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Assessing the Effectiveness and Cost Efficiency of Green Infrastructure Practices on Surface Runoff Reduction at an Urban Watershed in China

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Abstract: Studies on the assessment of green infrastructure (GI) practice implementation effect and cost efficiency on an urban watershed scale helps the GI practice selection and investment decisions for sponge city construction in China. However, few studies have been conducted for these topics at present. In this study, the Long-Term Hydrologic Impact Assessment—Low Impact Development (L-THIA-LID) 2.1 model was applied to assess the effectiveness and cost efficiency of GI practices on surface runoff volume reduction in an urban watershed—the Hexi watershed, Nanjing City, China. Grassed swales, bioretentions, green roofs, rain cisterns, permeable pavements, wet ponds, dry ponds, and wetlands were chosen as potential GI practices for sponge city construction based on feasibility analysis. Results showed that grassed swales were the most cost-effective practice (0.7 CNY/m^3/yr), but the total implementation effect of grassed swales was not obvious due to the small area of suitable locations. Permeable pavements performed best on runoff reduction, but the cost efficiency was much lower. Correspondingly, bioretentions were compromise practices. Green roofs were the least cost-effective practices, with the cost efficiency at 122.3 CNY/m^3/yr, but it was much lower for rain cisterns, which were 3.2 CNY/m^3/yr. Wet ponds, dry ponds, and wetlands were potential practices implemented in development areas, of which dry ponds were the most cost-effective (2.7 CNY/m^3/yr), followed by wet ponds (10.9 CNY/m^3/yr). The annual runoff volume of the total area could be reduced by up to 47.01% by implementing GI practices in buildup areas. Rain cisterns (RC) and permeable pavements (PP) were the best combination for this area, and bioretentions (BR) and green roofs (GR) followed. Grassed swales (GS$_1$), dry ponds (DP), wet ponds (WP), and wetlands (WL) were not wise choices due to the small suitable location areas. This study also demonstrated the feasibility of the L-THIA-LID 2.1 model for the evaluation of GI practice implementation effects and cost efficiency on urban runoff in sponge city construction in China.

Keywords: L-THIA-LID 2.1; green infrastructure practices; cost efficiency; runoff; urban watershed

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1. Introduction

Rapid urbanization leads to large areas of natural land transitioning into impervious surfaces, which significantly declines the urban rain-flood control ability [1–4]. When it comes to a strong rainfall event, traditional urban drainage systems cannot meet the requirements of rapid collection and discharge of surface runoff, and a large amount of surface runoff causes urban flood disasters [5]. In addition, impermeable surfaces reduce surface water infiltration, resulting in the groundwater recharge decreasing [6], and the increased surface water strengthens the erosion of urban surfaces, carrying pollutants into the surface water body and resulting in water pollution [7]. To cope with these problems, the concept proposed to minimally change the physical characteristics of land while utilizing the land for urban uses was promoted [8]. Typical development strategies internationally include the low-impact development (LID) in the U.S. [9,10], the sustainable urban drainage systems (SuDS) in the U.K. [11], the water-sensitive urban design (WSUD) in Australia [12], and the sponge city in China [5,13]. Green infrastructure (GI) practices are generally referred to as engineering measures used in urban stormwater management to treat surface runoff problems such as urban waterlogging and water pollution. Due to the different implementation conditions, commonly applied GI practices include LID practices and best management practices (BMPs) [4,14–16]. LID practices work by preventing the generation of surface runoff, which determines that LID practices are usually decentralized and small-scale. Commonly used LID practices refer to green roofs, bioretentions, grassed swales, grass strips, rain barrel/cisterns, and porous pavements [10]. On the contrary, the working principle of best management practices (BMPs) is to treat the generated runoff by collection, retention, and absorption, which determines that BMPs are usually centralized and large scale, such as with retention ponds and detentions [17].

Research on GI application was first conducted in the United States in the 1990s, and it has become a global strategy in dealing with urban flood problems until now. For example, Dreelin et al. [18] investigated the efficacy of porous pavements in controlling stormwater runoff on clay soils and found that permeable pavement parking produced 93% less runoff than the asphalt parking (Athens, GA, USA). Eckart et al. [19] developed a coupled optimization-simulation model by linking the storm water management model (SWMM) and the Borg multi-objective evolutionary algorithm (Borg MOEA) to evaluate LID stormwater controls, and they found that grassed swale was the most cost-effective LID in the reduction of flood peaks among rain barrels, permeable pavements, bioretentions, and grassed swales (Windsor, Canada). Goncalves et al. [20] evaluated the abilities of LID practices on reducing flood risk in a coastal region of South Brazil and found that a total flood volume reduction of between 30% and 75% could be achieved for seven LID scenarios. Radinja et al. [21] assessed the implementation effects and cost efficiencies of GI practices within an urban drainage system in the city of Girona, Spain, and they found that the scenario that included only infiltration basins was most favorable, and the rain cistern (underground storage tank) was the least favorable. Schmitter et al. [22] assessed the implementation effect of a green roof at a catchment in the heart of Singapore (100 km^2), where the annual runoff volumes could be reduced by 0.6%, 1.2%, and 2.4% when 25%, 50%, and 100% of the roofs were implemented with green roofs. The efficiency of infiltration trenches on runoff control was studied in an urban catchment in Johor, Malaysia, and results showed that the peak flow could be reduced by 17.5% to 20.95% [23]. Xu et al. [24] conducted a cost-combined life-cycle assessment to estimate the environmental and economic burdens of GI practices in a campus in Southern China and concluded that wetland exhibited the highest economic burdens, while grassed swale had the lowest economic burdens.

Based on the different research perspectives, existing research can be divided into two categories, which can also be regarded as two stages of research development. The first stage is the studies on the implementation effectiveness of individual GI practices based on experimental conditions [25–30]. For example, in the study of Frosi et al. [25], tree pits on both sides of the street (a city in Canada) were designed to be bioretentions to treat surface water problems. The results showed that soil organic matter in tree pits helped absorb the pollutant load, and permeable sidewalk also decreased the pollutant concentration and mass flux. Wang et al. [26] studied the implementation effects of bioretention cells, swales, and permeable pavements in Fuxing Island Park, Shanghai, which validated that LID practices could also perform well under the condition of high groundwater level and low soil permeability. Mai et al. [27] conducted a series of controlled experiments to measure the feasibility of greenbelts, permeable pavements, and green roofs in lateritic red soil regions, and they concluded that such LID practices were suitable for the region, and

LID practices with different design conditions showed obvious different implementation effects. The second stage refers to the supplement and development of research on GI implementation effectiveness assessment, studies on GI implementation optimization based on cost efficiency, and ecological environment effect, and policy environment also caught researchers' attention [24,31–37]. For example, Li et al. [34] studied the optimization scheme of GI practice combinations in a sports center (Guangxi, China) with a comprehensive evaluation system (including the economic, social, and ecological benefits) and concluded that when 34.5% and 46.0% of the total area were implemented with bioretention and sunken green space, respectively, the comprehensive benefits would be the best. Liu et al. [37] evaluated the cost efficiencies of 12 kinds of GI practices in an urban watershed of Indiana, USA, and they concluded that grassed strip was the most efficient, with the cost efficiency at $1/m^3/yr.

