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Assessment of Rainwater Utilization Potential of Sponge Facilities in the Dong–Kang–Ejin Urban Agglomeration

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Abstract

While various methods exist for assessing urban rainwater and flood resources, there is a lack of targeted evaluation for the rainwater harvesting potential of areas equipped with sponge city facilities. This study employs the Yield Before Spillage (YBS) principle to design rainwater collection tanks for sponge facilities under different design return periods, conducting a specialized assessment of the rainwater resource potential in built-up sponge facility areas within the "Dongsheng–Kangbashi–Ejin Horo Banner" urban cluster. The results indicate that the collection potential follows the patterns of "wet year > normal year > dry year" and "Ejin Horo Banner > Kangbashi District > Dongsheng District." A rainwater collection tank designed for a 5-year return period (p = 5a) is more applicable to the study area. The sponge facilities in the study area achieve an annual runoff volume control rate exceeding 85%, effectively alleviating drainage pressure. The conclusions demonstrate that the YBS method can effectively assess the rainwater and flood resources of sponge facilities in arid regions. Tanks designed for the three different return periods all meet the rainwater retention requirements of sponge cities across various hydrological years. In arid areas, tanks designed for lower return periods are sufficient for harnessing rainwater collection potential, offering lower costs.

Keywords: urban rainwater resource utilization; sponge city; water-use priority principle; rainwater resource potential; water balance

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Academic Editor: Suqing Wu

Received: 29 January 2026
Revised: 20 March 2026
Accepted: 24 March 2026
Published: 26 March 2026

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1. Introduction

Against the backdrop of rapid global urbanization, water scarcity, frequent flooding, and deteriorating water environments have emerged as critical constraints on sustainable urban development [1]. The traditional "drainage-oriented" stormwater management approach [2] not only struggles to cope with extreme climate events but also leads to significant loss of precious rainwater resources. Since the nationwide implementation of Sponge City pilot initiatives in 2015, Sponge City strategies—through integrated measures such as infiltration, retention, storage, purification, reuse, and controlled drainage—have shifted urban stormwater management from passive discharge toward proactive adaptation and resource utilization [3]. Therefore, assessing the potential for rainwater harvesting and utilization through Sponge City measures is of great importance.

International research on stormwater resource management has evolved from single-objective approaches to systematic governance [4,5]. Early studies primarily employed empirical methods, such as the SCS-CN model [6] developed by the U.S. Department of Agriculture, to estimate surface runoff based on soil type and land use. While straightforward, these methods often fail to capture the complex underlying surface conditions typical of urban areas [7]. With advancements in computing, physically based distributed hydrological models have become increasingly prevalent. Models such as SWMM [8–10] and MIKE URBAN [11,12] can simulate urban rainfall–runoff processes in detail. However, their application typically requires extensive monitoring data for calibration and validation [13–15], which limits their suitability in regions with relatively scarce baseline data. More recent assessment methods have emerged alongside the promotion of Low Impact Development (LID) [16,17] and Green Infrastructure (GI) [18,19]. The U.S. Environmental Protection Agency's SUSTAIN model, for example, integrates LID placement with water quality and quantity objectives [20]. The UK's rainwater harvesting benefits calculator [21] emphasize source-control treatment and economic analysis, respectively. Water balance models have also been widely used to assess system performance at various temporal scales [22].

Despite the aforementioned advances, significant research gaps remain in the assessment of rainwater resource utilization potential. Specifically, existing models and methods, while suitable for detailed design or continuous simulation, typically rely on extensive input data. This dependency makes them difficult to apply for rapid, regional-scale assessments in data-scarce arid regions. Furthermore, current research predominantly focuses on coarse estimations of total rainwater resources, lacking quantitative analysis of collectable rainwater by different land use types, systematic evaluations of rainwater harvesting across various temporal scales, and specialized studies on the utilization potential of different sponge facility types. In addition, the academic community has primarily concentrated on quantity control performance—namely, runoff reduction and peak flow attenuation—while the potential of using rainwater as a reliable alternative water source remains largely underexplored. These research imbalances are particularly pronounced in arid regions, where addressing water scarcity necessitates a refined assessment of every potential resource. Most critically, existing evaluation frameworks rarely establish effective linkages with core management indicators guiding China's Sponge City construction, such as the "annual runoff volume control rate." Consequently, assessments of utilization potential often exist in isolation, failing to provide a practical basis for decision-making on storage facility design or water supply reliability within the current policy framework.

To address these research gaps, this study adopts the Yield Before Spillage (YBS) [23–25] behavioral algorithm—grounded in the principle of "water use priority"—as the core logic for tank water balance simulation. The water-conservation-first concept embedded in this method aligns closely with water use practices in arid regions, rendering it suitable for assessing the rainwater utilization potential of sponge facilities in such environments. The key innovation of this study lies in the substantive extension of the YBS method's application scope: originally developed for reservoir yield analysis at a single-node scale, its core logic is adapted herein for the design of storage tanks in distributed sponge city facilities, effecting a functional shift from "evaluating existing storage capacity" to "determining tank size based on water demand"—a methodological transition from large-scale reservoir management to decentralized urban stormwater infrastructure. Specifically, the improved method conducts dynamic water balance simulations using the YBS algorithm based on design rainfall and sector-specific daily water demand, thereby determining optimal tank volumes and rainwater utilization potentials under varying hydrological conditions. In contrast to the Yield After Spillage (YAS) method, which follows

the principle of "storage first, release after overflow," the YBS method is characterized by "water use priority and dynamic regulation." The YAS method requires tanks to be filled to capacity before deducting overflow, aiming to mitigate peak runoff and alleviate waterlogging pressure, making it more suitable for regions with abundant rainfall and consequently resulting in larger tank sizes. The YBS method, by contrast, prioritizes water demand: during rainfall–runoff simulation, it first deducts expected daily water demand from stored volume and then utilizes the remaining capacity to capture incoming rainfall. This "simultaneous storage and use" strategy effectively treats the buffer space created by water demand as part of the effective collection capacity, significantly reducing tank size while maintaining collection efficiency. For arid and semi-arid regions with limited rainfall, tanks designed using the YBS method suffice to capture available rainwater resources, offering lower costs and greater cost-effectiveness—ensuring efficient rainwater utilization while avoiding over-construction.

Building upon this methodological foundation, this study conducts a regional-scale assessment in the built-up areas equipped with sponge facilities within the Dongsheng–Kangbashi–Ejin Horo urban agglomeration in Ordos City, Inner Mongolia. Focusing on physical infrastructure—including sponge parks, roads, residential complexes, and lakes—and using underlying surface types as fundamental evaluation units, the research systematically applies the "sizing storage based on usage" concept at the heart of the YBS approach. Through detailed surveys of facility water demand and design parameters, combined with performance modeling under different rainfall frequencies (5-year, 10-year, and 20-year return periods), this study provides a robust yet simplified methodology for regional-scale rainwater harvesting assessment that explicitly accounts for hydrological variability. It quantifies, for the first time in this region, the utilization potential of diverse sponge facility types as alternative water sources. Furthermore, by establishing a direct link between the calculated harvesting potential and tank design capacity, this research offers a scientific basis for optimizing storage tank design, assessing annual rainwater harvesting potential, evaluating payback periods, and determining annual runoff control rates, thereby contributing to innovative water resource management models and advancing sponge city construction in arid and semi-arid regions.

2. Materials and Methods

2.1. Description of the Study Area

2.1.1. Physical Geography and Socioeconomic Context

The study area is located in southwestern Inner Mongolia, on the northeastern side of Ordos City, within the middle reaches of the Yellow River Basin (37°35′24″–40°51′40″ N, 106°42′40″–111°27′20″ E). Ordos City lies in the southwestern Inner Mongolia Plateau (average elevation 1000–1500 m), with terrain higher in the northwest and lower in the southeast. The city has total water resources of 2.858 billion m^3 and per capita water resources of approximately 1299–1328 m^3, far below national and regional averages, making it one of the most water-scarce areas in China.

The study area covers 569.89 km^2 (built-up area: 174 km^2), encompassing key construction zones within Dongsheng District, Kangbashi District, and Ejin Horo Banner [26], as shown in Figure 1. The figures in this paper were created using ArcGIS Pro (Version 3.4.3), Microsoft Visio (Version 2602), Origin Pro 2024 (Version 10.1.0.178), and Microsoft PowerPoint 2016 (Version 16.0.19725.20126). These three districts are closely adjacent in a north–south belt-shaped pattern, forming an integrated urban agglomeration that includes both old districts and high-standard new towns. All three districts have a temperate continental climate, characterized by aridity, low rainfall, strong evaporation, abundant sunshine, and large diurnal temperature variation. Annual sunshine duration ranges from

2700 to 3200 h. Annual precipitation ranges from 150 to 350 mm (concentrated in summer), while annual evaporation reaches 2000–3000 mm, approximately six to eight times the precipitation.

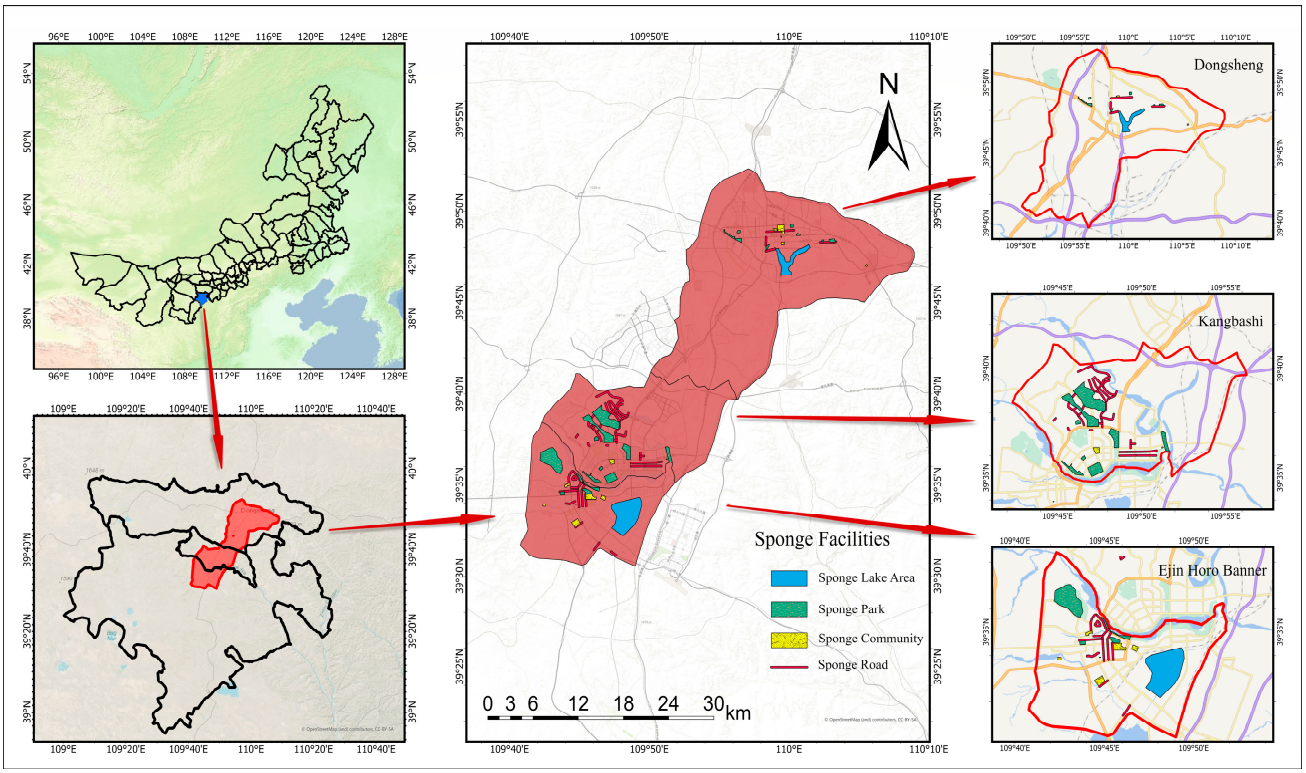

Figure 1. Location map of the study area.

