Review on mechanism and technical measures of urban rainwater harvesting

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Abstract. The urban water problem has become one of the most significant problems hindering sustainable urban development. Rainwater harvesting and utilization is a green solution to alleviate the urban water problem. However, existing urban rainwater management pays more attention to flood control and lacks systematic planning for rainwater harvesting in China. In this paper, the calculation methods of rainwater harvesting potential are investigated, and the difference of rainwater harvesting system between the traditional model and sponge model is compared based on the rainwater harvesting mechanism. In addition, the study progress of four representative rainwater harvesting measures (green roofs, bioretention ponds, infiltration wells, and rainwater tanks) is reviewed and four representative optimization tools are listed. Moreover, we summarized the challenge of rainwater harvesting and provided recommendations for future research on the rainwater harvesting system. This review aims to provide theoretical support for the comprehensive utilization of urban rainwater resources to promote the sustainable development of cities.

1. Introduction

As a natural water source, rainwater has been harvested and utilized by paddy fields and ponds thousands of years ago [1, 2]. Since the 1980s, rainwater utilization has been widely concerned in the world. Germany has introduced the standard of rainwater utilization facilities (DIN1989) [3]; Japan promoted rainwater retention and infiltration plan to replenish groundwater and improve the ecological environment [4]. Best Management Practices (BMPs) proposed in the United States aimed to manage rainwater from multiple perspectives. Australia had published guidelines for Water Sensitive Urban Design (WSUD) [5], followed by the United Kingdom and New Zealand [6]. The study of rainwater utilization in China began in the 1980s and has proliferated since the 1990s. In 2014, Sponge City was issued in China [7]. Sponge City refers to a city that, like a sponge, purifies and stores rainwater when it rains, and uses the stored water when necessary, so that the city can adapt to environmental changes and cope with natural disasters flexibly [8]. Rainwater utilization is one of the objectives of Sponge City, which indicated that rainwater harvesting and utilization would be closely combined with low impact development (LID) in the future.

Under the context of climate change and rapid urbanization, the urban water problem, such as water resource shortage, urban flood and waterlogging, and non-point source pollution, hinders cities' sustainable development [9]. Nevertheless, the rainwater harvesting system can alleviate these problems effectively. For example, the water stored in the rainwater tank can be used for toilet
flushing or car washing to reduce tap water supply. At the same time, the rainwater harvesting system can store rainwater at the source during rainstorms, which relieves the pressure of pipes downstream [10]. In addition, the green infrastructure can reduce non-point source pollutions with the vegetation system [5, 11]. Therefore, it is necessary to implement a rainwater harvesting system to alleviate urban water problems and promote sustainable urban development.

With the spread of the low impact development in cities, the research on rainwater management has entered a new stage, but the existing study lacks the systematic planning of rainwater harvesting system. For example, the existing plannings of Sponge Cities are more focused on urban floods, and few are concerned about rainwater utilization [12]. Therefore, this study analyzes the research progress of the rainwater harvesting system from the aspects of rainwater harvesting potential, mechanism and measures, to provide essential theoretical support for urban rainwater utilization.

2. Potential of rainwater harvesting

The potential of rainwater harvesting is essential for the plan of the rainwater harvesting system. There are many methods to estimate the potential, for example, empirical formula, water balance theory and influence factors. The equation and application of the three methods are shown in Table 1. The empirical formula relies on empirical values, but it takes many factors into consideration, such as the first flush and the seasonal variation of precipitation. With the development of remote sensing technology, the empirical formula has been improved because the rainwater harvesting potential can be calculated based on different land use types [13, 14]. In addition, the rainwater utilization potential refers to the surface runoff and groundwater runoff in the method of water balance [15, 16]. In contrast, the terrain and the way of rainwater utilization are considered in the method of influence factors. More details can refer to Yang [16]. Compared with the other two methods, the empirical formula has been widely used because of its comprehensive factors and easy access to the required data [17, 18]. Some other cases are based on the combination of these basic methods. For example, Liu et al. calculated the rainwater utilization potential (154.49 million m³) of Beijing in 2013 based on different land use types and water balance theory [19].

