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Study on Planning and Design of Blue-Green-Gray Transformation of Lakeside Cities to Deal with the Complex Urban Waterlogging Caused by Extreme Rainstorm

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Abstract: Some lakeside cities may suffer from urban waterlogging owing to the backwater effect caused by the rise of lake water levels under a extreme rainfall scenario in the basin, but it is not suitable for large-scale gray drainage infrastructure upgrading in high-density lakeside urban built-up areas. This study, as per this, constructs the blue-green-gray infrastructure reconstruction planning and design mode to alleviate the waterlogging in the extreme rainstorm scenario of the lakeside city. Extending the Shiwuli River Basin in Hefei City, Anhui Province, China as an example, this study uses SWMM software to simulate the waterlogging situation in the study area under an extreme rainstorm under the urban planning scenario. According to the waterlogging situation, different hydrological scenarios (scenarios where the pipe network can and cannot discharge normally) are used to plan and design the blue-green-gray infrastructure reconstruction of the study area with both constructed land and non-constructed land. The research results show that just the planning and design of blue and green space can effectively reduce the degree of urban waterlogging, and with the cooperation of artificial pre-drainage, its own hydrological characteristics and geographical conditions can be used to prevent urban waterlogging caused by the backwater effects of a lake. In this study, the blue-green-gray transformation planning and design model of lakeside cities can deal with the complex urban waterlogging caused by extreme rainstorms, and the model could be extended to other cities along rivers or lakes with similar conditions.

Keywords: blue-green-gray infrastructure transformation; rainstorm waterlogging lakeside city; watershed; backwater effects of lake

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Citation: Jinjin, G.; Xiaoqian, L.; Buyun, F.; Qiang, H.; Yuan, C. Study on Planning and Design of Blue-Green-Gray Transformation of Lakeside Cities to Deal with the Complex Urban Waterlogging Caused by Extreme Rainstorm. *Land* **2023**, *12*, 289. https://doi.org/10.3390/land12020289

Academic Editor: Teodoro Semeraro

Received: 22 December 2022
Revised: 11 January 2023
Accepted: 16 January 2023
Published: 19 January 2023

1. Introduction

The lakeside cities in some regions are faced with urban waterlogging caused by extreme urban rainfall or complex hydrological phenomena caused by extreme regional or watershed rainfall [1,2].

On the one hand, extreme rainfall is usually measured against once-in-a-century rainfall. Taking the extreme rainfall in a subtropical monsoon climate as an example, the hourly rainfall in some areas can reach about 100 mm, while the urban drainage pipe network is usually set once every year or once every three or five years. Under the scenario of extreme rainfall, serious waterlogging will occur in cities owing to the impermeable underlying surface changing the hydrological space–time process in urban areas [3].

On the other hand, lakeside cities are faced with the problem that urban rainwater cannot be discharged when encountering the backwater effects of a lake. The rainfall in the region or basin causes surface water to flow into rivers and lakes at low altitude. The rise of lake levels in extreme rainfall events will cause the water levels of rivers and lakes to be higher than the elevation of the urban pipe network or the city's inflow into rivers and banks [4]. Under the scenario that a waterproof dam is set at the lake inlet of an urban river, the height difference between the lake level on one side of the dam and the river level on the other side will be greater. The backwater effects of the lake caused by flooding will lead to urban rainwater being unable to be discharged into the lake from the pipe network or urban rivers under this scenario, thus causing waterlogging in urban areas [5].

The two problems above would affect the sustainable development for lakeside cities, and how to solve the problems represents the tasks and difficulties faced by urban planners and relevant decision-makers. It will consume huge costs for the first problem in upgrading the pipe network and building grey infrastructure such as reservoirs, which are far more than the economic losses caused by urban waterlogging [6,7]. In high-density cities, such large-scale construction activities and spaces are not allowed, more often than not, on account of the limitation of construction space [8]. For the phenomenon of the backwater effects of lake water in the second problem, urban rainwater cannot be solved just with an urban drainage pipe network [9]. At present, the commonly used method is to discharge with a pump, but the limitation of the pump's own power may lead to too long a time for relieving waterlogging, with the possibility that the pump will stop running as a failure.

Therefore, not only can the design of a set of methods save economic costs along with construction space, but it can effectively deal with an urban rainwater drainage system backed by lake water as well, which is of great significance for the healthy development of lakeside cities [10].

It is one of the common ways to solve urban water problems in the effective layout and collaborative transformation of urban blue-green-gray infrastructure [11].

Let us start with gray infrastructure, which, in the case of urban drainage, continues the use of buried pipes by cities for drainage, with the aim of safely and of quickly taking water away from urban spaces. The limitation of urban grey infrastructure represents that a relatively single drainage and flood control project has changed the intensity and capacity of the hydrological space–time process [12,13]. The rainfall per unit time, when heavy rainfall occurs, exceeds the urban drainage, which will lead to urban flooding. Blue-green infrastructure provides a new perspective to deal with urban rain and flood problems [14,15], defined as "an interconnected network consisting of waterways, wetlands, with wildlife habitats and other natural areas, with greenways, parks and other protected areas, with work farms, pastures and forests and with wilderness along with other open spaces. Blue-green infrastructure supports species, maintains natural ecological processes, air and water resources, and contributes to health as well as quality of life" [16]. BGI can penetrate, store and dredge urban rainwater in a natural way [17]. However, despite the fact that blue-green infrastructure has been proven to be effective in reducing flood risks and promoting multiple benefits [18,19], it may not be sufficient to deal with future extreme climate hazards [20]. Therefore, new trends indicate that the combination of blue-green and gray infrastructure may provide a new generation of solutions to strengthen community protection [21].

At present, most of the research on BGI to deal with rainwater focuses on urban areas, which represent complex systems formed by the interaction of nature, society and the building environment. In addition, the drainage system remains a complex structure as well, which contains many different measures, requiring corresponding space, and representing a significant investment and high uncertainty in the future [22]. It is a particularly noteworthy issue to integrate blue-green-gray infrastructure reasonably in the case of limited resources and space constraints at present [23]. Moreover, relevant research also includes cost calculation [24], management level [25], spatial optimization layout [26], facility type selection [27], how to build blue-green-gray infrastructures in high-density as well as underdeveloped areas [28–30], and obstacles faced by relevant facilities in implementation.

There are diverse approaches to blue-green-gray drainage infrastructure; besides the general theories of gray drainage infrastructure, many approaches are relevant, with blue-green infrastructure, such as water-sensitive urban design [31], water-sensitive planning [32], sustainable drainage systems [33], best management practices [34], low-impact development [35], nature-based solutions [36] and sponge cities [37], and these theories are basically for increasing a city's rainwater penetration capacity, water storage capacity and drainage capacity. In terms of methods for spatial layout of blue-green-gray facilities, in addition to the hydrodynamic methods for gray infrastructure, common technological processes are using hydrology simulation software or geographic analysis software to simulate the rainwater process effect of the planned schemes and then to optimize the combination and configuration of facilities according to the simulation results. The commonly used software includes Arc GIS (developed by Esri corporation) [38], EPA SWMM (developed by EPA) [39], MIKE 21 (developed by DHI Water & Environment) [40], Infoworks ICM (developed by Wallingford software corporation) [41] and other software, which are confirmed to have good hydrology simulation effects.

