

Article

Study of Comprehensive Utilization of Water Resources of Urban Water Distribution Network

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Abstract: China is a country where the levels of water resources per capita are extremely low. With the rapid development of urbanization, water resource shortages have become a bottleneck existing in more and more cities. This study considers the comprehensive management of urban flood control, water supply, water and the ecological environment, catches the main contradiction between “water deficient” and “water rich” in cities, puts forward a comprehensive utilization pattern for urban water resources by emphasizing the utilization of rain–flood resources. After a simulation study, a better regulation pattern is brought out and achieve multiple benefits based on the river system of Gucheng Lake, which is located in Nanjing, Gaochun district, by optimizing conventional regulation. The results show that two parameters, the low water level (LWL) below which Gucheng Lake stops supplying ecological water, and the high water level (HWL) where Gucheng Lake stops importing water from rivers, are the key parameters to decide the regulation benefits, and the LWL of 9 m and HWL of 12 m is the best combination in river network regulation, the annual potential utilizable of rain–flood resources of Gucheng Lake river system can reach 57 million m³ per year, through the comprehensive utilization of the rain–flood resources, the negative effect of flood is effectively reduced and the disaster is controlled on one hand; and the water demand of urban and rural water supply, 100,000 m³/day, is effectively guaranteed as well as the regional ecological environment is improved on the other hand.

Keywords: rain–flood resources; urban water distribution network; comprehensive utilization pattern; river system of Gucheng Lake



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1. Introduction

1.1. Contradiction between “Water Deficient” and “Water Rich” in Cities

China is a country with relatively poor water resources. The total amount of fresh water resources is 2.8 trillion m³ [1], and the water resources per capita are only 2300 m³, which is only 1/4 of the world average level. The contradiction between supply and demand of water resources is more prominent due to the uneven distribution of rainfall and water resources. At present, China is in a critical period of urbanization. In 2017, China's urban permanent resident population reached 813 million, and the urbanization rate reached 58.52% [2], significantly increasing by 357 million and 22.43% respectively compared with 2000 [3]. The continuous advancement and rapid development of urbanization in China have put forward new requirements for the carrying capacity of the urban water resources environment and the ability to deal with natural disasters such as flood and drought, so that traditional city construction and the management pattern is continuously challenged. Sufficient, insufficient and dirty water problems are growing. According to

statistics, more than 400 out of 600 cities in China are short of water in the year 2006, of which, 110 cities are in a state of severe shortage [4].

At the same time, flood and waterlogging in the cities has caused huge disasters [5]. According to statistics, from 2007 to 2013, more than 360 cities in China suffered from significant waterlogging, among which one in six of the cities experienced waterlogging for more than 12 h with a depth of more than 50 cm [6]. According to the statistical results of the Ministry of Housing and Urban–Rural Development, in 2010 alone, waterlogging occurred 724 times in 357 cities across the country, with disaster losses reaching CNY 2.3 billion [7]. With the rapid expansion of China’s urban scale and the fast accumulation of population and wealth to cities, the losses in cities suffering from flood disasters and their vulnerability to disasters will continue to rise.

Since the 20th century, the international community has gradually realized the importance of an urban water network to solve the contradiction between more and less urban water problems [8]. The new economic and social requirements of ecological and green development also put forward new demands for urban water network construction. However, at present, most cities only analyze and evaluate water as a resource or environmental element in a complex urban ecosystem. In conclusion, the comprehensive benefits of the urban water network for water resources, water ecology, water environment and water disasters need to be improved.

1.2. The Significance of Comprehensive Utilization of Water Resources in Urban Water Distribution Network

In recent years, new concepts of urban water management in some developed areas in the world, such as Low Impact Development (LID) in the United States, Sustainable Drainage (SUDS) in the United Kingdom, and Water Sensitive Urban Design (WSUD) in Australia, have gradually received attention and recognition [9]. In these developed areas of cities, it is a great change and a new exploration of the concept for urban water management by controlling and utilizing the water in a natural water system using a manmade water system and controls, to improve the ability to regulate and allocate water resources and improve the guarantee for people’s production activities, domestic use and ecological use. Its core goal is to solve, fundamentally, the contradiction between “water deficient” and “water rich” cities [10].

For the achievement of these goals, it is important to build a water distribution network with safe, reliable, ecologically healthy, high quality and sufficient water. Normally, a water distribution network is built by lakes, rivers, and artificial canals as the skeleton, with the aim to increase surface and underground water storage and its allocation capabilities, and then the network can control and use rain–flood resources by transforming the “disaster water” to “water resources”, so as to comprehensively improve the capacity for safe flood control and drainage, suitable water resources, be friendly to ecology and the environment, and further increase the amount of water available for production and living [11,12].

1.3. Research Progress

In the 21st century, people have noticed the importance of water management for environment and social benefits [11,13]. The main interests in the urban water distribution network mainly includes the definition and characteristics [14,15], ecological restoration, and dispatching and operation management [8,16]. For more examples, Wenger et al. [17] summarized the research status of the urban river system before, and put forward 26 key research issues, including the impact of the urban river water network on the physical, chemical and biological aspects of the urban water ecosystem, as well as the methods to deal with the relationship between planning and existing urban water conservancy projects. According to the EU Water Framework Agreement, the European water network should basically achieve good ecological and environmental effects by 2015 [18]. In China, the large and medium-sized cities have gradually carried out research on water network connectivity by combining natural rivers and lakes, with artificial water conservancy projects in aspects of storage, irrigation and drainage, Beijing has been stepping up the

construction of the urban water distribution network, improve the connectivity of water, urban rain–flood prevention and control [19,20]. All in all, a healthy water network is an effective water resources utilization system, which can provide a basic water security guarantee for economic and social development [21].