| Methods                  | Calculation equation                                                                 | Application                                                                 |
|--------------------------|--------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Empirical formula        | \( W_r = \sum_{i=1}^{n} A_i \times \varphi_i \times P \times \alpha \times \beta \times 10^{-3} \) | Suitable for areas with detailed underlying surface data.                   |
| Water balance            | \( W_r = W_{sp} + W_{simp} + W_g \)                                                  | Suitable for areas with few data.                                           |
| Influence factors        | \( W_r = P \times \lambda_p \times (\lambda_t + \lambda_s \times \lambda_y) \)        | Suitable for areas with detailed rainwater utilization data.                |

Where \( W_r \) is rainwater harvesting potential, m³; \( P \) is the amount of rainfall, mm; \( \alpha \) is the coefficient of the first flush; \( \beta \) is the reduction coefficient of rainfall season, which refers to the ratio of rainfall in the rainy season to annual rainfall; \( A_i \) is the area of the i-th land use, km²; \( \varphi_i \) is the runoff coefficient of the i-th land use; \( i = 1, 2, \ldots, n \), \( n \) is the total number of land use types; \( W_{sp} \) represents the surface runoff in the permeable area, \( W_{simp} \) is the surface runoff in the impermeable area, \( W_g \) is the groundwater runoff; \( \lambda_p \) is the rainfall characteristic factor, which represents the proportion of rainfall develop into runoff; \( \lambda_t \) represents the impact of terrain on rainwater harvesting; \( \lambda_s \) and \( \lambda_y \) represent the impact of utilization mode, \( \lambda_t \) refers to the rainwater utilization at local, \( \lambda_y \) refers to the rainwater utilization at other areas.
3. Mechanism of rainwater harvesting

The rainfall infiltrates into the soil or flows along the surface after evaporation, interception, and depression storage [20]. Correspondingly, there are two main ways of rainwater harvesting: infiltration and storage. Rainwater infiltrates into the soil and stays in the unsaturated zone or aquifer. Rainwater storage by the interception of surface runoff usually requires facilities with a specific volume.

3.1. Infiltration

Green infrastructure is an important carrier of rainwater infiltration and utilization. The rainwater, after infiltration, becomes a part of soil water or groundwater. The facilities with infiltration functions include green roofs, permeable pavements, sunken green space, bioretention ponds, infiltration ponds and infiltration wells [8]. These facilities can be generalized into a conceptual model with three layers: surface soil, storage, and sub-soil (Figure 1). The surface soil with good infiltration allows rainwater to penetrate the soil quickly. The storage layer usually consists of gravels or broken stones, which provide large voids for rainwater. The sub-soil layer is mostly composed of the local soil. When the rainwater leaves the sub-soil layer, the groundwater could be recharged locally [21]. However, there are some green infrastructures without a storage layer, and rainwater infiltrates directly from the surface to the sub-soil layer [22].

![Figure 1. Conceptual model of green infrastructure based on infiltration mechanism.](image)

3.2. Storage

In the traditional rainwater harvesting system based on residential, rainwater is usually stored in gray infrastructure [23, 24]. In Sponge City, green infrastructure and gray infrastructure are both carriers of rainwater. The green infrastructure mainly includes rainwater wetlands and wet ponds; gray infrastructure includes rain barrels and rainwater tanks [8]. Rainwater storage facilities are usually located downstream of urban drainage systems. Rainwater stored can be used according to specific needs. For example, the water stored in the rainwater tank can be used for irrigation, car washing and toilet flushing [25, 26]. The utilization of rainwater usually requires human intervention, such as the installation of pumping stations.