Many aspects as the current research on blue-green-gray infrastructure are covered, there still exist unsolved problems: (1) the city is growing and developing constantly, and only by analyzing the urban hydrological conditions in the future can we deal with the problems that may arise in the future. However, in the case of the simulation on the planning scheme, there exist built-up areas and unbuilt areas in the city. As such, they are not involved in the current research on how to update the blue-green-gray planning in the built-up areas with space constraints along with the unbuilt areas capable of modifying the planning at the same time during the blue-green-gray planning and transformation. (2) The concepts of urban areas are always isolated from watersheds in much of the research about municipal drainage; urban planning represents generally that urban rainwater can be smoothly discharged into rivers and lakes. In previous studies, the blue-green-gray planning rarely considered the situation where urban rainwater cannot be discharged because of the backwater effects of rivers or downstream lakes. Therefore, it is a problem of how to apply the blue-green-gray planning to treat urban rainwater under the scenario of the backwater effects of a lake.

Backed by this point, this study takes the Shiwuli River Basin in Hefei, Anhui Province, a subtropical monsoon climate zone, as an example, and investigates how to update the blue-green-gray planning in built-up and non-built-up areas within the city limits under extreme rainfall scenarios when a lakeside city encounters river and lake water overtopping and cannot drain. The innovation of the study includes (1) developing the mode of planning the blue-green-gray facilities in the study area when there exist built-up areas and non-built-up areas and (2) developing the method for the process of rainwater discharged from the city under the influence of backwater effects of a lake. In the study, the source and conflux of lakeside city rainwater is considered from the perspective of a watershed. The research results have important implications for sustainable urban stormwater management in cities with similar characteristics.

2. Case Study

The research case of this study is the Shiwuli River Basin in Hefei, Anhui Province, China. Hefei, the capital of Anhui Province, represents a high-density construction city, with a developed economy. The Shiwuli River Basin is within the urban area of Hefei City, with a drainage area of 111.25 km^2 and a total length of approximately 27.2 km. The Shiwuli River Basin in Hefei involves the built area and the area to be built. Originating on the south foot of Dashu Mountain in Hefei, the Shiwuli River flows from west to southeast, passing through Hebaohe District, Shushan District, Hefei, and flowing into Chaohu Lake at Tongxin Bridge. As per the layout of the artificial drainage network in the urban area, the Shiwuli River Basin can be divided into three sub-basins: the upstream, the middle and the downstream. There is Swan Lake, an artificial lake with a capacity of 9.33 million cubic meters, in the upper reaches of the Shiwuli River, with a large area of wetland at the estuary of Chaohu Lake in the lower reaches. The Shiwuli River is one of the main flood-discharge channels in the southwest of Hefei. The river is curved, with the source short, the flow fast and the flood- and dry-water levels changing greatly, where flood and drought disasters occur frequently.

The Shiwuli River basin is located in the subtropical monsoon climate area, in which the monsoon climate is characterized by simultaneous rainfall and heat, with the annual rainfall more than 1000 mm, with the summer accounting for about 50%. The area where the Shiwuli River is located is a wavy plain with flat terrain, which is not conducive to natural drainage and rainwater pipeline layout. According to the comprehensive drainage and waterlogging prevention planning of Hefei city, the drainage pipe network is mostly set once every three years; although the design criterion is reasonable, Hefei city is still at risk of waterlogging caused by extreme rainfall. That is because climate changes are becoming more evident, and extreme rainfall events occur more frequently [42,43]. Therefore, urban waterlogging occurs easily in the case of extreme rainfall. In 2020, Hefei experienced the once-in-a-century heavy rainfall, with the single-day rainfall intensity reaching 217 mm on 17 July 2020. Waterlogging occurred in many places in the urban area of Hefei, including the Shiwuli River Basin.

Hefei City is built next to Chaohu Lake, with many rivers flowing into Chaohu Lake. Chaohu Lake belongs to the Yangtze River Basin, with an area of 2046.14 km^2. In the case of floods in the Yangtze River Basin, Chaohu Lake also carries the functions of flood discharge for upstream cities and flood storage for downstream cities. Therefore, in the event of regional extreme rainfall events, Chaohu Lake will have an ultra-high water level once in a century. In the case of an ultra-high water level, the rivers in Chaohu Lake Basin cannot be discharged into Chaohu Lake owing to the backwater effects of Chaohu Lake. In this scenario, the water can only be discharged into Chaohu Lake through water pumps in the city.

The study area is listed in Figure 1.

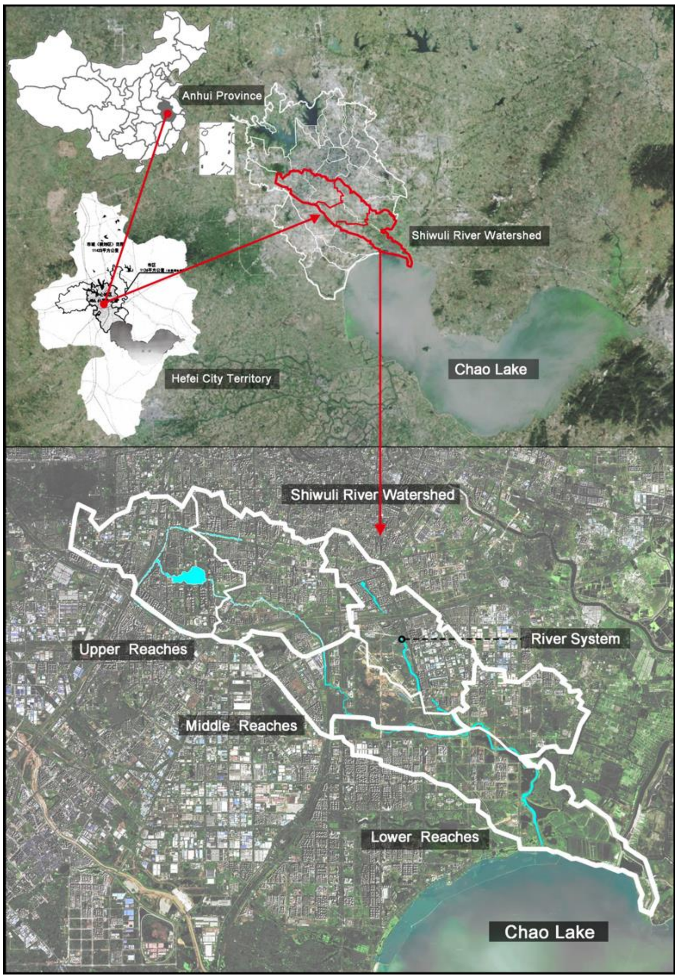

Figure 1. The study area.

