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HYDROLOGICAL IMPACTS OF SMART TECHNOLOGY IN URBAN RAINWATER GARDENS: A CASE-BASED SWMM ASSESSMENT

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This paper examines an urban rain garden as a case study and evaluates its hydrological performance using the SWMM model. It compares two design approaches—drainage-type rain gardens (RG-dr) and infiltration-type rain gardens (RG-inf)—to assess how design differences influence runoff control, pollutant mitigation, and perceived landscape value. For RG-dr, the mean total loads of four pollutant categories were 56.383 kg, 13.725 kg, 7.484 kg, and 0.904 kg, respectively. Average removal efficiencies for suspended solids (SS), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) were 29.30%, 33.15%, 31.52%, and 39.08%, respectively. Survey results indicate that users were generally satisfied with the visual and experiential quality of RG-dr: more than half of respondents in every age group rated the landscape effect as "good" or "very good," and over 60% across age groups described the landscape layering as "very rich" or "relatively rich."

Index Terms — rain garden, SWMM model, hydrological effects, runoff regulation, landscape benefits

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INTRODUCTION

In recent years, urban flooding has become an increasingly prominent problem. During rapid urbanization, the expansion of impervious surfaces has markedly reduced rainwater infiltration, while the decline of green spaces has weakened vegetation's capacity to intercept and retain rainfall. In addition, deficiencies in the planning and design of urban stormwater drainage systems have further limited surface water infiltration, exacerbating flood risks [1, 2, 3]. At the same time, many cities are facing acute challenges related to water scarcity and water pollution [4]. As urban development progresses, extensive areas of farmland and natural vegetation have been replaced by roads, industrial facilities, and residential buildings. These land-use changes significantly alter surface water retention, permeability, and thermal properties, thereby modifying the relationship between precipitation and runoff. Consequently, the natural storage capacity of urban watersheds is weakened, leading to corresponding changes in hydrological elements and processes within cities and their surrounding areas [5, 6, 7, 8]. The term *urban hydrological effects* is used to describe this series of impacts that urbanization exerts on hydrological processes [9]. Against this background, the concept of the "sponge city" has been proposed, emphasizing the capacity of urban areas to absorb, store, and release water in order to better adapt to natural environmental conditions and climate variability [10]. A fundamental principle of this approach is adherence to natural hydrological laws.

Rain gardens serve as the basic functional units for implementing the sponge city concept. They are capable of collecting stormwater from road surfaces and rooftops, providing effective storage and enabling rainwater reuse. With relatively low construction costs, rain gardens are required to balance water management functions with landscape aesthetics and practical usability [11, 12, 13]. Although typically small in scale, rain gardens closely resemble natural ecosystems. Through their application, urban runoff can be treated and purified, and the treated water can be reused for landscape irrigation, thereby realizing the integrated functions of landscaping, rainwater collection, and purification [14, 15, 16]. Rain gardens are generally categorized into permeable types and semi-storage/semi-permeable types. Permeable rain gardens primarily facilitate surface water infiltration [17], whereas semi-storage/semi-permeable rain gardens integrate both infiltration and storage functions during construction. By utilizing the ecological purification capacity of vegetation, these systems ensure that discharged water meets relevant standards. Such designs enhance rainwater purification and filtration, ultimately contributing to improved urban water quality [18, 19, 20]. Previous studies have shown that optimized rain garden layouts not only enhance pollutant removal efficiency but also reduce stormwater runoff, thereby mitigating urban flood risks [21]. Consequently, increasing research attention has been directed toward the hydrological effects of rain gardens.

Several studies have explored the hydrological performance of rain gardens through modeling and simulation. Reference [22] developed a numerical model to estimate the effective area of rain gardens and proposed evaluation methods for hydrological efficiency, thereby improving their application in drainage and water quality management. Reference [23] highlighted the close relationship between rain garden design and hydrological behavior, constructing an infiltration model that demonstrated the importance of considering water column height to minimize overflow risk during intense rainfall events.

