WATER CYCLE LANDSCAPE DESIGN AND ECOLOGICAL EFFECT ANALYSIS OF RAINWATER GARDEN IN SPONGE CITY

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Abstract. To address low efficiency of urban runoff control and insufficient reduction of runoff pollutants in China, this study designed a rainwater garden system based on Sponge City principles. The rainfall and hourly rainfall time series data for Sponge City were determined, using a Chicago rainfall pattern, based on local meteorological data including runoff coefficient, catchment area, and rainfall duration, and an evaluation system was established using the analytic hierarchy process. The water cycle landscape was visually planned, and a multi-layered garden structure was designed. Crucially, the soil composition (specifically, the proportional mixture of sand, loam, and clay) was systematically investigated as a key variable affecting the system's performance. Evapotranspiration was estimated via the crop coefficient method to analyze ecological benefits. Experimental results demonstrated that the optimized rainwater garden achieved a maximum runoff pollutant removal rate of 100% and a total runoff control rate of 87%. Specifically, Rainwater Garden No.3—with a soil ratio of 80% sand, 15% loam, and 5% clay—exhibited superior performance in infiltration, retention, and storage due to its balanced structure and high hydraulic conductivity. Additionally, the annual evapotranspiration of lawns reached 839 mm/year. Other composite measures, such as rain gardens and sunken green spaces, which incorporate diverse vegetation, showed even greater evapotranspiration capacity. These results indicate that rainwater utilization measures significantly enhance the urban land water cycle and promote ecological sustainability.
Keywords: *ecological effect, water cycle landscape, crop coefficient method, time series, data visualization*

Introduction

Over the past 60 years, urbanization has accelerated globally, with China experiencing particularly rapid growth. According to China's statistical yearbook, the country's urbanization rate has increased rapidly from 13.62% in 1953 to 50% in 2011, and had reached 65.2% by the end of 2023 (National Bureau of Statistics of China, 2024), indicating a continuing strong trend. As a basic natural resource, water is essential for the ecological environment and economic development (Chen, 2020; Xu, 2019; Zhang, 2017). Since the 1970s, global water consumption has increased rapidly with the acceleration of urbanization, and water pollution has become increasingly severe (Chen, 2021). Urbanization has significantly altered land use patterns through various human activities. Recent advancements focus on conserving water resources and enhancing rainwater utilization efficiency. Recent studies have explored rainwater garden designs in

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Sponge Cities, however, challenges still remain in optimizing pollutant removal efficiency and adapting to dynamic rainfall patterns.

Researchers proposed a landscape design method for rural rainwater utilization based on lid concept, which optimizes rainwater ecology in combination with rural terrain and environment, forms an ecological water cycle in combination with the use of water storage ditches, builds roof gardens in rural residential areas, transforms landscape ecological vegetable gardens, transforms permeable courtyards, and carries out landscape design. Through the ingenious combination of technology and art, we can realize the landscape design of rural rainwater collection, runoff mitigation, purification and infiltration, agricultural application, etc., meet the needs of domestic water and green irrigation, and improve the environmental quality of rural landscape. Through the use of low impact rainwater landscape design, the sustainable development of rural landscape ecology is highlighted (Gui and Zhang, 2020). Researchers proposed a landscape design method for rainwater reuse based on ecological natural environment. Through practice, it optimizes the combination of rainwater management and environmental landscape, and provides a specific scheme for the organic combination of rainwater management and residential environmental landscape (Guo, 2021). Researchers proposed the application of computer simulation and high-precision visual matching technology in green city landscape design, and selected patch area, landscape percentage, patch number, maximum patch index and average patch area as browsing index. The weight of the above landscape indicators is calculated by analytic hierarchy process, and the judgment results are changed and adjusted by matching test (Luo, 2021). Researchers proposed a rapid drainage design for Sponge City rainwater gardens based on “green structure”. When the strongest precipitation is observed, install a “green” roof (horizontal or inclined) with green plants to absorb water. Collect rainwater in special water storage tanks for watering lawns, cleaning, flushing toilets, cleaning floors, cleaning sidewalks, etc. Absorb and drain through natural terrestrial sponge facilities (Hlushchenko, 2021). Researcher proposed an ecological optimization method for the pipeline network layout of Sponge City rainwater gardens to solve the problem of rainwater regulation and storage in sponge cities and improve water quality. Using the SWMM model to simulate the changes in runoff before and after the ecological optimization layout of the pipeline network, design an ecological optimization layout plan for the Sponge City rainwater garden pipeline network (He, 2023). Researcher designed a wetland rainwater garden that can effectively purify rainwater. This paper monitored the quality of urban rainwater and constructed various rainwater gardens with different plants and substrates to analyze the purification effect of wetlands on rainwater. Select wetlands with optimal parameters to ensure that the effluent can be reused (Zheng, 2021).

The above methods can all improve the utilization rate of urban rainwater, but the reduction rate of runoff pollutants is less than 90%, and the water pollution treatment effect is insufficient. In order to improve the reduction rate of runoff pollutants, this article designs a water cycle landscape for Sponge City rainwater gardens. In response to the problem that each independent unit in traditional rainwater gardens can only handle the runoff generated by small catchment areas, and the removal effect of pollutants such as household waste, animal excrement, and dead branches and leaves in the overall discharge of the garden is limited, this paper designs a water circulation landscape for Sponge City rainwater gardens, which uses honeycomb overflow wells to enhance the overflow capacity and improve the reduction effect of pollutants in runoff water; Setting up underground water storage tanks to store overflow rainwater, and using pumping

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systems to reuse rainwater for plant irrigation and landscape water replenishment, achieving the recycling of rainwater resources. Considering that the runoff and pollutants of each independent unit in the rainwater gardens are different, this paper does not adopt the fixed soil ratio in traditional design. Instead, based on the rainfall time series of sponge cities, rainwater flood analysis results, geographic data visualization module, and evapotranspiration calculation results, the ratio combination of mixed sandy soil, loam soil, and clay is dynamically configured to achieve the best pollutant reduction effect.

Materials and methods

The core methodology of this study is to construct an optimized design scheme for a rainwater garden suitable for a specific region through a combination of field investigations and data analysis. The research begins with a comprehensive examination of the geographical and climatic characteristics of the target area, which serves as the basis for all subsequent design decisions. On this basis, key rainfall pattern parameters were determined, providing a quantitative basis for subsequent hydrological analysis.

Subsequently, the research entered the design phase, with a focus on building a multi-level rainwater management facility. The design of this facility fully considers the movement of water in the soil and the absorption and transpiration of water by plants, aiming to achieve natural accumulation, infiltration, and purification of rainwater. The design process emphasizes dynamically adjusting the internal structure ratio of the facility based on local environmental conditions, rather than adopting a fixed and unchanging pattern.

To verify the effectiveness of the design scheme, simulation experiments and effect comparisons were used in the study. By establishing a reference benchmark, the new design scheme is compared with existing methods in multiple dimensions such as controlling runoff, reducing pollutants, and improving water resource utilization efficiency, in order to objectively evaluate its performance improvement. The entire methodology runs through the complete process from current situation analysis, model construction to effect verification, ensuring that research results have both theoretical innovation and practical application value.

Geographic data of rainwater garden in sponge city

Determination of rainfall and time series in sponge city

The construction of sponge residential quarter can increase the permeable area, reduce the rainwater runoff, and control the non-point source pollution caused by rainwater scouring from the source. The significance of building sponge residential quarters is manifold. As a theoretical practice of the concept of Sponge City, it is not only the product of the combination of planning and design and rainwater and flood management, but also a method to achieve optimal management in both architecture and landscape under the guidance of the concept of Sponge City (Cheng, 2020; Fang et al., 2020; Guo et al., 2021; Pan, 2021; Zhang, 2020). Sponge residential quarter is a natural and coordinated residential quarter with functional, landscape and applicability values. Under the promotion of the state for the construction of energy-saving cities, the construction of sponge residential quarter is an effective practice for the balance of ecological development in the future urban construction.