To summarize the characteristics of the Shiwulihe River Basin in Hefei: (1) the basin is located in a high-density urban area, with built-up areas and areas to be built within the basin; (2) the lower reaches of the Shiwuli River is Chaohu Lake, which carries the catchment of the basin; and (3) there are artificial lakes and wetlands that can store large amounts of rainwater in the upper and lower reaches of the Shiwuli River Basin.

To summarize the problems that need to be solved in the prevention and control of waterlogging in the Shiwuli River Basin of Hefei City: (1) there is not much surface space for blue-green infrastructure transformation in high-density built-up areas, while it will cost a lot of money in the gray infrastructure transformation, such as drainage pipe network and reservoir construction; and (2) how to solve the problem of urban waterlogging in the context of Chaohu Lake.

3. Methods

The method of this study is divided into two scenarios: the scenario where the pipe network in the built-up area can normally discharge into rivers and lakes and the scenario where rivers and lakes can be supported.

In this study, the blue-green-gray transformation planning and design model of lakeside cities is constructed to deal with urban waterlogging under extreme rainstorm scenarios. Backed by the study area planning map, this model (1) uses SWMM software to simulate the hydrological conditions of the study area, identifying waterlogging points and waterlogging degree in the study area, and (2) plans and designs blue-green-gray transformation on the basis of hydrological simulation. The planning and design are divided into the scenarios where the pipe network in the built-up area can normally drain into rivers and lakes and the scenarios where rivers and lakes can be supported, with the blue-green-gray transformation planning and design carried out, respectively, for the built-up areas and non-built-up areas in the study area.

3.1. Establishment of Key Area Identification Model of Urban Waterlogging Point

Select SWMM software to simulate an urban flood waterlogging area.

Collect basic data of the urban area: topographic map of urban area, distribution map of drainage pipe network, pipe network data (pipe position size, pipe bottom elevation, ground elevation, pipe length, pipe flow direction, etc.), watershed area, basin area, land use map, soil database, etc. In the study, the topographic map (ASTER GDEM 30 m) could be obtained from the Geospatial Data Cloud website; the pipe network map, pipe data, watershed and basin area are from Hefei City drainage planning; land-use maps are from Hefei City master planning; the soil database (1:1 million) is from the Nanjing soil school.

The model base data collected are processed and the simulation base is established: generalization of the drainage network (drawing in SWMM according to drainage network map); we classify sub-catchments based on the comprehensive drainage and waterlogging prevention planning, generalize the urban river network and use the Chicago rainfall process line synthesis method (KC method) for storm water design.

Model parameter setting: set pipe network parameters (pipe network shape, maximum section depth, roughness, inlet and outlet water offset); set sub-catchment area parameters (slope, Manning N value, depression storage depth, non-depression storage impervious area ratio, etc.); set model simulation parameters (process model, time step, infiltration model, routing model, etc.). In the study, the pipe network shape and the maximum section depth are set according to the comprehensive planning map; the roughness is 0.013, and the offset is set as 0. In the sub-catchment parameters, the slope could be obtained by slope analysis of GIS software, roughness is set based on the land-use type according to the SWMM operation manual, and the ratio could be calculated according to the area of different types of land. In model simulation parameters, rainfall/runoff and flow routing are chosen for the process model; Horton is for the infiltration model, dynamic wave is for the routing model, and time steps are set as 1 min.

See Table 1 for SWMM parameter settings.

Table 1. SWMM parameter settings.

Data Category	Data Category Name	Data Attribute	Data Source
Spatial data	Topographic data	DEM Sub-catchment area Average slope	ASTER GDEM 30M Calculation GIS
	Pipe data	Node type, top and bottom elevation of nodes Pipe type, pipe elevation (start and end point), pipe radius, pipe length, pipe texture	Hefei drainage planning
Attribute data	Land-use data	Land-use type, range and area Soil data Runoff coefficient	Hefei master planning Hefei land-use map Urban drainage design manual
	Meteorological data	Storm frequency and duration Rainfall intensity	Scene simulation KC method
Model-related data	Deterministic parameters	Width	Sub-catchment area/the longest path of water spreading
		Imperv	Weighted average calculation for different land use runoff coefficient
	Probabilistic parameters	N-Imperv	SWMM operation manual
		N-Perv	SWMM operation manual
		Dstore-Imperv Dstore-Perv	According to the surface condition, soil type and suggested scope of SWMM manual
		Zero-Imperv	Empirical value (25%)
		Infiltration Data (HORTON): Max.Infil.Rate Min.Infil.Rate Decay Constant Drying Time	According to the soil type and suggested scope of SWMM manual
		Roughness	According to the field research and suggested scope of SWMM manual

Calibrate and verify the model parameters; the simulation result represents the overflow of each sub-catchment area, with the waterlogging degree of each sub-catchment area judged as per the overflow.

3.2. Building Blue-Green-Grey Planning and Design Based on Waterlogging Control

Basic analysis of the study area: we analyzed the overflow points and overflows of each sub-catchment area in keeping with the terrain, road network, land-use nature and pipe network, the location of depressions, lakes and rivers that can carry surface runoff, the direction of surface runoff and the pipe network settings and the urban landscape.

(1) Scenarios of normal drainage of pipe network to rivers and lakes

Layout plan of blue-green-gray infrastructures in the built-up area: in waterlogging area, analyze whether blue infrastructure can be arranged for drainage rainwater, analyze whether green infrastructure can be arranged for drainage when blue infrastructure cannot be arranged, and arrange gray infrastructure when green infrastructure cannot be arranged.

Layout plan of blue-green-gray infrastructures in the non-built-up area: blue-green infrastructure will be arranged first, with gray infrastructure to follow.

We use SWMM software to simulate and judge whether the effect of blue-green infrastructure can effectively alleviate the waterlogging in the study area. Assuming that no effect is achieved, gray infrastructure should be considered for arranging.

(2) Scenarios of backwater effects of river and lake

① Calculate the amount of water that cannot be naturally discharged into the lake owing to the backwater effects of the lake

Through historical news records, we can discover the drainage volume forced by water pumps at the downstream lake inlet of the basin during the extreme rainfall scenario. In the absence of news records of pump discharge, the hydrological model can be used to simulate the amount of water discharged from the river at similar levels of flooding as per historical records of the extent and degree of flooding caused by the backwater effects of the river and lake.

As per historical data, in the extreme rainy season of 2020, the water pump at the mouth of the Shiwuli River pumps 542.5×10^4 m^3 of water into Chaohu Lake to prevent the water level of the Shiwuli River from rising and Chaohu Lake flood control dam from overflowing into the urban area when Chaohu Lake water is propped up. As such, a rainwater storage area with the same capacity, in this study, is set to help the Shiwuli River Basin to quickly receive excessive rainwater from the upstream when extreme rainfall occurs.

② Calculate the space for storing excess rainwater in the study area

Calculate the space for the amount of rainwater that can be carried by the existing water area: we found relevant data or used GIS tools to calculate the surface area of the water area, the depth of the water area and the volume of the water area. We measured the existing terrain, judged the land parcel that can be used as storage space and calculated whether it meets the storage conditions. Assuming that it did not meet the requirements for calculating the space that can store rainwater in the unbuilt area, we calculated the possible quantities. We calculated the amount of storage that may be added by gray infrastructure transformation.