The three districts exhibit notable differences in urban development characteristics. Within the study area, Dongsheng District (north) is the old urban area with predominantly community-based sponge facilities. Kangbashi District (center) is a high-standard new urban area with high green space ratio and diverse sponge facilities. Ejin Horo Banner (south) is a functional expansion area combining urban construction and ecological land use, with sponge facility construction currently in a progressive phase. These differences in underlying surface conditions provide important spatial heterogeneity for analyzing rainwater resource utilization efficiency across different urban typologies.

2.1.2. Current Status of Sponge Infrastructure Construction

Figure 2 illustrates the target distribution of the annual runoff volume control rate across the regulated subzones within the central urban area of the Dong Kang Ejin urban agglomeration. In assessing the performance of sponge city infrastructure, it is essential to differentiate between two key indicators: the annual runoff volume control rate and the peak flow reduction rate. The former measures the cumulative volume of rainfall retained or utilized over a long-term scale, reflecting a region's capacity for rainwater resource utilization and source control. The latter focuses on the attenuation of instantaneous peak flow during individual storm events, which is critical for mitigating urban waterlogging. Given that this study aims to evaluate the potential of rainwater harvesting as an alternative water source in arid regions where water scarcity is the primary concern, the annual runoff volume control rate is adopted as the more relevant indicator, and the subsequent analysis is centered on this metric. The annual runoff volume control rate [27] is defined as the proportion of total annual rainfall runoff that is controlled within a specific urban area through

natural and engineered measures. It is typically expressed as a percentage and calculated using the following formula: Annual Runoff Volume Control Rate = (Total Annual Rainfall − Annual Runoff Discharged)/Total Annual Rainfall × 100%. As shown in the figure, the control rate targets within the study area range from 75% to 95%. Kangbashi New District, as a high-standard planned urban core, exhibits the highest targets, with its key landscape zones and major public building areas generally exceeding 80%. The newly developed areas of Ejin Horo Banner follow a similarly high standard. In contrast, the older urban areas of Dongsheng District adopt more pragmatic targets, mostly concentrated between 75% and 85%, due to the constraints associated with retrofitting existing infrastructure. This tiered target system reflects a construction strategy tailored to local conditions.

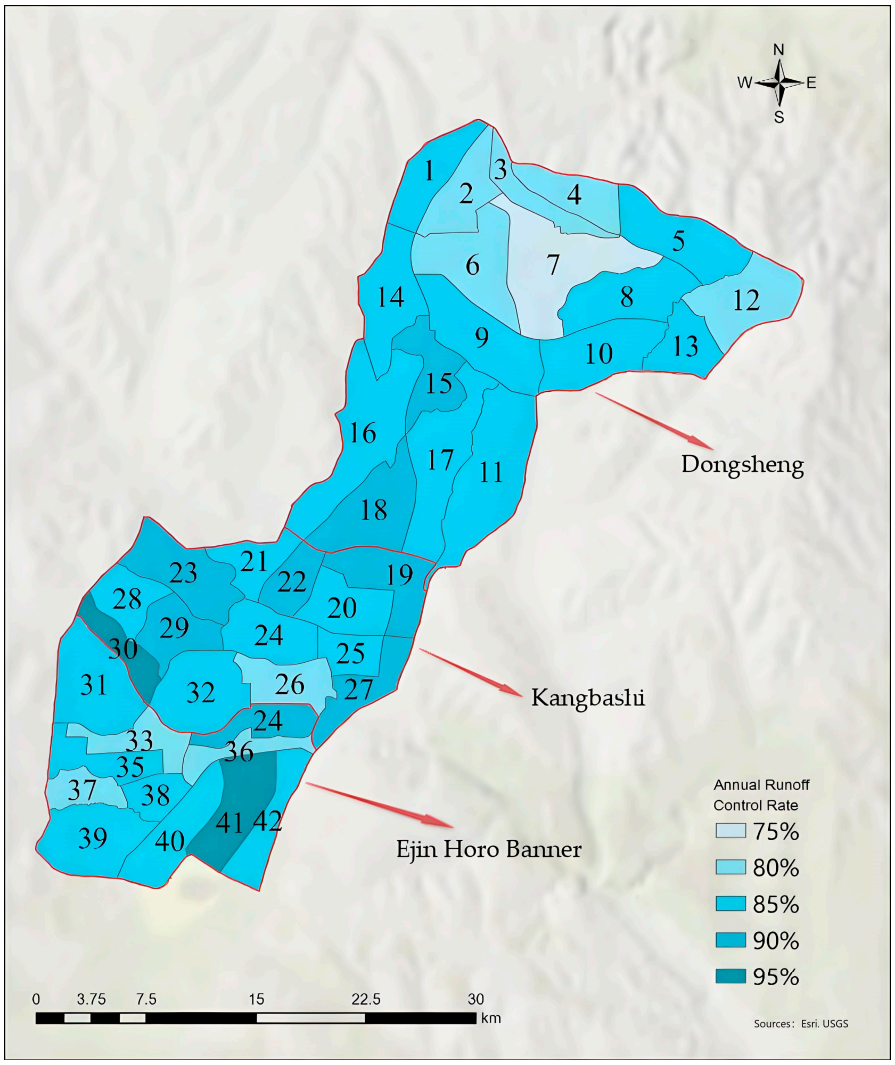

Figure 2. Distribution of annual runoff volume capture rate in the regulatory subareas of the central urban area.

This study systematically classifies the sponge facilities within the region into four major categories: sponge buildings, sponge parks, sponge roads, and sponge lake areas, based on field surveys. The construction status across each district is summarized as follows:

In Dongsheng District, the implemented facilities include 1 sponge lake area, 7 sponge parks, 3 sponge roads, and 7 sponge residential complexes, covering a total area of 4.7 km^2. Representative projects such as the Bronze Culture Plaza renovation and the

sponge retrofitting of older residential communities demonstrate the integration of sponge city principles within urban renewal contexts.

Kangbashi District has established 25 sponge roads, 8 sponge parks, 1 sponge lake area, and 1 sponge residential complex, with a total area of 7.9 km^2. Notable examples include the Wulanmulun River landscape corridor, the Ordos Sports Center, and Ordos Avenue, which highlight the application of sponge concepts in ecological landscaping and urban public spaces.

In Ejin Horo Banner, 7 sponge roads, 5 sponge residential complexes, 3 sponge lake areas, and 4 sponge parks have been constructed, spanning a total area of 13.6 km^2. Typical projects such as the Aletengxire Town Forest Park and the Civil Servant Residential Community reflect the progress in implementing sponge systems within both residential and ecological recreational spaces in the region. The classification of sponge facilities for the three regions is presented in Table 1 below.

2.2. Data Sources and Processing

2.2.1. Meteorological Data

In this study, daily precipitation observation data (1985–2022) from 11 national meteorological stations in Ordos City, Inner Mongolia Autonomous Region, were obtained from the National Tibetan Plateau/Third Pole Environment Data Center (https://data.tpdc.ac.cn). Using the 1985–2022 precipitation dataset, the Pearson Type III (P-III) distribution was fitted with a goodness-of-fit of 0.94. The calculated statistical parameters were mean (Ex) = 325.78 mm, coefficient of variation (Cv) = 0.25, and skewness-to-variation coefficient ratio (Cs/Cv) = −5. The estimated precipitation amounts corresponding to frequencies of 10% (wet year), 25% (relatively wet year), 50% (normal year), 75% (relatively dry year), and 90% (dry year) were 433.12 mm, 368.08 mm, 309.73 mm, 267.23 mm, and 239.37 mm, respectively. To address partial data gaps, more complete and detailed daily rainfall observation records (2009–2020) from the Ordos Meteorological Bureau (http://nm.cma.gov.cn) were incorporated. On this basis, representative years were selected as analysis samples: wet year (2016, 596.6 mm), normal year (2019, 363.5 mm), and dry year (2015, 261.4 mm).

Using the Yield Before Spillage (YBS) method [28,29], with rainfall data and underlying surface parameters from these three typical years as core inputs, the rainwater harvestable potential of sponge facilities in Dongsheng, Kangbashi, and Ejin Horo Banner was calculated under different hydrological conditions. This approach enhances the scientific validity and representativeness of the assessment results. The core of the method lies in estimating the collectable and utilizable rainwater volume for different usage pathways according to rainwater quality and priority of water demand.

In this study, based on relevant hydrometeorological principles and using the local rainstorm intensity formula, calculations were performed for rainfall frequency scenarios corresponding to 5-year, 10-year, and 20-year return periods. In the calculation process, the rainfall duration was set to 180 min, and the rain peak coefficient was taken as 0.27. The storm intensity formula is given as follows:

$$q = \frac{1394.042 \times (1 + 0.997 \lg P)}{(t + 8.413)^{0.796}} \quad (1)$$

In the equation, q represents the rainfall intensity in mm/min; P denotes the design return period in years; t represents the rainfall duration, in minutes, and is set to 180 min in this study.

Table 1. Classification and Distribution of Sponge Facilities in the Dongsheng–Kangbashi–Ejin Horo Banner Urban Agglomeration.

Region	Category	Name	Sub-Region
Dongsheng	Sponge Park	Jingshan Park	6
		Bayin Park	6
		Yikezhao Park	7
		Sanjiaozhou (Delta) Park	6
		Yueji Culture Park	7
	Sponge Community	Jingdi Mansion	7
		Community in the TV University Area	7
		Pharmaceutical Building	7
		Forestry Area	7
		Jinshan Model Community	7
	Sponge Roads	Tianjiao Road West Side Road	7
		Fangzhi East Street	7
		Fangzhi West Street	7
	Sponge Lake Area	Sanjitai Lake Area	7
Ejin Horo Banner	Sponge Park	Ordos Shuian Xincheng Central Park	33
		Muqin Park	33
		Ajinai Park	35
		Yihe Ecological Expo Garden	31
	Sponge Community	Hongtai Shuijing Licheng	33
		Shuian Xincheng	36
	Sponge Roads	Liugouhe South Street 1	33
		Liugouhe South Street 2	33
		No. 4 Primary School	33
		Binhe Avenue	33, 34
		Aletengxire Road	33
		Anda Road	35
		Zasake Street	33
		North Ring Road	31
		Ejin Horo Banner Railway Underpass	33
	Sponge Lake Area	Donghonghaizi Wetland Park Circular Road Landscape	41
		Wulanmulun Lake Landscape Park 1	33
		Wulanmulun Lake Landscape Park 2	33
Kangbashi	Sponge Park	Smart Sports Park	31
		Cultural and Creative Industry Park	32
	Sponge Community	People's Government Parking Shed Demonstration Project	26
	Sponge Roads	Jingsi Road	24
		Xijing Jiuzhi Road	24
		Zhiwu Road	29
		Zhisi Road	29
		Zhier Road	29
		Zhisan Road	29
		Binshui West Road	29
		Beiwei Si Road	29
		Zhilu 1	29
		Taikang Street	32
		Weiliu Street	23
		Weisi Street	23
		Weisan West Street	23
		Weier Street	23
		Xijing Liuzhi Road	23
		Dongwei Er Road	26
		Dongwei Yi Road	26
		Dongjing West Road	26
		Dongjing San Road	23
		Jinger Road	23
		Zhijiu Road	29
		Zhiliu Road	30
		Huatai No.1 Factory Branch Road	26
		Road on the South Side of Xihu Mingzhu: Beiwei Si Road	29
		Road on the West Side of Xihu Mingzhu: Binshui West Road	29
	Sponge Lake Area	Leijiapo Wetland Park	29
		Wulanmulun Lake Upper Lake Park	32

According to the Ordos Central Urban Area Sponge City Special Plan, the annual runoff volume control rate in Ordos City is maintained at approximately 80% to 90%. A 90% annual runoff volume control rate corresponds to a design rainfall of 27.2 mm. To meet the design standards specified in the Sponge City guidelines, rainwater collection tanks were designed for three different return periods. Under the condition of complete retention, the corresponding rainfall amounts are 39.11 mm for a 5-year return period, 46.39 mm for a 10-year return period, and 53 mm for a 20-year return period.

As shown in Figure 3, precipitation in Ordos City [30] exhibits a marked seasonal concentration, a pattern consistently observed across different hydrological years and intensifying with increased annual precipitation [31]. Specifically, rainfall predominantly occurs from April to November, with the summer-autumn period of July to October being the key phase: in dry, average, and wet years, rainfall during this period accounts for approximately 75%, 80%, and 90% of the annual total, respectively. This pattern indicates that the summer-autumn season represents a critical window for rainwater harvesting [32], while also imposing greater demands on the storage and regulation capacity of water retention facilities.