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According to the code for design of outdoor drainage, and in combination with the functions and flood control layout of each sub region of Ningnan County, Liangshan Prefecture, as *Figure 1*.

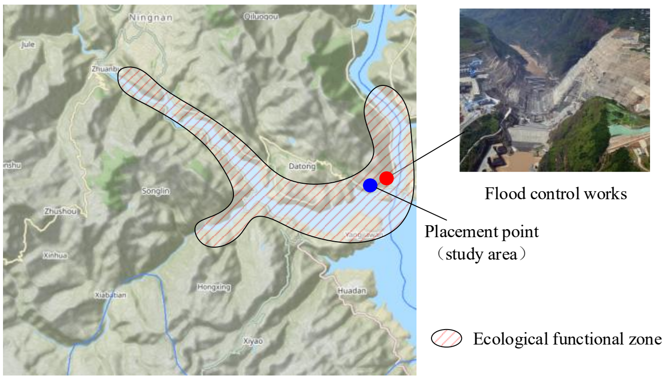

***Figure 1.** Zoning function and flood control layout*

Figure 1 specifically indicates ecological functional areas, while other unmarked areas are administrative regions. The research area in *Figure 1* is Ningnan County, which belongs to Liangshan Yi Autonomous Prefecture in Sichuan Province and is located in the southeast of Liangshan Prefecture. Ningnan County belongs to the South Asian tropical monsoon climate, with an average annual temperature of 19.3℃; Annual rainfall of 960 mm; The annual frost-free period is 321 days, with a sunshine duration of 2257.7 h. Ningnan County is located in the northeast of the Hengduan Mountains and on the southeastern edge of the Qinghai Tibet Plateau. It is bordered by the remnants of the Daliang Mountains to the east and northeast, and the eastern slope of the Lunan Mountains to the west and southwest. The Heishui River runs north-south and flows into the Jinsha River, forming a large landform of two mountains sandwiching a valley and the west bank of the Jinsha River. The mountains within the territory are undulating, with ravines crisscrossing. The mountains gradually increase from east to northwest, forming a terrain that is high in the northwest and low in the southeast. The terrain is mainly mountainous, with a small amount of flat dams and riverbanks. Ningnan County governs 13 towns, 79 administrative villages and 12 communities, with a registered residence population of about 203000. The forest coverage rate of the county is 55.2%, with over 545 species of plants and more than 110 species of wildlife. It belongs to the national key ecological functional zone, with Jinsha River and Heishui River as the main streams of water resources, and 13 mountain streams including Longdong River and Sancha River as tributaries. Based on unique climate and ecology, it is positioned as a popular tourist destination.

The water cycle landscape design of the designed rainwater garden is located in the centralized resettlement site of Yijia Xinzhai in Feidi Village, Paoma Town, Ningnan County. The resettlement site has a volume of 500 households, with a total area of 34070.66 m^2. The main building covers an area of 10021.32 m^2.

The design return period of rainwater pipeline in Ningnan County is preliminarily determined as 1-3 years (hourly rainfall), and local areas can be appropriately adjusted according to their own development needs. Therefore, the return period of the pipeline is determined as $p = 3a$.

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To calculate the rainstorm intensity in Ningnan County, it is necessary to query the runoff coefficient, catchment area, rainfall duration and other data recorded by the meteorological station in this area. With reference to the design return period and design rainwater flow, the calculation results are obtained according to the rainstorm intensity calculation formula. Among them, the runoff coefficient is 0.82, the catchment area is 3306.63 ha, the design return period is 2 years, and the rainfall duration is 5 min; In this paper, Chicago rainfall pattern is used to distribute rainfall and generate rainfall hydrograph.

Analysis on spatial rainwater flood of rainwater garden in sponge city

Before establishing the spatial rainwater and flood analysis module of the rainwater garden in Sponge City, it is necessary to identify the relevant elements of the natural environment. Record the climate characteristics of the city where the gardens is located, the topography and landforms within the city, the hydrological and soil conditions of various regions and land types, so as to make a more accurate hydrological runoff module (Zhao et al., 2022; Yang et al., 2025). The rainfall intensity is as shown in *Equation 1*:

$$Q_{\mathrm{hm}} = \frac{2677(1+0.659\,p_{\mathrm{jy}} g_c)}{(T_r+9)^{0.725}} \tag{Eq.1}$$

where: Q_{hm} represents the standard value of rainstorm intensity under the rainwater garden of Sponge City (mm/h); p_{jy} refers to the annual average rainstorm intensity of the city (mm). The determination of this parameter is based on the outdoor drainage design code and the local hydrology manual, and the average value of rainstorm data over the years (such as the annual maximum daily rainfall series) is obtained; g_c refers to rainstorm constant, which is generally taken as 1, 2, 3 and 4. The value is determined according to China's climate zoning and rainstorm pattern characteristics; T_r refers to the average daily rainstorm time of each year (min). The determination method is the annual average duration of all rainfall events that meet the rainstorm standard (daily rainfall ≥ 50 mm) recorded by Ningnan County Meteorological Station. These historical disaster records are maintained and quality-controlled by the station itself, forming part of the standard meteorological dataset for the region. The use of a single, authoritative station's data ensures internal consistency for the hydrological modeling of the specific study site (Wang, 2021b). After improving the data system of the natural environment, it is also necessary to calculate the total amount of annual runoff control in the rainwater garden of the Sponge City by *Equation 2*, especially its annual runoff control rate.

$$\alpha_n = \left(1 - \frac{Q_z}{10 \cdot S_z \cdot P_{\mathrm{jy}}}\right) \cdot 100\% \tag{Eq.2}$$

where: α_n represents the control rate under the total annual runoff; Q_z refers to the total runoff inside the rainwater garden of the sponge city in a year, in m3; S_z refers to the total area of rainwater garden in sponge City, in m^2; P_{jy} refers to rainfall intensity, in mm. After the total amount of annual runoff is calculated, the buffer zone analysis and spatial superposition calculation of absorbing supply can be made through ArcGIS, and vector data can be established for all natural and artificial facilities in the rainwater garden of

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Sponge City, and the evaluation value is assigned (Wang, 2021a; Yu et al., 2021). Among them, the analysis and treatment of underlying surface is the core of the water cycle landscape design of the whole Sponge City rainwater garden. Its key content is the information construction of hydrology and land cover content. The overall environment of the whole Sponge City rainwater garden is taken as an overall control unit, and the boundary characteristics of its water and soil roads are comprehensively analyzed, especially the land types related to wetlands, rivers, lakes and groundwater runoff. Then, the analytic hierarchy process is used to establish the corresponding rain and flood spatial evaluation system, to make a comprehensive evaluation of the precipitation storage, soil rain infiltration, river confluence and other data in the gardens, and to build a Sponge City rainwater garden spatial rain and flood analysis module.

Water circulation landscape design of rainwater garden in sponge city

Sponge structure water circulation design for rainwater garden

The water cycle landscape design of the whole Sponge City rainwater garden needs to be analyzed according to the actual situation, as shown in *Figure 2*.