③ Cooperate with manual intervention

We can discharge a certain amount of water into rivers and lakes in the study area in advance prior to the arrival of extreme rainfall, so as to make room for the storage of water brought by extreme rainfall.

The technical flow chart of the scheme is shown in Figure 2.

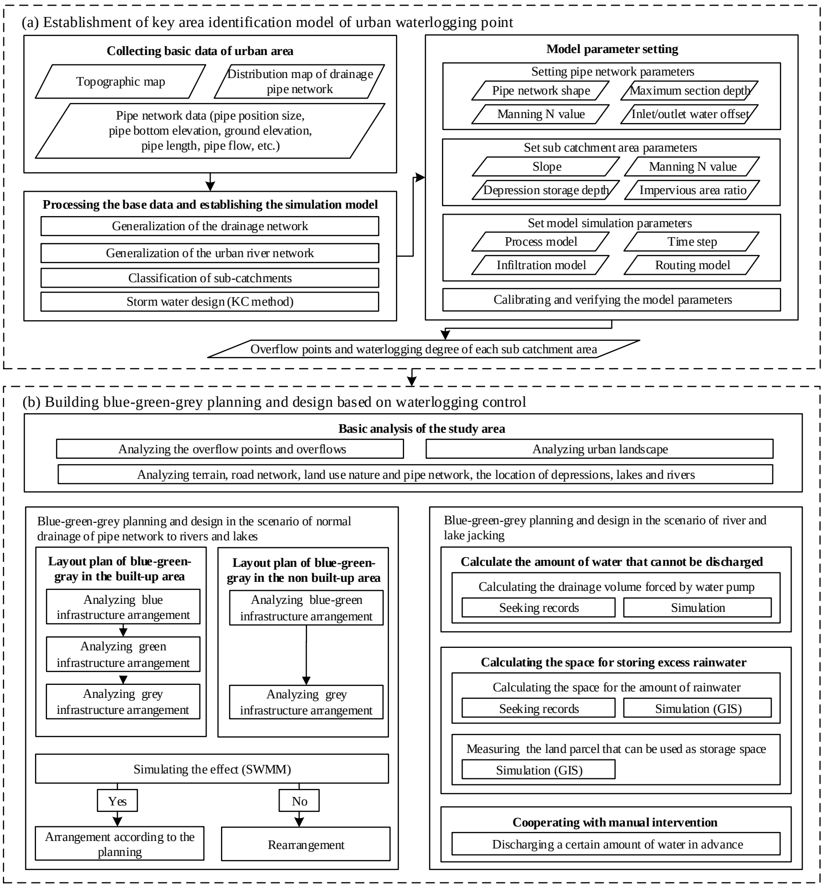

Figure 2. The flow scheme.

4. Results

4.1. Hydrological Simulation of the Shiwuli River

In this study, SWMM software is selected as the hydrological simulation software to simulate the hydrological conditions of the Shiwuli River Basin under a one-in-a-century rainfall intensity.

The SWMM simulations yielded the rainfall received in the upper, middle and lower reaches of the Fifteen Mile River Basin, the nodal overflow volume of the drainage network, the pipe network diversion volume and the storage volume, as shown in Table 2.

Table 2. The nodal overflow volume of the drainage network, the pipe network diversion volume and the storage volume (10^4 m^3).

Flow Routing Continuity	Basin	Upper Stream	Middle Stream	Lower Stream
Wet-weather inflow	842.11	301.15	301.52	239.44
External outflow	355.44	98.20	98.10	159.14
Flooding loss	477.14	189.63	204.45	83.06
Final stored volume	13.63	13.32	0	0.31

It has overflowed in most of the nodes of the drainage network in the study area under the once-in-a-century rainfall scenario. Figures 3 and 4 show the distribution of overflow nodes with overflows exceeding 5×10^4 m^3 and 10×10^4 m^3, respectively.

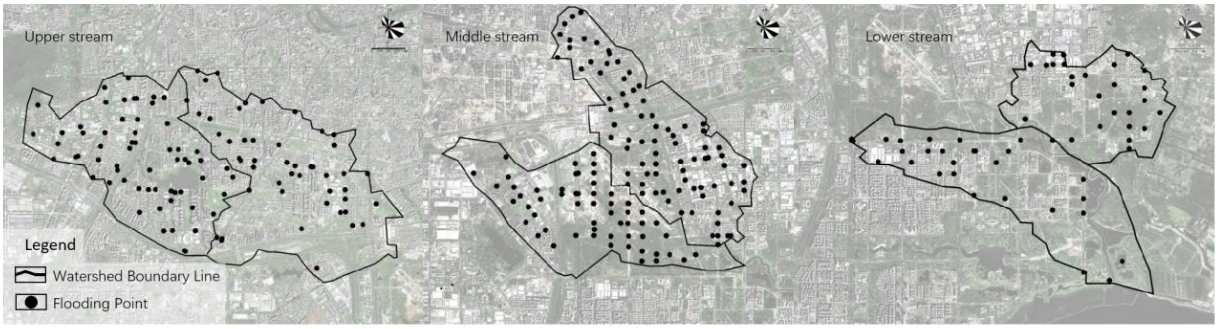

Figure 3. The distribution of overflow nodes with overflows exceeding 5×10^4 m^3.

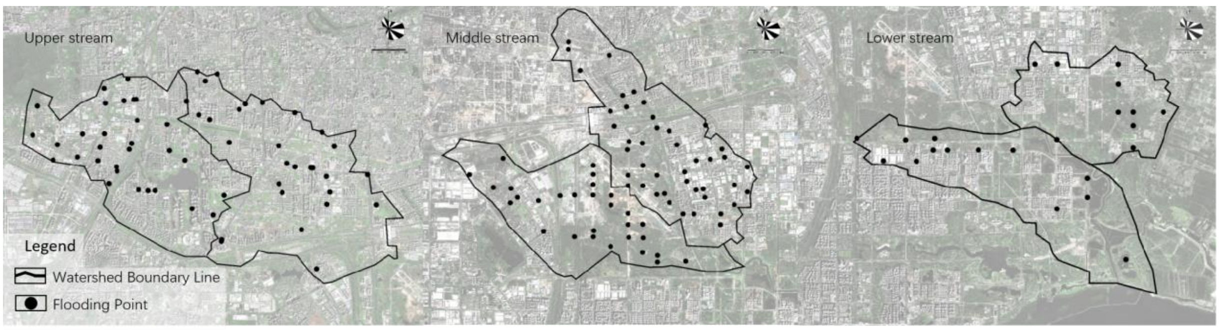

Figure 4. The distribution of overflow nodes with overflows exceeding 10×10^4 m^3.