For many years, the traditional concept in China for urban stormwater management was to collect and discharge surface runoff quickly [12,13]. From 2014 to 2015, two guiding documents on the construction of sponge cities were issued one after another in China, defining sponge city construction as a special urban construction plan [38,39], which promoted the development of sponge city construction and research. Based on the "guiding opinions", 70% of rainfall should be consumed and utilized locally in more than 80% of the urban built-up areas by 2030. Sponge cities are being built in 30 pilot cities in China, with the total investment at approximately $6.4 billion [40]. Sponge city construction needs huge capital investment, not only on the initial construction process but also on the maintenance process. Due to the uncertainty of the project's life cycle and performance, it is difficult to evaluate the comprehensive environmental, ecological, and social benefits of sponge city construction [31]. Economic burden causes the local governments to generally be less enthusiastic to use financial funds to promote the construction of sponge cities. Thus, it is of great importance to assess the implementation effect and cost efficiency of GI practices on runoff reduction for guiding the government managers in decision making.

GI practices are the main engineering measures of sponge city construction in China; assessment of the implementation effectiveness and cost efficiency of GI practices on runoff reduction is the foundation of the sponge city construction plan and research of GI practice decision optimization [35]. However, relevant studies at present are insufficient. On one hand, relative research about GI practice implementation effectiveness mainly focuses on the assessment of runoff control and water quality improvement of individual GI practices, and it has failed to study the implementation effectiveness of combined GI practices and the cost efficiency. On the other hand, existing studies are mainly case studies on individual small projects or site scales, and researchers have failed to study the implementation efficiency of combined GI practices on an urban watershed scale. In China, a densely populated country with crowded cities, international research results are not suitable to be directly used as decision-making bases in sponge city construction. Therefore, the objective of this study is to assess the implementation effectiveness and cost efficiency of GI practices on surface runoff reduction in sponge city construction at an urban watershed in China.

The article consists of four sections. Section 2 describe data sources, the backgrounds and principle of the Long-Term Hydrologic Impact Assessment—Low Impact Development (L-THIA-LID) 2.1 model, and the scenario design method. Section 3 presents the scenario simulation results and discussions. Section 4 contains the conclusions of this study.

2. Materials and Methods

2.1. Study Area

An urban watershed called Hexi located in Nanjing City, China, which has an area of 58.94 km^2 (Figure 1), was selected as the study site, since it was identified as a target runoff control zone by the city [41]. This watershed is surrounded by the Qinhuai River located on the East and the Yangtze River on the West. Water logging in this watershed is serious in rainy seasons due to its low elevation. According to the Google Maps high definition aerial photography in 2017 from the Google Earth Pro (version 7.3.2.5776, 2019, Google LLC, Mountain View, CA, USA), 22.14% of the total area was open space (refers to the lands expropriated by the government, but not developed), which is mainly located in the south of the watershed. In addition, 3.99% of the area was industrial land, 30.52% of the area was residential area, 15.74% of the area was administrative and commercial service land, 8.91% of the area was water, and 16.21% of the area was public roads. In 2016, the municipal government issued "Implementation Opinions on Promoting Sponge City Construction", which clarified the overall goal, main tasks, and division of responsibilities of sponge city construction in Nanjing City. The Hexi watershed will come under sponge city construction before 2030. Green infrastructure (GI) practices, such as grassed swales (GS_1), GS_2, bioretentions (BR), permeable pavements (PP), rain cisterns (RC), and green roofs (GR), will be implemented in two test sites (two other target runoff control zones located outside of the Hexi watershed) before then. Considering that this watershed is under development and has construction that is very representative in China, it is of great importance to evaluate the implementation effects and cost efficiency of GI practices on runoff reduction for sponge city construction.

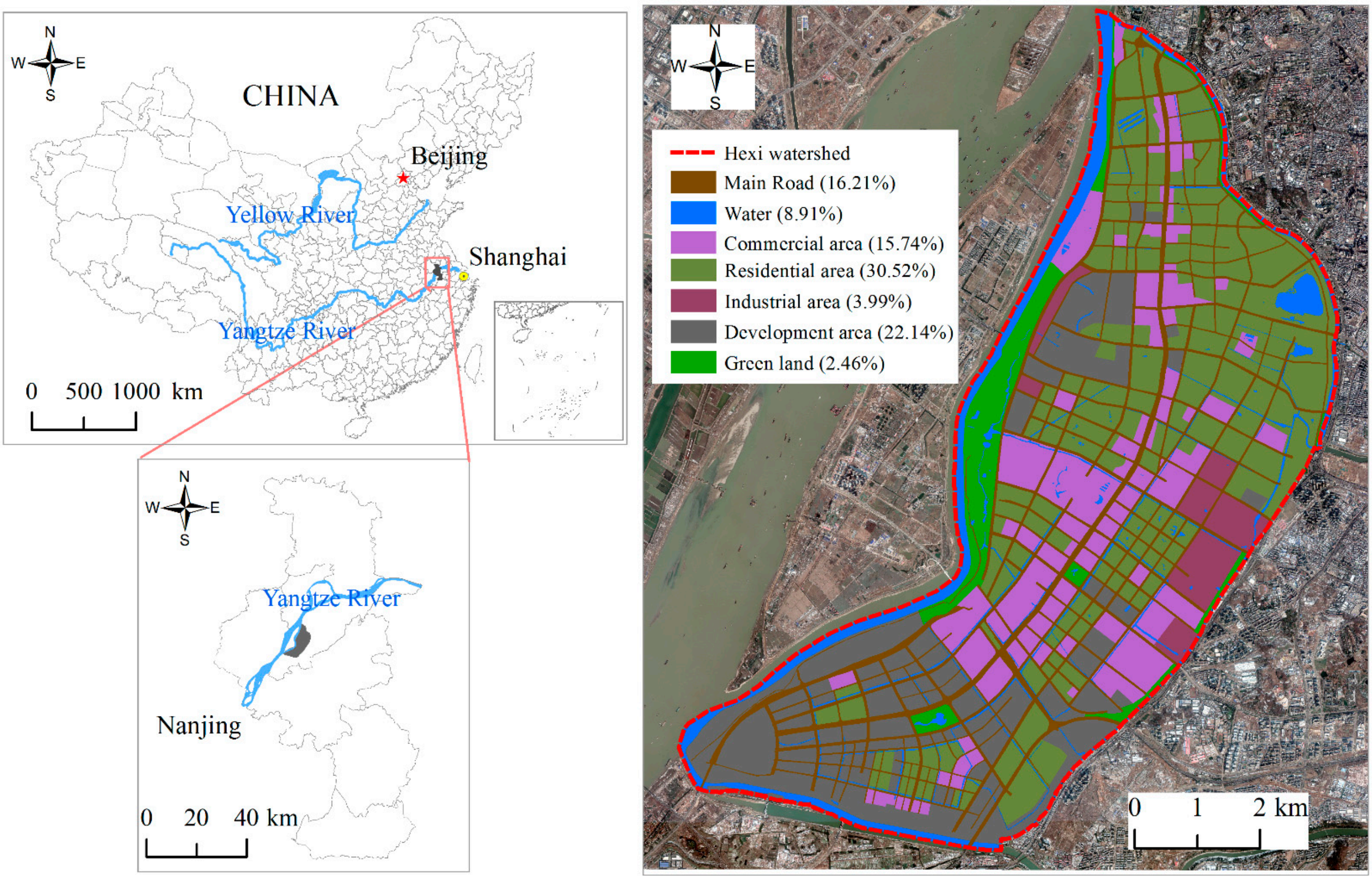

Figure 1. Location of the Hexi watershed in Nanjing, China.