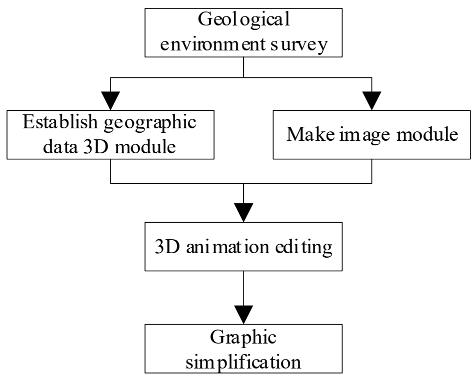

Figure 2. *Implementation path of water circulation landscape design of rainwater garden in sponge city*

As shown in *Figure 2*, it is necessary to carefully investigate the geographical environment inside the rainwater garden in Sponge City, determine the hydrological, geological, climatic, soil and other parameters of the geographical environment, and then establish the 3D module of geographical data. At the same time, it is also necessary to input the intelligent individual environment module of the Sponge City rainwater garden into the computer software ArcGIS 10.8, and edit the animation through the relevant 3D software Autodesk 3ds Max 2024. Finally, realized the design of the water circulation landscape of the Sponge City rainwater garden (Xu, 2020).

The rainwater garden is an ecologically sustainable rainwater flood control and rainwater utilization facility, which is composed of plant layer, water storage layer, covering layer, planting soil layer, filling layer and drainage layer. The plant layer is composed of drought resistant perennial herbaceous plants or shrubs and other natural facilities. Absorb pollutants such as nitrogen and phosphorus from rainwater through plant roots. Loose soil roots maintain smooth infiltration pathways. Specially select drought resistant varieties to adapt to the distinct climate characteristics of the local rainy and dry seasons, and reduce maintenance frequency. The water storage layer is composed

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of gravel with a particle size of 20 mm, forming a cavity or void layer for temporarily storing rainwater that has not been timely infiltrated by the upper soil layer. This effectively reduces the peak flow of rainwater runoff and alleviates the pressure on downstream drainage systems, which is the core link to achieve the functions of "stagnation" and "storage". The specific thickness of the water storage layer can be appropriately adjusted according to the site characteristics and rainfall characteristics. Bark and gravel can be used as covering materials for the covering layer, and its thickness is generally 50-80 mm. The main function of the overburden is to protect the soil (Saltan et al., 2025). The planting soil layer is generally red soil with a thickness of about 250 mm. The filling layer is the key layer for purifying water in the rainwater garden, and the selected material is zeolite with strong purification ability, with a thickness of 0.6-1.2 m. The drainage layer is composed of gravel and perforated water collecting pipe, and the selected gravel specification is generally Φ 20 mm, with a thickness of 200-30 mm. PVC perforated pipes with a diameter of 100 mm can be used as perforated water collecting pipes. From the above description, it can be inferred that the sponge city rain garden designed in this study is a composite ecosystem, and its facilities can be clearly divided into two categories: natural facilities and artificial facilities. They work together to achieve the infiltration, retention, storage, purification, and utilization of rainwater. Natural facilities mainly refer to the natural material layer and biological community that constitute the ecological purification core of the rainwater garden, including drought resistant perennial herbaceous plants or shrubs in the plant layer, bark and gravel in the covering layer, red soil in the planting soil layer, zeolite in the filling layer, and gravel in the gravel drainage layer. Artificial facilities are engineering structures constructed to enhance the regulation, discharge, and reuse functions of rainwater gardens, including perforated collection pipes for gravel drainage layers, honeycomb overflow wells, underground reservoirs, pumping systems, geotextiles between cover layers and fill layers, diversion channels and retention ponds at the entrance of rainwater gardens. The advantages and disadvantages of traditional rainwater gardens rainwater garden are as follows.

Advantages: high removal rate of suspended particles, heavy metals, nitrogen, phosphorus and pathogens; It is very suitable for new urban development areas; Each independent unit has low requirements for floor area, but it can handle the runoff of large catchment area through unit combination; High integration with natural landscape.

Disadvantages: each independent unit can only handle the runoff generated in a small catchment area; High requirements for removal frequency of domestic garbage, animal excreta and withered branches and leaves; The upper soil is easy to harden, which is easy to occur even if the topsoil is replaced; High requirements for maintenance frequency of vegetation and root protection layer; High requirements for soil drainage performance.

The soil of planting soil layer can be divided into sandy soil, loam, clay or mixed component soil due to different parameters such as permeability coefficient and porosity. *Table 1* shows the characteristics of different types of soils.

The thickness of the planting soil layer varies according to the plants planted: the thickness of the planting soil when planting herbaceous plants is 200~300 mm, while the thickness required when planting shrubs is larger, generally 500~800 mm.

In order to solve the problem of runoff pollution in traditional garden rainwater gardens, the sponge structure water cycle designed in this article selects plants with developed roots, large biomass, and strong purification ability to solve the problem of high maintenance frequency requirements for vegetation and root protection layers; Considering the weather

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changes, the plants planted in the rainwater garden will go through two periods: rainy season and dry season, with relatively high concentrations of runoff pollutants flowing into the rainwater garden. Therefore, the rainwater garden water circulation sponge structure designed in this article uses drought resistant perennial herbaceous plants or shrubs with a thickness of 200 mm to 500 mm. Using zeolite as a filler to delay peak runoff, reduce pollutant concentration, permeability, and water storage capacity.

Table 1. *Characteristics of different types of soil (Zhu, 2020)*

Soil tissue type	K	Ψ	ϕ	FC	WP
Sand	4.74	1.93	0.437	0.062	0.024
Loamy sand	1.18	2.4	0.437	0.105	0.047
Sandy loam	0.43	4.33	0.453	0.19	0.085
Loam	0.13	3.5	0.463	0.232	0.116
Silty loam	0.26	6.69	0.501	0.284	0.135
Sandy clay loam	0.06	8.66	0.398	0.244	0.136
Clayey loam	0.04	8.27	0.464	0.31	0.187
Silty clay loam	0.04	10.63	0.471	0.342	0.21
Sandy clay	0.02	9.45	0.43	0.321	0.221
Silty clay	0.02	11.42	0.479	0.371	0.251
Clay	0.01	12.6	0.475	0.378	0.265

K = saturated hydraulic conductivity, in/h; Ψ = suction head, in; ϕ = porosity, fraction; FC = water production capacity, fraction; WP = shrinking point, fraction

In response to the problem that each independent unit in traditional rainwater gardens can only handle the runoff generated by small catchment areas, and has limited effectiveness in removing pollutants such as household waste, animal excrement, and dead branches and leaves from the overall discharge of the garden, the gravel drainage layer designed in this paper collects and filters some rainwater from the upper layer of plants and discharges it into the soil to supplement groundwater. The thickness of the gravel drainage layer is 200~500 mm, and the filling material is gravel with a particle size of 1~2 cm. Rainwater exceeding the maximum runoff processing capacity of each independent unit is treated through a slope (with a catchment slope controlled at 1%-3%) at the entrance of the rainwater garden to achieve self-flow and reduce runoff velocity. The road rainwater is guided into the retention pool through the diversion channel, and the bottom is sloped and discharged into the overflow well as a whole. The elevation of the overflow wellhead is set at the design water level + 10 cm, and a honeycomb overflow well is used to enhance the overflow capacity. Excess rainwater from the overflow wellhead is discharged into the municipal rainwater pipe network to further control runoff and enhance the reduction effect of pollutants in the runoff water; Setting up underground water storage tanks to store overflow rainwater, and using pumping systems to reuse rainwater for plant irrigation and landscape water replenishment, achieving the recycling of rainwater resources. In order to prevent the upper soil from hardening and filter pollutants, geotextiles from overflow wellheads are used to filter suspended particles such as soil, reducing their entry into the filling layer or gravel drainage layer.

Due to the different runoff and pollutants of each independent unit in the rainwater garden, this article does not use the fixed soil ratio in traditional designs. Instead, based

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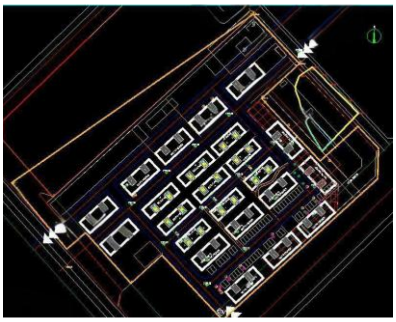
on the rainfall and rainfall time series of sponge cities, the spatial rainwater flood analysis results of Sponge City rainwater gardens, the geographic data visualization module of Sponge City rainwater gardens, and the calculation results of evapotranspiration, the proportion combination of mixed sandy soil, loam soil, and clay is dynamically configured to achieve the best pollutant reduction effect. The rainwater garden water circulation landscape, which includes water supply, drainage, and rainwater in the design of this area, is shown in *Figure 3* of the overall floor plan.