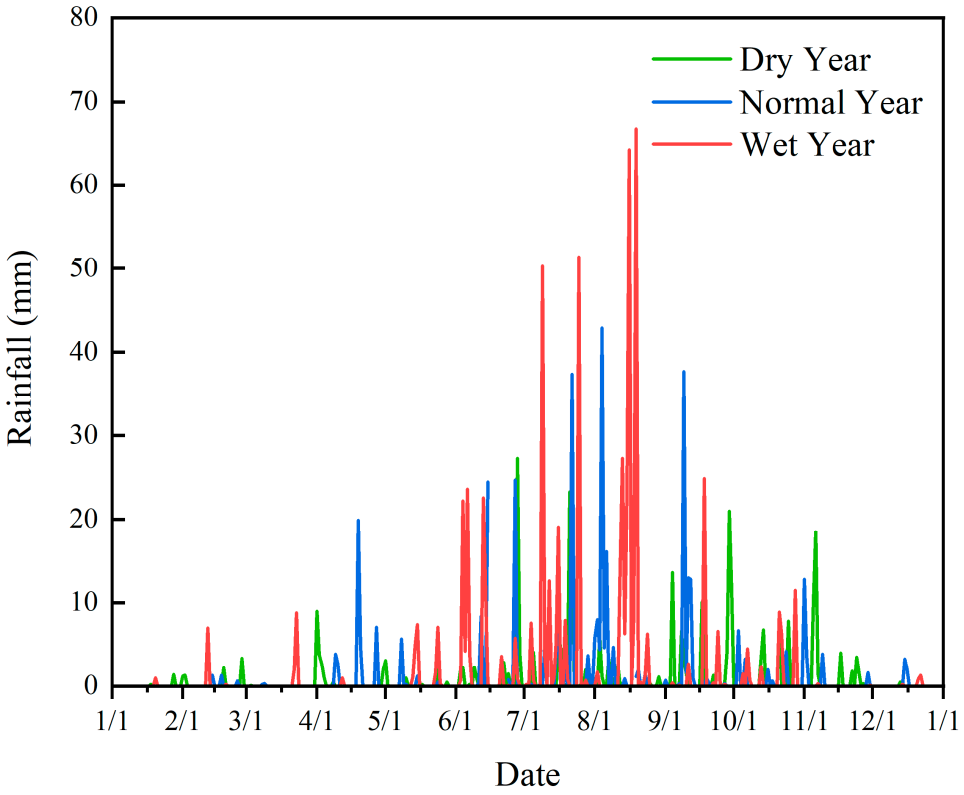

Figure 3. Daily rainfall time series.

2.2.2. Underlying Surface Data

Underlying surface data [33] is used to accurately characterize the composition and spatial distribution of surface cover during rainfall events, directly determining the processes of rainwater infiltration, retention, and runoff transformation across different interfaces. As shown in Figure 4, the total area of sponge facilities in Dongsheng District is 4.7 km^2, predominantly consisting of green spaces (35.5%) and buildings (32.3%), which together form the core of the underlying surface structure in this area. In Kangbashi District, the total area of sponge facilities is 7.9 km^2, with green spaces accounting for the highest proportion (48.7%), followed by lakes (24.1%), while permeable pavements have the lowest proportion (5%), reflecting the region's strong ecological foundation and land-

scape water features. In Ejin Horo Banner District [34], the total area of sponge facilities is 13.6 km^2, with lake areas comprising 50%, followed by green spaces (32.3%), and impervious pavements accounting for the smallest proportion (5%), highlighting the region's significant advantages in water retention and ecological storage. The differences in underlying surface structures among the three districts reflect their respective functional priorities in sponge facility construction and rainwater runoff regulation pathways, providing key spatial parameters for subsequent analysis of regional rainwater resource potential.

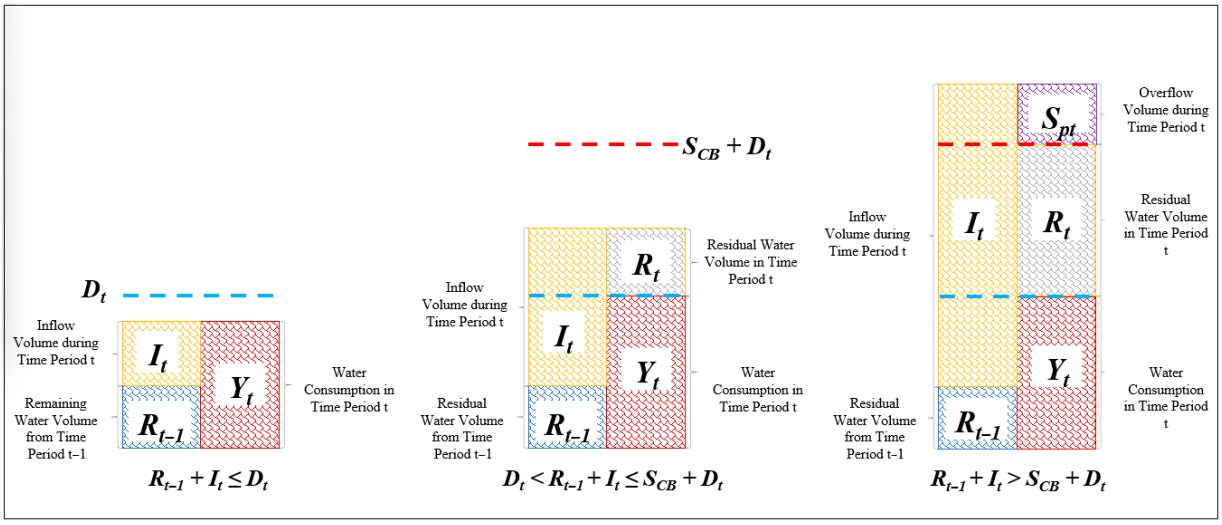

Figure 4. Schematic diagram of the YBS method.

The distribution of sponge facilities varies across the three regions. In Dongsheng District, the total area occupied by sponge facilities is 4.7 km^2; in Kangbashi District, it is 7.9 km^2; and in Ejin Horo Banner, it reaches 13.6 km^2. In Dongsheng District, sponge facilities are primarily concentrated in small-scale residential communities and parks, including 8 sponge communities and 6 sponge parks [35]. Notably, its sole sponge lake area, Sanjitai Lake, covers 3.1 km^2, accounting for 66% of the district's total sponge facility area. Kangbashi District exhibits the highest level of urbanization. In its sponge facility planning, the focus has been primarily on sponge parks. Among these, the Qiantingshan Cultural Scenic Area and Leijiapo Wetland Park are the most representative in terms of area. These sites were designed to integrate harmoniously with the local environment, preserving existing water bodies, natural ecological woodlands, hills, and other original landforms, thereby creating a unified landscape of mountains and water. Leijiapo Wetland Park, constructed in a low-lying area of a hill, utilizes six ponds to collect water from surrounding depressions and rainfall, serving as a water source for nearby residents. Ejin Horo Banner has a relatively lower degree of urbanization. Its most representative sponge facilities are the Donghonghaizi Wetland Park and the Yihe Ecological Expo Garden. Donghonghaizi Wetland Park covers an area of 7.9 km^2, constituting 58% of the banner's total sponge facility area, while the Yihe Ecological Expo Garden spans 3.5 km^2, accounting for 26%.

2.3. Yield Before Spillage Assessment Method

2.3.1. Fundamentals of Yield Before Spill

$$S_{pt} = \begin{cases} 0,\ R_{t-1} + I_t \leq D_t \\ 0,\ R_{t-1} + I_t \leq S_{CB} + D_t \\ R_{t-1} + I_t - S_{CB} - D_t,\ R_{t-1} + I_t > S_{CB} + D_t \end{cases}, \quad (2)$$

$$R_t = \begin{cases} 0,\ R_{t-1} + I_t \le D_t \\ R_{t-1} + I_t - D_t,\ D_t < R_{t-1} + I_t \le S_{CB} + D_t \\ S_{CB},\ R_{t-1} + I_t > S_{CB} + D_t \end{cases}, \quad (3)$$

$$Y_t = \begin{cases} R_{t-1} + I_t,\ R_{t-1} + I_t \le D_t \\ D_t,\ R_{t-1} + I_t > D_t \end{cases}, \quad (4)$$

In the equation, S_{pt} represents the spillover volume, R_{t-1} denotes the residual water volume at time t − 1, I_t indicates the inflow volume during period t, D_t stands for the water demand during period t, and S_{CB} is the tank storage capacity. R_t refers to the residual water volume at time t, while Y_t represents the water consumption at time t. The tanks are assumed to be initially empty. In arid regions, local water supply often falls short of water demand, necessitating water diversion from other areas. Rainfall events are infrequent with prolonged dry spells, ensuring that any stored water is fully utilized between rainfall events.

In contrast to the YAS (Yield After Spillage) method, which follows the principle of "storage first, drainage later, and water use after overflow," the core mechanism of the YBS method (water-priority method) lies in "water use priority and dynamic regulation". Specifically, when calculating water yield, the YAS method requires that the tank first be filled to capacity and overflow occurs, after which the overflow portion is deducted from the total water yield. Its primary design objective is to maximize peak runoff reduction and alleviate waterlogging pressure, making it more suitable for regions with abundant rainfall and high waterlogging risks, aiming to effectively respond to extreme rainfall events.

In comparison, the YBS method prioritizes water demand at the forefront of the process: during rainfall–runoff simulation, the system first deducts the expected daily water demand from the stored water volume, and then uses the remaining storage capacity to capture the incoming rainfall. This strategy of "simultaneous storage and use, pre-release to accommodate rainfall" essentially treats the buffer space created by daily water demand as part of the effective collection capacity. Consequently, it significantly reduces the design scale of tanks while maintaining collection efficiency.

The key difference lies in their operational principles: under the YAS method, water is not used during the storage process and is only utilized after storage ceases, whereas the YBS method allows for simultaneous collection and usage. Following the YAS design philosophy, tank sizes tend to be larger than those designed with YBS. For arid and semi-arid regions with limited rainfall, tanks designed with the YBS method are sufficient to capture available rainwater, offering lower costs and greater cost-effectiveness. This design philosophy—sizing based on water use, determining capacity by demand—demonstrates significant advantages in arid and semi-arid regions such as Ordos. It not only precisely addresses the core challenge of local water scarcity by prioritizing water use to enhance rainwater utilization, but also substantially reduces construction costs through optimized facility scale, reflecting higher economic efficiency and practicality. This represents an important technical pathway for maximizing the benefits of rainwater resource utilization.

2.3.2. Multi-Tier Classification-Based Stormwater Resource Utilization Scheme

The schematic diagram of the multitier classification-based stormwater resource utilization system is divided into three parts: sponge facilities, underlying surfaces, and end uses, as shown in Figure 5. The underlying surface classification system further subdivides four major types of sponge facilities (sponge parks, sponge residential areas, sponge lake zones, and sponge roads) into five specific categories: rooftops, green spaces, permeable pavements, impermeable pavements, and lake surfaces, integrating their spatial distribu-

tion as well as runoff yield and concentration parameters. Based on relevant literature [36], a first flush diversion of 3 mm is adopted in the calculation to ensure the quality of the reclaimed water.