2.2. Model Background

2.2.1. Principle and Framework for GI Practices Simulation

The L-THIA-LID 2.1 model was developed from the L-THIA model [37,42–44], which is easy to use and understand and has been successfully applied to many simulation studies of hydrological effects in China [2,45,46]. It has been widely used for the assessment of the implementation effectiveness and cost efficiency of GI practices on runoff control and improvement in many case studies in the U.S. [4,47–49]. The model provides an evaluation system to choose suitable locations of GI practices, which can also be adjusted based on actual conditions. It also contains a cost estimation model, which can easily estimate the construction cost and maintenance cost. Considering its feasible configuration capability, the L-THIA-LID 2.1 model was regarded as suitable for this study. Common GI practices include the rain barrels/cisterns (RB/RC), permeable pavements (PP), green roofs (GR), grassed swales (GS_1), grass strips (GS_2), wetland channels (WC), bioretentions (BR), wet ponds (WP), dry ponds (DP), and wetlands (WL). These were chosen as potential practices, and a feasibility analysis of each potential practice was conducted to determine the final practices based on the actual conditions of the study area. The implementation effectiveness and cost efficiency of GI practices on surface runoff volume reduction were evaluated, and a multi-scenario combination of GI practices was also assessed to understand the implementation impact of GI practices on urban runoff reduction.

The L-THIA-LID 2.1 model was developed with the Python language [9,37,44]. The curve number (CN) method is used in the model for runoff estimation [50]. Detailed urban land use types were first refined, and each combination of urban land type and hydrologic soil group (HSG) had a CN value. A set of evaluation criteria, including the natural factors, implementation conditions, and decision maker's willingness, was conducted to select the feasible locations of each kind of GI practice. Unique combinations of land use types, HSG, and GI practices were regarded as the same hydrologic response units (HRUs). Each HRU was implemented with a GI practice individually or in a series (of which, GR and RB/RC could be implemented in a series, while GS_1, GS_2, WC, WP, DP, and WL were all parallel to each other). The runoff control capacity of part kinds of GI practices (including RB/RC, PP, GR, and BR) was represented by the CN value adjustment method, and others (GS_1, GS_2, WC, WP, DP, and WL) were represented by the percent runoff reduction method [4,9,44,51,52]. Figure 2 shows the assessment process of the runoff control capacity of GI practices in a single HRU: the whole figure represented a hydrological unit; in this unit, each GI practice treated runoff generated form suitable locations and runoff coming from other locations; GR, RB/RC, and PP treated runoff generated from the suitable sites; BR treated 15% of the remaining runoff from the sites of GR, RB/RC, and PP; GS_1, GS_2, or WC treated the remaining runoff after being treated by GR, RB/RC, PP, and BR; WP, DP, or WL treated the remaining runoff after being treated by GR, RB/RC, PP, BR, GS_1, GS_2, and WC.

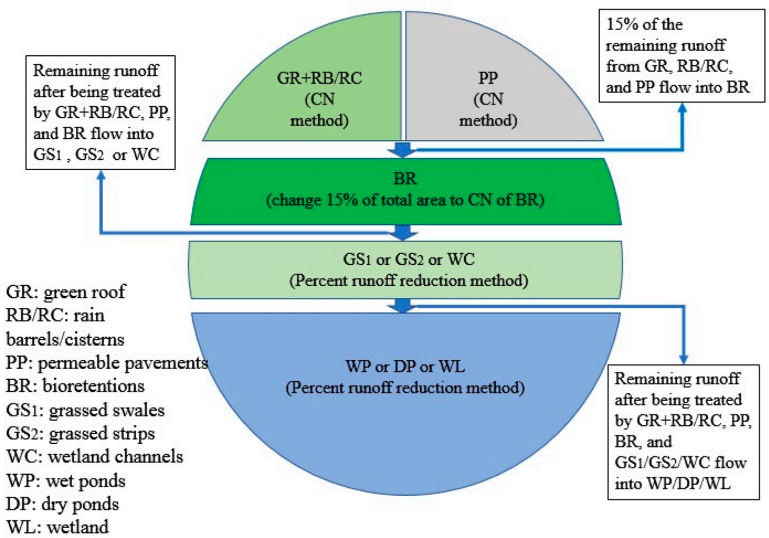

Figure 2. Assessment process of runoff control capacity of green infrastructure (GI) practices in a single hydrologic response unit (HRU).

2.2.2. Cost Assessment

The total cost of each GI practice could be calculated with initial construction cost, maintenance cost, interest rate, and GI practice design life. For detailed calculation information, see the research by Liu et al. [37,47] and Chen et al. [4]. The service life of all the GI practices was designed to be 20 years in this study. The interest rate was based on that of 2017, which was 2.5%. The construction costs of GI practices were based on the prices listed in the guiding document issued in 2014 [38]. Prices in the "Technology Guide" were not calculated based on the drainage area of each GI practice, but on the construction area or the runoff volume reduction. However, the drainage area and construction area of the green roof were the same; the highest price per construction area of the green roof was used as the construction cost per drainage area. Costs of other kinds of GI practices were calculated based on the ratios of the construction costs per drainage area to green roof construction cost per drainage area [37,53]. Maintenance costs were assessed as a percentage of construction costs [37]. All the costs were converted to 2017 price levels (Table 1).

Table 1. Initial construction cost and maintenance cost per drainage area of each GI practice [37,48].

GI Practice	Construction Cost (CNY/m^2)	Maintenance Cost (Percentage of Construction Cost, %)
GS_1 (grass swales)	1.34	6
RC (rain cisterns)	12.75	1
GR (green roof)	249.78	6
GR + RC (green roof and rain cisterns)	262.53	5.76
BR (bioretentions)	22.43	6
PP (permeable pavements)	87.83	1
WP (wet ponds)	1.81	4
DP (dry ponds)	2.1	4
WL (wetland)	2.3	4

Note: Construction costs of each GI practice were indicative values that may differ in different areas.

2.3. Input Data

Daily precipitation data, HSG data, land use data, digital elevation model (DEM), and building footprints were the basic input data of the L-THIA-LID 2.1 model. Data sources were described as follows.

Daily precipitation data from 2000 to 2017 were provided by the National Meteorological Information Center (http://data.cma.cn/site/index.html), which was from two monitoring stations located to the West and East of the watershed, with station numbers 58,238 and 58,237 and latitude and longitude coordinates of 118.9° E, 35.2° N, and 118.58° E, 46.6° N, respectively. There were no outliers in the data records, which can meet the needs of the research. Of the rainfall in the study area, 51.0% was in June, July, and August. The average rainfall depths were 191 mm in June, 251 mm in July, and 178 mm in August. Mean values of the daily precipitation from the two monitoring stations were calculated for model input, and the total rainfall depth in 2017 was 1349 mm.

HSG data: based on the research results of the Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) with an accuracy of 250 m (https://daac.ornl.gov/) [54]. The hydrologic soil groups A, B, C, and D represents the permeability of soil. Each kind of combination of HSG type and land-use type defined a CN value in the L-THIA-LID 2.1 model.