(a) Before design

(b) Design of the rainwater garden and water circulation landscape

Figure 3. *Water circulation landscape design drawing of rainwater garden*

Calculation of evapotranspiration by crop coefficient method

In this section, the evapotranspiration under the rainwater garden arranged in the southeast area of the main urban area of Ningnan County is calculated by the crop coefficient method, and the evapotranspiration under the condition of no rainwater garden is compared and analyzed to obtain the evapotranspiration effect of the rainwater garden.

It is assumed that the rainwater gardens are all set as open type, the vegetation is covered by a single lawn, and the crop coefficient method is used to calculate the evapotranspiration. Evaporation of impervious surface is calculated according to rainfall.

1. Evaporation calculation in impervious area

The evaporation of impervious surface is composed of evaporation during the rain period and evaporation of intercepted water after the rain. In the rainless period, its evaporation is zero. Evaporation in rainy season due to the saturation of air humidity during rainfall, the evaporation is small and can be ignored. The evaporation of intercepted water after rain is calculated according to the runoff generation characteristics of impervious surface and depression savings. Monthly evaporation of impervious surface calculated by *Equation 3*:

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$$E_{ye} = C \times n + p \tag{Eq.3}$$

where: E_{ye} is the total monthly evaporation in the region, mm; C is the evaporation critical index of impervious surface, mm; n refers to the number of times when the monthly rainfall is greater than C; p is the total amount of rainfall with monthly rainfall less than C, mm. According to the literature (Chen et al., 2020), the tile roof $C = 1.9$, the cement roof $C = 1.7$, and the asphalt pavement $C = 2.3$. According to the rainfall characteristics of Ningnan County, C is set as 2.0 mm. Rainfall events are calculated at an interval of 6 h in flood season, and rainfall days in non-flood season.

2. Evapotranspiration calculation of permeable surface

The crop coefficient method is used to calculate the evapotranspiration of the permeable surface. First, the reference crop evapotranspiration (ET_0) is calculated, and then the actual evapotranspiration of the permeable surface can be obtained by multiplying the crop type and soil moisture by the corresponding correction coefficient. The reference crop evapotranspiration (ET_0) is the reference crop evapotranspiration rate under the assumption that the crop height is 0.12 M, the fixed leaf resistance is 70 s/m, and the reflectance is 0.23. There are many calculation methods. In this paper, penman Monteith (PM) formula is used for calculation. The methods are as follows.

Penman Monteith formula is a reference crop evapotranspiration calculation method based on water vapor diffusion and energy conservation. This method is widely used in the world and has high accuracy in different climatic regions. It is an ET_0 calculation method recommended by FAO as shown as *Equation 4*. This method requires a large amount of meteorological data and is suitable for use when meteorological data are sufficient.

$$ET_0(PM) = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} u_2 (e_a - e_d)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{Eq.4}$$

where: $ET_0(PM)$ is the reference crop evapotranspiration calculated by penman Monteith formula, mm/d; Δ is the slope of the relationship curve between saturated water vapor pressure and temperature, kPa·°C^{-1} (calculated physical constants based on local altitude and temperature, rather than directly recorded.); R_n is the net surface radiation, MJ·m^{-2}·d^{-1} (obtained directly from the net radiometer in the meteorological station.); G is soil heat flux, MJ·m^{-2}·d^{-1}(Based on temperature changes, it is estimated to be negligible on a daily scale.); γ is the constant of hygrometer, kPa·°C^{-1} (directly measured and recorded by the meteorological station.); T is the average temperature, °C (Derived from the daily scheduled observation records of Ningnan County Meteorological Station. By recording temperature readings at multiple fixed times of the day (usually 02:00, 08:00, 14:00, 20:00), calculate the arithmetic mean as the daily average temperature.); u_2 is the wind speed at 2 m height, m/s (Directly recorded by automatic weather sensors within the meteorological station. The anemometer is installed at a standard height of 10 m above the ground, and the measured wind speed data is converted into a representative value at a height of 2 m using the logarithmic wind speed profile formula. e_a is the saturated water

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vapor pressure, kPa; e_d is the actual water vapor pressure, kPa. The saturated vapor pressure and actual vapor pressure parameters are not directly recorded, but are calculated based on temperature and relative humidity data. Firstly, the saturated vapor pressure is calculated based on the daily maximum and minimum temperatures recorded by the meteorological station. Meanwhile, by utilizing the average relative humidity data recorded by sensors, the actual water vapor pressure can be calculated. The calculation method of each parameter in the formula is detailed in the references. The parameter calculation in Hargreaves formula is the same as the above references.

3. Calculation of actual evapotranspiration (ET_a)

The actual evapotranspiration (ET_a) is calculated indirectly by referring to the evapotranspiration of crops by *Equation 5*:

$$ET_a = K_s \cdot K_c \cdot ET_0 \quad \text{(Eq.5)}$$

where: ET_a is the actual evapotranspiration, mm/d; K_s is the soil moisture correction coefficient; K_c is crop coefficient; ET0 is the reference crop evapotranspiration, mm/d.

Establish regression equation to modify *HG* by *Equation 6*:

$$HG(ET_a) = 0.8056HG(ET_a)' + 0.0501 \quad \text{(Eq.6)}$$

where: $HG(ET_a)$ is the result corrected by HG formula, mm/d; $HG(ET_a)'$ is the calculated value before correction, mm/d.

Results

Experimental preparation

The experimental data is sourced from publicly available data from the meteorological station in Ningnan County, the research area. According to the recommendations of the World Meteorological Organization, the annual average value (such as annual average rainfall, average rainstorm days) is calculated according to the latest complete 30-year climate normal period from 1991 to 2020. Collect runoff coefficient, catchment area, rainfall duration, annual total rainstorm, rainstorm days, average intensity of single rainstorm, crop evapotranspiration, soil quality correction coefficient and other data. The runoff coefficient is 0.82, the catchment area is 3306.63 ha, the design return period is 2 years, and the rainfall duration is 5 min. The total amount of annual rainstorm is 960 mm, the average annual average of rainstorm days (daily rainfall ≥ 50 mm) is about 6-8 days, and the average intensity of a single rainstorm is 30-50 mm/h. The crop evapotranspiration is 3.5-4.5 mm/day, and the starting value of soil correction coefficient (based on soil saturation hydraulic conductivity) is taken as 0.4. But during rainfall events, this value is usually assumed to be 1.0 (indicating no water stress). For continuous simulation or drought periods, it is necessary to dynamically update the initial values of the water balance model.

To ensure the accuracy and reliability of public data collection above the Ningnan County Meteorological Station, the following quality control measures are implemented, including calibration, verification, and data integrity management procedures:

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Calibration: Using standard rainfall and automatic weather station data as benchmarks, calibrate the systematic errors of rainfall and soil evaporation data. Compare with literature parameter libraries (such as data from the Loess Plateau region) to correct errors. Using Penman Monteith formula to calculate theoretical evapotranspiration, comparing it with measured evapotranspiration data, and adjusting for incorrect data.