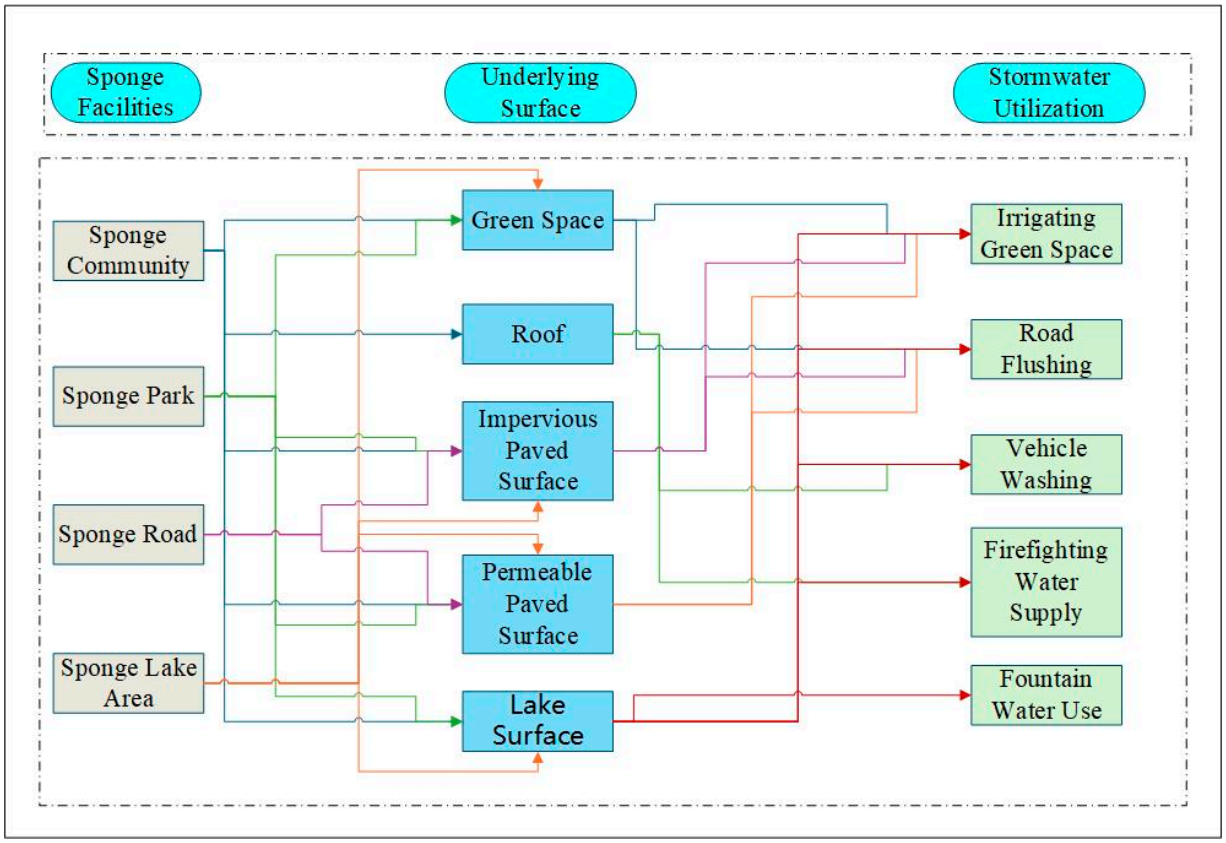

Figure 5. Graded classification and stormwater utilization scheme for sponge city facilities.

The core calculation adopts a standardized method, designing independent water collection systems for each of the five underlying surface types. Given the differences in actual catchment area among the surface types, three storage tanks corresponding to different design return periods (p = 5a, p = 10a, p = 20a) are configured for each surface category. Even under the same return period, the designed tank sizes vary significantly due to differences in catchment area and runoff coefficients (0.9 for rooftops, 0.9 for impermeable pavements, 0.3 for permeable pavements, 0.15 for green spaces, and 1 for lake surfaces) [37–39], ensuring the scientific rationality of the system configuration.

Following the calculation of tank sizes based on design rainfall, the "water use priority" principle is further implemented through the economic optimization of the effective tank volume. This involves deducting the representative daily water consumption of the underlying surface unit associated with each tank. The engineering rationale behind this design is that such daily water consumption can function as a dynamic buffer space: during a design rainfall event, the capacity freed up by the water consumed that day can complement the static volume of the tank in capturing the runoff from the rainfall. This approach effectively reduces the required constructed size of the tank without compromising collection efficiency, thereby significantly lowering the initial investment cost of the system [40]. Since the primary uses of rainwater collected from different underlying surfaces vary [41] (for example, water collected in green space units is mainly used for irrigating the area itself and adjacent green spaces [42]; water from road units is primarily utilized for street cleaning [43]; and water from rooftop units may be applied for car washing, firefighting, or miscellaneous purposes [44]), the corresponding "daily water consumption" also differs

for each tank type. This results in a more targeted and economical determination of the effective volume for each final tank design [45].

2.3.3. Tank Volume Design Under Different Underlying Surface Conditions and Return Periods

For the five underlying surface types, with a catchment area of 1000 m^2 and one storage tank installed per 1000 m^2, we applied the water-use priority principle to design tank sizes based on the daily water demand for rainwater collected from each surface type.

Volume calculation follows a demand-oriented approach, considering the following three key factors:

(1) Basic water demand: Water demand varies across different underlying surfaces. For example, water collected from green spaces is used for irrigation; water from road surfaces is allocated for firefighting and road spraying; rainwater harvested from rooftops is designated for car washing and road irrigation; and water collected from lake surfaces is utilized for fountain facilities.
(2) Variation in runoff coefficients: Runoff coefficients differ among underlying surface types, resulting in varying volumes of rainwater collected per unit area.
(3) Rainwater replenishment cycle: Determined based on the local duration of drought periods.

The formula for calculating tank volume is as follows:

$$V_B = F \times (h_y - \delta) \times \varphi - (U \times 1), \quad (5)$$

V_B represents the storage tank volume; F denotes the catchment area; h_y indicates the design rainfall; δ is the first-flush diversion depth; φ refers to the runoff coefficient; U stands for the average daily water consumption.

The catchment area F shall exclude ineffective areas [46]. The design rainfall h_y shall comply with local sponge city planning requirements [47] and should, in principle, exceed the design rainfall standard corresponding to the regional annual runoff volume control rate. Its specific value shall be determined according to the engineering grade using design rainfalls of different return periods, typically including 5-year, 10-year, and 20-year return periods. The initial diversion depth δ [48] is set between 1 mm and 5 mm based on the pollution level of the underlying surface, and is taken as 3 mm in this study. The runoff coefficient φ is determined according to the characteristics of the underlying surface [49].

The average daily water consumption U is determined based on the actual water demand of different sectors, as referenced from relevant literature [50–53]. This approach is applicable in water-scarce regions where resource use efficiency is emphasized.

When the rainfall intensity is lower than the design return period of the storage tank, no overflow occurs and the tank is not fully filled. In this case, the water volume stored in the tank equals the runoff generated from the catchment area and collected by the tank during the rainfall event, minus the average daily water demand corresponding to the underlying surface type. When the rainfall intensity exactly matches the design return period of the tank, the tank becomes fully filled, reaching its design volume V_B. When the rainfall intensity exceeds the design return period, overflow occurs, but the stored water volume remains at V_B. The study area is located in an arid region, with an average of only 10 to 30 rainfall events per year. Local water demand far exceeds the available water supply, necessitating external water supplementation. Meanwhile, storage tanks corresponding to different underlying surface types supply water for various usage purposes, such as green space irrigation and road cleaning, ensuring that the stored water is typically fully utilized during the intervals between rainfall events. As rainfall events generally occur within a

single day, the average daily water demand U deducted in the tank volume calculation reflects the actual water demand of the specific underlying surface type. This design fully embodies the core principle of the YBS method, namely "simultaneous storage and use," where water storage and consumption proceed in parallel. By effectively utilizing the storage space created by daily water demand, this approach achieves efficient rainwater harvesting and maximized utilization while meeting water demand requirements.

After completing the differentiated design of storage tanks, the assessment proceeds to the resource potential accounting stage. Rainfall sequences from three typical hydrological years (wet, normal, and dry) are input into the system to simulate the operation of each catchment unit. For each rainfall event, whether it exceeds the first-flush diversion threshold is determined, and the corresponding runoff volume is calculated. Rainwater is collected only when the runoff volume does not exceed the effective capacity of the corresponding tank (i.e., after deducting daily water consumption); any excess volume overflows. By simulating the performance of tanks with different return periods and underlying surface types across the three hydrological years, a multi-dimensional analytical framework is established to quantify the total rainwater harvestable volume in the study area under different yearly conditions. Finally, the collected volume is allocated according to water use priorities (green space irrigation, road cleaning, landscape water replenishment, groundwater recharge, and municipal miscellaneous uses), and treatment losses are considered to calculate the usable rainwater resource potential. This process enables a refined assessment from rainfall input to resource potential output.

2.3.4. Calculation of Water Consumption Potential and Its Economic Benefits

Assume that a represents the number of rainfall events within one year with a return period greater than 5 years but less than 10 years; b denotes the number of rainfall events within one year with a return period greater than 10 years but less than 20 years; c indicates the number of rainfall events within one year with a 20-year return period; and u_1 stands for the total rainfall amount within one year from events with a return period less than 5 years. Based on these definitions, the following is derived:

$$Q_B = \begin{cases} u_1\varphi F + (a+b+c)V_a, \ V_p \le 5 \\ (u_1 + aH_a)\varphi F + (b+c)V_b, \ 5 < V_p \le 10 \\ (u_1 + aH_a + bH_b)\varphi F + cV_c, \ 10 < V_p \le 20 \end{cases}, \quad (6)$$

$$Q_{B,p,i} = (Q_B + U \times T) \times \mu, \quad (7)$$

Q_B represents the annual water consumption of ordinary rainwater collection tanks with different design sizes; V_p(p = a, b, c) corresponds to the design volumes of rainwater collection tanks for the 5-year, 10-year, and 20-year return periods, respectively; H_a, H_b denote the design rainfall depths for the 5-year and 10-year return periods within one year; φ is the runoff coefficient, which varies with different underlying surface types (see Table 2 for details); F represents the catchment area, taken as 1000 m^2; $Q_{B,p,i}$(p = a, b, c; i = wet, normal, dry) refers to the annual water consumption based on the YBS concept for different design sizes and different hydrological years (wet, normal, dry); U is the average daily water consumption; T is the total number of rainy days within the year when rainfall exceeds the return period of the corresponding storage tank.; μ [54–56] represents the net rainwater utilization efficiency, defined as the proportion of collected rainwater that can be effectively used. In this study, μ is set to 0.85. This formula quantifies the maximum rainwater harvesting potential of sponge facilities under ideal conditions by calculating the theoretical annual water consumption for a given tank design size, thereby providing

a basis for determining the upper limit of resource utilization under the "sizing storage based on usage" strategy.

Table 2. Design and Parameter Values of Storage Tanks for Different Return Periods.

Different Underlying Surface Types	Green Space	Impermeable Pavement	Permeable Pavement	Rooftop	Lake Surface
Runoff coefficient	0.15	0.9	0.3	0.9	1
Water Consumption: L/(day·m^2)	2	4	4	4	2
Design Volume (m^3) for p = 5a	4	31	8	31	Water Surface
Water Tank Cost (yuan)	4992	30,264	7488	30,264	0
Design Volume (m^3) for p = 10a	5	37	10	37	Water Surface
Water Tank Cost (yuan)	5928	36,816	10,608	36,816	0
Design Volume (m^3) for p = 20a	6	44	12	44	Water Surface
Water Tank Cost (yuan)	6864	42,432	11,856	42,432	0

Rainwater collected from different underlying surfaces varies in impurity content and treatment methods, leading to corresponding differences in usage allocation. Rainwater harvested from green spaces is primarily used for vegetation irrigation and road cleaning. Roof-collected rainwater, which is relatively better in quality, is mainly allocated for car washing and road cleaning, with a small portion used for green space irrigation. Road-collected rainwater is primarily supplied for road cleaning and firefighting purposes. Lake-collected rainwater, being less polluted and easier to treat, can be used for various purposes such as irrigation, ecological water replenishment, landscape fountains, firefighting, road cleaning, and car washing. The specific water usage allocation ratios are shown in Figure 6.