Land use data: Google Earth aerial photography of 2017 (Google Earth Pro, version 7.3.2.5776, 2019, Google LLC, Mountain View, CA, USA) was first adjusted through geographic registration based on the road lines using the ArcGIS10.1 software. Then, urban land was reclassified into grass land (open space that has not been developed), industrial land, administrative and commercial service land, residential land, water, public road, and green land (forest land), according to the aerial photography. Thirdly, the vector data were transferred to raster data with a resolution of 30 m to obtain the model input land-use data. On the one hand, land-use data, can be combined with HSG data to get CN values; on the other hand, it can be used to define which kind of GI practice could be used (a data overlay analysis was used to determine whether the raster units with 30 m accuracy were suitable for implementing GI practices, and the proportions of each GI practice could also be calculated).

DEM data: provided by Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn). The DEM was used to do hydrological analysis and define the potential locations of each of GI practice.

Building footprints and road lines: provided by the BIGEMAP LLC (www.bigemap.com, Chengdu city, Sichuan province, China). The building footprints were used to define the locations of roof tops, and the road lines was used to define the road surface.

2.4. Feasibility Analysis of GI Practices

High building density, large numbers of high-rise buildings, busy road systems, and large flows of people and traffic are typical characteristics of a city. In China, this can be even worse due to large populations and limited land. The implementation of GI practices will inevitably have many constraints, so, feasibility analysis of GI practices was conducted as follows.

Best management practices (BMPs) of WP, DP, and WL were considered for locations at outlets of drainage basins to treat surface runoff [37,44]. In this watershed, the area of paved surfaces (including road surfaces, sidewalks, and driveways) and building footprints occupied 52.3% of the total area, and the proportion was even higher in built-up areas, which greatly changed the runoff flow path. In addition, the construction of BMPs would occupy large areas of open space, which is not practical for built-up areas. However, for development areas, it could be potential practices; thus, WP, DP, and WL were only considered in development areas.

This watershed is a highly developed area, and there are existing green belts between and beside main roads for landscape and environmental needs, which could also collect some runoff. However, existing green belts are always implemented with curbs or located above the road surface level, which stops the surface runoff flowing into the green belts. GS_1, GS_2, and WC are designed to be implemented on both sides of road surfaces, which play a role in the infiltration, retention, and transmission of surface runoff. Research has shown that GS_1, GS_2, and WC are cost-efficient practices in stormwater management [33,37]. Considering that suitable locations of WL were mainly located in the development areas, and the total area was small, WC was not used to simplify the model. Based on the criteria for GI practices [37,55], the suitable locations of GS_1 occupied 93% of the suitable locations of GS_2 in this watershed. Meanwhile, the runoff mitigation capacities of these two GI practices were represented by the percent runoff reduction method, with the GS_1 having a lower ratio of outflow volume to inflow volume [43]. Thus, only GS_1 was considered for the reconstruction of existing green belts to treat runoff volume from public road systems.

Similarly, existing green lands in residential or industrial areas were initially designed for landscape and environmental needs, which are not able to effectively reduce runoff. The reconstruction of green lands with BR can potentially improve runoff reduction.

GR and RC are the two main GI practices in sponge city construction. The guiding document issued in 2014 [38] pointed out the suitability of GR and RC for building tops in residential, industrial, and commercial (RIC) areas. Thus, GR and RC were regarded as feasible practices for this area.

There are many types of PP depending on the implementation location, such as permeable main urban roads, permeable sidewalks, permeable driveways, permeable parking lots, and permeable patios. However, there were few large open parking lots and no obvious patios in this study area. Thus, impervious pavement in this area mainly refers to road surfaces, sidewalks, and driveways.

From the above, only GR, RC, GS1, BR, PP, WP, DP, and WL were used in this study to simulate and assess the implementation effects of GI practices.

2.5. Suitable Locations of GI Practices

The L-THIA-LID 2.1 model provided a series of criteria to select suitable locations of each GI practice, including the drainage area, drainage slope, imperviousness, HSG, road buffer, and stream buffer (Table 2) [37,55,56]. In general, GI practices could be implemented far from stream lines with a distance of 30.48 m to reduce the construction cost and workload; GS_1 and BR should be implemented near the road surface to collect road surface runoff. The implementation of GS_1, BR, and PP needed less drainage areas and slopes, while WP, DP, and WL could be implemented on locations with large drainage areas and slopes. In addition to these criteria, some other criteria could also be added based on actual demands.

Table 2. Criteria for GI practice locations [37,55,56].

No.	GI Practice	Drainage Area (ha)	Slope (%)	Imperviousness (%)	HSG	Road Buffer (m)	Stream Buffer (m)	Other
1	RC	Area of building footprint	/	/	/	/	/	Implemented near building
2	GR	Area of building footprint	/	/	A/B/C/D	/	/	Implemented on roof top
3	GS_1	<2.02	<4	>0	A/B/C/D	<30.48	/	Central separation area of the road; grassy area of sidewalk
4	BR	<0.81	<5	>0	A/B/C/D	<30.48	>30.48	Rain garden implemented in industrial area, commercial area, and residential area
5	PP	<1.22	<2	>0	A/B/C/D	/	/	Impermeable pavement including public road, sidewalk way, driveway.
6	WP	>10.12	<15	>0	A/B/C/D	/	>30.48	Development areas
7	DP	>4.05	<15	>0	A/B/C/D	/	>30.48	Development areas
8	WL	>10.12	<15	>0	A/B/C/D	/	>30.48	Development areas

1. Green roofs (GR)/rain cisterns (RC)

Suitable locations for GR were all the building footprints in RIC areas. The drainage area for GR was the area of the building footprint. RC were implemented near buildings for the capture and reuse of runoff treated by GR. The drainage area of RC was also the area of the building footprint.

2. Grass swales (GS_1)

The public road system after the reconstruction of GI practices was designed to be composed of main road surfaces, central separation areas of roads, separation areas of sidewalks and main roads, and green belts for sidewalks (Figure 3) [38,57]. Using the ArcGIS 10.1 software, a 7 m and 5 m buffer were used separately on both sides of the urban first-level road lines and second-level road lines to get the main road surfaces; central parts of the main road surfaces were central separation areas; a 1.5 m buffer was used on the outside of the road surfaces to get the side separation areas of sidewalks and road surfaces; a 2.5 m buffer was used on the outside of the side separation areas to get the sidewalk surfaces, and a 1.5 m buffer was used on the outside of the sidewalks to get the green belts of sidewalks. The central separation areas, side separation areas, and green belts were designed to be the potential suitable locations for GS_1.