Up to now, the construction pattern and the comprehensive utilization technology in the urban water distribution network has become a very important point in the control of urban water circulation and allocation, especially for regions with rivers that crisscross but lack rich water resources and regulation ability, where the controllability of rain–flood resources is the core to protect regional water security. Research on the utilization technology of rain–flood resources mostly focuses on the study of flood risk control and its utilization pattern of a specific region. For example, Wang Yintang et al. [22] systematically studied several key technical issues in the utilization of rain–flood resources in the basin by a combination of city scale and river basin scale. Ye Jianchun et al. [23] summarized the practice of flood risk management in the Taihu Lake Basin at different development stages and looked forward to the future directions. Lu Zhihua et al. [24] defined the rain–flood resources of Taihu Lake, established the framework of rain–flood resources utilization and the evaluation index system, and carried out simulation analysis. Xu Weiping et al. [21] discussed the utilization and compensation mechanism of rain–flood resources in cities with water shortages, and pointed out that rational utilization of rain–flood resources is conducive to alleviating urban waterlogging, reducing disasters, improving water environment and solving water shortage.

In conclusion, the above studies on the definition and availability of rain–flood resources fully demonstrated that the utilization of rain–flood resources is an important measure for the comprehensive utilization of water resources in water-deficient cities. This study takes the urban water distribution network as the carrier to integrate the use of rain–flood resources into the available allocated water resources in urban areas, so as to ensure flood control safety, water supply safety and ecological safety, and to improve the comprehensive utilization efficiency of water resources in the urban water-distribution network.

2. Study Area, Materials and Methods

2.1. Study Area

Gaochun District, located at the south of Nanjing, China, is a typical plain river network area, where the Gucheng Lake water system, close to the south, is the core water system of Gaochun District. The Shuibiqiao River, Guanxi River, Shigu River and Xu River are the four main rivers connected with Gucheng Lake. Among them, Shuibiqiao River and Guanxi River connect with Gucheng Lake and Shuiyang River (upper level rivers which flow into Changjiang), Shigu River connects with Gucheng Lake and Shijiu Lake, and Xu River connects with Gucheng Lake and Taihu Lake. Some artificial water control projects have also been made, such as the Shuibiqiao sluice, Yangjiawan sluice, Sheshan sluice and Maodong sluice have already been constructed on Shuibiqiao river, Guanxi river, Shigu river and Xu river, respectively. To be easily remembered, they are also named Shuibiqiao Sluice, Guanxi Sluice, Shigu Sluice and Xu Sluice in the paper. In practice, the Xu Sluice is usually closed to stop water exchange between this watershed and its neighbor.

2.2. Materials

Precipitation in Gaochun District is heterogeneous in time and space. Precipitation in the flood season (from May to August) accounts for 60% of the annual precipitation. According to the measured daily rainfall of Gaochun Station in 2016 and the data from Nanjing Rainfall Station from 1980 to 2009, provided by the website of National Meteorological Information Center, the years of 1991, 1982 and 1986 were selected as typical examples of a wet year (5%), a normal year (50%) and a dry year (95%), and the rainfall was 1819.9 mm, 1049.9 mm and 722.5 mm, respectively. The daily rainfall process was assumed according to the rainfall rule in 2016.

Combining the DEM data and the conditions of the river and lake water systems, the total catchment area of Gucheng Lake water system is calculated to be 589 km². According to the confluence situation of the rivers, the catchment area of Gucheng Lake is divided into seven catchment areas: Shuibiqiao River, Guanxi River, Shigu River, Qiqiao River, the Southern Mountains and Gucheng Lake (Figure 1). According to the current situation of land use in the Gucheng Lake catchment area, the underlying surface of each catchment area and the comprehensive runoff coefficient before and after urban development are shown in Table 1.

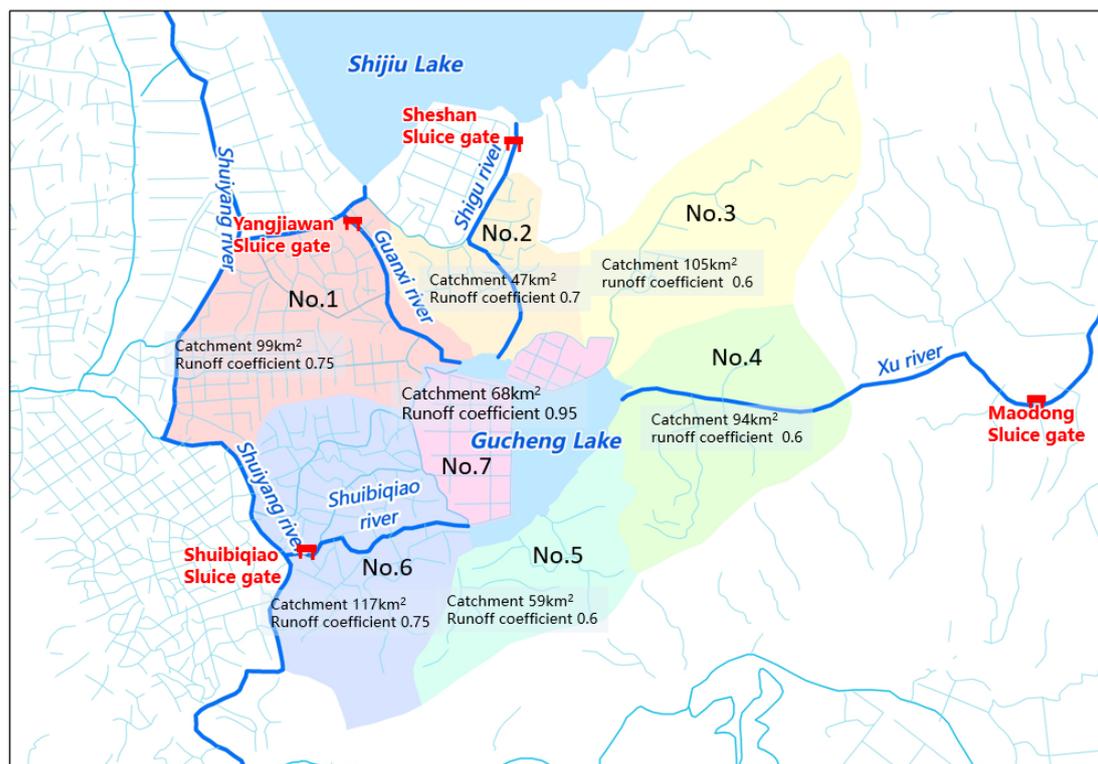


Figure 1. Gucheng Lake catchment area and its subregion.