Validation: The composite analysis method moving average method is used to identify the abnormal fluctuations of rainfall duration and annual rainstorm total amount. Cross validation with data from neighboring meteorological stations (such as Puge County Meteorological Bureau in Puji Town, Puge County, about 50 km northeast of Ningnan County) to ensure consistency in regional climate characteristics. The extreme values of rainstorm days, average intensity of single rainstorm and other extreme values are verified again in combination with historical disaster records. Input meteorological and soil data into the hydrological model SWMM, simulate runoff coefficients, and evaluate the fit with measured runoff data. The evaluation result shows that the Nash Sutcliffe efficiency coefficient is greater than 0.6, and the evaluation data is qualified.

Data integrity management: For continuously missing rainfall duration data, meteorological reanalysis data ERA5 is used to complete it. Label the data collection time, instrument model, and calibration records to ensure completeness.

Before the experiment, after the transformation of the common landscape of the rainwater garden site, through intelligent artificial simulated rainfall device system Tsjy 2.0 simulated rainfall animation to display the underground drainage organization in the site, provide the design basis for the water circulation landscape of the rainwater garden in Sponge City, and understand the principle and process of rainwater regulation and storage of the water circulation landscape facilities of the rainwater garden in Sponge City. In combination with the site analysis report, according to the main principles of facility transformation, select the sponge landscape facilities suitable for the site according to the characteristics and scope of application of each sponge landscape facility, simulate the whole process of the rainwater system in sections in the scene according to different paths of the rainwater system process, and analyze the ecological regulation and storage of the sponge landscape facilities on rainwater infiltration, overflow, sewage interception, purification, etc.

Selection of experimental indicators

The expression of rainwater utilization rate is as shown as *Equation 7*:

$$W = \alpha \psi HA \tag{Eq.7}$$

where: α is the seasonal reduction coefficient; ψ is the comprehensive runoff coefficient; H refers to annual average rainfall; A represents catchment area.

The expression of runoff pollutant reduction rate is as shown as *Equation 8*:

$$R = \frac{(A-B)D}{H} \cdot 100\% \tag{Eq.8}$$

where: A represents the pollutant concentration at the water inlet; B refers to the pollutant concentration at the water outlet; D represents the water volume of the day.

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In order to verify the effectiveness of the landscape design in this paper, the benefit comparison before and after the design is evaluated through three important indicators: total runoff control rate, rainwater utilization rate and runoff pollutant reduction rate, so as to verify the rationality of the design scheme.

Select seasonal reduction coefficient α, comprehensive runoff coefficient, and soil correction coefficient from the calculation formula parameters of rainwater utilization rate and runoff pollutant reduction rate for sensitivity analysis, and fix other parameter values each time. The sensitivity analysis results are shown in *Table 2*.

Table 2. *Parameter sensitivity analysis*

Parameter	Change range of rainwater utilization rate	Change range of pollutant reduction rate	Sensitivity ranking
Seasonal reduction coefficient α	±18%-22%	±20%-25%	Highest
Comprehensive runoff coefficient	±15%-18%	±10%-15%	Second high
Soil correction coefficient	±8%-12%	±5%-8%	Lowest

According to *Table 2,* the comprehensive runoff coefficient is the dominant parameter with high sensitivity. Based on the above results, priority should be given to controlling the comprehensive runoff coefficient and soil correction coefficient, and improving system stability through measures such as permeable paving and soil improvement.

Experimental test results

Total runoff control rate

Compare the total runoff control rate before and after the design of the methods proposed in this article, Gui and Zhang (2020), and Gui (2020). The comparison results are shown in *Figure 4*. The uncertainty of estimating runoff control rate is quantified using confidence intervals. The confidence level of the experimental results of runoff control rate in *Figure 4* is tested using the coupled hydrological model SWMM. The confidence level tested is 95%, indicating that the difference between the control rate test results and the true values is less than 0.5 m, indicating that the model has high reliability in simulating the runoff process.

According to *Figure 4,* the total runoff control rate of the rainwater garden designed in this article can reach 87%, while the total runoff control rate before design only reaches 82%. The total runoff control rates of the other two methods for the rainwater garden are both lower than 85%, which is lower than the design method in this article. This indicates that the total runoff control rate of the rainwater garden designed in this article is relatively high.

Rainwater utilization rate

Rainwater utilization rate is the index to evaluate the total rainwater utilization. The rainwater utilization rate before and after the method proposed by Gui and Zhang (2020) and the method proposed by Gui (2020) are compared, as shown in *Table 3*.

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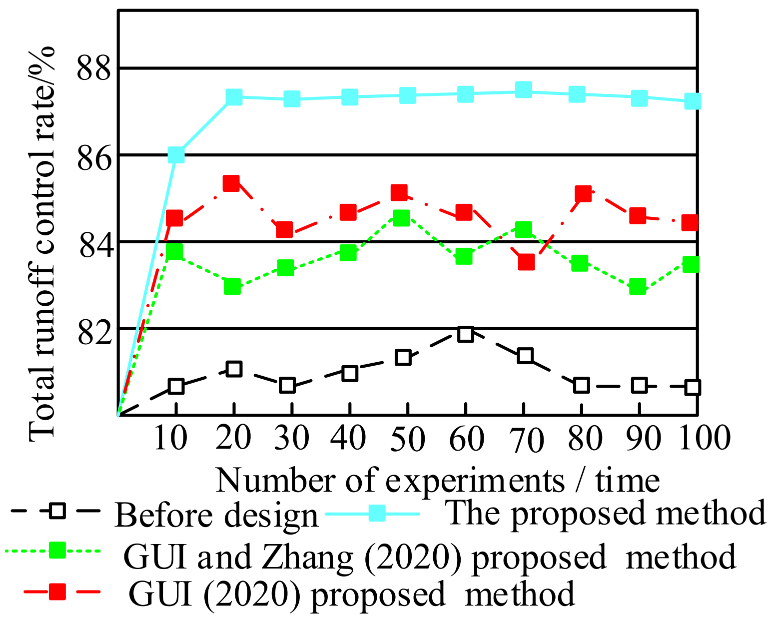

Figure 4. *Total runoff control rate*

Table 3. *comparison results of rainwater utilization ratio /%*

Number of experiments/time	Before the design of this article	After this design	GUI (2020) proposed method	GUI and Zhang (2020) proposed method
10	81.2	98.2	83.6	84.5
20	80.3	91.2	84.9	82.4
30	81.6	94.5	86.2	83.6
40	81.6	91.6	85.8	84.2
50	83.6	97.6	84.3	85.2
60	84.2	92.6	87.9	86.2
70	85.2	94.4	88.3	87.5
80	86.3	93.8	88.7	88.6
90	84.5	98.1	86.2	87.6
100	86.9	98.4	89.8	89.2

According to *Table 3,* the maximum rainwater utilization rate before the design of the system in this paper is only 88.9%, while the maximum rainwater utilization rate after the design of the system in this paper can reach 98.4%. Although the rainwater utilization rates after the other two methods were higher than before the design, they remained below 90%, indicating that the rainwater utilization rate of the virtual simulation experiment system for sponge gardens renewal design designed in this paper is high.

Runoff pollutant reduction rate

The runoff reduction rate of each pollutant before and after the design of the three comparison systems is calculated, the results are shown in *Figure5*.

From *Figure 5,* it can be seen that the maximum reduction rate of garden runoff pollutants before the design of the three methods is less than 60%. After the design of this

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paper, the maximum reduction rate of runoff pollutants can reach 100%, while the maximum reduction rate of the other two designs after application is still less than 90%, indicating that the rainwater garden designed in this paper has the highest reduction rate of runoff pollutants.