3.3. Comparison between traditional model and sponge model

In the traditional urban development model, rainwater is harvested and used mainly by gray infrastructures, such as pipes, rainwater tanks and pumps [27]. In the combined drainage system of the traditional model, rainwater flows into the sewage treatment plant along with sewage [28]. However, the traditional urban drainage system could no longer meet urban development’s needs due to rapid urbanization. Therefore, the Chinese government began to explore the development model of Sponge City. In the Sponge City drainage system, part of the rainwater is retained and stored in the green infrastructure through infiltration. The rainwater that exceeds the field capacity of the soil will overflow or enter the underdrain from the bottom. Subsequently, the rainwater will be stored in the rainwater storage facilities by the rainwater pipe network [8]. In contrast, rainwater is harvested mainly by storage in the traditional model but by infiltration and storage in the sponge model. In addition, the harvested rainwater is usually of poor water quality due to non-point source pollution in
the traditional model, while the runoff can be purified by green infrastructure in the sponge model. The harvested rainwater with relatively good quality is more suitable for utilization [29].

4. Technical measures of rainwater harvesting

4.1. Green roofs
Rooftop rainwater harvesting has always been one of the important ways of rainwater harvesting. Rooftop rainwater can be used for flushing and landscaping after being treated, and it is considered an alternative water source [30]. With the promotion of Sponge City, green roofs, as shown in Figure 2, have gradually shown advantages in regulating climate and purifying water quality. Ojwang et al. estimated rainwater harvesting potential (2.3 to 23 million m$^3$/yr) by identifying roof areas through supervised image classification in Mombasa [25]. An et al. analyzed the feasibility of rainwater harvesting in Hong Kong and evaluated the cooling effect of green roofs [31]. Li et al. found that the runoff reduction rate of green roofs was between 30% and 86%, and the peak reduction rate was between 22% and 93% by reviewing the relevant literature with laboratory or field experiments [32]. Czemiel and Vijayaraghavan believed that medium type, vegetation, rainfall and local pollution sources are important factors affecting the pollutant reduction effect of green roofs [33, 34]. Green roofs are suitable for popularization in large cities with limited land and high land prices considering the effects on runoff, microclimate and air quality. However, existing researches on green roofs are mainly concentrated in small areas, and green roofs have not been promoted and applied on a large scale in China [35, 36].

![Figure 2. Four typical measures of rainwater harvesting.](image)

4.2. Bioretention ponds
The Bioretention pond has been widely used in the United States, the United Kingdom and southern China due to its good effect on runoff and pollution control [37, 38]. Bioretention ponds with underdrain will carry excess rainwater to rainwater pipes when the storage layer is filled. In contrast, the bioretention ponds without underdrain more focus on concentrated infiltration to recharge groundwater. Existing studies evaluated the performance of bioretention ponds by experiments and model simulation. For example, Jiang et al. found that the bioretention ponds can reduce runoff by 68.2% under medium and light rainfall (< 25 mm) and annually remove pollutants by 60% at least through field experiments [39]. Li et al. optimized the critical parameters of the bioretention pond through a combination of experiment and model simulation. They found that the bioretention pond with an artificial filler of flyash + sand or planting soil is effective under more rainfall scenarios [40].
In general, the study about bioretention ponds focuses on evaluating and optimizing the performance of pollution and water quantity control, and improving the performance is still important in future study [38, 41].

4.3. Infiltration wells
The infiltration well is a facility that allows rainwater to seep through the wall and bottom of the well. In order to increase the infiltration, horizontal infiltration drainage pipes with gravel around can be set across the infiltration wells [8]. Infiltration wells are suitable to be set up in the areas where groundwater is scarce because they occupy a small area and have low construction and maintenance costs. Zhang et al. believed that infiltration wells are suitable for first laying in Tibet, Xinjiang, Heilongjiang and Tianjin in China based on contrastive analysis [42]. Wang found that the removal rate of COD by infiltration wells ranged from 2.5% to 24.1% based on field experiments [43]. Cheng et al. proposed a new technology of infiltration well, which can introduce rainwater penetrate into the deep soil layer quickly by the permeable filter element [44]. Unlike green roofs and bioretention ponds, current studies of infiltration wells not only focused on the infiltration performance but also concerned about the impact of rainwater infiltration on groundwater. For example, Wang found that the infiltration of rainwater had minimal impact on groundwater quality after the purification of infiltration wells [43].