Table 1. The underlying surface of each catchment area of Gucheng Lake.

Catchment	Area (km ²)	Comprehensive Runoff Coefficient	
		Before Urban Development	After Urban Development
No. 1	99	0.55	0.75
No. 2	47	0.55	0.7
No. 3	105	0.5	0.6
No. 4	94	0.55	0.6
No. 5	59	0.5	0.6
No. 6	117	0.55	0.75
No. 7	68	0.75	0.95
Total	589	0.559	0.703

2.3. Demands of Comprehensive Utilization of Water Network

With reference to the relevant literature and reports [25], the comprehensive utilization demands of the water network in Gucheng Lake river system are defined as follows:

- Flood control safety. The water level of Gucheng Lake to be controlled below 12 m (below the water level of once-in-20-year incidents) as far as possible, and the storage capacity above 12 m should be reserved for flood control. According to the water level relations of Gucheng Lake, Shuibiqiao River, Guanxi River, Shigu River, Xu River and

the capacity of flood control projects, the relevant water level control requirements are formulated as follows in Table 2.

- Urban and rural water supply. In order to meet the water demands of societal living, the total centralized water supply demand of the whole district is 480,000 m³/d. It is planned by local government to build a new water plant in Gaochun District with Gucheng Lake as the drinking-water source, the water intake capacity for Gucheng Lake is 100,000 m³/d, which is defined as the water supply amount in our model.
- Water ecological environment. Gucheng Lake is directly connected with Shigu River, Guanxi River, Shuibiqiao River, etc. At present, the water flow of the river is not smooth, which not only fails to meet the ecological water demands of the river, but also fails to reduce pollutant deposition, self-purification capacity is insufficient, and the water quality deteriorates continuously. According to the pollution points along the river courses, in order to meet the ecological and environmental requirements and maintain the water quality to be standard III, the water level of Gucheng Lake should be stabilized at more than 8.0 m, and the discharge of the Guanxi River, Shigu River and Shuibiqiao River should be above 3.73 m³/s, 2.47 m³/s and 1.89 m³/s, respectively.

Table 2. Regulation water level of each main lake and river.

Name	Gucheng Lake	Shuibiqiao River	Guanxi River	Shigu River	Xuhe River
Maximum water level (m)	12	13	12	11	14
Minimum water Level (m)	8	8	5.5	6	4

2.4. Analysis of Potential Utilizable Rain–Flood Resources

The comprehensive utilizable potential of urban rain–flood resources refers to the incremental value of annual rainfall that can be retained in the region through feasible technical means such as retention, infiltration and utilization, on the premise of ensuring the water demands of the urban and downstream ecological environments under the current natural conditions. Its connotation refers to the comprehensive rain–flood quantity that should be retained in the region in order to restore the ecologically balanced state before regional development and construction under the current natural conditions and technical level. The annual potential utilizable value is calculated on a daily basis. The arithmetic average value of the potential utilizable value calculated from the annual rainfall series is the average annual potential utilizable value of the region. The upper limit for the utilization of rain–flood resources is: firstly, the minimum water demand for retaining the urban and downstream river and lake ecology should be considered, which is generally about 30% of river runoff, which cannot be used as potential; secondly, for major natural floods above the urban flood control standard, which is impossible or not worth using at present, the upper potential limit should be the smaller value of the total runoff after deducting the above two items, respectively.

According to the daily rainfall series data, the utilizable potential of the urban rain–flood resources can be calculated by the following method:

$$W = \sum_{i=1}^{365} W_{ip} \quad (1)$$

$$W_{ip} = 0.3P_i(\varphi_2 - \varphi_1)F \quad (2)$$

$$P_i = \begin{cases} I_{cons}, & I_i \geq I_s \\ I_i, & I_i \leq I_s \end{cases} \quad (3)$$

W is the annual comprehensive utilizable potential of rain–flood resources, the unit is 10,000 m³, W_{ip} is the comprehensive utilizable potential of rain–flood resources of i th daily rainfall, the unit is 10,000 m³; φ_1 and φ_2 are, respectively, the comprehensive runoff

coefficients before and after urban development and construction; F is the area of the city, the unit is km^2 ; P_i is the rainfall for daily calculation, the unit is mm, I_i is the actual daily rainfall, the unit is mm, I_{cons} is the designed daily rainfall, which used to be 80~90% of local annual rainfall, the unit is mm.

2.5. The Regulation Method for Comprehensive Utilization of the Water Network

2.5.1. Optimal Scheduling Analysis

Since the combinations of different sets of key parameters are very important for optimization in a water network, researchers, such as [26–29], pay much attention and give us very significant inspiration.