In recent years, intelligent technologies have increasingly been applied to rain garden research and management. Reference [24] employed the Zebra optimization algorithm to enhance backpropagation neural networks, support vector machines, and random forest models, developing a predictive framework for evaluating rain garden runoff control performance, with the optimized BP model achieving the best results. Reference [25] proposed a deep learning-based approach to predict concentrations of total suspended solids, chemical oxygen demand, total nitrogen, and total phosphorus, using a long short-term memory network to monitor stormwater runoff characteristics and assess pollutant removal and runoff reduction under varying hydrological conditions. Reference [26] combined the Phillips model, gradient boosting machines, and deep learning techniques to analyze infiltration rates under different vegetation types, planting densities, and flow conditions in rain gardens, finding that gradient boosting provided superior predictive performance. In addition, reference [27] utilized three-dimensional modeling and digital twin technologies to visualize hydrological data in Hankou, Wuhan, enabling data–scene interaction and simulating flood evolution to support decision-making. Reference [28] introduced an outdoor multi-hop wireless sensor network for collecting hydrological and environmental data, constructing a sensor-based system for basin-scale hydrological analysis.

In this study, the definitions and classifications of rain gardens are first introduced, followed by a systematic discussion of their design and construction methods. The principles of the Storm Water Management Model (SWMM) are then explained from hydrological and hydraulic perspectives, with the dynamic wave method applied to simulate node water depths and pressurized flow behavior within stormwater pipe networks. Based on collected baseline data from the study area, a hydrological model is established. Focusing on RG-dr and RG-inf rain garden types, the impacts of different design configurations on runoff regulation, peak detention time, and pollutant loads are quantitatively analyzed. By integrating case study data with user survey results, the study further provides a comprehensive evaluation of the multi-dimensional benefits of rain gardens.

RESEARCH ON THE HYDROLOGICAL EFFECTS OF URBAN RAIN GARDENS BASED ON THE SWMM MODEL

Design and Construction of Rain Gardens

Under the combined pressures of global climate change and rapid urbanization, urban stormwater management is facing increasingly severe challenges. As a key facility within the framework of low impact development (LID), rain gardens have attracted significant research attention, particularly with regard to optimizing their hydrological performance and environmental benefits.

Site Selection

Appropriate site selection is a critical prerequisite for effective rain garden construction. Rational use of local topography can reduce construction workload and costs. Site selection should adhere to the following principles:

1. Rain gardens should be located in relatively low-lying areas without long-term waterlogging, or in locations where surface runoff can naturally flow through;
2. A minimum distance of 4 m from buildings should be maintained to prevent seepage from affecting building foundations and causing potential safety risks;
3. Priority should be given to sites with sufficient sunlight to support plant growth and ecological functions.

Depth and Slope

Rain gardens require an appropriate ground slope to facilitate runoff collection, and drainage channels should be arranged along the slope to guide rainwater effectively into the facility. A suitable slope promotes adequate contact among stormwater, vegetation, and soil, thereby enhancing purification efficiency. The surface slope of a rain garden should not exceed 15%, and a design depth of approximately 13 cm is generally recommended.

Design Methods

At present, rain garden design commonly adopts three approaches: the infiltration method based on Darcy's law, the effective storage volume method, and the proportional estimation method based on catchment area. The Darcy-based infiltration method determines design parameters according to soil infiltration capacity and Darcy's law, but neglects the storage effect of structural voids within the rain garden. The effective storage volume method focuses primarily on the water retention capacity of the storage layer, without considering infiltration capacity or void storage. The catchment-area-based proportional method typically recommends that the rain garden area account for 5%–10% of the contributing catchment area; however, this approach lacks sufficient accuracy.