4.4. Rainwater tanks
Rainwater tanks are the most common facilities for rainwater harvesting. In Australia, 19% of households use stormwater pools as their water source [30]. In addition to rainwater utilization, rainwater tanks also have the function of waterlogging prevention and pollution control. The design return periods of rainwater tanks with different functions are different, and the calculation methods of storage capacity are also different. The methods of model trial, water balance and inference formula are often used to design the size of rainwater tanks [10]. Fu et al. determined the total volume of the rainwater tanks \(2.3\times10^4\text{m}^3\) in Ximen District of Pingxiang city through inference formula and hydrological and hydrodynamic simulation [10]. In addition to storage capacity, the location of the rainwater tank is also important. Wang et al. analyzed the difference between decentralized layout and centralized layout. The results showed that the centralized layout is suitable for areas with severe and concentrated waterlogging, while the decentralized layout is suitable for areas with limited land use [45]. Similar to other rainwater harvesting measures, the performance evaluation of runoff and pollution reduction is the kernel of the study on rainwater tanks [46]. Khastagir et al. developed a daily water balance model for performance analysis and decision support of rainwater management [47].

4.5. Combined technical measures
The type and location of sponge measures are the main factors affecting the efficiency of rainwater harvesting systems [48-51]. Therefore, it is necessary to determine the optimal scheme to maximize the benefits of rainwater harvesting systems. Scenario analysis based on model simulation is the primary method to estimate the effect of different design schemes [52]. First of all, it is vital to choose a suitable simulation model. Kaykhosravi et al. compared 11 models of sponge measures from general characteristics, hydrology and hydrodynamic characteristics [53]. Zhang and Chui analyzed the structure and system types of LID-BMP-GI space optimization tools [48]. Three ways to simulate rainwater harvesting measures are listed through a comprehensive comparison with existing studies. (1) There are preset options for sponge measures in the model, and the detailed parameters of sponge measures are required, such as the Storm Water Management Model (SWMM). (2) Generalizing some modules in the model to simulate the sponge measures. For example, rainwater barrels could be simulated by generalizing reservoirs in the Soil & Water Assessment Tool (SWAT) [54]. (3) A single sponge measure can be simulated through the combination and connection of different media layers, such as the Green Infrastructure Flexible Model (GIFMOD) [55]. It allows the combination of the required sponge measures with six media types freely. In addition, there are models with automatic
combination and cost-benefit analysis, such as the System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) [56]. Its genetic algorithm module and cost module can be used to determine the best type, quantity and location of sponge measures [57]. Four representative models are listed in Table 2. SWMM is one of the common models to study the effect of sponge measures on runoff reduction [58, 59]. Due to its open-source characteristics, SWMM has become the common coupling or calling object in sponge measures design. For example, Digitalwater Simulation (DS) model invokes SWMM to simulate the benefits of sponge measures [60]. So do the SUSTAIN and MIKE URBAN [61]. Existing models meet the basic design and evaluation requirements for rainwater harvesting measures, but they still have deficiencies. For example, the SWMM cannot simulate water flow from one LID module to another in the same sub-catchment. At the same time, a complete design and optimization model of sponge measures covering the whole process (from monomer design to optimization evaluation) has not yet appeared.

| Type                        | Name   | Functions                                  | Service stage               |
|-----------------------------|--------|--------------------------------------------|-----------------------------|
| Medium Combination          | GIFMOD | Single sponge facility design              | Single measure design       |
| Module Generalization       | SWAT   | Combined facilities design under large watershed | Combinations design         |
| Module Preset               | SWMM   | Runoff and pollution effects evaluation of sponge facility combinations | Combinations design and evaluation |
| Combination Optimization    | SUSTAIN| Cost analysis and automatic optimization of sponge facility combinations | Combinations design and optimization |