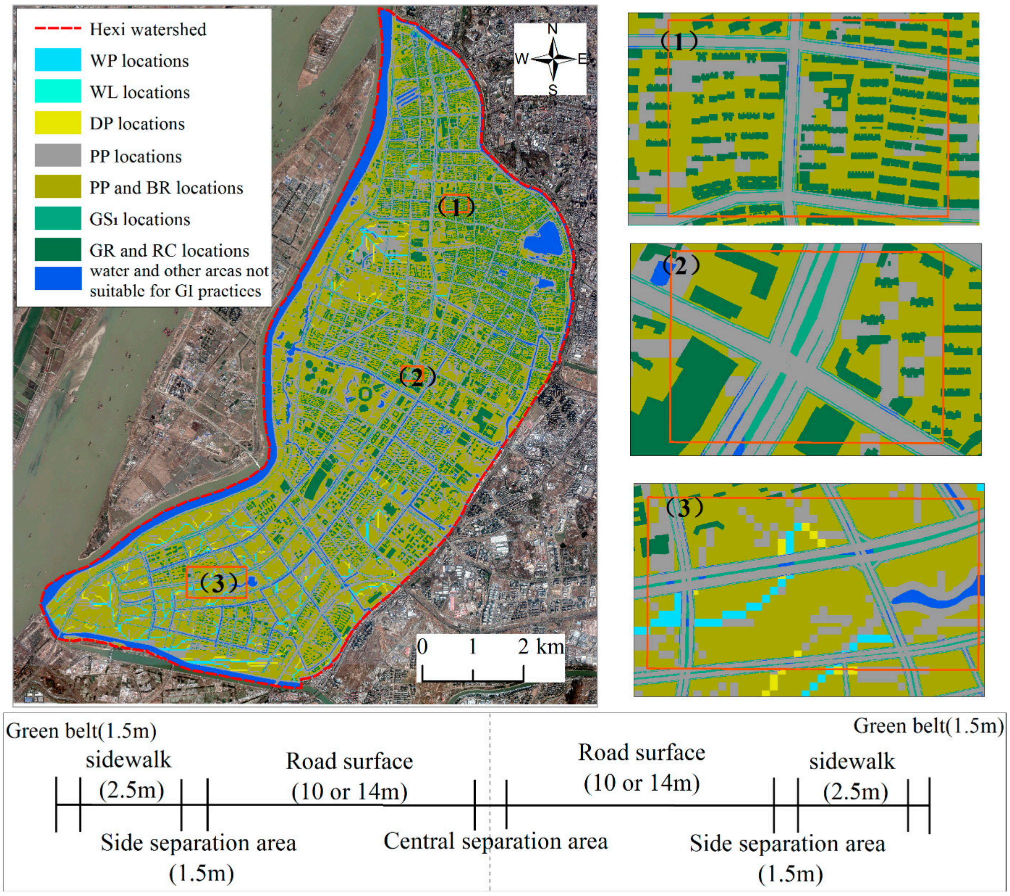

Figure 3. Suitable locations of GI practices.

3. Bioretentions (BR)

BR were used for the reconstruction of existing green lands in RIC areas. Based on the Standard for Greening of Residential District and Companies in Jiangsu Province [58], the area of green lands in a residential area is no less than 30% of the total area, while it is 15% in an industrial or commercial area. Areas of green lands and driveways in RIC areas could be calculated with the areas of building footprints. All the green lands were regarded as potential suitable locations for BR. Thus, the brown areas in Figure 3 represent suitable locations for BR or PP, and accurate areas of suitable locations of BR in each RIC area could be calculated by the proportional relation.

4. Permeable pavements (PP)

Theoretically, public road surfaces, sidewalks, and driveways where the drainage area was less than 1.22 ha and slope was less than 2% could be all regarded as potential suitable locations for PP. Gray areas in Figure 3 represent public road surfaces, sidewalks, and parts of driveways. Most parts of driveways were represented in brown, which was mixed with BR. Road reconstruction, especially the busy urban roads, could be a particularly complicated work. In a scenario design, the percentage could be adjusted to assess the implementation effect of a certain area of PP.

5. Wet ponds, dry ponds, and wetlands (WP, DP, and WL)

Wet ponds, dry ponds, and wetlands were usually implemented at the end of the basin to collect surface runoff, and they were parallel practices that cannot be implemented in a series. However, the criteria for WP, DP, and WL were similar, which meant that the suitable locations of these three practices in Figure 3 could be superimposed. Thus, in the following scenario design, the total proportion of WP, DP, and WL could not have been larger than 100% to avoid conflict. In addition, considering that the built-up areas had high building density and the runoff flow path changed a lot due to human construction, which meant that BMPs were not practical, and WP, DP, and WL were only implemented in development areas.

2.6. Scenario Design

The implementation effect and cost efficiency of each kind of GI practice are important bases for choosing a suitable GI practice in sponge city construction. To assess the implementation effect and cost efficiency of each kind of GI practice, an individual type of GI practice was first implemented in suitable locations in the whole watershed. Secondly, considering that the implementation of sponge city construction engineering is usually carried out in sub-regions, combined GI practices were implemented in different areas to assess the potential of GI practices for runoff reduction in this watershed (Table 3). There were 14 scenarios designed in total, of which S0 was the basic scenario without any GI practices, S1–S8 represented scenarios with a suitable area implemented with an individual type of GI practice, and S9–S13 represented scenarios implemented with different combinations of GI practices.

Table 3. GI practice combination in each scenario.

Scenario	GS_1 (%)	BR (%)	PP (%)	RC (%)	GR (%)	GR + RC (%)	WP (%)	DP (%)	WL (%)	Introduction
S0	0	0	0	0	0	0	0	0	0	With no GI practice implemented.
S1	25	0	0	0	0	0	0	0	0	GS_1 on road central separation area and green belt of sidewalk.
S2	0	25	0	0	0	0	0	0	0	BR on RIC area.
S3	0	0	25	0	0	0	0	0	0	PP on public road, sidewalk, and driveway.
S4	0	0	0	25	0		0	0	0	25% of building tops implemented with RC.
S5	0	0	0	0	25		0	0	0	25% of building tops implemented with GR.
S6	0	0	0	0	0	0	5.7	0	0	Only development areas were implemented with WP by 25%, which equaled 5.7% of the total suitable locations of the watershed.
S7	0	0	0	0	0	0	0	5.7	0	Only development areas were implemented with DP by 25%, which equaled 5.7% of the total suitable locations of the watershed.
S8	0	0	0	0	0	0	0	0	5.7	Only development areas were implemented with WL by 25%, which equaled 5.7% of the total suitable locations of the watershed.
S9	0	0	0	25	0	25	0	0	0	25% of building tops implemented with GR and RC.
S10	100	0	32.08	0	0	0	0	0	0	Road system implemented with GI practices, including permeable public road surface, permeable sidewalk, and GS_1. The implementation percentage of PP (32.08%) was the total ratio of suitable area of permeable public road surface and permeable sidewalk in all of the suitable areas of PP.
S11	0	50	33.96	50	0	50	0	0	0	50% of RIC areas were implemented with BR, PP, GR, and RC. The implementation percentage of PP (33.96%) was total ratio of suitable area of permeable roads (in 50% of RIC areas) in all of the suitable areas of PP.
S12	0	100	67.92	100	0	100	0	0	0	100% of RIC areas were implemented with BR, PP, GR, and RC. The implementation percentage of PP (67.92%) was total ratio of suitable area of permeable roads (in 100% of RIC areas) for all of the suitable areas of PP.
S13	100	100	100	100	0	100	0	0	0	All suitable locations were implemented with GI practices.

2.7. Model Calibration/Validation

A commonly used method for model calibration/validation is to compare the observed and simulated annual runoff volume (ARV) values, which can be measured by regression coefficient (R^2) and Nash–Sutcliffe efficiency (NSE) [37,59,60]. Given a lack of observation data in this research area, indirect calibration and validation was conducted. First, based on the research of Li et al. [2], the land-use dataset of 2015 (same with the dataset in research of Li et al.) and daily rainfall dataset from 2000 to 2017 (same with the rainfall dataset in this study) were used to simulate ARVs of the research area to get the comparison results (Table 4). Secondly, land-use data in this study and rainfall data from 2000 to 2009 were used to simulate ARV from 2000 to 2009 with the L-THIA-LID 2.1 model (baseline scenario, used for model calibration). The CN value of each land-use type in this study can be reduced by 1% each time until the simulated results matched the comparison results well. The R^2 and NSE were calculated to be 0.918 and 0.741 after the calibration.