To address these limitations, Xiang Lulu *et al.* proposed a comprehensive water balance method that simultaneously accounts for soil permeability and storage capacity. The rain garden surface area can be calculated using

$$A_f = \frac{\varphi A_d H}{KT + d_f + h + h_m - v_f d_f n}, \tag{1}$$

where A_f is the rain garden area (m^2), A_d is the catchment area (m^2), H is the design rainfall depth (m), φ is the runoff coefficient, d_f is the rain garden depth (m), K is the soil permeability coefficient (m/s), T is the calculation period (min), typically 15 min for short-duration rainfall events, h is the design average water depth of the storage layer (m), h_m is the maximum storage depth (m), v_f is the ratio of plant cross-sectional area to storage layer surface area (usually about 15%), and n is the average porosity of the planting soil and fill layer (generally around 0.4).

SWMM Modeling Principles

In the Storm Water Management Model (SWMM), sub-catchments represent the smallest independent computational units. They are used to simulate and analyze the impacts of surface characteristics on hydrological processes under varying land-use conditions.

Principles of Surface Runoff Calculation

Surface runoff refers to the portion of rainfall that remains after accounting for losses due to infiltration, evaporation, vegetation interception, and depression storage. When applying the SWMM model, the study area is first divided into multiple sub-catchments. Each sub-catchment is further classified into permeable areas and impermeable areas, with the latter consisting of impermeable zones with depression storage (S_2) and impermeable zones without depression storage (S_3).

Runoff generation within each sub-catchment is calculated independently. The total runoff from a sub-catchment is obtained by summing the runoff contributions from permeable and impermeable areas.

The runoff yield from the permeable area (S_1) is expressed as

$$R_1 = (i - f)\Delta t, \tag{2}$$

where R_1 is the runoff depth from the permeable area (mm), i is the rainfall intensity (mm/s), f is the infiltration rate (mm/s), and Δt is the time step.

The runoff from impermeable areas with depression storage (S_2) is given by

$$R_2 = P - D, \tag{3}$$

where R_2 is the runoff depth (mm), P is rainfall depth (mm), and D is the depression storage capacity (mm).

For impermeable areas without depression storage (S_3), runoff is calculated as

$$R_3 = P - E, \tag{4}$$

where R_3 is the runoff depth (mm) and E represents evaporation losses (mm).

Infiltration Calculation Principles

Infiltration describes the process by which rainfall penetrates the ground surface and enters permeable soil layers. The SWMM model provides several infiltration options, including the Horton model, the Green–Ampt model, and the SCS-CN model.

Horton Model The Horton model assumes that infiltration capacity decreases exponentially from an initial maximum value to a stable minimum value during rainfall. Because it does not explicitly distinguish between saturated and unsaturated soil layers, this model was adopted in this study. The infiltration rate is expressed as

$$f_p(t) = f_\infty + (f_0 - f_\infty)e^{-kt}, \tag{5}$$

where f_p is the infiltration rate (mm/h), f_0 is the initial infiltration rate (mm/h), f_∞ is the steady-state infiltration rate (mm/h), k is the decay coefficient (1/h), and t is the infiltration duration (h).

Green–Ampt Model The Green–Ampt model divides the soil profile into an initial moisture zone and a saturated zone, separated by a wetting front. The infiltration rate is given by

$$i = \frac{K_s S_w (\theta_s - \theta_i)}{F}, \tag{6}$$

where θ_s and θ_i are the saturated and initial soil moisture contents, respectively, S_w is the suction head at the wetting front, F is cumulative infiltration, i is rainfall intensity (mm), and K_s is the saturated hydraulic conductivity.

SCS-CN Model The SCS-CN model establishes a relationship between soil water storage capacity and the curve number (CN). The effective rainfall is calculated as

$$PE = \frac{(P - I_a)^2}{P - I_a + S}, \tag{7}$$

where PE is cumulative effective rainfall, P is cumulative rainfall, I_a is the initial abstraction, and S is the potential maximum retention.