This study enhances the water resources regulation and storage capacity of Gucheng Lake water system through various means, by optimizing the operation scheme of the lake and seeing it as a reservoir, enhancing its “flood control storage capacity” as the flood regulation function in the water system, and enhancing its “usable capacity” as the water source. Annual regulation rules for water network are detailed showed in Table 3. The fluctuation water level of Gucheng Lake is from minimum (8 m) to maximum (12 m), and we are engaged in formulating the regulation rule to control the water system, for which we shall come up with two key parameters: the low water level (named LWL) below which Gucheng Lake stops supplying ecological water to the rivers, during which Gucheng Lake is trying to ensure the lowest ecology water level (8 m); the high water level (named HWL) where Gucheng Lake stops importing water from the rivers to ensure flood safety (12 m). The LWL and HWL are the key values and their optimization results are shown in Section 4.

2.5.2. Model Establishment

The objective function is showed as below.

$$\min\left(\sum_{i=1}^3 D_1^i + \sum_{j=1}^5 D_2^j\right) \left\{ \begin{array}{l} (D_1^i, D_2^j) = f(H_L, H_H) \\ 8 \leq H_L \leq 10 \\ 10 \leq H_H \leq 12 \end{array} \right. \quad (4)$$

where D_1^i is the days when simulated ecological flow is lower than the demands of the Shuibiqiao River, Guanxi River, Shigu River, D_2^j is the days when the simulated water level is higher than flood control demands of Shuibiqiao River, Guanxi River, Shigu River, Xu River and Gucheng Lake. H_L is the acceptable lowest water level (LWL), H_H is the acceptable highest water level (HWL). f means the functional relation between D_1^i, D_2^j and H_L, H_H , which is more clearly described below.

Water balance analysis is widely applied in the water allocation process [30–33]. According to the water balance principles, the balance equation for Gucheng Lake is described as,

$$\frac{dW}{dt} = PF\varphi - ES + \sum Q_i \quad (5)$$

where W is the water storage capacity of Gucheng Lake; t is the time. P is rainfall intensity; F is the direct catchment area of Gucheng Lake; φ is the comprehensive runoff coefficient of the direct catchment area of Gucheng Lake; E is evaporation intensity; S is the water area of Gucheng Lake; Q_i is the discharge into the lake of the first river. It is worth noting that underground water resources are the double-counted value in a plain area, just like Gaochun district, and are less compared with flood resources, meanwhile, in the plain area, people do not use underground water as the normal water source. In the end, this equation ignores the underground water and leakage influence.

Table 3. Annual regulation rules for water network.

Periods	Regulation Rules
Pre-rainy season (April)	<ul style="list-style-type: none"> • When the water level of Gucheng Lake is lower than 8 m, all the outer discharge sluice stations will be closed, and the water from all rivers will flow into the lake. • When the water level of Gucheng Lake is lower than LWL, water from Shuibiqiao River and Xuhe River will flow into the lake, and Guanxi Sluice and Shigu Sluice will be restricted to open, and the lake water will flow out by itself to ensure the ecological flow of Guanxi River and Shigu River. • When the water level of Gucheng Lake is higher than LWL, water from Shuibiqiao river and Xuhe River flows into the lake, and the Guanxi River Sluice and Shigu River Sluice are fully opened to discharge the lake water into the outer river according to the channel's flow capacity. <p>(apply when the outer river's water level is lower than 8 m so inner water can outflow by gravity)</p>
Rainy season (May to August)	<ul style="list-style-type: none"> • When the water level of Gucheng Lake is lower than LWL, the regulation rule is followed as for pre-rainy season. • When the water level of the lake is over LWL and the water levels of the Shigu River and Guanxi River are higher than the water level of Gucheng Lake, the two rivers shall be closed to restrict the water intake into the lake. At the same time, the Guanxi River Sluice and Shigu River Sluice will be opened to discharge the flood, depending on the internal and external water level conditions. • When the water level of the lake is above LWL and the water level of Shigu River and Guanxi River is lower than the water level of Gucheng Lake, the two rivers' sluice gates will be opened so that the flood water of the lake is discharged through the two rivers. At the same time opening the Guanxi River Sluice, Shigu River Sluice to discharge the flood, depending on the internal and external water level conditions. <p>(apply when outer river's water level is higher than 10 m)</p>
End of rainy season (September)	<ul style="list-style-type: none"> • When the water level of the lake is lower than HWL, all the sluices inside the water system will be opened and the sluice outside the water system will be closed. Try to make use of the flow between rivers and lake to meet the demand of ecological flow. • When the water level of the lake is higher than HWL, the lower water level of the outer river (about 10–11 m) is used to open the Guanxi River Sluice, Shigu River Sluice and Shuibiqiao Sluice to collect water from the artesian drainage system.
Dry season (October to March)	<ul style="list-style-type: none"> • When the water level of the lake is above LWL, the lake receives water from each river by gravity. If the catchment flow of Guanxi River and Shigu River is low and the hydrodynamic power is insufficient due to the lack of rainfall, the sluice gate of the two rivers should be properly opened and the water stored in the lake should be discharged to meet the ecological flow requirements of the river. • When the water level of the lake is below LWL, all the sluice gates should be closed to ensure the water supply demand of the water system.

The equation for Shigu River is:

$$\frac{dW_i}{dt} = PF_i\varphi_i - ES_i - Q_i - q_i \quad (6)$$

where W_i is the instantaneous water storage of the i th river; F_i is the catchment area of the i th river; φ_i is the comprehensive runoff coefficient in the catchment area of the i th river; S_i is the water area of the i th river; q_i refers to the discharge of the river outside the drainage system of the i th river.

According to the topographic conditions of the lake and the transverse and vertical section of the river channel, we have equations:

$$W = f(H) \quad (7)$$

$$W_i = f_i(H_i). \quad (8)$$

$$S = g(H) \quad (9)$$

$$S_i = g_i(H_i) \quad (10)$$

where f and g are the relationship between volume ~ water level and water area ~ water level of Gucheng Lake, respectively; f_i and g_i are, respectively, the relationship between volume ~ water level, water area ~ water level of the i th river; H and H_i are, respectively, the water level of Gucheng Lake and the i th river.