Table 4. Surface runoff volume for the scenario without any GI practices implemented (S0).

Year	ARV for Calibration (1×10^7 m^3)	Simulated ARV (1×10^7 m^3)	Year	ARV for Validation (1×10^7 m^3)	Simulated ARV (1×10^7 m^3)
2000	2.61	2.65	2010	3.08	3.23
2001	1.36	1.58	2011	2.34	2.59
2002	2.07	2.35	2012	2.04	2.13
2003	3.97	4.35	2013	2.16	2.27
2004	1.92	2.21	2014	2.22	2.40
2005	1.69	2.11	2015	4.39	5.21
2006	1.78	2.25	2016	4.06	4.52
2007	2.31	2.60	2017	3.38	3.39
2008	2.65	2.52			
2009	2.62	3.25			

Note: 2000–2009 and 2010–2017 represent calibrated and validated events, respectively.

Then, ARVs from 2010 to 2017 were simulated with the calibrated model (S0) to verify the accuracy of the model (Table 4). R^2 and NSE were also calculated, which were 0.975 and 0.827, respectively. Thus, the model built in this study was regarded as performing well.

3. Results and Discussion

3.1. Implementation Effects and Cost Efficiency of Individual GI Practices

The simulation results of each scenario are shown in Table 5. In the baseline scenario (S0), the ARV of this urban watershed was simulated to be 3.38 million m^3 in 2017, with the ARV per unit area 5773 m^3/ha.

Table 5. Simulation results for the implementation effect of GI practices for each scenario.

Scenario	ARV (Million m^3)	ARV Per Unit Area (m^3/ha)	ARV Reduction (%)	Total Cost for 20 Years (Million CNY)	Cost Efficiency (CNY/m^3/yr)
S0	3.38	5773	0.00	0	0.0
S1 (25% GS_1)	3.38	5754	0.33	0.16	0.7
S2 (25% BR)	3.11	5657	2.01	71.86	5.3
S3 (25% PP)	3.33	5300	8.19	85.12	15.3
S4 (25% RC)	3.33	5678	1.64	3.54	3.2
S5 (25% GR)	3.31	5678	1.64	135.71	122.3
S6 (5.7% WP)	3.38	5737	0.20	1.47	10.9
S7 (5.7% DP)	3.36	5695	0.93	1.69	2.7
S8 (5.7% WL)	3.39	5740	0.14	1.87	19.4
S9 (25% GR + 25% RC)	3.31	5638	2.34	139.84	88.0
S10 (100% GS_1 + 32.08 PP)	3.0	5101	11.64	107.84	13.7
S11 (50% BR + 33.96% PP + 50% GR + 50% RC)	2.75	4684	18.86	410.70	32.1
S12 (100% BR + 67.92% PP + 100% GR + 100% RC)	2.18	3720	35.56	821.40	34.1
S13 (100% GS_1 + 100% BR + 100% PP + 100% GR + 100% RC)	1.8	3059	47.01	929.24	29.2

S1: In S1, only 25% of GS_1 was implemented in the watershed, and 0.33% of ARV was reduced. GS_1 was proven to be the most cost-effective practice for runoff control at 0.7 CNY/m^3/yr. Similar conclusions have also been confirmed in other studies [37,61]. This is highly related to the relatively low construction cost and good performance on water quality control and quantity reduction. Furthermore, GS_1 was assessed to have the lowest negative impacts on the environment in construction processes [24]. However, the cheapest variant of practice is not always a good solution. S1 showed that the implementation of GS_1 did not perform well on water reduction in this area. GS_1 was designed to be located only on road systems to treat surface runoff from road surfaces with an area of only 3.34% of the total area, and valuable land resources in urban areas limited its promotion and application, resulting in a poor overall effect.

S2: In S2, 25% of BR suitable locations in RIC areas were reconstructed, which resulted in 2.01% ARV reduction with the cost efficiency at 5.3 CNY/m^3/yr. Compared with the GS_1, BR seemed to be a more suitable practice for this area, for the BR had a more obvious runoff volume reduction effect but with a low cost. Compared with BMPs, the BR system usually occupies smaller areas, but it performed well on controlling runoff and improving water quality [30,62]. Thus, in urban areas with precious land resources, BR showed superiority and has been recognized as an effective measure worldwide.

S3: In S3, 25% of impervious surface was implemented with PP, and 8.19% of the ARV was reduced with a cost per unit runoff reduction per year at 15.3 CNY/m^3/yr. PP played a key role in urban runoff reduction; in addition to its good performance, the large area of road surface in the city was the main reason. In the research of Hu et al. [63], the flood inundation hazard area was assessed using the recorded maximum 24-h rainfall data in the last 65 years, with the non-public road surface in Hexi watershed implemented with permeable pavements. Results showed that the maximum inundated depth would be reduced by 5% when 50% of the non-public road surface was reconstructed. In contrast, results in this study reflected the runoff volume change of the total area. Results could also be calculated that if all the non-public road surfaces were implemented with PP (about 67.92% of the total impervious pavement in S9), region-wide surface runoff could be reduced by 22.25%. Both research efforts proved the suitability of PP for rainwater retention in this watershed.

S4: In S4, 25% of the roof tops were implemented with RC, and results showed that ARV reduction would be 1.64%, with a cost per unit runoff reduction per year at 3.2 CNY/m^3/yr. RC were proven to be the third most cost-effective GI practice following GS_1 and DP (in S7). Hu et al. [63] assessed the implementation effect of RC on rooftops with cisterns in Hexi watershed and concluded that RC would reduce high flood hazard areas by 6% to 14% based on different capacities of cisterns. Similar results indicated that RC had good applicability in this area. RC harvest rainwater from roof tops and helps reduce surface runoff, but another advantage of RC is that they promote the recycling of rainwater. Rainwater from RC could be used for urban greening and flushing toilets. Rainwater harvesting with RC has become a common practice in many countries with water scarcity problems [9].

S5: Runoff reduction effects of GR in the L-THIA-LID 2.1 model were represented with CN values, which were assumed to be the same with RC when they were implemented separately. In addition, the drainage area of GR and RC were both the area of the rooftops. Thus, when 25% of the roofs were implemented with GR in S5, the ARV reduction percentage was the same with RC at 1.64%. Although the implementation effects of GR and RC were the same, the cost efficiencies were quite different. GR were proven to be the least cost-effective practice, with the cost efficiency at 122.3 CNY/m^3/yr. GR have been used in many cities across the world to treat the eco-environmental problems, and many studies have proven the good performance in runoff reduction. For example, Gong et al. [28] studied the rainwater retention and peak flow reduction effects of extensive GR in Beijing, China, and they concluded that different depths of rainfall could cause 30.8% to 85.4% of peak runoff reduction. Talebi et al. [64] studied the performance of GR in six cities with various Canadian climates and concluded that the performance of GR in runoff reduction varied from 17% to 50%. In contrast with these studies, the implementation effect of GR in this study was reflected by the ARV reduction percentage of the total research area. Considering that the roof area only accounted for 11.68% of the total area of the watershed, GR could be regarded as having performed well.