Surface Runoff Routing

For watershed-scale surface runoff simulation, SWMM applies nonlinear reservoir theory to represent sub-catchment runoff. The model accounts for parameters such as sub-catchment area, slope, and rainfall intensity, combining the water balance equation with Manning's formula:

$$\frac{dV}{dt} = Ai - Q, \tag{8}$$

$$Q = \frac{1.49}{n} W (h - h_p)^{5/3} S^{1/2}, \tag{9}$$

where V is runoff volume, A is the sub-catchment area (m^2), i is net rainfall intensity (mm/s), Q is discharge (m^3/s), W is the characteristic width (m), n is Manning's roughness coefficient, h is water depth (m), h_p is storage depth (m), and S is the sub-catchment slope.

Pipeline Flow Routing Principles

Pipeline routing describes the convergence of runoff into inspection wells, its transport through the drainage network, and eventual discharge. SWMM provides three flow routing methods: steady flow, kinematic wave, and dynamic wave.

The steady flow method assumes uniform flow during each time step and is suitable only for simple tree-like networks. The kinematic wave method solves simplified continuity and momentum equations, allowing stable computation but with limitations in representing backflow and pressurized flow.

The dynamic wave method solves the full Saint-Venant equations and can simulate complex hydraulic phenomena, including backflow, surcharge, and pressurized flow. Owing to its high accuracy and broad applicability, this method was adopted in this study. The governing equations are

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0, \tag{10}$$

$$\frac{\partial H}{\partial x} + \frac{v}{g}\frac{\partial v}{\partial x} + \frac{1}{g}\frac{\partial v}{\partial t} = S_0 - S_f, \tag{11}$$

$$Q = \frac{A R^{2/3} S^{1/2}}{n}, \tag{12}$$

where Q is flow rate (m^3/s), A is cross-sectional area (m^2), v is flow velocity (m/s), x is pipe length (m), R is hydraulic radius (m), H is water depth (m), S_f is the friction slope, S_0 is the bed slope, g is gravitational acceleration (9.8 m/s^2), and n is Manning's coefficient.

CASE STUDY ON THE HYDROLOGICAL EFFECTS OF SMART TECHNOLOGIES IN URBAN RAIN GARDEN DESIGN

Overview of the Study Area

Geographic Location

City A is situated between latitudes 40°21′–41°45′ N and longitudes 120°78′–122°99′ E, in the northern region of Province X, China. The study area is an administrative district established alongside the urban development of City A and functions as its primary urban core. As the city's political, economic, educational, cultural, and transportation center, the area has received several national recognitions, including the titles of National Water-Saving City and National Hygienic City.

Climate Conditions

The study area benefits from abundant solar and thermal resources and exhibits a warm temperate monsoon climate with clearly defined seasons and generally mild temperatures. Prevailing winds are predominantly from the southeast in spring and summer, and from the northeast in autumn and winter. Climatic characteristics include variable spring temperatures, hot summers, cold winters, and clear, pleasant autumns. The long-term average annual temperature is approximately 15.2°C. Precipitation is strongly influenced by monsoonal circulation, showing limited interannual variability but pronounced seasonal unevenness: spring droughts, summer flooding, and dry conditions in autumn and winter are common. The long-term mean annual precipitation is about 905.3 mm.

Meteorological records from the past 20 years indicate an overall upward trend in annual average temperature, ranging from a minimum of 12.1°C to a maximum of 16.2°C. Wind speed and sunshine duration have gradually declined, while annual precipitation has increased, with notably high rainfall in 2000, 2002, and 2003, reaching 1301.5 mm, 1399.2 mm, and 1295.4 mm, respectively. Summer precipitation has increased markedly, whereas autumn precipitation has shown a decreasing trend.

Hydrological Landforms

City A is characterized by pronounced topographic variation, with terrain generally sloping from high elevations in the northwest to lower elevations in the southeast. Most areas lie below 50 m above sea level, with maximum and minimum elevations of 69.4 m and 3.3 m, respectively. The city possesses a dense river network and several major flood control channels, which collectively convey floodwaters from the middle and upper reaches over an area of approximately 18 km^2.