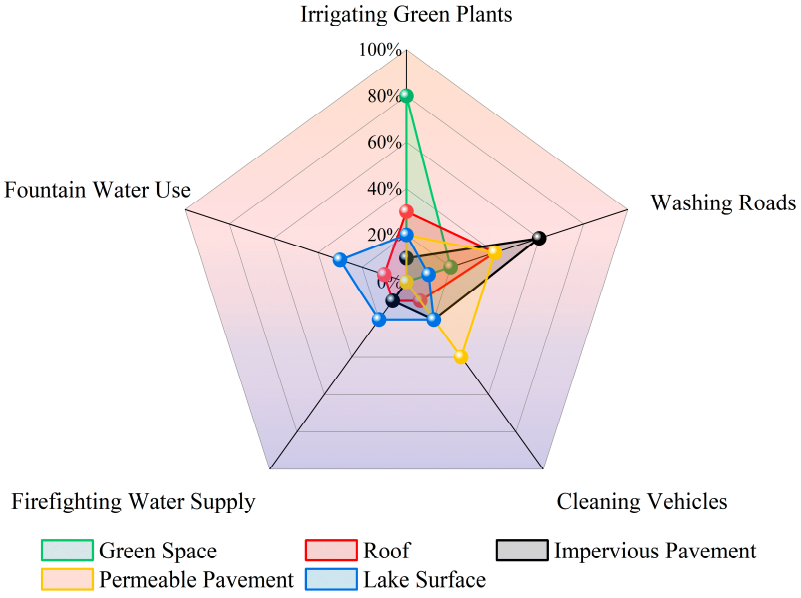

Figure 6. Radar chart of water allocation for storage tanks under different underlying surface conditions.

Based on the water usage patterns of different underlying surfaces and the corresponding water prices [57,58] (as shown in Figure 7), the water use benefits of the five underlying surface types under different tank sizes and across wet, normal, and dry years can be calculated. Using the occurrence frequency of wet, normal, and dry years, the average annual water use benefit is derived. By further incorporating tank costs, the water use benefits of the four types of sponge facilities in the three regions under the corresponding years are analyzed.

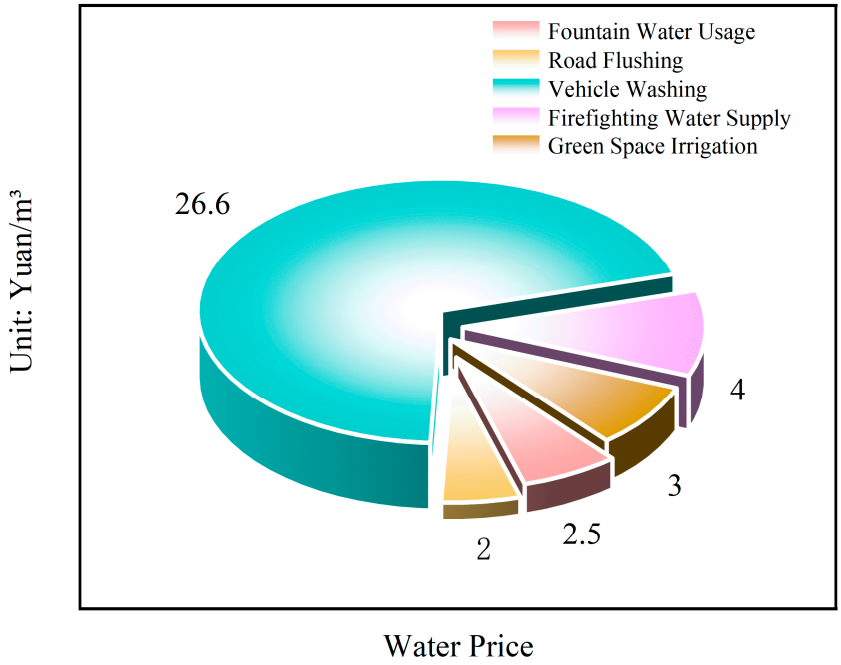

Figure 7. Water pricing chart.

2.3.5. Calculation of Net Present Value and Payback Period

Net Present Value (NPV) was used to evaluate the economic feasibility of the rainwater harvesting systems. NPV represents the difference between the present value of cash inflows and outflows over the project's lifetime, discounted at a given rate. The calculation formula is as follows:

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+r)^t} - C_0, \quad (8)$$

In the formula, C_0 represents the initial investment cost, and R_t denotes the net benefit in year t, calculated as the annual water cost savings minus the annual operation and maintenance (Operation and Maintenance) costs. The discount rate is denoted by r (%), and n represents the project lifespan (years).

In this study, the discount rate [59] was determined based on the average yield of China's long-term government bonds during the study period (approximately 1.81%), with comprehensive consideration of the risk premium associated with rainwater harvesting projects as municipal infrastructure [60]. Accordingly, a social discount rate of 5% was ultimately adopted. Annual O&M costs were estimated as 5% [61,62] of the initial investment, covering routine maintenance and cleaning expenses. A project lifespan of 20 years was assumed for all tank systems.

3. Results

3.1. Spatio-Temporal Distribution Characteristics and Utilization Potential of Rainwater Resources

For the five types of sponge facilities in the three regions, after designing water tanks for different underlying surface types based on water-use priority, water allocation is carried out according to the underlying surface types. The water allocation proportions for different sponge facilities in the three regions are shown in Figure 8 below.

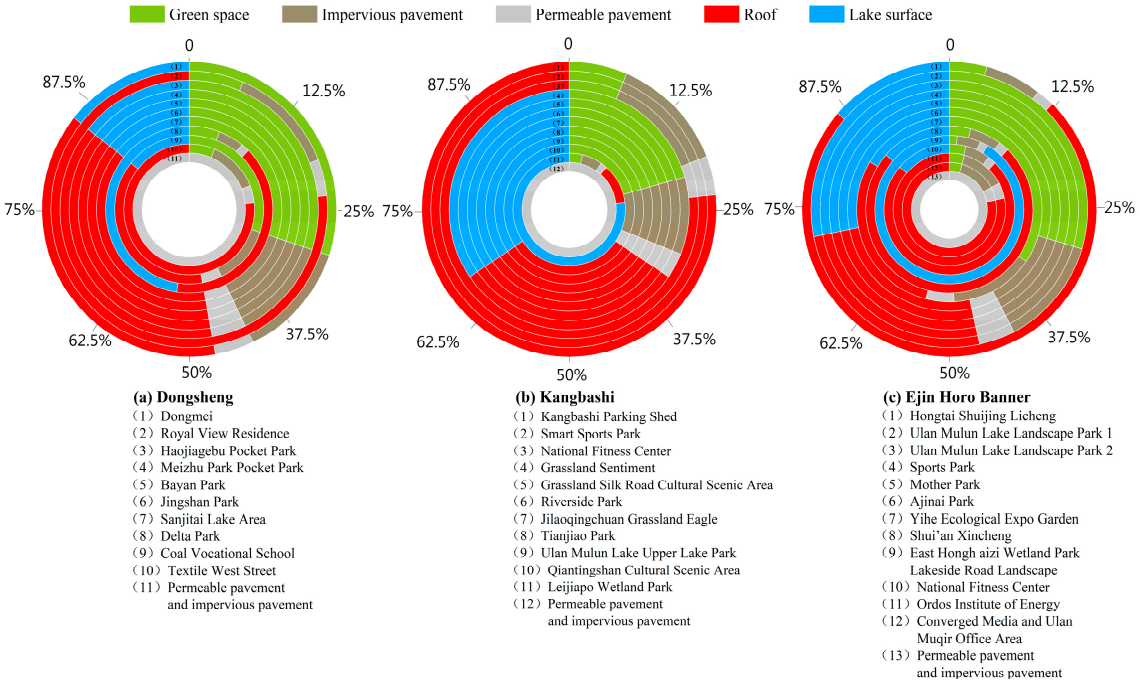

Figure 8. Annual water use proportion of underlying surfaces corresponding to various sponge facilities.

In Dongsheng District, sponge facilities have been established, including one sponge lake area, seven sponge parks, three sponge roads, and seven sponge communities, with a total area of 4.7 km^2. Evaluation results indicate that the rainwater harvesting capacity of these sponge facilities exhibits significant interannual variability. Under dry year conditions, storage tanks designed for three different return periods (p = 5a, p = 10a, p = 20a) all achieve full collection, with an annual harvest volume stabilizing at 492,000 m^3. During normal years, harvesting capacity shows an increasing trend with higher design standards, reaching 779,000 m^3 under the p = 5a design, and rising to 790,000 m^3 under both the p = 10a and p = 20a designs. In wet years, the performance differences among the design standards become more pronounced, with harvest volumes increasing from 1.2 million m^3 under the p = 5a design to 1.368 million m^3 under the p = 20a design.

In terms of water harvesting structure, rooftop collection dominates in Dongsheng District's sponge facilities, accounting for 46.4% of the total, while permeable pavements contribute the least at only 2.4%. Particularly noteworthy is the Sanjitai Lake Area, a key sponge facility in the region, which alone contributes 74.5% of the total harvested water, playing a central role in the system. After implementing the design of tanks with different return periods, the comprehensive annual runoff control rate remained between 85.45% and 92.1% across different hydrological years.

As an old urban area, Dongsheng District is characterized by high building density and extensive impervious surfaces. The relatively high proportion of rooftop rainwater harvesting reflects the "inserting green wherever possible" approach typical of sponge city construction under urban renewal contexts. The significant contribution of the Sanjitai Lake Area demonstrates that preserving and utilizing existing water bodies in the sponge city retrofitting of old districts can achieve considerable rainwater harvesting benefits with a limited water surface area. The annual water consumption in the sponge construction area of Dongsheng District is presented in Figure 9 below.

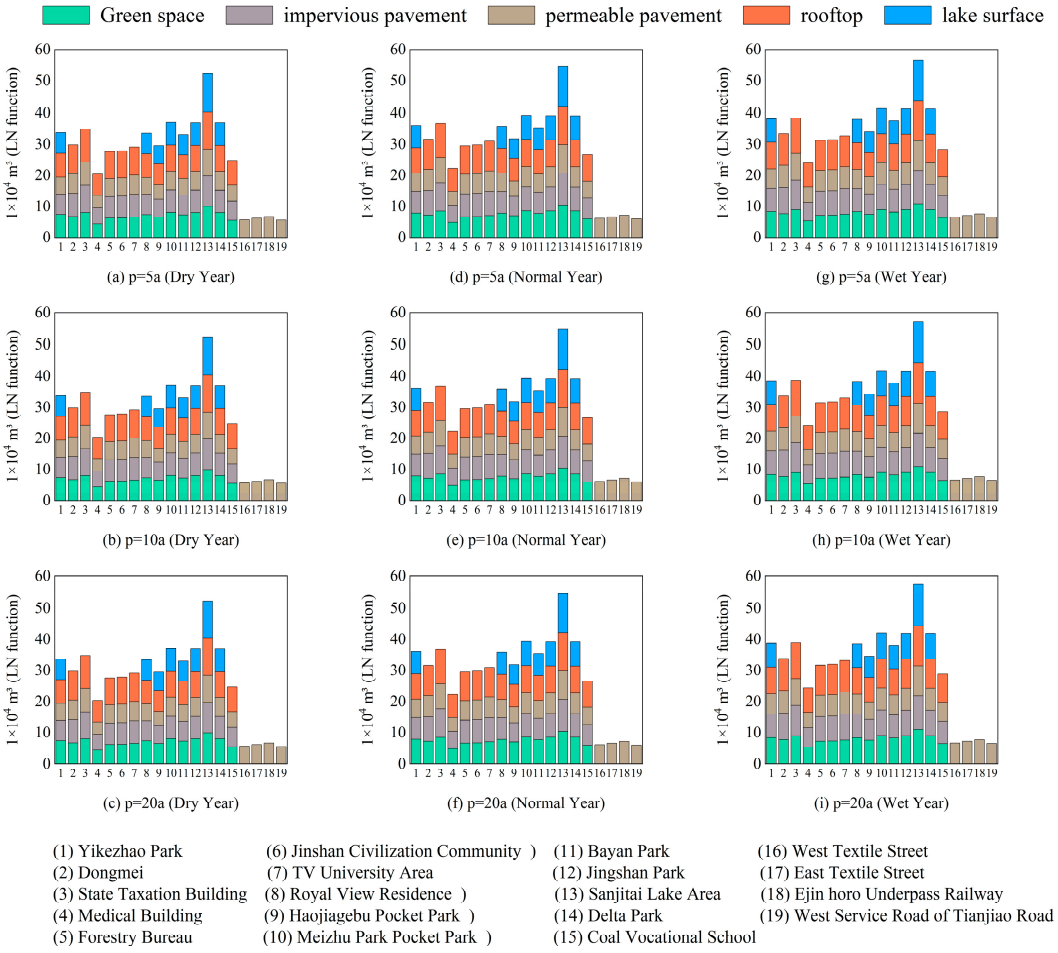

Figure 9. Annual water consumption in the sponge construction area of Dongsheng District.