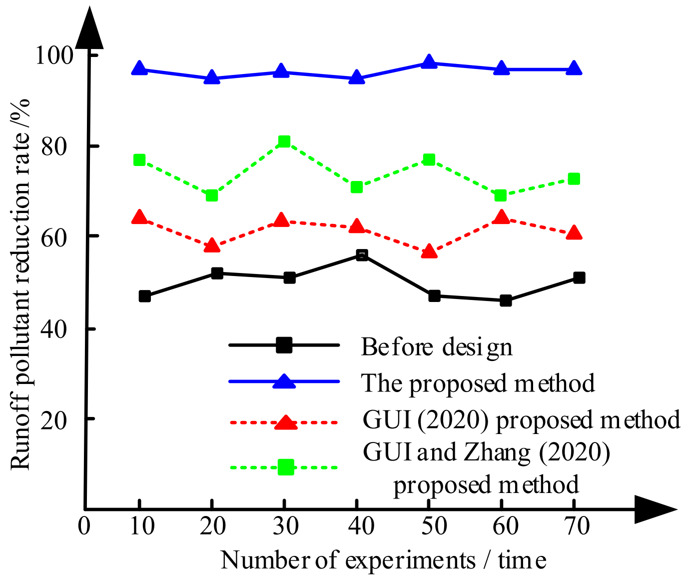

Figure 5. *Comparison results of runoff pollutant reduction rate*

Simulation analysis on the effect of "infiltration", "stagnation", "storage" and "purification" of rainwater garden with different planting soil and soil ratio

Setting of LID parameters of rainwater garden

The best effect of rainwater garden on "infiltration", "stagnation", "storage" and "purification" in the study area is that the soil is sandy soil. However, in actual project construction, rainwater gardens not only need to consider runoff control and pollutant removal effects, but also need to evaluate the impact of soil composition on the hydrological and purification effects of rainwater gardens. For this purpose, 15 different soil mixtures of sand, loam, and clay with varying proportions were selected as the main experimental factors. Therefore, in this paper, sandy soil, loam and clay are mixed according to different proportions, and a total of 15 groups of rainwater gardens with different soil proportions are configured to study the hydrological and water quality changes of rainwater gardens with different soil proportions in the study area (see *Table 4* for different soil proportions of 15 groups and *Table 5* for other LID parameters).

Simulation analysis of "seepage", "stagnation" and "storage" effects of rainwater garden with different soil ratios

Input the determined parameters of the cover plate into SWMM, and use SWMM to simulate and compare the results of different rainwater garden designs before and after implementation in the study area using analysis of variance (ANOVA). Simulate and analyze the "infiltration", "retention", and "storage" effects of rainwater gardens with different soil ratios on the study area, mainly reflected in the infiltration volume, runoff volume, elevation runoff, and runoff coefficient of the sub catchment area. The

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hydrological simulation results are shown in *Table 6*. Verify whether the observed difference (reduction rate) is statistically significant by t-test P-value. Set the alpha value to 0.05, indicating the threshold for rejecting the null hypothesis. If the p-value of the observed difference hypothesis is less than α, the null hypothesis is rejected and the difference is considered statistically significant.

Checking images/Rainwater gardens with different soil ratios have different effects on the “infiltration”, “retention”, and “storage” of the study area. Fifteen groups of rainwater gardens with different soil ratios increased the average infiltration in the study area by 36.39%, 37.12%, 37.12%, 35.25%, 35.66%, 36.27%, 33.53%, 34.76%, 35.33%, 32.14%, 33.08%, 34.43%, 31.31%, 31.31%, and 32.59%, respectively. Among them, Rainwater Garden No. 3 had the best effect; Reduced the average runoff by 28.13%, 29.43%, 31.10%, 23.57%, 25.75%, 27.26%, 22.27%, 22.95%, 24.46%, 15.22%, 15.34%, 15.81%, 15.11%, 15.11%, and 15.34%, respectively; Reduced peak runoff by 22.12%, 25.45%, 26.61%, 21.05%, 24.32%, 25.45%, 23.21%, 22.12%, 24.32%, 16.95%, 17.95%, 18.97%, 12.20%, 13.11%, 15.00%, respectively; The average runoff coefficient was reduced by 30.80%, 31.72%, 34.29%, 29.26%, 31.49%, 33.80%, 26.70%, 28.83%, 29.39%, 23.19%, 24.71%, 23.58%, 14.39%, 14.39%, and 14.84%, respectively; In summary, among the 15 rainwater gardens with different soil ratios, the third rainwater garden had the best effect on “infiltration”, “retention”, and “storage” in the study area. The soil ratio for the third rainwater garden was 80% sand, 15% loam, and 5% clay. The rainwater garden designed in this article has large sand particles, high porosity, and good permeability. This allows rainwater to quickly infiltrate into the soil, reducing the generation of surface runoff and thus improving the effectiveness of infiltration. Loam soil has a certain degree of viscosity and water retention, while clay has stronger viscosity and can better retain moisture. This soil ratio enables the rainwater garden to retain more rainwater during rainfall and slowly release it after the rainfall ends, improving the “retention” and “storage” effects, thereby increasing the reduction rate of runoff pollutants.

Analysis on hydrological ecological effect of rainwater resources utilization in rainwater garden

Flood control, waterlogging reduction and water purification

Urban rainwater utilization measures can treat rainwater by different means, relieve the drainage pressure of pipe network, and solve the problem of urban waterlogging to some extent. At the same time, the filtering effect of green space, permeable pavement and other facilities can purify the rainwater quality. A large number of existing studies have shown that urban rainwater utilization facilities have a strong capacity of flood control, waterlogging reduction and water purification. According to the simulation of different lid development modes in the study area in the fifth chapter of this paper, it also shows that the urban rainwater utilization facilities have good rainwater flood control ability.

Compared with ordinary concrete and asphalt pavement, permeable pavement with the function of infiltration mainly reduces the amount of pollutants in the discharged rainwater and plays a role in purifying the water quality to a certain extent. This structure makes the rainwater utilization facilities have strong infiltration capacity and water storage function. At the same time, it can filter the pollutants in the rainwater, and play the role of flood control, waterlogging reduction and water purification. From the perspective of hydrological and ecological benefits, the utilization of rainwater resources

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in the rainwater garden can balance the water volume, fill the dry water in the dry season and reduce the flood peak in the flood season. By collecting rainwater from different underlying surfaces such as roofs and pavements, such facilities as reservoirs and storage tanks with rainwater storage function can effectively relieve the pressure of urban drainage system and reduce urban waterlogging.At the same time, such facilities are generally equipped with filtration devices to realize the preliminary purification of rainwater and reduce the total amount of pollutants in rainwater. In conclusion, from the perspective of hydrological ecology, rainwater utilization measures have a strong evapotranspiration effect, which can effectively promote the land water cycle in the city, regulate the surface water volume of the city in different time and space, help to form a good hydrological ecological environment and promote the harmonious development of urban ecology.

Table 4. *Soil ratio of rainwater garden*

Rainwater garden No	Sandy soil	Loam	Clay
No. 1 rainwater garden	80.00%	0.00%	20.00%
No. 2 rainwater garden	80.00%	10.00%	10.00%
No. 3 rainwater garden	80.00%	15.00%	5.00%
No. 4 rainwater garden	70.00%	0.00%	30.00%
No. 5 rainwater garden	70.00%	10.00%	20.00%
No. 6 rainwater garden	70.00%	20.00%	10.00%
No. 7 rainwater garden	60.00%	0.00%	40.00%
No. 8 rainwater garden	60.00%	20.00%	20.00%
No. 9 rainwater garden	60.00%	30.00%	10.00%
No. 10 rainwater garden	50.00%	0.00%	50.00%
No. 11 rainwater garden	50.00%	20.00%	30.00%
No. 12 rainwater garden	50.00%	40.00%	10.00%
No. 13 rainwater garden	40.00%	0.00%	60.00%
No. 14 rainwater garden	40.00%	20.00%	40.00%
No. 15 rainwater garden	40.00%	40.00%	20.00%

Table 5. *Lid parameters of rainwater garden*

LID parameter	Name	Numerical value
Surface	Berm height (mm)	300
	Vegetation volume	0.3
	Surface Manning n value	0.1
	Surface slope	0.33
Impounding	Thickness (mm)	300
	Void ratio	0.4
	Water seepage rate (mm/h)	0.5
	Plugging factor	0
Under canal	Discharge coefficient	0
	Flow index	0.5
	Offset height	6