Land Use Types

The proportions of different land use categories within the study area are summarized in Table 1. The land use structure exhibits strong urbanization characteristics. Highways have the highest imperviousness rate (85%) and account for 12.22% of the total area, exerting a substantial influence on regional runoff processes.

Table 1: Proportion of land use types in the study area

No.	Land use type	Imperviousness (%)	Area (ha)	Area proportion (%)
1	Park	28	40.79	13.16
2	Government buildings	55	15.58	5.03
3	Squares	70	15.17	4.89
4	Building areas	78	100.51	32.42
5	Construction areas	79	50.97	16.44
6	Grassland	5	37.33	12.04
7	River channels	–	8.67	2.80
8	Scenic lakes	2	3.11	1.00
9	Highways	85	37.87	12.22
Total	–	–	310.00	100.00

Hydrological and Environmental Effects of Rain Gardens

To examine the hydrological behavior of LID facilities and the performance differences associated with alternative drainage configurations, a paired experimental monitoring approach was adopted using local rainfall data. Two rain gardens were constructed in an area with shallow groundwater: one drainage-type rain garden (RG-dr) equipped with an underdrain system, and one infiltration-type rain garden (RG-inf) without drainage. This design aimed to provide empirical support for sponge city implementation by evaluating the effectiveness of rainwater storage, retention, purification, utilization, and discharge.

Hydrological Effects

The runoff process of RG-inf consists of inflow and outflow components, whereas RG-dr includes inflow, outflow, and drainage processes. With urbanization, natural surfaces have been progressively replaced by impervious pavements and buildings, significantly inhibiting infiltration. As a result, runoff concentration times during intense rainfall events have shortened, peak flows occur earlier, and runoff volumes have increased, often leading to surface ponding and aggravated flooding.

Comparative analysis of runoff processes before and after urban development shows that post-development flood peaks are both higher and earlier. The implementation of LID measures such as rain gardens seeks to restore hydrological responses toward pre-development conditions.

Representative rainfall events recorded between June and July 2024 were analyzed. Among eight rainfall events, the average peak detention time of RG-inf was 89.125 min, compared with 34.125 min for RG-dr, indicating a clear advantage of the drainage-type design in peak flow regulation. During the July 31 event, RG-inf achieved complete peak attenuation, while RG-dr reached a peak reduction rate of 96.5%. However, under heavy rainfall, RG-inf exhibited lower peak reduction efficiency than RG-dr, suggesting that drainage-type rain gardens are better suited to extreme precipitation.

Due to variations in rainfall intensity, duration, and antecedent dry periods, inflow and outflow patterns differed considerably among events. Two typical rainfall patterns (Huff1 and Huff2) were selected for detailed analysis. In both cases, inflow rates were closely correlated with rainfall intensity and temporal distribution. When inflow exceeded infiltration capacity, surface ponding developed within the storage layer. Once water levels surpassed the outlet weir height, excess runoff was discharged into the conventional stormwater system, establishing a dynamic equilibrium.

Hydraulic Effects

The main outfalls of the stormwater drainage system are typically located near natural receiving waters. Analysis of flow and water depth at these outlets provides a scientific basis for flood control and drainage planning. The study area contains three primary outfalls connected to the municipal drainage network. Taking the O1 outfall on the southern boundary as an example, simulations under RG-inf conditions show that flow and water depth trends closely follow rainfall patterns, with water depth responding more gradually than flow. Under the Huff2 rainfall scenario, the minimum peak flow reached 0.25 m/s.

For RG-dr conditions, simulations revealed smaller variations in water depth and peak timing compared to RG-inf, accompanied by significant reductions in total discharge and peak flow. Similar patterns were observed at the O2 and O3 outfalls, confirming the effectiveness of drainage-type rain gardens in mitigating hydraulic loads on urban drainage systems.

