–benefit analysis of rainwater collection and utilization in urban units, which is calculated in the time unit of year. Method ⑥ is the comprehensive benefit analysis of rainwater resource utilization, mainly the fuzzy logic method. Method ⑦ uses the AHP to calculate the comprehensive benefit.

Most URWH measures in Chinese cities are government investment activities, primarily through low-impact development infrastructures such as permeable paving, sunken green space and shallow grass ditch in public areas such as urban parks, green spaces, municipal roads and squares (Chai *et al.* 2019). From the literature review results, the benefits of such URWH projects are mainly reflected in social benefits and ecological benefits (Fan & Matsumoto 2019). Especially since the construction of sponge cities in China, URWH measures have been implemented as important sponge city measures (Hai *et al.* 2017; Hu *et al.* 2019). Considering the economic, social and environmental benefits, the comprehensive benefits of rainwater harvesting measures are even greater (Hai *et al.* 2017). In some areas, rainwater conversion measures have effectively alleviated the flooding problem and avoided the economic impact caused by urban floods and can effectively protect people's lives and property.

6. DEVELOPMENT AND RESEARCH CHALLENGES AND SUGGESTIONS

1. URWH research topic needs to be expanded

URWH research topics in China are mainly focused on rainwater harvesting, rainwater management and urban runoff management (Feng *et al.* 2022). The shortcomings and deficiencies of URWH research include benefit evaluation, relevant policies and laws, professional technical standards and rainwater quality (Jing *et al.* 2018). The main reason for this may be that rapid urban development in China has brought about the demand for the rapid development of URWH. In the process of the rapid development of URWH, attention has been paid mainly to rainwater utilization methods and technology (Mi *et al.* 2018). The development of supporting laws and regulations, special policies, benefit evaluation and other aspects is relatively lagging.

Attention should be paid to rainwater treatment, water quality, economic benefit evaluation, laws and regulations regarding construction in future research on URWH in China. We hope to further enrich and expand related research topics, which would be helpful to solve the problem of URWH promotion and construction in Chinese cities.

2. URWH policies lack mandatory requirements and legal protection

Beijing, Dalian, Shenzhen and other cities have formulated rainwater utilization planning or technical regulations, but most of the other regions in China have not carried out relevant research and applications. Such areas merely refer to the relevant standards and documents of the national files (Yang 2018). From the state to local governments, China has not yet issued laws related to urban rainwater harvesting (Lei *et al.* 2018), this may be one reason why URWH has not become an important means of sustainable development in China, unlike Germany, the United States, the United Kingdom and Australia. These developed countries have issued laws or regulations related to rainwater harvesting and they have mandatory requirements, which may be one reason for the large-scale promotion of rainwater harvesting in these countries. In addition, China's urban rainwater resources are mainly government investment, lacking the participation of social capital and the financing of financial markets. If the legal construction of rainwater collection and utilization is not strengthened, it is difficult to ensure the promotion and implementation of rainwater resources in Chinese cities.

It is necessary for the Chinese government to strengthen the construction of laws and regulations related to urban rainwater resources and increase mandatory government documents. Particularly in cities with abundant rainwater resources but few urban water resources, laws on rainwater resource utilization could help the government to supervise and promote the construction of urban rainwater resource utilization and improve utilization of urban rainwater resources.

3. Construction scope and implementation scale of URWH are small

URWH methods are relatively comprehensive in China, including roof RWH, hardened ground RWH and green land RWH (Chiu 2012). However, the scale of URWH construction and rainwater use volume in Chinese cities is still quite small. For example, for Beijing, which is the leader in URWH development in China, according to preliminary estimates, the rainwater collection area of URWH was less than 2% of the total area in 2020. The rainwater collection capacity of Beijing in 2020 was 70,267,400 m^3, which accounts for 0.78% of total annual rainfall. China has carried out sponge city pilot construction since 2015 (Hai *et al.* 2017; Zhou *et al.* 2018). The construction of sponge cities has promoted the development of rainwater resource utilization (Ma *et al.* 2019; Liu *et al.* 2020). As a comprehensive measure capable of intercepting, collecting and utilizing rainwater resources, URWH has been widely used in sponge city construction (Zhang *et al.* 2018; Feng *et al.* 2022). However, the number of sponge cities in China is not large at present, and each pilot city selects only a small area for construction (Dai *et al.* 2019; Sun *et al.* 2020). Therefore, the current URWH construction scale of sponge cities in China is not large.

Based on expanding the research theme and strengthening the formulation of laws and regulations, it is necessary to strengthen the standardization of construction of URWH projects, promote the construction scale of URWH in Chinese cities and expand project coverage. In particular, it is necessary to formulate engineering standards and technical requirements for rainwater harvesting and treatment measures to ensure the replicability of URWH projects and engineering.