S6–S8: Most of the suitable locations of WP, DP, and WL were the same based on the criteria in Table 2, but the implementation of these three kinds of BMP was parallel. Assuming the suitable locations were the same, the total amount of the implemented percentages of WP, DP, and WL could not be greater than 100. Thus, in S6, S7, and S8, only the development areas were implemented with WP, DP, and WL by 25% (the "25%" was the implementation proportion of the suitable locations in the development area), which equaled 5.7% of the total suitable locations of the watershed, respectively. Results showed that with the same implemented percentage of WP, DP, and WL, the implemented effects were different. Specifically, the DP performed best (in S7), which could reduce the ARV of the total watershed by 0.93%. In addition, DP was also the second most cost-effective practice with the cost efficiency at 2.7 CNY/m^3/yr in all the GI practices. Following was the WP (in S6), with the ARV reduced by 0.2%, and the cost efficiency was at 10.9 CNY/m^3/yr. The performance of WL was the worst (in S8), with the same implementation percentage with WP and DP; only 0.14% of surface runoff was reduced, and the cost per unit runoff reduction per year was up to 19.4 CNY/m^3/yr. As BMPs were implemented only in development areas, the implementation effects on runoff reduction did not look very strong.

3.2. Implementation Effects of GI Practice Combination Scenarios

S9: When GR and RC were implemented in a series, the implementation effect was still represented by the CN method, so the implementation effect of the combination scenario would not be same with the total amount of individual implementation effects of GR and RC. In S9, RC were implemented with GR together; the total implementation cost was still high at 139.84 million CNY, but this kind of combination looked more cost-effective, with the cost efficiency at 88 CNY/m^3/yr. Thus, it would be a better choice to implement both GR and RC for urban watersheds rather than only implementing GR.

S10: Apart from the combination of GR and RC, some other combination scenarios were also conducted. The reconstruction of public road systems was first assessed in S10. All the central separation areas, side separation areas, and green belts suitable for GS_1 were simulated as GS_1, and all the main road surfaces and sidewalks were turned into PP. With those GI practices implemented, ARV in 2017 would be reduced by 11.64%, with the cost efficiency at 13.7 CNY/m^3/yr.

S11: Half (50%) of the RIC areas were implemented with GI practices, including GR, RC, BR, and permeable driveways. ARV would be reduced by 18.86%, with the cost efficiency of 32.1 CNY/m^3/yr.

S12: All (100%) of the RIC areas were implemented with GI practices, and the ARV reduction would be up to 35.56%, with a cost efficiency of 34.1 CNY/m^3/yr. A similar conclusion could also be found in research by Mao et al. [65], where the ecological benefits of aggregate GI practices, including rain barrels (RB), GR, BR, PP, GS_1, and WP in Foshan New City, China, were assessed and resulted in a 40% reduction in ARV.

S13: The total study area was implemented with GI practices, and the results showed that the ARV per unit area would decrease to 3059 m^3/ha, and the ARV reduction would be 47.01%, with cost efficiency at 29.2 CNY/m^3/yr.

3.3. Relationship between Implementation of GI Practices and the Cost

The implementation of GI practices is a process with a large project volume, high investment, and long period. An optimization analysis on the implementation of GI practices helps decision making, which has important practical application values. High investment increases financial burden, and the basic requirement for the implementation of GI practices is to achieve efficiency and cost optimization. In this study, an implementation optimization analysis was carried out to get the best implementation effect and the lowest cost.

With the condition that all the GI practices were implemented independently, GS_1, with the best cost efficiency, was first implemented in this research area. Based on the simulation results, the ARV of the total area could be reduced by 1.32% if all of the suitable area was implemented with GS_1 (Figure 4b). Then, DP, with the second cost-efficiency, was additionally implemented, which could reduce another 0.93% of ARV (DP was implemented only in undeveloped areas. Considering that DP, WP, and WL were parallel practices, only 25% of suitable areas were implemented). Thirdly, RC was additionally implemented in the total area, which could reduce ARV by another 8.81%. GI practices, such as BR, WP, PP, WL, and GR, could be additionally implemented one by one. The relationship between the cost and the annual runoff reduction percentage is shown in Figure 4.

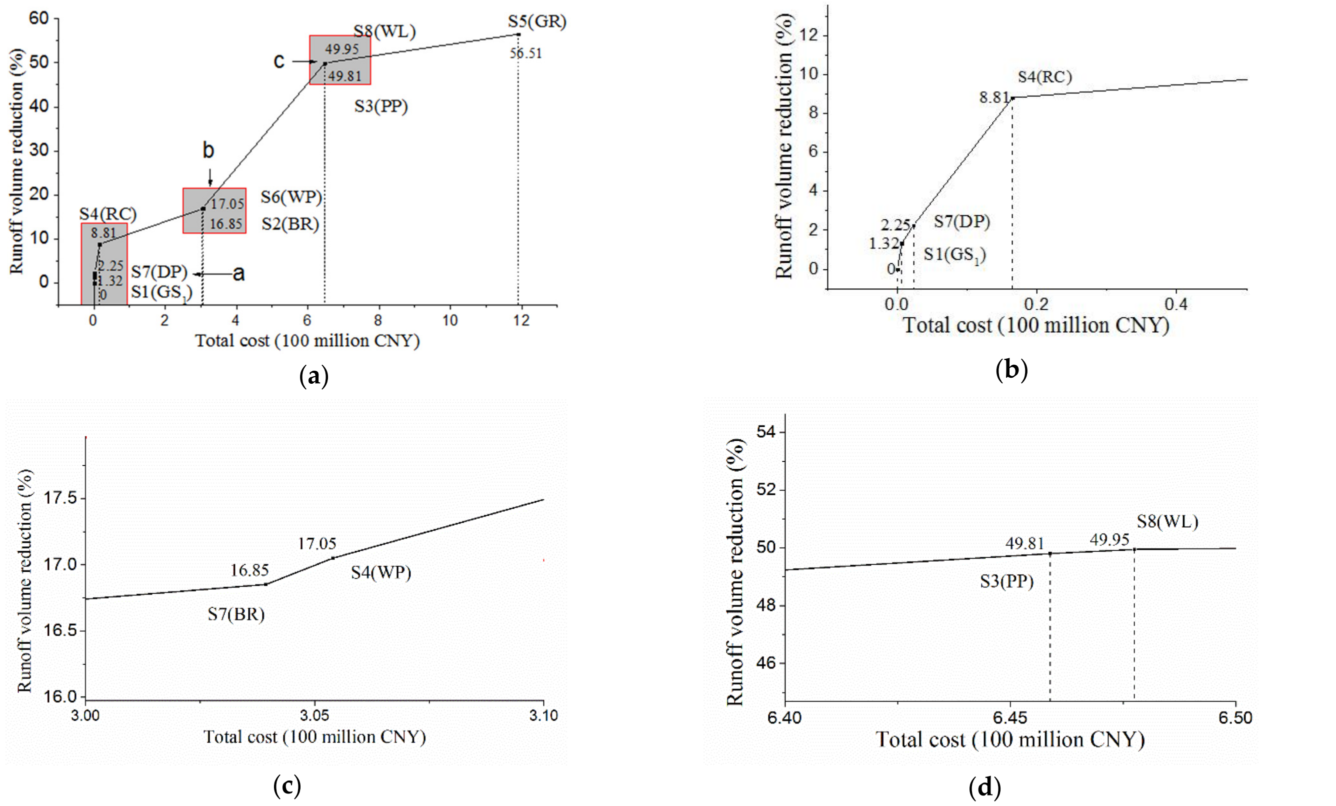

Figure 4. Relationship between total cost and runoff volume reduction with GI practices implemented independently. (**b**–**d**) were a partial magnification of (**a**).