Environmental Effects

To evaluate pollutant control performance, four water quality indicators—suspended solids (SS), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP)—were analyzed. The total pollutant loads for each runoff scenario are summarized in Table 2. Average total loads of SS, COD, TN, and TP for RG-inf were 79.750 kg, 20.532 kg, 10.929 kg, and 1.484 kg, respectively, while corresponding values for RG-dr were 56.383 kg, 13.725 kg, 7.484 kg, and 0.904 kg. The average removal efficiencies were 29.30% for SS, 33.15% for COD, 31.52% for TN, and 39.08% for TP. These results demonstrate that RG-dr provides effective regulation of non-point source pollution by reducing runoff volume and pollutant loads through sedimentation, filtration, and adsorption processes.

Table 2: Total pollutant loads under different rain garden configurations

Indicator	Mode	Huff1 (kg)	Huff2 (kg)	Mean (kg)
SS	RG-inf	79.386	80.114	79.750
	RG-dr	56.228	56.538	56.383
COD	RG-inf	20.486	20.578	20.532
	RG-dr	13.554	13.896	13.725
TN	RG-inf	10.772	11.086	10.929
	RG-dr	7.337	7.631	7.484
TP	RG-inf	1.462	1.506	1.484
	RG-dr	0.895	0.913	0.904

Landscape Effect Analysis

User Preference Analysis

A questionnaire survey involving 207 users from different age groups was conducted to assess landscape preferences. The results indicate that RG-dr achieved higher overall satisfaction, with more than 50% of respondents in each age group rating its landscape quality as "very good" or "good." In contrast, RG-inf received comparatively lower evaluations, with over 20% of respondents expressing dissatisfaction.

Landscape Hierarchy Analysis

Analysis of perceived landscape hierarchy further revealed that RG-dr was regarded as having a richer and more diverse spatial structure. More than 60% of respondents across all age groups evaluated the landscape hierarchy of RG-dr as "very rich" or "relatively rich," highlighting its advantages in visual quality and spatial organization.

CONCLUSION

By integrating the Storm Water Management Model (SWMM) with field monitoring data, this study demonstrates that the application of smart technologies can effectively enhance both the hydrological performance and environmental benefits of urban rain gardens. The main findings can be summarized as follows.

First, analysis of eight rainfall events shows that the average peak detention time for infiltration-type rain gardens (RG-inf) reached 89.125 min, whereas drainage-type rain gardens (RG-dr) exhibited a much shorter average peak detention time of 34.125 min. During the rainfall event on July 31, RG-inf achieved complete peak attenuation, while RG-dr achieved a peak reduction rate of 96.5%. However, under heavy rainfall conditions, the peak reduction efficiency of RG-inf was significantly lower than that of RG-dr, indicating that drainage-type rain garden designs possess stronger adaptability and stability when coping with intense precipitation events.

Second, under RG-dr conditions, variations in total outlet water depth and the timing of peak flow were smaller than those observed under RG-inf conditions, reflecting a more stable hydraulic response. At the same time, both total runoff volume and peak discharge were substantially reduced. The average total pollutant loads of suspended solids (SS), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) under RG-dr were 56.383 kg, 13.725 kg, 7.484 kg, and 0.904 kg, respectively. Correspondingly, the average removal efficiencies for SS, COD, TN, and TP reached 29.30%, 33.15%, 31.52%, and 39.08%, demonstrating the effectiveness of drainage-type rain gardens in controlling non-point source pollution.

Finally, from the perspective of landscape benefits, user survey results indicate that RG-dr provides superior visual and spatial quality. More than 50% of respondents across all age groups rated the landscape performance of RG-dr as "very good" or "good," whereas over 20% of users expressed negative evaluations of RG-inf. In addition, the landscape hierarchy of RG-dr was generally perceived as richer and more diverse, with over 60% of respondents rating it as "very rich" or "relatively rich." These findings suggest that drainage-type rain gardens offer comprehensive advantages in hydrological regulation, environmental protection, and landscape quality.

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