The assessment indicates that the sponge facilities in the region demonstrate strong rainwater harvesting capacity across different hydrological years. In dry years, the annual rainwater collection volume for all three types of rainwater collection tanks is 671,000 m^3. In normal years, the collection volume increases from 1.062 million m^3 for the p = 5a design to 1.077 million m^3 for both the p = 10a and p = 20a designs. During wet years, the collection volumes show significant variation: the p = 5a design collects 1.653 million m^3 of rainwater, the p = 10a design collects 1.775 million m^3, and the p = 20a design collects 1.885 million m^3.

Regarding the water harvesting structure, Kangbashi District is characterized by lake surface collection as the dominant contributor, accounting for 46.9% of the total, while permeable pavements remain the lowest contributor (2.9%). Among these, the Qianjingshan Cultural Scenic Area, as a key sponge facility, contributes 31.2% of the district's total harvested water. After implementing the design of tanks with different return periods, the comprehensive annual runoff control rate remained between 88.9% and 95.3% across different hydrological years. The runoff reduction effect of the sponge facilities in this region is significant, fully complying with the standards for sponge city construction.

As a high-standard planned new urban area, the sponge facility construction in Kangbashi District fully embodies the concept of "planning-led, systematic layout." The high green space ratio (48.7%) and lake surface proportion (24.1%) jointly form a composite regulation and storage system of "green sponge + blue reservoir"—the green space system achieves source reduction through infiltration and retention, while the water body system exerts process control through regulation and replenishment. Their synergy enhances the

overall rainwater resource regulation capacity of the region. The annual water consumption in the sponge construction area of Kangbashi District is shown in Figure 10 below.

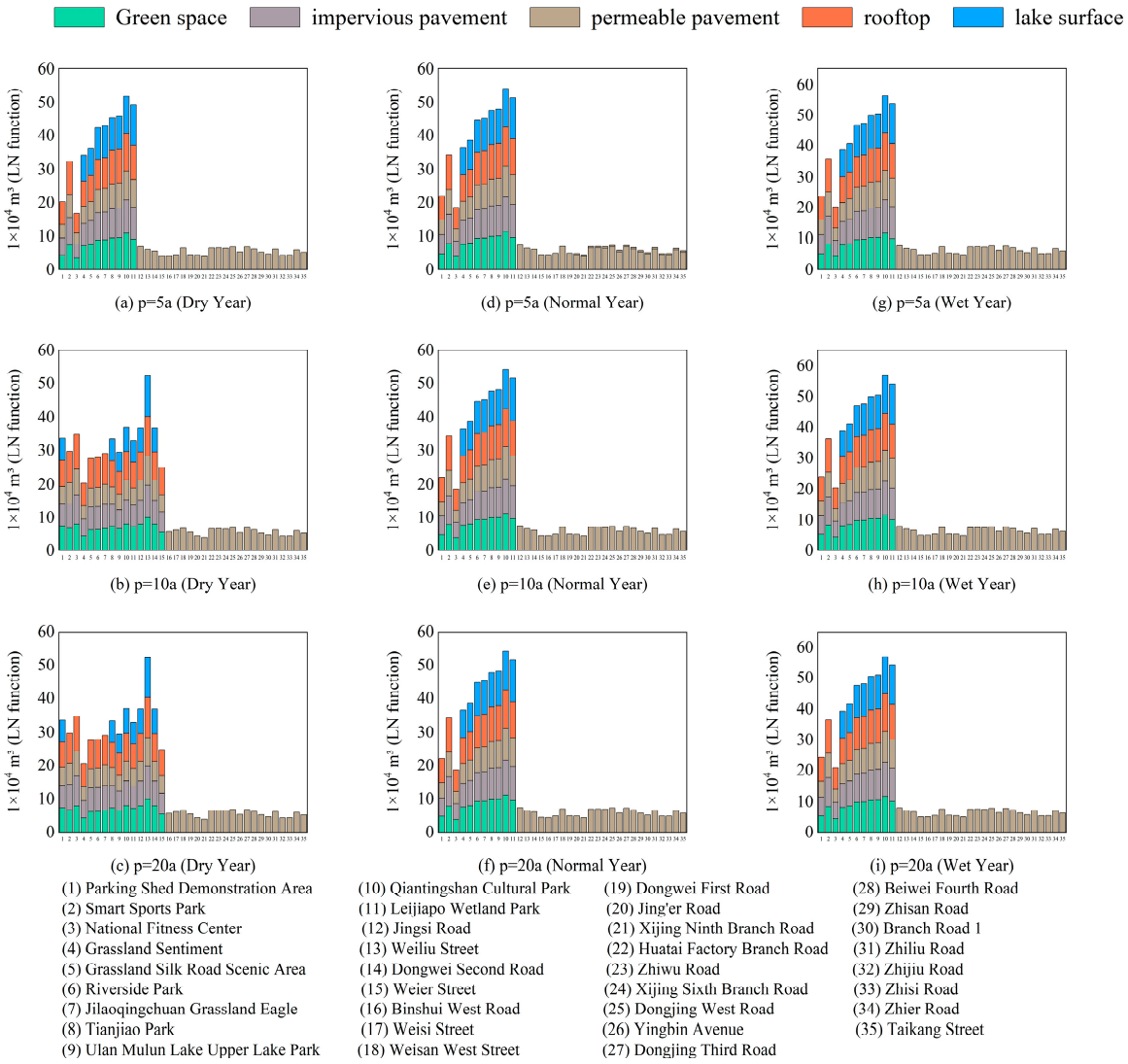

Figure 10. Annual water consumption in the sponge construction area of Kangbashi District.

For the Ejin Horo Banner area, the sponge facilities in this region demonstrate outstanding rainwater harvesting capacity. In dry years, the annual collection volume for all three types of tanks reaches 1.48 million m^3. In normal years, the collection volume increases from 2.334 million m^3 for the p = 5a design to 2.367 million m^3 for both the p = 10a and p = 20a designs. During wet years, the growth is most pronounced: the p = 5a tank collects 3.595 million m^3, the p = 10a tank collects 3.858 million m^3, and the p = 20a tank collects 4.098 million m^3.

The water harvesting structure of the sponge facilities in this region is dominated by lake surfaces, with a contribution rate as high as 73.4%, while permeable pavements have the lowest contribution (2.3%). Among these, the Donghonghaizi Wetland Park plays a decisive role, contributing 76.6% of the total harvested water for the entire banner. After implementing the design of tanks with different return periods, the comprehensive annual runoff control rate remained between 86.2% and 92.5% across different hydrological years.

Ejin Horo Banner has a lake surface ratio of 50%, resulting in rainwater harvesting capacity far exceeding that of the other two districts. The Donghonghaizi Wetland Park, with its 7.9 km^2 lake surface, functions as a substantial natural regulation and storage reservoir,

providing considerable collection capacity while enabling cascaded utilization of rainwater resources through ecological water replenishment. The annual water consumption in the sponge construction area of Ejin Horo Banner is shown in Figure 11 below.

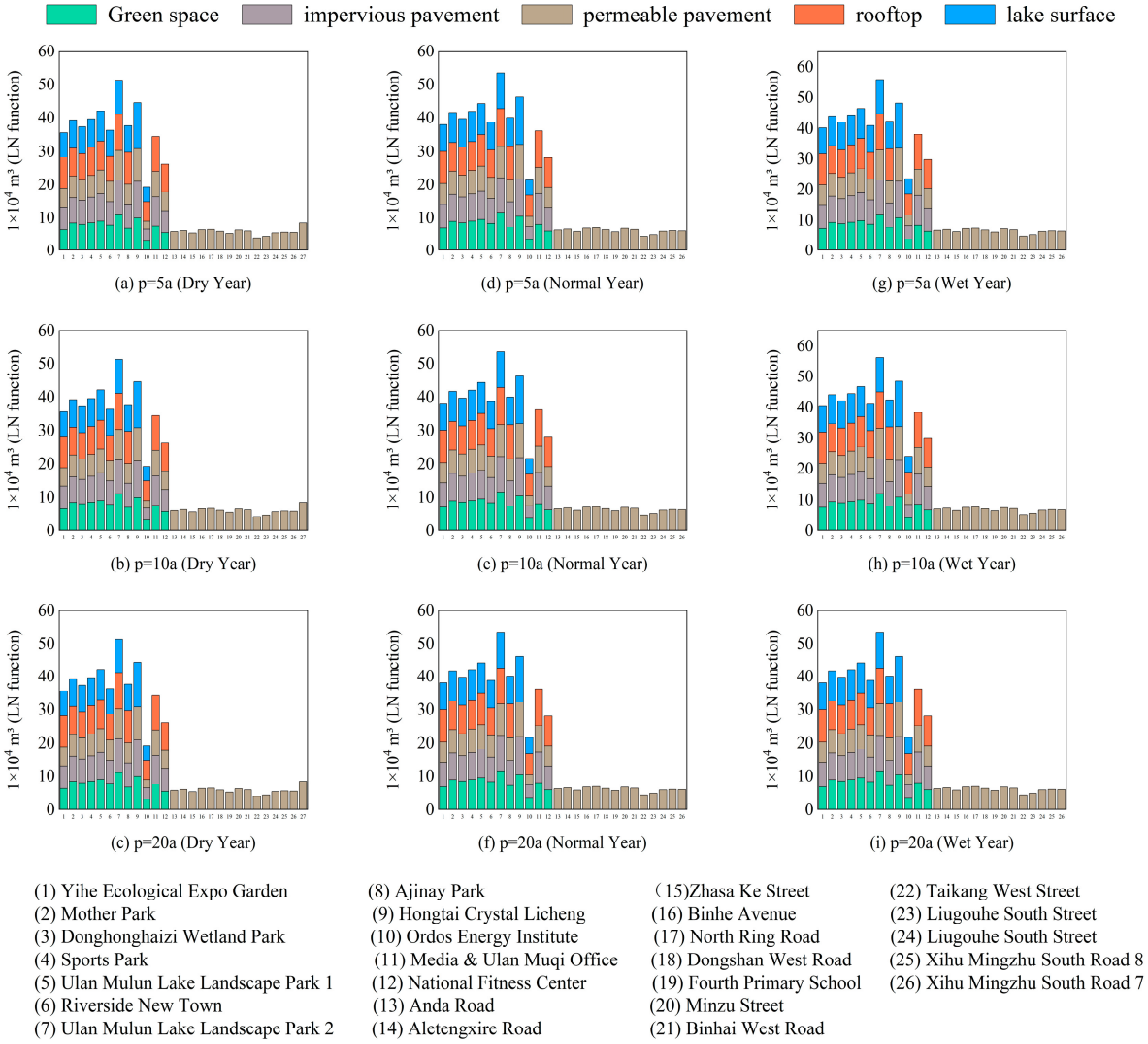

Figure 11. Annual water consumption in the sponge construction area of Ejin Horo Banner.

The comprehensive evaluation shows that rainwater collection tanks designed for different return periods perform differently under varying annual rainfall levels. Specifically, under dry year conditions, rainwater collection containers designed for all three return periods can fully capture all rainfall. Considering cost and construction time, the p = 5a design offers the best cost-effectiveness. In normal years, differences in collection efficiency begin to emerge among tanks designed for different return periods. The p = 5a design cannot fully capture all rainfall, resulting in overflow, while the p = 10a design achieves full capture and reaches the maximum reduction potential. During wet years, the rainfall reduction potential varies significantly across designs for different return periods. Neither the p = 5a nor the p = 10a designs can fully collect all rainfall. The p = 20a design performs optimally, demonstrating the highest reduction potential.

In terms of water collection structure, notable differences exist among regions: the sponge development area in Dongsheng District is dominated by rooftop collection, whereas those in Kangbashi District and Ejin Horo Banner rely primarily on lake surface collection. It is particularly noteworthy that large-scale landscape water bodies—such

as the Sanjitai Lake Area and the Donghonghaizi Wetland Park—contribute especially prominently to the total regional rainwater collection volume. Furthermore, storage tanks corresponding to all three design return periods achieve comprehensive runoff reduction rates exceeding 90%, fully meeting the runoff control requirements for sponge city construction in each region. Uncollected rainwater primarily infiltrates to replenish groundwater, enabling multi-path utilization of rainwater resources and supporting the natural restoration of the hydrological cycle. These results validate the adaptability and reliability of the YBS method under varying hydrological conditions, providing important technical support for advancing sponge city development in arid and semi-arid regions.