4. Direct economic benefits from URWH projects are poor

From the viewpoint of benefit evaluation, China's URWH pays more attention to social and ecological benefits, which may be because most URWH construction occurs in public spaces or regions (Zhang *et al.* 2020). URWH projects are mainly municipal projects or environmental projects paid for by the government. In particular, since the implementation of sponge city construction, China has invested heavily in URWH construction in pilot cities (Fan & Matsumoto 2019; Leong *et al.* 2019). According to our literature analysis, URWH is a comprehensive measure with high investment cost, and its construction cost per unit area in sponge city construction, is 230 million yuan/km^2 which is twice the cost of non-URWH measures (Fan & Matsumoto 2019). Although China attaches importance to the economic benefit analysis of URWH, such analysis mostly consists of qualitative analysis of the costs and benefits of rainwater use, while quantitative analysis is lacking (Wang *et al.* 2021a, 2021b, 2021c), which may be due to the small scale of urban rainwater utilization in China, the low degree of quantitative construction or the imperfect evaluation system. Some scholars have used cost–benefit analysis methods to analyze urban rainwater resource utilization (Zuo *et al.* 2010; Jing *et al.* 2017), but this needs further refinement regarding direct economic benefits.

China should pay more attention to the evaluation of the economic benefits of URWH construction, especially to strengthen the analysis of direct economic benefits, reduce the investment cost of construction, improve the utilization efficiency of rainwater resources and attract more social capital to participate in URWH construction.

5. Difficulties and problems of URWH construction in China

With the development of more than 30 years, China has achieved good technical development and built a number of international typical sample projects of rainwater resource utilization (Yang 2020; Li *et al.* 2021). Since the further implementation of sponge city construction, pilot cities have adopted rainwater harvesting measures (Liu *et al.* 2022). However, the current construction process of scale and standardization of urban rainwater harvesting in China is slow, and there are some major difficulties and problems. The funding source of the construction is relatively single, dominated by government investment, and lacks the introduction of social capital (Liu *et al.* 2022). In China, rainwater recycling seems to be a public welfare cause, which lacks public participation and the attention and support of the whole society (Zhong *et al.* 2022). Rainwater harvesting project has low economic benefits, low return on investment, and lack of effective and sustainable project operation management (Meng *et al.* 2023). RWH lacks the mandatory and legal protection of laws, and the lack of incentive policies, and the enthusiasm of enterprises and the public to participate in the RWH is poor. Rainwater harvesting in Chinese cities is an important way to increase urban alternative water sources, reduce the risk of urban flood disaster and improve urban water environment and water ecology.

7. CONCLUSION

In this study, the bibliometric analysis results showed that URWH development in China is focused on rainwater harvesting, rainwater management, rainwater utilization and other technical aspects; there is insufficient research on standardization of construction, benefit evaluation and legal development. Compared to URWH research in developed countries, the research topics related to URWH in China should focus on economic benefit analysis, rainwater treatment and legal development.

URWH in China has been developing since the 1990s and has experienced three stages: initial development; rapid construction and sponge city construction. During these stages, China's URWH policy has moved from single to comprehensive, and technical standards have changed from rainwater harvesting and utilization to sponge city. Since the implementation of sponge city construction in 2015, China's URWH development direction is green, low-carbon and sustainable. And China's URWH policy has been developing in terms of professional technical standards and economic and efficient rainwater resource utilization technologies. The construction and development of laws and regulations should be emphasized in China in the future.

The construction of URWH projects in China is uneven. Beijing is in a leading position in terms of policies, standards, technology and other aspects, with several typical URWH projects that are examples and models for Chinese cities. However, in terms of the construction and development scale of Beijing, the coverage of rainwater recycling projects remains small, and the penetration of URWH is insufficient. There are significant differences in URWH construction among Chinese cities. Cities that have implemented sponge city construction have had a better implementation effect from URWH projects, while other cities have lagged relatively behind in URWH construction. URWH projects in Chinese cities need to improve the utilization rate of rainwater harvesting. For large-scale construction, further consideration needs to be given to rainwater recycling in cities with different climatic regions and different levels of economic development.

China's URWH construction constitutes government-led investment projects embodying positive social and ecological benefits. The investment cost of Chinese URWH implementation is generally higher, especially in the context of sponge city construction. The economic benefits of URWH have been low, even representing a deficit investment. Therefore, it is necessary to optimize the design of URWH projects, reducing the cost of URWH engineering and attracting more social capital to invest in future URWH projects.

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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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