4.2. Reconstruction Planning for Blue-Green-Gray Infrastructure

4.2.1. Scenarios of Urban Rainwater Flowing Smoothly into Rivers and Lakes

The Shiwuli River in the study area runs from northwest to southeast, with Swan Lake in the upstream and an estuarine wetland in the downstream. In this study, the areas along the river and lake and the blocks will be transformed into blue green facility layout space, with the rest areas to be planned as gray infrastructure layout space, and the blue green facility could be a grass gutter, low elevation greenbelt for transporting rainwater into rivers or lakes, and so on. The plans are shown in Figures 5–7, and the blue line areas represent the spaces for blue green facility transformation, and all these spaces are adjacent to the river or lake.

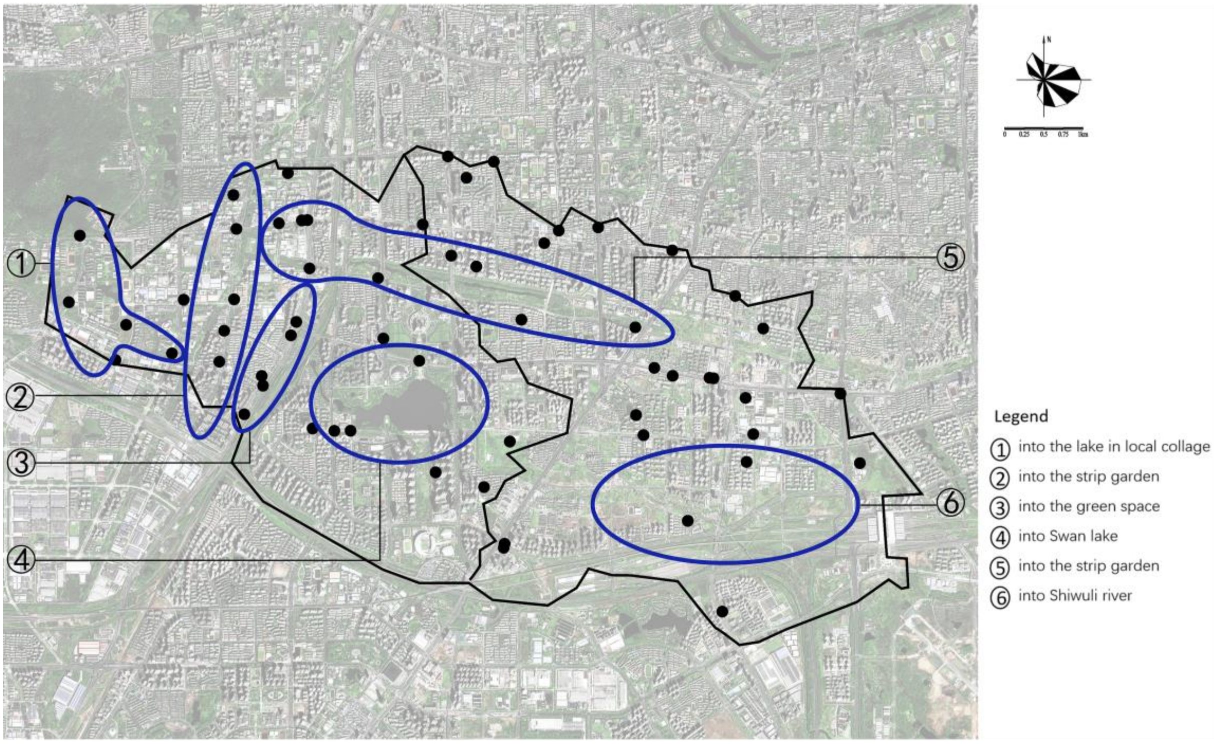

Figure 5. The region of blue-green transformation planning in the upper stream.

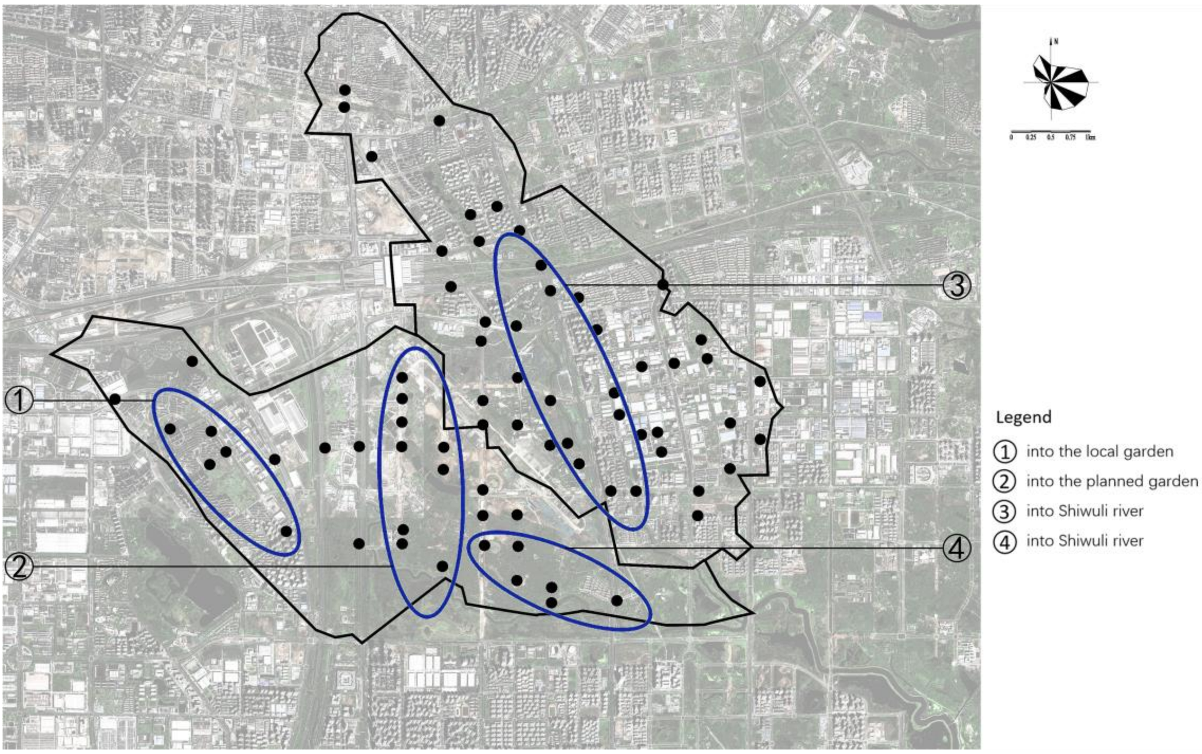

Figure 6. The region of blue-green transformation planning in the middle stream.

The planning and design ideas are as follows: (1) it is easy for the blue-green infrastructure to be arranged in the area adjacent to the river and lake to guide the surplus rainwater into the river and lake. The road, which blocks the river and lake, can be reconstructed and designed accordingly, so that the overflowing rainwater can be directed into rivers and lakes (see Figure 8). (2) In the non-adjacent river and lake area, it is difficult to set up blue-green infrastructure that can guide rainwater across the road because the elevation of the road between the plots is lower than the elevation of the plots on both sides of the road. Therefore, the area far from rivers and lakes is arranged as a gray infrastructure reconstruction area. (3) The study area has built areas and unfinished areas. The blue-green facility reconstruction plan of the built area mainly focuses on the local modification of green land terrain or the modification of green space to blue space on the basis of the existing available land layout. In the unfinished area, the transformation is carried out by way of a modification of the plan. Taking an unfinished plot as an example, the blue-green space leading to the river in space is designed in the detailed planning (as shown in Figure 9).