In addition to controlling the connected river and lake sections, the river channel is simplified as an open channel uniform flow, and the discharge into the lake is calculated by the Chezy formula:

$$Q = AC\sqrt{RJ} \quad (11)$$

where A is the area of river crossing section; C is Chezy coefficient, $C = (1/n)R^{1/6}$; R is the hydraulic radius of river channel $R = A/P$; J is the wet circumferential length of river course.

3. Analysis of Comprehensive Utilization of Water Distribution Network

3.1. The Optimization of Regulation Rules

In order to find the optimal LWL and HWL values, which could ensure flood safety, satisfy the ecological water demand and, more importantly, be applied in practice in Gaochun district, combined with the previous study, the LWL and HWL were set to be 8–10 m and 10–12 m scale. To make the overall search, the LWL started with 8 m with 0.2 m increments to 10 m, and HWL started with 10 m with 0.2 m increments to 12 m. In total, there were 121 scenarios, in which 15 scenarios had minor differences (less than 1 m) between LWL and HWL, in the end we simulated 106 scenarios.

As can be seen in the results (Figure 2 and Table 4): the days of unsatisfactory ecological flow in the Guanxi river are more sensitive to the variation of different LWLs and HWLs, the ratio between maximum and minimum days of unsatisfactory ecological flow in the Guanxi river reaches 8.42 while the standard deviation is 20.91. The Shigu river and Shuibiqiao river are also sensitive to the variation of different LWLs and HWLs but less so than the Guanxi river. The combination of a LWL of 9 m and a HWL of 12 m is relatively better in these scenarios, in terms of ecological flow.

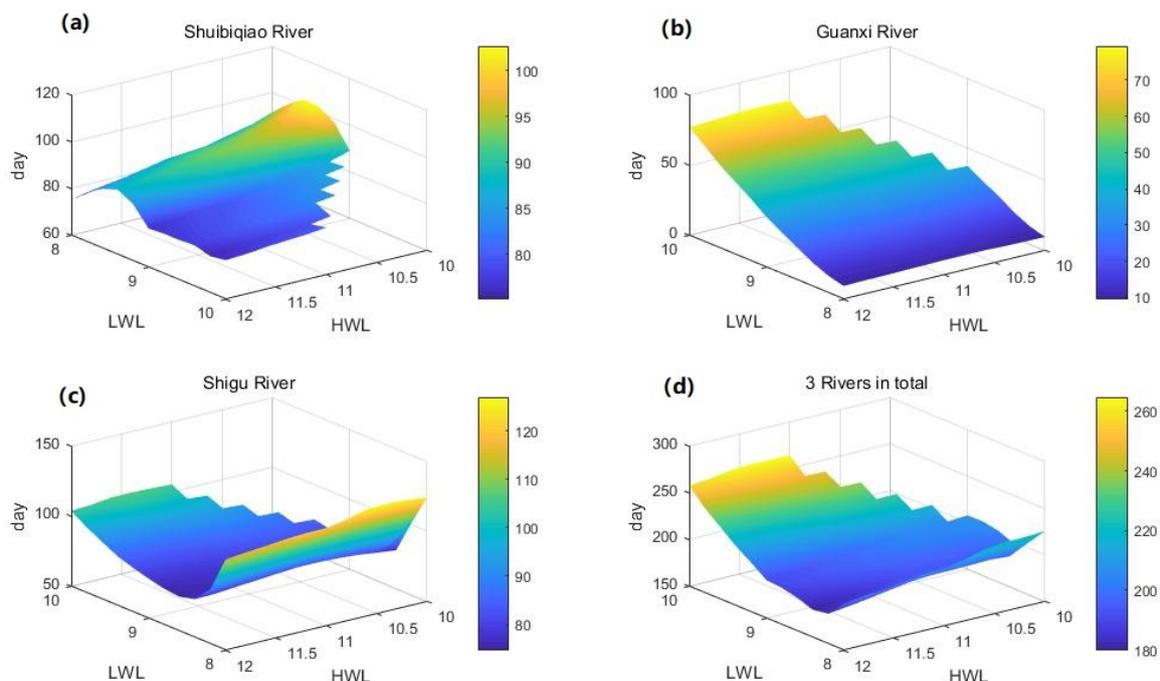


Figure 2. The mean annual number of days of unsatisfactory ecological flow of (a) Shuibiqiao River, (b) Guanxi River, (c) Shigu River and (d) Three rivers in total, under different regulation scenarios combined by LWL and HWL.

Table 4. The number of unsatisfactory days of ecological flow under different regulation scenarios.

River Name	Shuibiqiao River	Guanxi River	Shigu River
The mean annual unsatisfactory flow days	85.01	36.26	90.01
The Maximum unsatisfactory flow days	102.63	79.43	126.93
The Minimum unsatisfactory flow days	75.10	9.43	74.67
Ratio between maximum and minimum unsatisfactory flow days	1.37	8.42	1.70
Standard deviation of unsatisfactory flow days	6.59	20.91	13.41

Note: Xuhe river only has ecological water level demand so it is disregarded here.

In terms of the water level to guarantee flood control safety, the total days when the rivers' and lake's water level are higher than maximum water level under different regulation scenarios show two kinds of trends (Figure 3 and Table 5):

- Guanxi river, Shigu river and Gucheng Lake show an obvious inflection point at a LWL of 9 m and a HWL of 12 m, when the value is minimum, which means more safety in flood control. Meanwhile, the Guanxi river, Shigu river and Gucheng Lake are less sensitive in the variations with LWL and HWL than the Shuibiqiao river and Xu river.
- The Shuibiqiao and Xu rivers show a slight inflection point at a LWL of 9 m and a HWL of 12 m, because the sluices in these two rivers are not usually open, compared to the other two rivers. Meanwhile, the Shuibiqiao and Xu rivers are more sensitive.