5. Challenges and strategies for the urban rainwater harvesting system

5.1. System optimization

Although the existing technology has met the basic requirement of rainwater harvesting and utilization, system optimization is essential to improve the efficiency of rainwater utilization [48, 62, 63]. According to the whole process of rainwater harvesting and utilization, the urban rainwater harvesting system can be optimized from three aspects: source, process and end. The source of the rainwater harvesting system is precipitation. The accuracy of precipitation forecast can be improved by refined precipitation simulation. Xu's research showed that the flood peak time could be delayed with the help of a relatively long prediction time window [64]. Process optimization refers to optimizing the rainwater infiltration and storage facilities, such as combination type, layout area, spatial location and water flow path, which aims to maximize the amount of water stored and optimize the water quality. Selecting measures according to local conditions is conducive to improving the effectiveness of the rainwater harvesting system. Green roofs are suitable for urban areas with high land prices as they do not occupy ground space, while they may not be suitable for areas with little precipitation because of the water demand of vegetation. The infiltration wells are suitable for groundwater recharge in arid and semi-arid areas with poor surface infiltration capacity, given their strong infiltration capacity [65]. Rainwater tanks and bioretention ponds are widely used. Although the rainwater tanks can be used for both flood control and rainwater utilization, their high cost may hinder its promotion [66]. Due to the diversity of structures, the bioretention pond can be adjusted to meet the local needs according to the local climate and geological conditions. However, for special geological conditions, such as collapsible loess areas, it is necessary to pay attention to the anti-seepage measures [8]. End optimization aims to the maximum utilization of rainwater resources through water management. Real-time control technology can optimize the scheduling rules and maximize the benefits of rainwater tanks [67].
5.2. Policy support

Many countries have developed rainwater use policies, such as Japan, Australia and the United States [4, 5]. China is no exception. Although the rainwater utilization rate is one of the evaluation indexes of Sponge City, detailed planning for the rainwater harvesting system is still not widely carried out in Sponge City pilots. Therefore, it is suggested that the planning departments draw up a comprehensive scheme for the urban rainwater harvesting system according to local conditions. In addition to professional standards, supporting laws and regulations on rainwater utilization should be established [68]. At the same time, more policy support on the economy should be provided for rainwater harvesting and utilization. For example, Australia provides the availability of rebates for households to offset the cost of installing a rainwater tank [30]. In addition, rainwater market trading should be supported. The first rainwater transaction was successfully completed in China on December 11, 2020, and the treated rainwater is sold at 3.8 RMB/m³ [69].

5.3. Climate change

Under the background of climate change, extreme precipitation events occurred frequently. With rapid urbanization, the hydrological process changed significantly [70, 71]. Under the dual background, it is imperative to study the evolution characteristics of precipitation and the hydrological cycle process. On the one hand, it is necessary to strengthen the research on the evolution law of precipitation and runoff so that the regional rainwater harvesting potential would be estimated reasonably. On the other hand, the carbon emission and sink of green and gray infrastructure during the whole life cycle should be fully considered due to the "carbon neutral" target [72, 73].

6. Conclusions

Rainwater harvesting is an effective measure to alleviate the impact of urbanization and climate change. The infiltration and storage are the main mechanisms of rainwater harvesting. Green roofs, bioretention ponds, infiltration wells, and rainwater tanks are typical rainwater harvesting measures. Existing studies have focused on the effect evaluation of sponge measures on runoff and pollution reduction. An appropriate simulation model is required to evaluate the effect of the urban rainwater harvesting system and determine the optimal scheme. In addition, the efficiency of the rainwater harvesting system should be improved from source to end. Moreover, a comprehensive plan and supporting laws and regulations are also essential for the rainwater harvesting system.

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