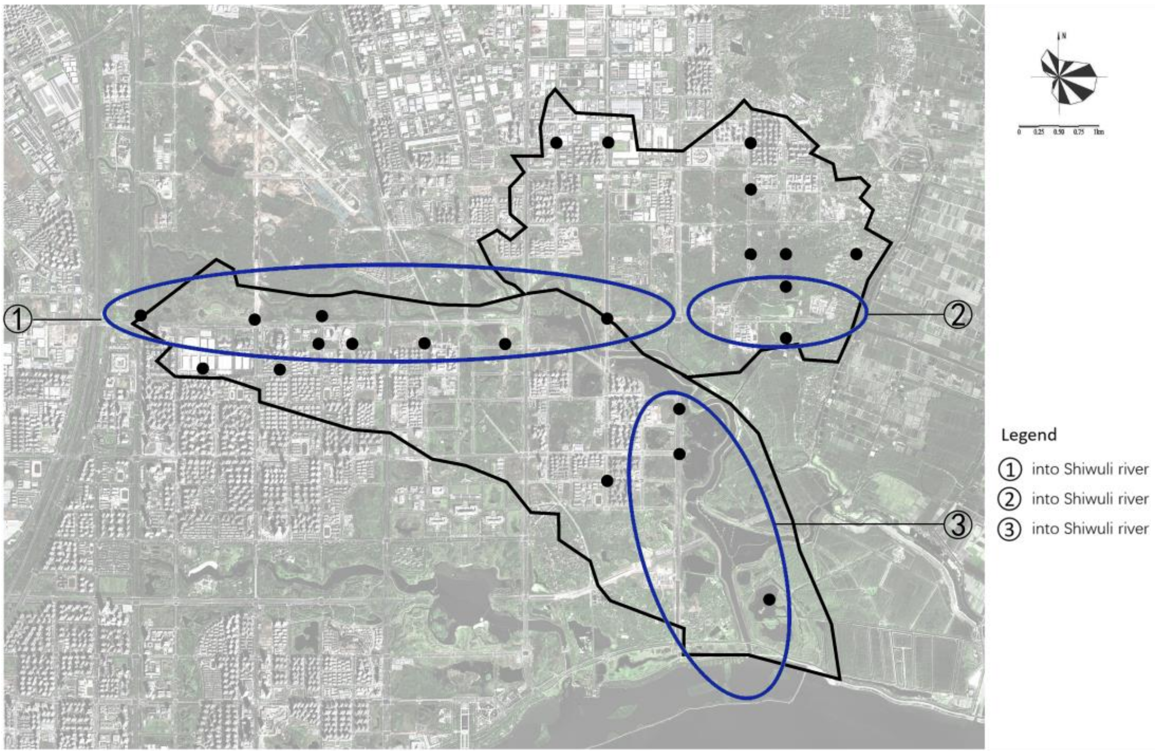

Figure 7. The region of blue-green transformation planning in the lower stream.

4.2.2. Scenarios of Backwater Effects of Lake

In this study, the capacity of the upstream Swan Lake is 993×10^4 m^3, with the upstream rainwater flowing into it exceeding 140×10^4 m^3 under the scenario of a once-in-a-century rainfall. The area of the wetland and pond near the downstream optical channel is about 220×10^4 m^3, with the average depth of the wetland pond more than 2 m, which can accommodate more than 440×10^4 m^3 of rainwater. In this study, notwithstanding that the sufficient wetland pond at the lower reaches of the Swan Lake River is to withstand the rainfall in extreme rainfall years, this should be coordinated with the drainage in advance when extreme rainfall is coming. Therefore, the upstream Swan Lake and the downstream wetland can be used as rainwater storage spaces under the backwater effects scenario (as shown in Figure 10).

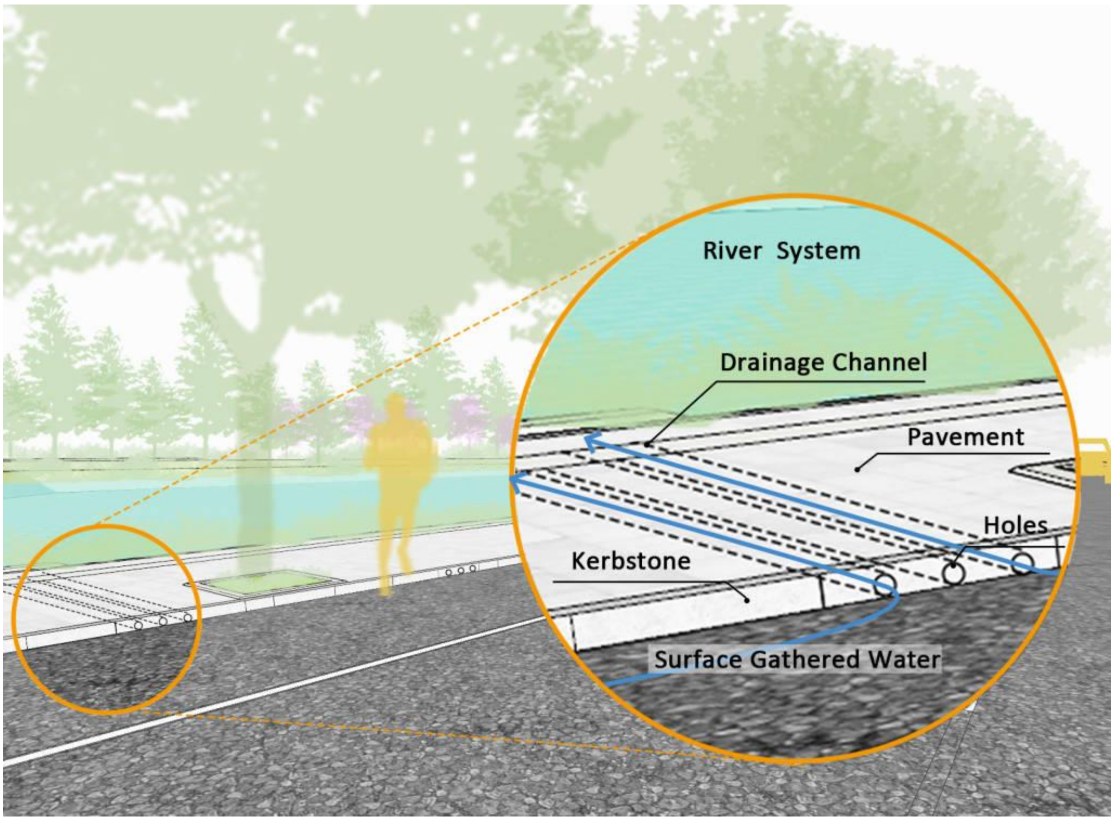

Figure 8. Road design plan.