Table 5. The statistical days when the water level is higher than maximum water level under different regulation scenarios.

River Name	Shuibiqiao River	Guanxi River	Shigu River	Xu River	Gucheng Lake
The mean annual days when the water level is higher than maximum water level	15.39	7.99	7.61	20.57	8.10
The maximum yearly days when the water level is higher than maximum water level	36.77	11.57	11.23	72.90	11.83
The minimum yearly days when the water level is higher than maximum water level	8.93	5.83	5.50	8.53	5.90
Ratio value between maximum and minimum	4.12	1.98	2.04	8.54	2.01
Standard deviation of annual days when the water level is higher than maximum water level	5.61	1.59	1.56	12.45	1.74

All in all, a LWL of 9 m and a HWL of 12 m are the best combination for flood control and ecological water demands, and this combination is selected in the following analysis.

3.2. The Utilizable Quantity of Rain–Flood Resources

According to the above calculation method for the utilizable potential of rain–flood resources, the average annual utilizable potential rain–flood resources of the Gucheng Lake catchment area is 56.68 million m³. In a wet year (5% frequency, year 1991), a normal year (50% frequency, year 1982) and a dry year (95% frequency, year 1986), the utilizable potential of the rain–flood resources were 6883 m³, 5769 m³ and 46.76 million m³, respectively.

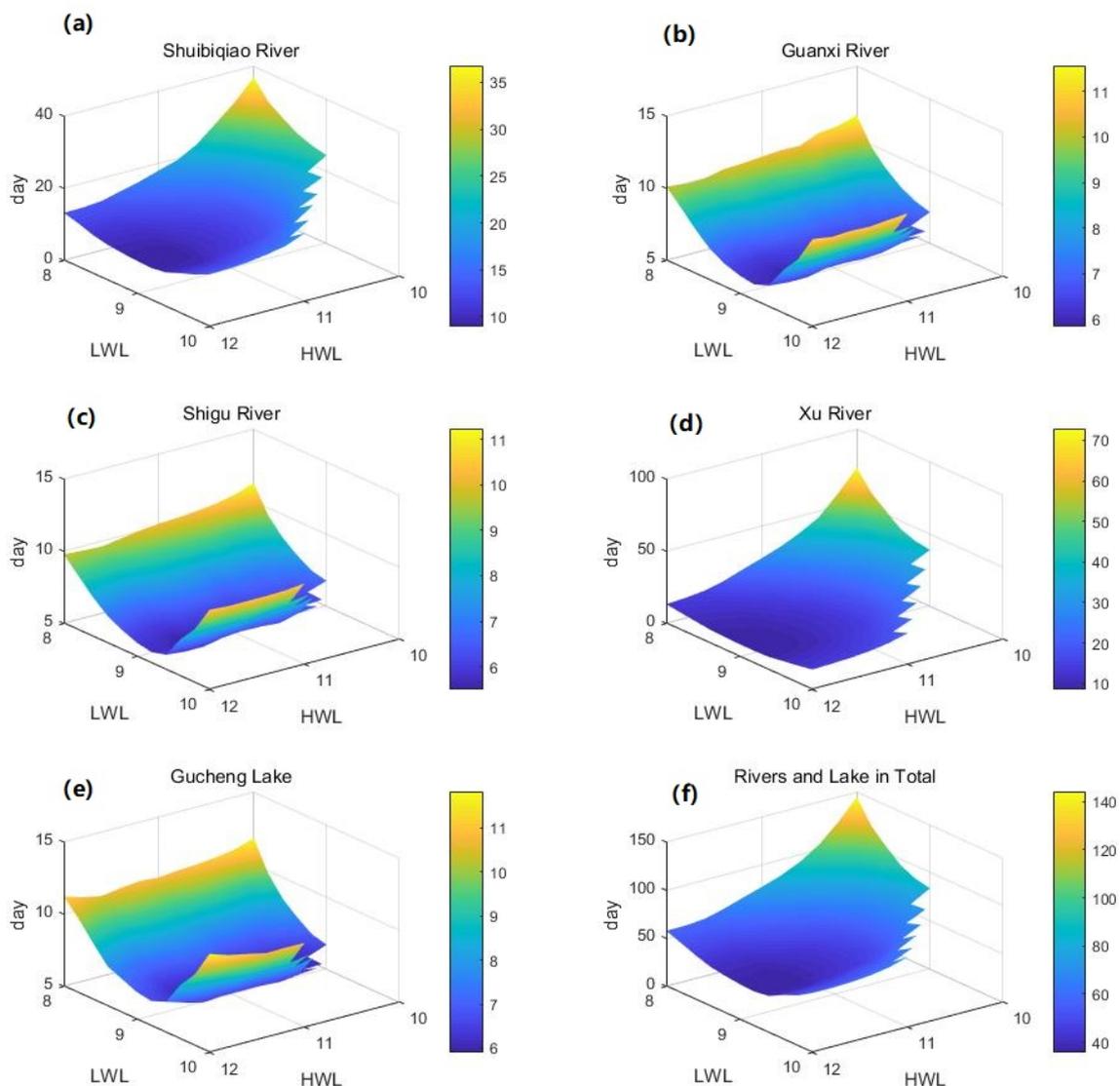


Figure 3. The mean annual days when the water level is higher than the maximum water level of the (a) Shuibiqiao River, (b) Guanxi River, (c) Shigu River, (d) Xu River, (e) Gucheng Lake and (f) Rivers and Lake in Total, under different regulation scenarios combined by LWL and HWL.