Figure 4a shows that within the seven GI practices, the implementation of RC and PP had the best runoff reduction effect while the cost was low, and then BR and GR followed. A similar research conclusion can also be found in a study by Hu et al. [63], where the implementation effect of RC and PP was also assessed in the Hexi watershed, and it was concluded that RC and PP could effectively reduce runoff water. On the contrary, GS_1, DP, WP, and WL were not good choices for this area, because the suitable locations were small, which limited the effect on runoff control. However, different cities had different needs for GI practices in dealing with urban rainstorms. Li et al. [66] assessed the comprehensive benefits of different combinations of GI practices (including BR, RB, GS_1, GR, and PP) with a case in Xi'an, China, and they concluded that "BR + GR" was the optimal GI combination.

However, S9 in Table 5 showed that when GR and RC were implemented in a series, the cost efficiency could be increased largely. Although the construction cost of GR was high, GR could have lots of other eco-environmental benefits, such as an increase of green land, purifying the air, and improving the landscape. The case study in Xi'an, China showed that GR had better comprehensive benefits than PP [66]. In lots of case studies, GR and RC are always encouraged to be implemented in a series to get the best comprehensive benefits [37,67,68]. Figure 5 showed the relationship between the implementation effects of GI practices and the costs when GR and RC were implemented in a series. We could conclude that if the GR and RC were implemented in a series, the best combination was "BR + PP" for this area, and "GR + RC" followed.

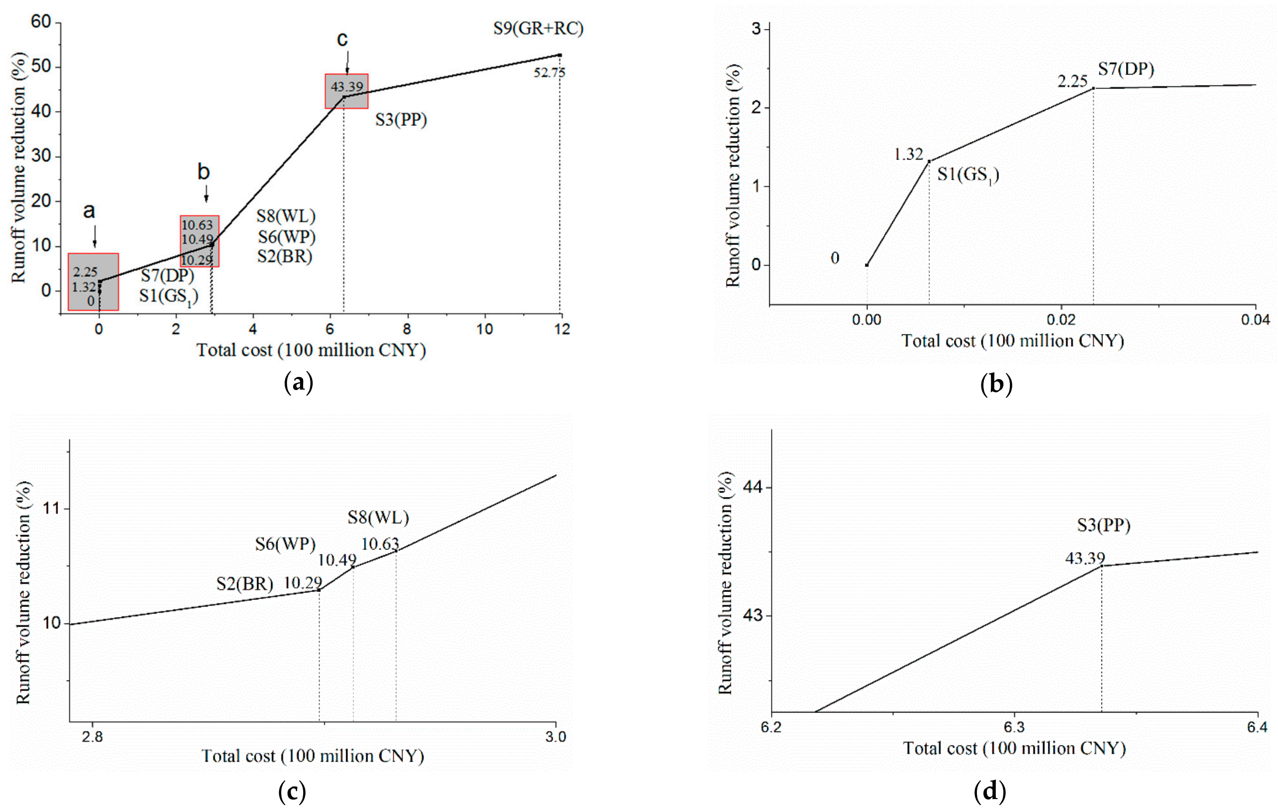

Figure 5. Relationship between total cost and runoff volume reduction with green roofs (GR) and rain cisterns (RC) implemented in series. (**b–d**) were partial magnifications of (**a**).

4. Conclusions

The implementation effectiveness and cost efficiency of GI practices on surface runoff reduction in the sponge city construction on an urban watershed scale in China were evaluated. Taking the Hexi watershed in Nanjing, China, as an example, the criteria for a suitable location for GI practice were redefined according to actual construction conditions. Various scenarios were explored to assess the cost efficiency of individual GI practices on ARV reduction and the implementation impact of GI practice combinations on surface runoff. The main conclusions are as follows.

(1) GI practices performed well in reduction of surface runoff, of which GS_1 had the highest cost efficiency at 0.7 CNY/m^3/yr. However, the high-intensity construction of the city limited the implementation scope of GS_1, which resulted in quite small overall effects on ARV reduction. Correspondingly, PP performed the best, but the cost efficiency also decreased to 15.3 CNY/m^3/yr. BR was a compromise practice with a better runoff reduction effect than GS_1, and the cost efficiency was 5.3 CNY/m^3/yr. RC had a high cost efficiency but limited runoff reductions, while GR had low efficiency but better runoff reduction effects. WP, DP, and WL implemented in development areas also performed well on runoff reduction, of which DP was the most cost-effective (2.7 CNY/m^3/yr), followed by WP (10.9 CNY/m^3/yr).

(2) ARV could be reduced by 11.64% and 35.56%, respectively, with the public road system implemented with GS_1 and PP, and the RIC areas implemented with PP, BR, GR, and RC; ARV in Hexi watershed could be reduced by up to 47.01% at the most through implementing GS_1, BR, PP, RC, and GR in buildup areas. The implementation limitations of BMPs in buildup areas decreased the runoff reduction capacity of GI practices.

(3) When GI practices were implemented independently, RC and PP were the best combination for this area, and BR and GR followed. If GR and RC were implemented in a series, the best combination of GI practices was "BR + PP", and "GR + RC" followed.

In this study, the cost efficiency of each scenario with different GI practices combination was evaluated, and the best GI practices combination was selected. This framework and method could be used for scenario comparison in future sponge city planning. The optimization of GI practice combinations can also be carried out in further studies. Based on the research results of this study, more factors, such as urban construction demand, natural condition, willingness of interest subject, the investment, and the land-use planning, could be taken into consideration to perform multi-criteria decision analysis in the space optimization of GI practices.

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