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Table 6. *simulation results of "seepage", "stagnation" and "storage" effects of rainwater gardens with different soil ratios*

Hydrological parameters	Average infiltration	Average runoff	Peak runoff	Average runoff coefficient	The t-test P-value
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 1 rainwater garden	61.1434	0.2707	0.0156	0.6993	-
Reduction rate	-36.39%	28.13%	22.12%	30.80%	0.03
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 2 rainwater garden	61.8518	0.2680	0.0151	0.6944	-
Reduction rate	-37.12%	29.43%	25.45%	31.72%	0.01
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 3 rainwater garden	61.8506	0.2645	0.0150	0.6811	-
Reduction rate	-37.12%	31.10%	26.61%	34.29%	0.02
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 4 rainwater garden	60.0670	0.2807	0.0157	0.7076	-
Reduction rate	-35.25%	23.57%	21.05%	29.26%	0.03
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 5 rainwater garden	60.4491	0.2758	0.0153	0.6956	-
Reduction rate	-35.66%	25.75%	24.32%	31.49%	0.03
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 6 rainwater garden	61.0245	0.2725	0.0151	0.6836	-
Reduction rate	-36.27%	27.26%	25.45%	33.80%	0.02
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 7 rainwater garden	58.5085	0.2836	0.0154	0.7219	-
Reduction rate	-33.53%	22.27%	23.21%	26.70%	0.02
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 8 rainwater garden	59.6170	0.2821	0.0156	0.7100	-
Reduction rate	-34.76%	22.95%	22.12%	28.83%	0.03
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 9 rainwater garden	60.1411	0.2787	0.0153	0.7069	-
Reduction rate	-35.33%	24.46%	24.32%	29.39%	0.03
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 10 rainwater garden	57.3157	0.3010	0.0162	0.7425	-
Reduction rate	-32.14%	15.22%	16.95%	23.19%	0.01
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 11 rainwater garden	58.1142	0.3007	0.0161	0.7335	-
Reduction rate	-33.08%	15.34%	17.95%	24.71%	0.02
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 12 rainwater garden	59.3115	0.2995	0.0160	0.7401	-
Reduction rate	-34.43%	15.81%	18.97%	23.58%	0.03
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 13 rainwater garden	56.6194	0.3013	0.0169	0.7996	-
Reduction rate	-31.31%	15.11%	12.20%	14.39%	0.02
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 14 rainwater garden	56.6189	0.3013	0.0168	0.7996	-
Reduction rate	-31.31%	15.11%	13.11%	14.39%	0.03
After urbanization	38.8919	0.3468	0.0190	0.9147	-
No. 15 rainwater garden	57.6966	0.3007	0.0165	0.7965	-
Reduction rate	-32.59%	15.34%	15.00%	14.84%	0.03

The reduction rate of average infiltration in the table is negative, indicating that the average infiltration in the study area is increasing. The unit of average infiltration and average runoff in the table is mm, and the unit of peak runoff is m3/s. The "After urbanization" category represents the baseline simulation scenario reflecting the hydrological conditions of the study area with predominantly impervious surfaces, before the implementation of any rainwater garden measures

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Evapotranspiration effect

In the process of urbanization, the nature of regional underlying surface has changed significantly, and the land use types such as green space, cultivated land and forest land have been transformed into impervious underlying surface. The change of underlying surface will lead to the change of regional evapotranspiration. Studies by many domestic scholars have shown that the decrease of vegetation in the process of urban construction and the continuous increase of urban land use have significantly reduced the evapotranspiration within the city(Luo et al., 2020). In recent years, China has put forward the concept of "Sponge City" to solve the problem of urban waterlogging, and realized the rational utilization of rainwater resources through various ways. Among them, various measures (such as concave green space, permeable pavement, green roof and rainwater garden, etc.) with the functions of infiltration and water retention are mainly characterized by vegetation coverage, which is used to reduce the peak flow and reduce the surface runoff. Such measures can not only achieve better utilization of rainwater resources(Arsenio et al., 2020; Faris and Sanaz, 2020; Karen, 2020; Thompson, 2020; Sachanowicz, 2020), but also have good evapotranspiration effect. The corrected results are shown in *Figure 6*.

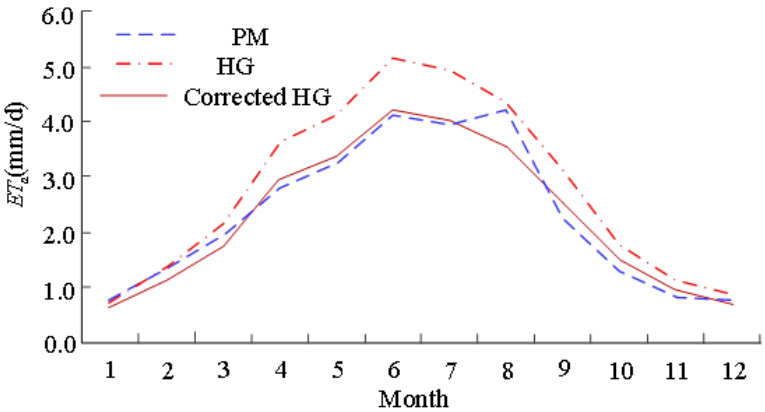

Figure 6. *Comparison of calculation results of PM formula, Hg formula and modified Hg formula*

It can be seen from *Figure 6* that the calculation results of the modified *HG* formula are very close to those of the *PM* formula, and their values are more accurate. Therefore, the calculation results of the *PM* formula and the modified *HG* formula are used as the actual daily evapotranspiration of the lawn(Cai and Xu, 2021; Jashari and Zogiani, 2020; Wang C et al., 2021; Salviano et al., 2021).

Calculation results and analysis of evapotranspiration

Summarize the evapotranspiration results of impervious surface and permeable surface to obtain the monthly evapotranspiration of impervious surface and the daily and monthly actual evapotranspiration of lawn, as shown in *Table 7*.

It can be seen from *Table 7* that the area of rainwater garden in lid facility layout is 3.9 km^2, and its surface vegetation is lawn. Using the monthly impervious surface evaporation and lawn $ET_a(PM)$ in *Table 6,* according to *Equation 9*, the annual evapotranspiration generated by the presence or absence of rainwater garden in the area

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of rainwater garden in the study area can be calculated as 328.13 × 104 m^3, 49.48 × 104 m^3, with a difference of about 6 times, indicating that the rainwater garden has a strong evapotranspiration effect.

$$V = 0.1\sum_{i=1}^{12} E_{iye} \times \mathrm{A} \tag{Eq.9}$$

where: V is the total annual evapotranspiration of the region, 10000 m^3; E_{iye} is the total evapotranspiration of the ith, mm; A is the area of the study area, km^2.