As can be seen from Figures 4 and 5, there is a significant correlation between the rain–flood resources utilizable potential and the annual rainfall in Gucheng Lake catchment area, and the linear correlation coefficient R^2 of the two is 0.451 ($n = 59$, $p < 0.001$). In general, the greater the annual rainfall, the greater the utilizable potential of the stormwater resources. Statistically, every increase of 1 mm in annual rainfall will increase the utilizable potential of the stormwater resources by 19,300 m³.

Results show that the utilizable potential of the rain–flood resources is high from March to August, which is mainly related to the high total rainfall during this period. However, the monthly difference in the utilizable potential of the rain–flood resources is not as great as the monthly difference in rainfall, which is mainly because a large amount of short-term heavy rainfall in the flood season often turns into flood water that must be discharged, and there are no conditions for the utilization of rain–flood resources.

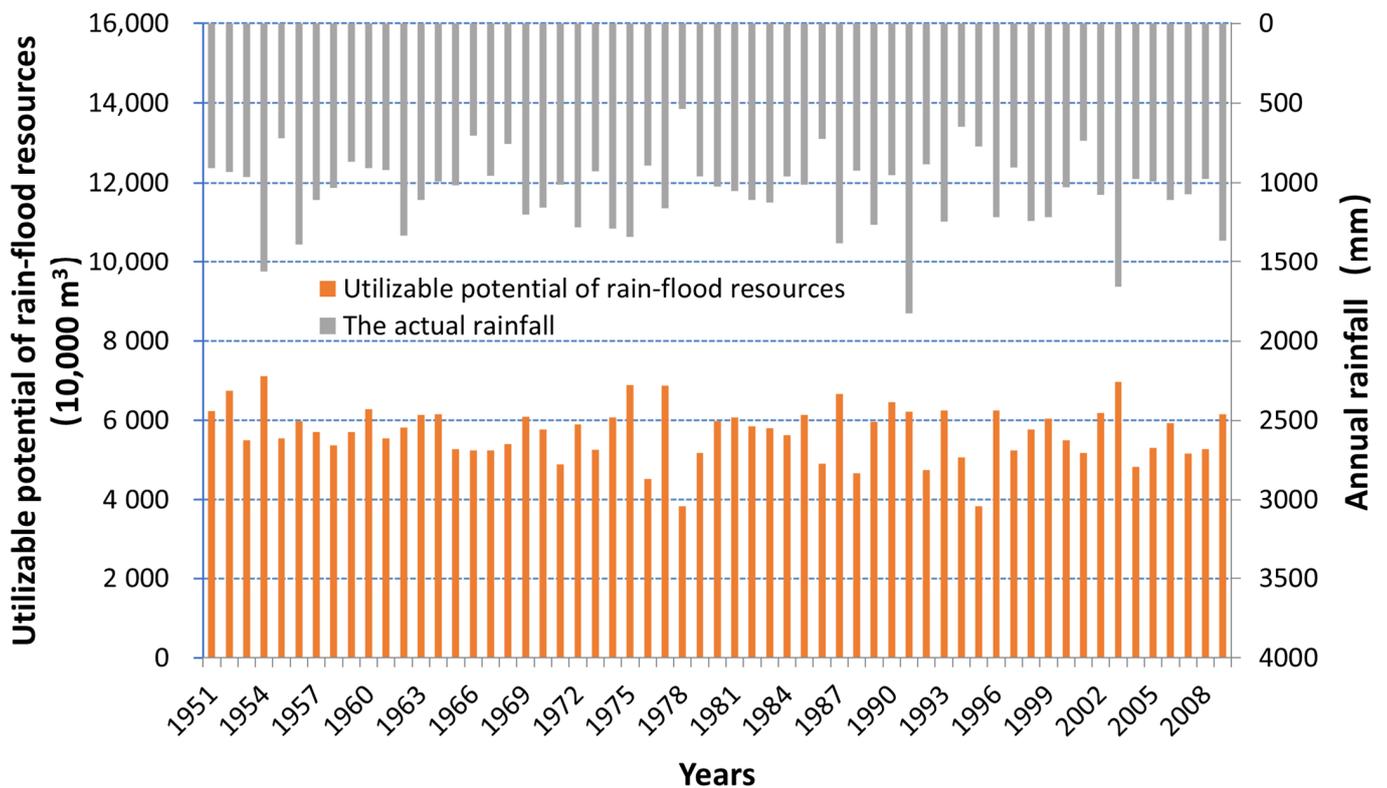


Figure 4. The annual rainfall and utilizable potential of rain–flood resources in Gucheng Lake catchment area.

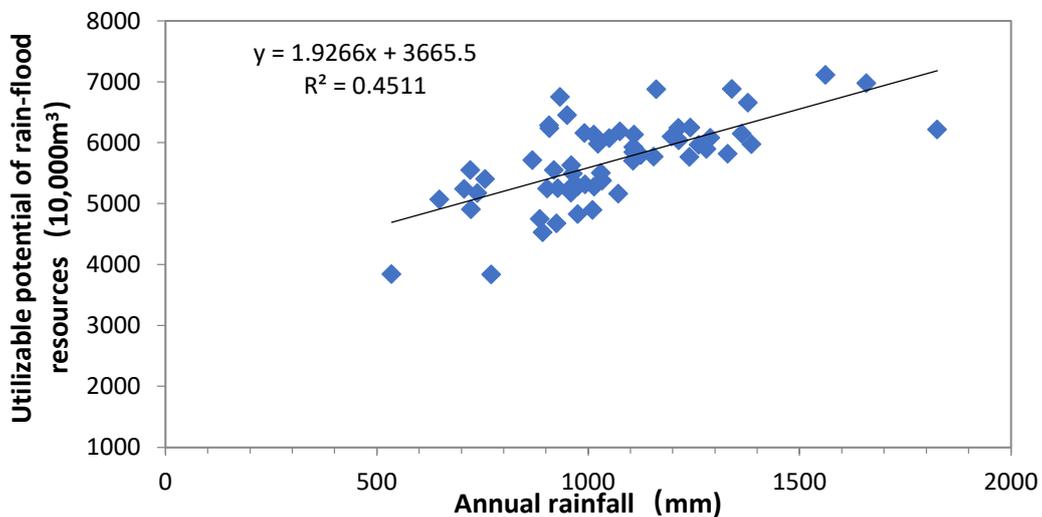


Figure 5. The relationship between the utilizable potential of rain–flood resources and rainfall.