3.2. Economic Benefit Evaluation of the Sponge Facility System Under Different Hydrological Years

Based on an economic benefit evaluation system following the water-use priority principle, this study quantifies the economic benefit potential of the sponge facility system in the "Dongsheng–Kangbashi–Ejin Horo Banner" urban agglomeration under different hydrological conditions. The assessment comprehensively considers multiple factors, including rainwater harvesting volume, utilization pathways, and the value of alternative water resources. By establishing a complete calculation chain of "rainfall-collection-utilization-benefit," it systematically reveals the economic value of sponge facilities over their entire life cycle. A multi-scenario analysis framework was developed to fully capture the hydrological response patterns and economies-of-scale characteristics of the economic benefits of sponge facilities.

The following sections detail the economic benefit evaluation results of sponge facilities under different hydrological years for the three regions: Dongsheng District, Kangbashi District, and Ejin Horo Banner.

The sponge facility area in Dongsheng District demonstrates favorable economic benefit potential for rainwater resource utilization. Under dry year conditions, where the total volume of rainwater resources becomes the primary limiting factor, the annual economic benefit potential corresponding to rainwater tanks designed for different return periods (p = 5a, p = 10a, p = 20a) converges at 8.2 million CNY. In normal years, differences in economic benefit potential emerge with higher design standards, where the annual economic benefit potential under the p = 5a design is 12.98 million CNY, while that for p = 10a and p = 20a increases to 13.18 million CNY. Under wet year conditions, the economic benefits of elevated engineering design standards become more pronounced, with annual economic benefit potential reaching 19.99 million CNY for p = 5a, rising to 21.46 million CNY for p = 10a, and further increasing to 22.79 million CNY for p = 20a. The economic benefit potential of sponge facilities under different hydrological years in Dongsheng District is shown in Figure 12 below.

The economic benefit assessment of the sponge facility area in Kangbashi District shows a growth trend similar to that of Dongsheng District. In dry years, the annual economic benefit potential generated by rainwater collected by tanks designed for the three return periods is consistently 8.24 million CNY. Under normal year conditions, the economic benefit potential begins to diverge with higher design standards: the p = 5a design yields an economic benefit potential of 13.03 million CNY, while the p = 10a and p = 20a designs increase this value to 13.22 million CNY. During wet years, the improvement in economic benefits is most pronounced, with the annual economic benefit potential reaching 20.06 million CNY for the p = 5a design, increasing to 21.54 million CNY for p = 10a, and further rising to 22.87 million CNY for p = 20a. The economic benefit potential of sponge facilities under different hydrological years in Kangbashi District is shown in Figure 13 below.

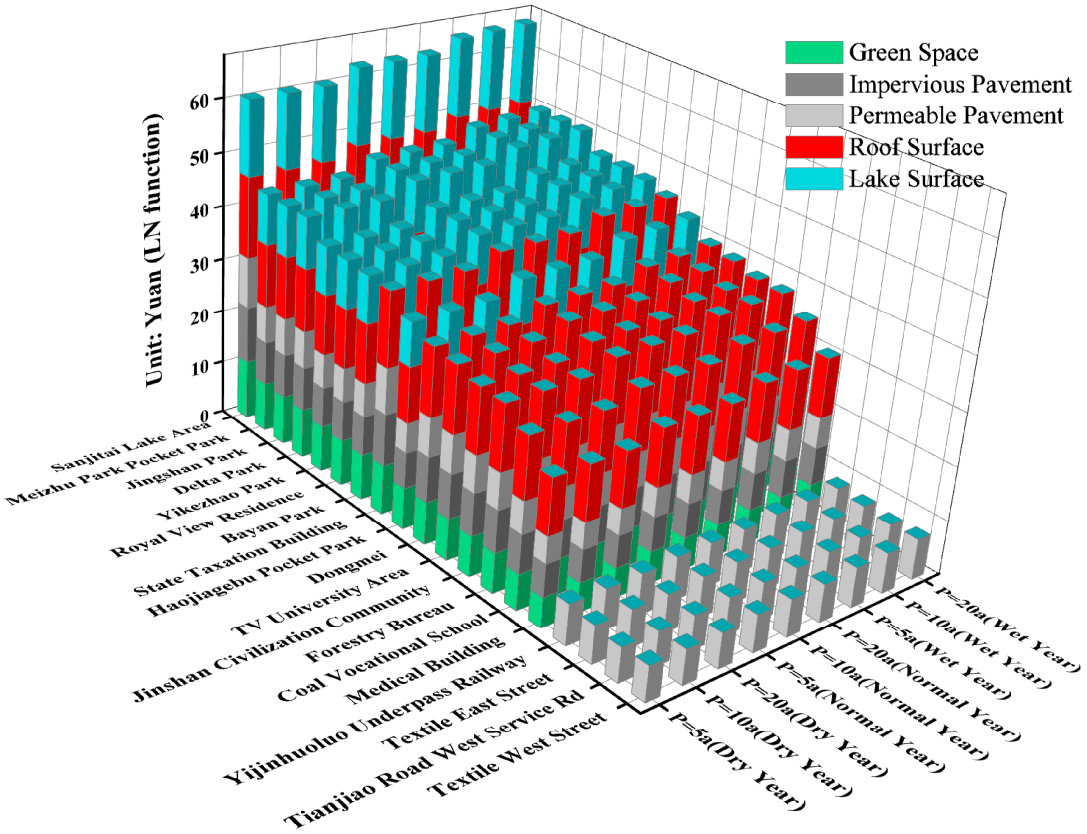

Figure 12. Economic benefit potential of sponge facilities under different hydrological years in Dongsheng District.

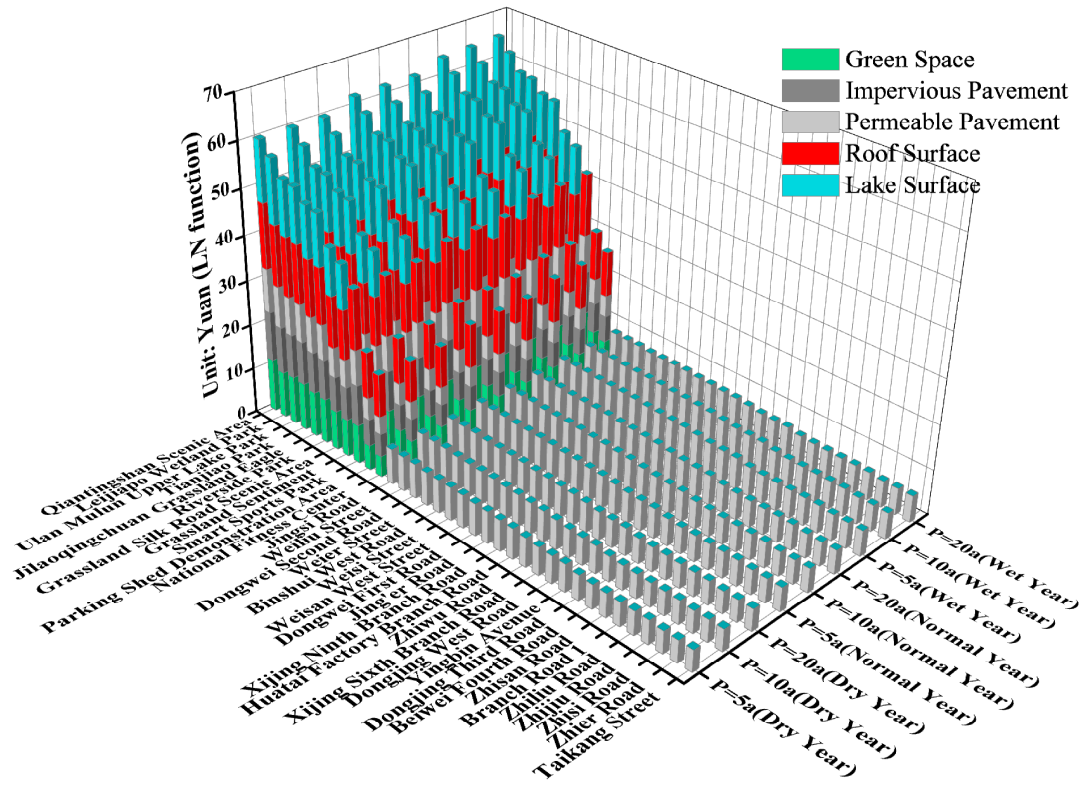

Figure 13. Economic benefit potential of sponge facilities under different hydrological years in Kangbashi District.

The sponge facility area in Ejin Horo Banner demonstrates the most significant potential for economic benefits. Under dry year conditions, the annual economic benefit potential corresponding to the three design return periods is consistently 14.05 million CNY. During normal years, the annual economic benefit potential generated by rainwater collection under the p = 5a design reaches 22.23 million CNY, while the potential under the p = 10a and p = 20a designs further increases to 22.56 million CNY. Under wet year conditions, the growth in economic benefits is most pronounced: the annual economic benefit potential from rainwater collection with the p = 5a design is 34.23 million CNY, rising to 36.74 million CNY for p = 10a, and reaching 39.02 million CNY for p = 20a. The economic benefit potential of sponge facilities under different hydrological years in Ejin Horo Banner is presented in Figure 14 below.

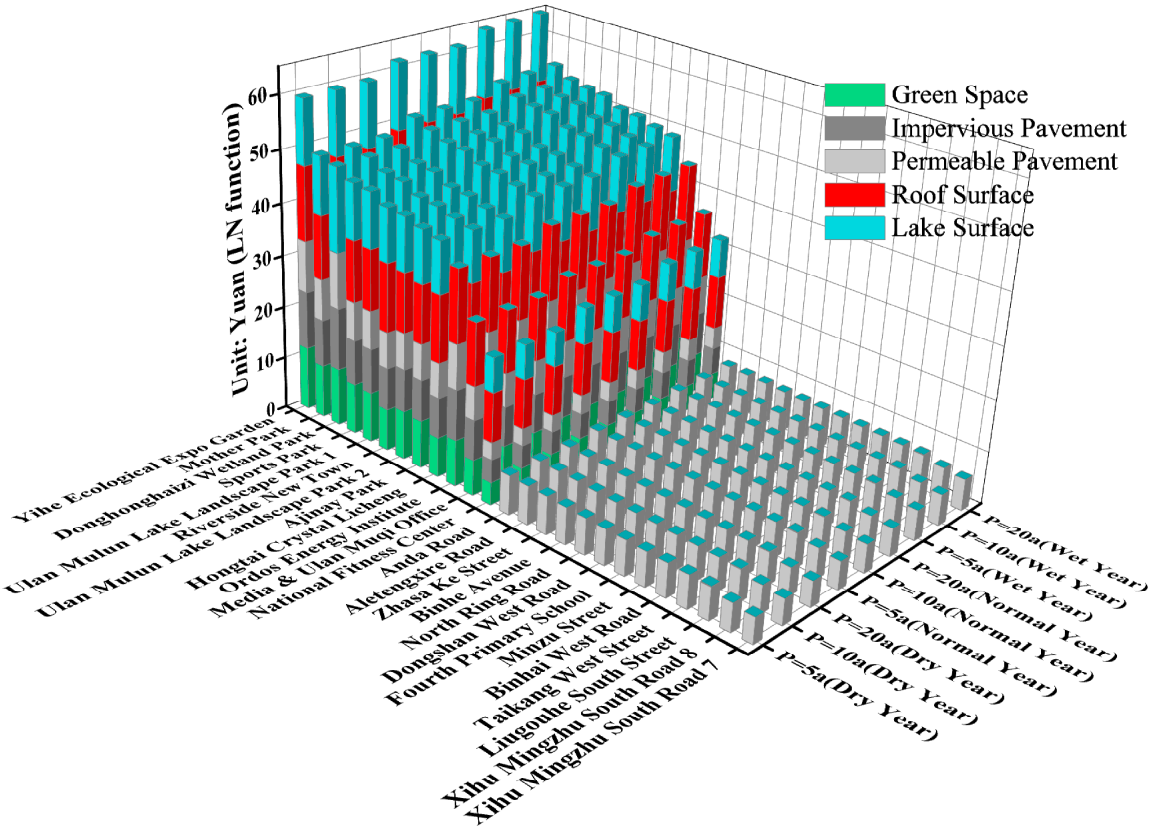

Figure 14. Economic benefit potential of sponge facilities under different hydrological years in Ejin Horo Banner.