Table 7. *Summary of actual evapotranspiration on different underlying surfaces*

Month	**Impervious surface evaporation**	**Lawn ET_a (PM)**	**Lawn ET_a(corrected HG)**	**Lawn ET_a (PM)**	**Lawn ET_a (corrected HG)**
	Average monthly (mm/month)			**Average per day (mm/d)**	
1	1.4	22.05	20.07	0.71	0.65
2	2.2	39.01	33.46	1.35	1.15
3	5.6	60.71	54.92	1.96	1.77
4	8.8	84.36	89.60	2.81	2.98
5	16	101.09	104.73	3.26	3.37
6	16.4	123.62	126.88	4.12	4.22
7	19.2	122.14	124.84	3.94	4.02
8	9	130.14	110.55	4.20	3.56
9	11.2	67.94	77.59	2.26	2.58
10	24	39.70	45.93	1.28	1.48
11	7.6	24.37	28.45	0.81	0.95
12	5.2	24.52	22.64	0.79	0.74

From the above analysis, it can be seen that the increase of impervious surface in the process of urbanization will greatly reduce the evaporation of the region and seriously affect the land water circulation process within the city(Jia and Zhessakov, 2021; Kocan, 2021; Lehmann et al., 2021; Xin et al., 2021; Yuan et al., 2021; Yun, 2021; Zhu et al., 2021). Among the rainwater utilization measures, the measures characterized by vegetation coverage have strong evaporation capacity. As the simplest facility in rainwater utilization, the evaporation of grass has reached 839 mm (PM formula) in the whole year. Other rainwater utilization measures such as rainwater garden Sunken green space and biological detention facilities are the combination of a variety of vegetation (including trees, shrubs, grasslands, etc.), and their evapotranspiration capacity is greater than that of a single lawn facility. Therefore, from the perspective of hydrological ecology, rainwater utilization measures have a strong evapotranspiration effect, which can effectively promote the land water cycle in the city, regulate the surface water volume of the city in different time and space, help to form a good hydrological ecological environment and promote the harmonious development of urban ecology(Zhang et al., 2021; Gao et al., 2021; Liu et al., 2021).

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Reduce regional temperature and mitigate heat island effect

At present, the underlying surface of the city is mostly made of cement, concrete, floor tiles and other materials with high thermal conductivity and large thermal capacity. If you want to alleviate the heat island effect, you must fundamentally change the nature of the underlying surface. Vegetation can effectively alleviate the heat island effect through transpiration and shading. The calculated lawn evapotranspiration shows that the green roof has a strong evapotranspiration effect, and the evapotranspiration process can effectively reduce the ambient air temperature to mitigate the heat island effect. The comparative observation of green roofs with different structures and concrete roofs also shows that the green roof has a good heat insulation and energy saving effect.

The green roof, rainwater utilization facilities, sunken green spaces, and other facilities of the designed rainwater garden use rainwater by changing the urban surface and increasing vegetation coverage, which has the effect of reducing surface temperature and alleviating the heat island effect on the local urban climate. In addition to the rainwater utilization facilities of the designed rainwater garden with vegetation coverage, permeable pavement can also reduce the underlying surface temperature and mitigate the heat island effect through the evaporation effect of water. Therefore, most urban rainwater utilization facilities can mitigate the heat island effect through the evaporation effect of water. Each link of urban rainwater utilization facilities can alleviate the urban heat island effect by reducing carbon dioxide emissions. Various facilities with vegetation cover can directly realize ecological effects such as carbon fixation, oxygen release, cooling and humidification through photosynthesis of vegetation. When the vegetation coverage in the city reaches a certain index, the temperature in the city will decrease, so as to reduce various energy consumption, reduce the use frequency of air conditioning and reduce the consumption of fossil energy, realizing a virtuous cycle. The construction of urban rainwater utilization facilities will effectively reduce the runoff and purify the water quality. The reduction of runoff directly reduces the drainage pressure of rainwater pumping stations in the pipe network, and greatly reduces the carbon emissions generated by the operation consumption of pumping stations. The role of rainwater utilization facilities in purifying the water quality will effectively relieve the pressure of sewage treatment plants, and reduce the carbon dioxide emissions generated by the treatment of COD and other pollutants. In conclusion, the construction of urban rainwater utilization facilities will reduce the regional temperature to a certain extent and mitigate the heat island effect. Therefore, from the perspective of hydrological and ecological benefits, the rainwater resources utilization facilities of the rainwater garden can regulate runoff, conserve water sources, reduce flood peaks, conserve water and soil, improve water quality and improve the environment.

Building micro ecosystems to enhance biodiversity

Rainwater gardens can enhance regional biodiversity through ecological creation, environmental optimization, and rainwater utilization design. At the same time, through comprehensive ecological effects such as retention, purification, and regulation, a stable and sustainable urban micro ecosystem can be constructed. Rainwater gardens have an impact on biodiversity and ecological effects. Rainwater gardens create habitats for birds, butterflies, and other animals through low-lying terrain and diverse vegetation (such as flood resistant herbaceous plants and shrubs), and provide them with food resources such as nectar and fruits, which can promote microbial growth and form small biological

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communities. Plant communities attract pollinating insects, promote food chain extension, and enhance the symbiotic relationship between animals and plants. The layered structure of different vegetation layers (herbs, shrubs, trees) in the rainwater garden further supports multi-level ecological niches. Rainwater gardens reduce the toxicity of water pollution to aquatic organisms through soil infiltration and plant root adsorption of pollutants such as heavy metals and organic matter. Plants reduce air pollution and improve the respiratory environment of animals by adsorbing and degrading volatile gases.

Discussion

The fundamental difference between the rain garden model proposed in this article and existing models is that our model stands out through its integrated design, which combines dynamic soil ratio optimization with engineering structures such as honeycomb overflow wells and underground storage tanks, surpassing the static design focus of traditional model design. The outstanding performance of the model in total runoff control and maximum pollutant reduction in this article directly proves this point. There are significant performance differences between different soil structures, and by balancing hydraulic conductivity and retention rate, a ratio of 80% sand: 15% loam: 5% clay has been proven to be optimal. The close consistency between Penman Monteith and the improved Hargreaves evapotranspiration calculation model provides a validated simplified alternative. These differences from existing models are crucial for optimizing the design and application of sponge city infrastructure.

Conclusion

This paper designs a water cycle landscape for a Sponge City rainwater garden. By designing dynamic soil ratios, it overcomes the limitations of traditional rainwater garden fixed ratios, adapts to different rainfall scenarios, and combines geographic data visualization, analytic hierarchy process, and hydrological models to analyze its ecological effects. The precipitation time characteristics of the Sponge City are determined, and the composition structure of the rainwater garden is designed; And the ecological effects of water cycle landscapes were analyzed using the crop coefficient method. The experimental results show that the rainwater garden designed in this paper significantly improves the total runoff control rate and the reduction rate of runoff pollutants. Among them, the No. 3 Rainwater Garden has the best “infiltration”, “retention” and “water storage” effects, with a soil ratio of 80% sandy soil, 15% loam soil, and 5% clay soil. By optimizing the soil ratio of Rainwater Garden No. 3, the annual runoff total control rate (infiltration) can be improved, peak runoff (retention) can be reduced, and rainwater resources can be stored. The effectiveness of the rainwater garden designed in this paper has been verified, significantly improving its performance in pollutant reduction and total runoff control. And it was concluded that the combined vegetation facility has a higher evapotranspiration capacity than a single lawn facility, and has a stronger evapotranspiration effect. This indicates that the rainwater utilization measures of the water cycle landscape in the Sponge City rainwater garden designed in this paper can effectively promote the land water cycle within the city, promote the harmonious development of urban ecology, and provide new ideas and methods for urban ecological construction. This provides a quantifiable urban water resource management

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plan to cope with extreme rainfall events and effectively reduce the risk of urban waterlogging. In addition, the rainfall spatiotemporal characteristic analysis model and water cycle visualization module constructed in this paper enable urban managers to dynamically monitor the system response under different rainfall recurrence periods, providing data support for optimizing the spatial layout of sponge facilities and achieving dual ecological benefits of water resource cycling and microclimate improvement. However, due to limited conditions and reliance on publicly available data from the past year, the scope of application of the research findings in this paper is limited. Therefore, future research will focus on long-term monitoring of rainwater gardens to obtain more experimental data. For example, setting a continuous monitoring period of at least 3-5 years, covering different climate scenarios such as wet years, normal years, and dry years, to analyze the response patterns of rainwater gardens to extreme precipitation and drought. Collect data monthly or quarterly (such as soil moisture, plant growth status, water quality indicators) to reveal the annual dynamic changes in the water cycle.

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