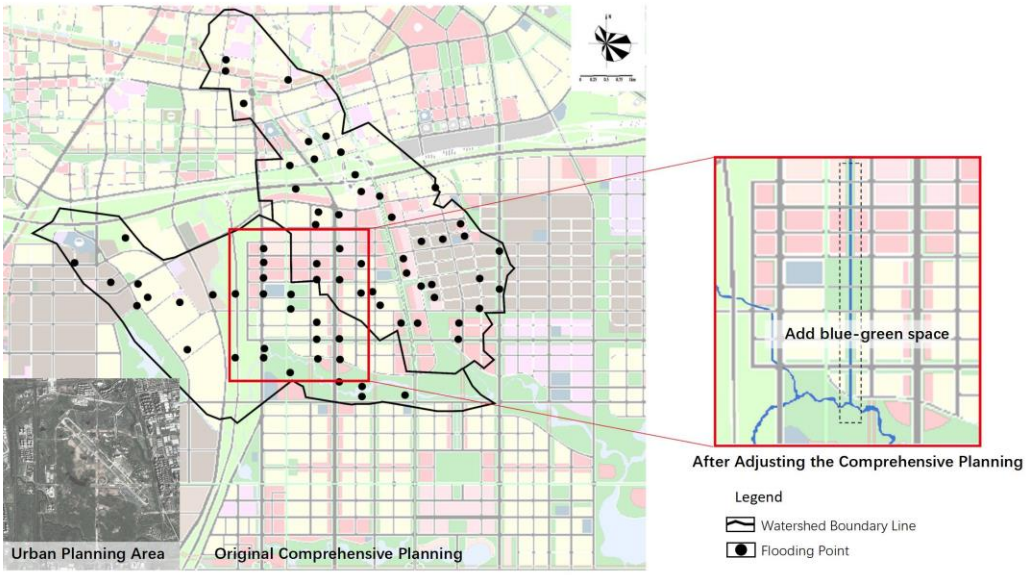

Figure 9. Planning modification.

4.2.3. Post-Transformation Scenario

Following the transformation of the blue-green space in the blue-green transformation area, not only can the rainwater at the serious overflow points in the transformation area be dredged, but the overflow points in the area where the blue-green space is located can be dredged to the nearby rivers and lakes through the blue-green facilities as well; as such, the waterlogging points in this part of the area disappear to boot.

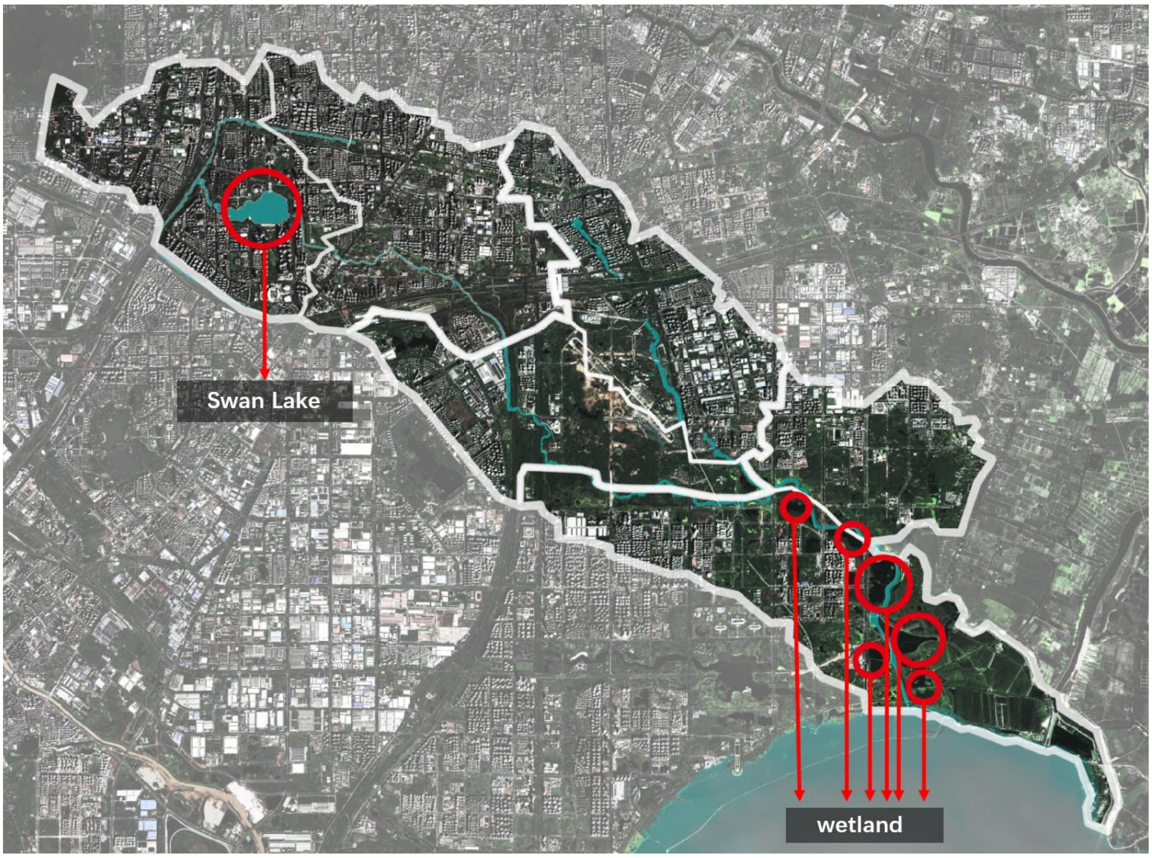

Figure 10. Swan Lake and the downstream wetland.

See Table 3 for the reduced overflow of waterlogging points through the blue-green space following reconstruction.

Table 3. The reduced overflow through the blue-green space reconstruction (10^4 m^3).

	Upper Stream	Middle Stream	Lower Stream
The reduced overflow	92.27	74.85	39.29

5. Discussion

(1) With SWMM simulating the overflow point along with volume in the study area under the once-in-a-century rainstorm scenario, the blue-green-gray is the demarcated transformation area. There are 109 overflow nodes with overflows exceeding 5×10^4 m^3 and 59 overflow nodes with 10×10^4 m^3 before the transformation, and in the SWMM simulation, all the overflow nodes vanish in the districts of blue-green transformation planning after the construction; it shows that there are significant reductions in the overflows of the upstream, middle and downstream nodes, and it always means that the ability of the lakeside city to cope with waterlogging could be greatly improved by the transformation. What is more, through setting the downstream ponds and wetlands as the spaces for accommodating the rainwater that cannot be discharged smoothly because of the backwater effects of the lake, the waterlogging risk of the city proper could be diminished and the capacity of the urban drainage system could also be improved. The study only defines the transformation scope but does not set the transformation degree of gray infrastructure.