Based on a comprehensive cost-inclusive economic benefit analysis, the following results are obtained:

Based on the comprehensive economic benefit analysis incorporating costs, for Dongsheng District, the economic benefits brought by rainwater collected by the p = 5a design tank outperform those of p = 10a and p = 20a, achieving payback in the 6th year with a net present value (NPV) of 51,000 CNY. In contrast, the economic benefits of rainwater collected by p = 10a and p = 20a design tanks achieve payback in the 8th and 9th years, respectively.

For Kangbashi District, the annual economic benefits of the p = 5a design tank outperform those of p = 10a and p = 20a, achieving payback in the 7th year with an NPV of 2.53 million CNY. The p = 10a and p = 20a design tanks achieve payback in the 9th and 10th years, respectively, with NPVs of 5.568 million CNY and 1.162 million CNY in those

years—both lower than the 20 million CNY NPV brought by the p = 5a design tank in the 9th year.

For Ejin Horo Banner, the economic benefits of the p = 5a design tank outperform those of p = 10a and p = 20a. The p = 5a design tank achieves payback in the 4th year, with an NPV of 2.345 million CNY. The p = 10a and p = 20a design tanks achieve payback in the 5th and 6th years, respectively, with NPVs of 5.02 million CNY and 9.845 million CNY in those years. Details are shown in Figure 15.

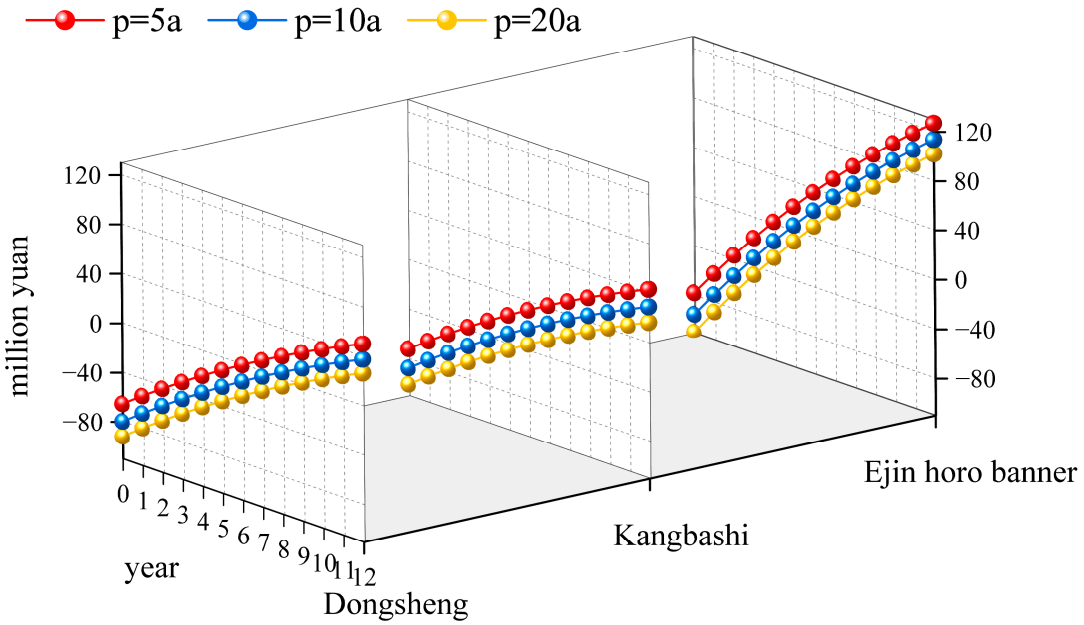

Figure 15. Annual Economic Benefits for Different Water Tank Design Sizes in Three Regions Under Various Return Periods.

4. Discussion

Several limitations of this study should be acknowledged and addressed in future research. First, given the nature of this study, its primary objective was to assess the theoretical maximum potential of regional rainwater harvesting at a macro scale, rather than to conduct precise hydrological simulations of specific engineering processes. Consequently, traditional model calibration and validation were not performed. Second, due to constraints in data availability, this study did not carry out systematic sensitivity analysis or uncertainty quantification. It should be noted that this study employs constant runoff coefficients in runoff calculation without considering the influence of antecedent soil moisture conditions. For permeable pavements and green spaces, this simplification neglects the inhibitory effects of initial abstraction and infiltration dynamics on runoff generation during prolonged dry periods, which may lead to an overestimation of runoff from the first rainfall event following an extended drought. Therefore, the estimated rainwater harvesting potential can be regarded as an upper-limit reference value under ideal conditions, and the actual collectable runoff may be lower than the theoretical calculation. This implies that the rainwater utilization potentials presented in this study represent maximum benchmark values for resource assessment at the planning stage. This study also focuses solely on rainwater harvesting without comparative analysis with other non-traditional water sources such as reclaimed water and groundwater, which together form a diversified urban water supply system. Future studies are recommended to incorporate antecedent moisture correction or continuous hydrological simulation to improve accuracy and to comprehensively consider the complementary relationships among multiple water sources

for joint optimal allocation. It is hoped that more scholars will further refine this method and promote its application in more regions to validate its universality and reliability.

This study reveals that the rainwater resource potential of sponge facilities in arid regions is jointly influenced by hydrological year types, design return periods [63,64], and underlying surface characteristics [65]. Collection performance follows the pattern of "wet year > normal year > dry year" across all three districts, with regional differences showing "Ejin Horo Banner > Kangbashi District > Dongsheng District." This spatial variation is strongly correlated with lake surface proportions—Ejin Horo Banner's lake area accounts for 73.4% of its sponge facility area, resulting in collection volumes far exceeding the other districts. This finding underscores the imperative of preserving and utilizing existing water bodies to improve rainwater harvesting capacity in sponge city planning in arid regions. Regarding design standards, p = 5a tanks achieve full collection during dry years; p = 10a tanks reach collection capacity during normal years; while p = 20a tanks are needed to maximize potential during wet years. This suggests that arid region facility design should balance between p = 5a and p = 20a standards based on local water scarcity and investment capacity, avoiding over-design that leads to idle capacity or under-design that wastes potential. In terms of economic benefits, p = 5a tanks outperform higher-standard designs across all three districts, with payback periods of 6 years (Dongsheng), 7 years (Kangbashi), and 4 years (Ejin Horo). This indicates that lower-standard designs offer better economic feasibility in arid regions—lower construction costs and faster returns—making them preferable as the primary option.

For practical applications, the research findings provide the following guidance for sponge city construction in arid and semi-arid regions: first, p = 5a tanks are recommended as the dominant design standard, balancing basic collection functions with rapid payback; second, new urban areas should prioritize planning water body facilities such as lakes for their high collection efficiency [66]; third, old city renovations can focus on rooftop space utilization, drawing on Dongsheng District's experience where rooftop collection accounts for 46.4%; fourth, the "sizing storage based on usage" method can inform local technical guidelines for tank design parameters across different underlying surfaces.

5. Conclusions

This study systematically evaluated the rainwater resource regulation capacity of sponge facilities in the "Dongsheng–Kangbashi–Ejin Horo Banner" urban agglomeration of Ordos City, leading to the following main conclusions:

(1) An assessment method for evaluating the rainwater utilization benefits of sponge facilities in arid and semi-arid regions is proposed. This study introduces the YBS method into the study area and, based on its mechanism of "water use priority and dynamic regulation," establishes an assessment framework that balances rainwater collection efficiency and facility construction costs. This approach overcomes the limitations of traditional runoff control assessments that focus on a single objective, achieving a paradigm shift from "runoff reduction" to "resource utilization." It provides technical support for the collaborative assessment of rainwater resource potential and economic benefits of sponge facilities at the urban agglomeration scale.

(2) The potential of rainwater resources is influenced by hydrological year types and the distribution of underlying surfaces under different sponge facilities. The rainwater harvesting capacity of sponge facilities in the three regions follows the patterns of "wet year > normal year > dry year" and " Ejin Horo Banner > Kangbashi District > Dongsheng District." There are notable differences among the three regions in terms of the types, scales, and spatial layouts of sponge facilities: Dongsheng District is dominated by "sponge communities + sponge parks," Kangbashi District emphasizes the

construction of sponge parks, while Ejin Horo Banner possesses the largest and most comprehensive facility system. Correspondingly, the dominant rainwater harvesting underlying surfaces also vary: roof collection predominates in Dongsheng District (46.4%), whereas lake surface collection is central in both Kangbashi District and Ejin Horo Banner (contributing 46.9% and 73.4%, respectively). Large-scale landscape water bodies, such as the Sanjitai Lake Area and Donghonghaizi Wetland Park, play a particularly prominent role as individual contributors to the regional total rainwater collection volume. Rainwater tanks designed for the three different return periods all meet the rainwater reduction requirements of sponge cities across varying annual rainfall levels.

(3) In terms of economic benefit potential, the economic performance is influenced by costs and the volume of rainwater collected from different underlying surfaces under various hydrological years. For Dongsheng District, Kangbashi District, and Ejin Horo Banner, the p = 5a design tank is recommended. Under this tank design, the payback periods for the three districts are the 6th year, the 7th year, and the 4th year, respectively. In Dongsheng District, the economic benefits of existing sponge facilities are primarily concentrated on rooftops and lake surfaces, accounting for 79% and 18% of the total economic benefit potential, respectively. Similarly, in Kangbashi District, rooftops and lake surfaces remain the main contributors, comprising 60% and 34% of the total. In Ejin Horo Banner, the economic benefit potential structure is more diversified: impervious roads and rooftops contribute significantly, accounting for 29% and 21%, respectively; green spaces and lake surfaces each represent 17%; while pervious pavements contribute 16% of the economic benefit potential. In arid regions, rainwater tanks designed for lower return periods are already sufficient to fulfill rainwater collection potential, offering lower costs and greater cost-effectiveness.

In summary, this study introduces the YBS method into the assessment of rainwater resource potential of sponge facilities in arid regions. It systematically evaluates, under different return period scenarios (5-year, 10-year, and 20-year), the rainwater resource potential, economic benefits, and payback periods of four types of sponge facilities (sponge parks, sponge roads, sponge residential complexes, and sponge lakes) across five underlying surface types (green space, rooftop, impervious pavement, permeable pavement, and water surface) under different hydrological year types (wet, normal, and dry). At the theoretical and methodological levels, the research explores the transition pathway of the Sponge City concept from single-objective runoff control toward integrated water resource management in arid and semi-arid regions. It provides a quantifiable and referable systematic framework and technical support for rainwater utilization assessment, tank optimization design, and relevant policy formulation in similar regions.

Author Contributions: Conceptualization, C.X. and J.Z.; methodology, J.Z. and H.R.; software, H.R.; validation, H.R.; formal analysis, H.R.; investigation, S.W. and H.R.; resources, P.M., H.M. and S.B.; data curation, H.R. and S.W.; writing—original draft preparation, H.R.; writing—review and editing, C.X. and J.Z.; visualization, Y.Y. and Y.Q.; supervision, C.X. and J.Z.; project administration, Y.Y. and J.Z.; funding acquisition, C.X. and J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Major Science and Technology Innovation Pilot Project for Water Resources Protection and Integrated-Saving Utilization in the Yellow River Basin of Inner Mongolia Autonomous Region (grant number: 2023JBGS0007), Beijing Natural Science Foundation (grant number: 8242003). Supported by the Open Research Fund of Key Laboratory of River Basin Digital Twinning of Ministry of Water Resources, grant number. Z0202042022; Supported by Chongqing Natural Science Foundation (grant number: CSTB2024NSCQ-MSX0557) Supported

by Open Research Fund Program of State key Laboratory of Hydroscience and Engineering grant number sklhse-2024-C-03.

Data Availability Statement: The original contributions presented in this study are included in the article. Further in-quiries can be directed to the corresponding author.

Conflicts of Interest: Author Shiming Bai was employed by the company Ordos Shengyuan Water Affairs Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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