(2) In this study, the area near the river and lake is directly introduced into the lake by setting blue-green space. If there are roads blocking the area near the river and lake, the road near the river and lake is designed to be the form that rainwater

can cross, while the area farther away from the river and lake lacks conditions to make the rainwater in the area overflow from the ground surface into the river and lake. It follows that the rest of the area is planned to be the area dominated by gray infrastructure, such as setting reservoirs or pipe network transformation.

(3) This study failed to consider the problem of water pollution when the overflow rainwater was directly introduced into rivers and lakes through the blue-green space in the area adjacent to rivers and lakes, given that the rainwater with higher pollutants at the initial stage entered the rainwater pipe network, and the overflow rainwater only entered the rivers and lakes. In the extreme rainstorm scenario, the prevention of waterlogging needs more attention than water pollution.

(4) In this study, the blue-green-gray reconstruction area is defined based on the overflow at the overflow point of the pipe network. Usually, the standard reflecting the degree of waterlogging is considered in combination with the overflow and the depth of ponding caused by the terrain at the overflow point. With the terrain of this study area relatively flat, this study directly calculates the overflow.

(5) This study provides a way for urban waterlogging prevention and control according to scenarios. In the case of a hundred-year flood in the basin, Swan Lake and the downstream wetland pond can be used as the regulation and storage pools under the backwater scenario of Chaohu Lake through calculations, but urban managers and Chaohu Lake managers should discharge water in advance to prevent waterlogging.

(6) In this study, we did not select multiple scenarios such as the once-in-10-year or the once-in-50-year but only the once-in-a-century as the standard. As per the historical records, the scenarios that cause serious waterlogging are all once-in-10-years, with the blue-green space set up with the once-in-a-century scenario capable of being used as the drainage and storage space for rainstorms occurring as once-in-10-years or once-in-50-years. In the specific pipe network transformation and reservoir construction, the higher involved engineering transformation costs, as witnessed for the specific corresponding standard year, need to be considered.

(7) In this study, there are built-up areas and unbuilt areas. In built-up areas, renewal planning is adopted. Therefore, the hazard of extreme rainfall shall be dealt with by changing the planning in the unbuilt area.

(8) In the scenario of the backwater effects of the lake, because several rivers flow into Chaohu Lake in the downstream, and Chaohu Lake is also a space for flood storage to secure the important downstream cities during rainstorm times, it means that the water levels of Chaohu Lake are actually manually controlled, and it is difficult to calculate the precise water level simply according to the natural factors such as topography, inflow, etc., and it is also difficult to calculate the volume of the rainwater that cannot be discharged because of the backwater effect. The volume of rainwater that cannot be drained, in this study, is set in keeping with the pump discharge in the study area under extreme annual scenarios.

(9) The storage space for the rainwater that cannot be discharged is accumulated by checking the information of the lake in the upper stream and calculating the space of the ponds and wetlands in the downstream with GIS software, and the method of the storage space could be accumulated accurately. Regardless of whether there is enough area of the upstream lake and downstream wetland pond in this study to store rainwater, on condition that there is not enough space in other areas to cope with the backwater effects of flood, the way to consider it remains to excavate earthwork in the downstream, or set up blue space and water conservancy facilities in the unbuilt area.

(10) SWMM software, in this study, is used to simulate the hydrological conditions in the study area, which can accurately simulate the overflow point, as well as the flow of the urban pipe network, reflecting the waterlogging situation.

(11) The limited data have witnessed unconsidered factors such as sewage interceptors in this study.

6. Conclusions

(1) This study takes the Shiwuli River Basin in Hefei, a lakeside city, as the research object, with a view to providing strategies for eliminating waterlogging in the lakeside city through blue-green-gray infrastructure transformation planning. This study provides the blue-green-gray transformation planning paradigm of the lakeside city under the backwater effects of the downstream Chaohu Lake water along with the co-existence of built and unbuilt areas within the city. The innovation of this study lies in: (1) how to quickly deal with rainwater discharged from the city under the influence of the backwater effects of a lake; (2) how to plan the blue-green-gray facilities in the study area when there exist built-up areas and non-built-up areas.

(2) The previous research on urban blue-green-gray transformation was mostly focused on urban built-up areas; this is not involved in the current research on how to update the blue-green-gray planning in the space where there are built-up areas with space constraints and the unbuilt areas, which is capable of modifying the planning. What is more, it is generally considered that urban rainwater can be discharged into rivers or lakes smoothly, but there is very little consideration is for the links between city and watershed. This study is for the limitation.

(3) In this study, the urban land planning along with drainage pipe network planning in the urban planning period are taken as the research object, with the blue-green-gray transformation capable of effectively dealing with the waterlogging disaster that may be brought on by extreme rainfall in the future. SWMM hydrological software, in this study, can clearly and accurately simulate the hydrological process and waterlogging scenarios prior to and following the blue-green-gray transformation in the study area, being capable of clearly expressing the effect comparison before and after the transformation. The water quantity that can be stored in lakes and downstream wetlands in the basin can be accurately calculated by using historical data and GIS software.

(4) The research path of this study is divided into scenario analysis, which is divided into an urban pipe network capable of a smoothly discharged rainwater scenario and the backwater effects of river and lake scenario. In the scenario where the rainwater can be discharged smoothly from the urban pipe network and the built-up area, the urban blocks near the river and lake represent mainly blue-green dredging, while in the non-riverside lake blocks, the gray infrastructure reconstruction remains mainly used. In the areas to be built, the blue-green space location can be mainly used by modifying the planning through which capital investment and construction quantities can be reduced in the high-density construction cities, with a good hydrological transformation effect to be achieved. In the backwater scenario, the water storage of lakes and wetlands in the study area in combination with artificial pre-drainage can resist the backwater effects of rivers and lakes.

(5) It can clearly show how the city plans and transforms blue-green infrastructure in different scenarios and sites with different construction conditions by comparing different scenarios.

(6) This study provides a solution to urban flooding in lakefront cities, which can be extended to other lakefront cities and also to riverine cities where top support exists.

(7) However, this paradigm also has its own limitations, which lie in that there happens to be lakes and wetlands that can bear excessive rainfall and do not encroach on the area during the initial urban planning in the study area. However, on the condition that there exist no natural conditions in this study in other lakeside cities, it is necessary to use GIS terrain analysis technology to analyze whether the drainage basin can bear excessive rainfall.

(8) Another limitation of this study is the use of the historical pump pumping capacity as the calculation model. In the calculation, more accurate methods can be used to generalize the river and lake setting scenarios to calculate the water volume that cannot be discharged because of the backwater effects.

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

Funding: This research was funded by the National Natural Science Foundation of China (Grant No. 41601581), the Young Teacher's Educational Reform Funds of Hefei University of Technology (Grant No. JYQN2107) and the Fundamental Research Funds for the Central Universities (Grant No. PA2021KCPY0038).

Institutional Review Board Statement: Not applicable. There is no human experiment or animal experiment in the study, and the study does not address the ethical issue.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare that there are no conflict of interest regarding the publication of this paper.

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