3.3. The Comprehensive Benefit of Water Distribution Network

The years of 1991, 1982 and 1986 were selected as the typical examples of a wet year (5%), a normal year (50%) and a dry year (95%). The calculation results of optimal scheduling are shown in (Figures 6–9). It can be seen from the Figures that the water level of Gucheng Lake is stable within 8–12 m under the optimal dispatching condition, which not only meets the requirements of the ecological water level of the lake, but also ensures the flood control safety of the lake.

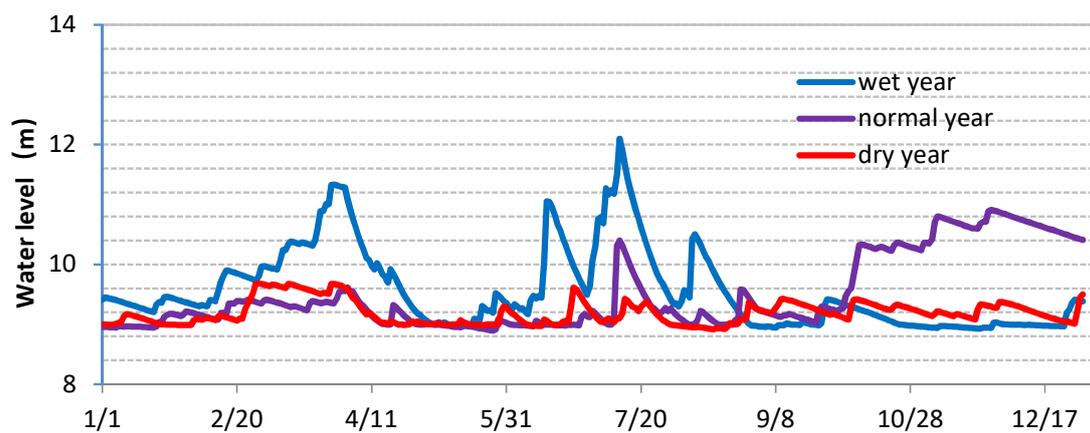


Figure 6. The water level variation of Gucheng Lake under optimal scheduling in wet, normal and dry years.

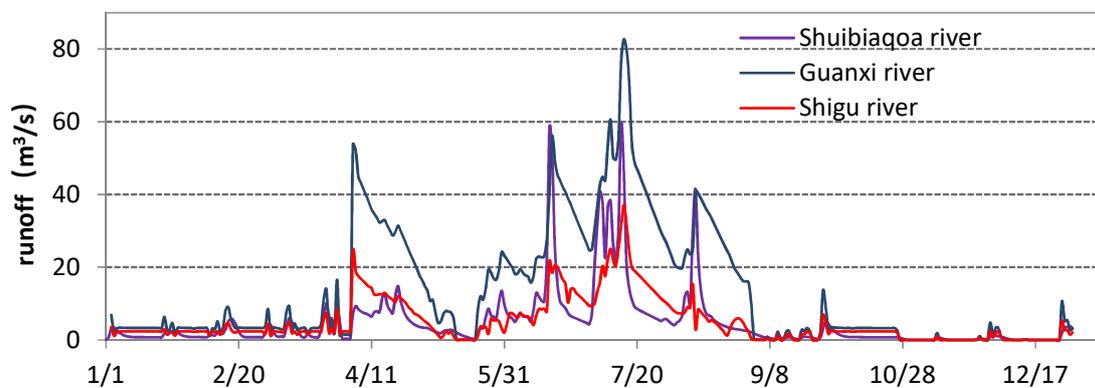


Figure 7. Runoff variation of river channels in a wet year (5%).

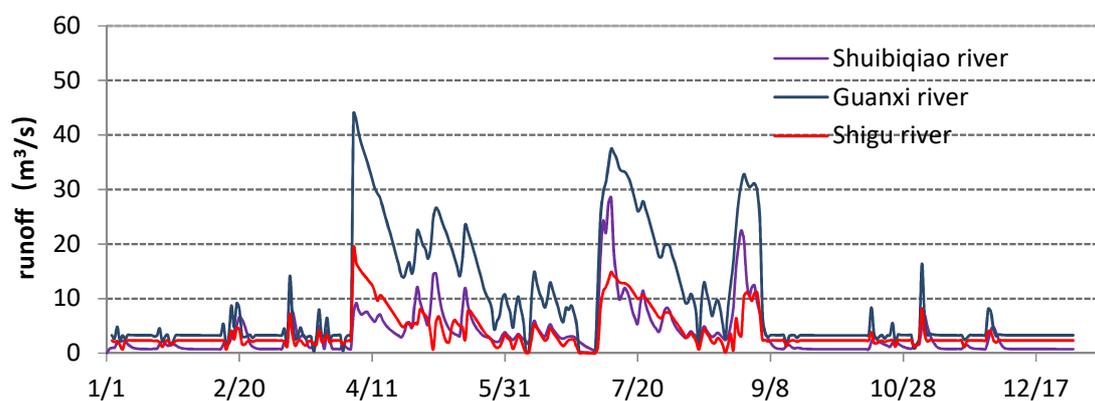


Figure 8. Runoff variation of river channels in a normal year (50%).

From the function of flood control regulation and storage, as shown in Figures 10–12, through the regulation and storage of runoff by lakes, a significant peak-cutting of the runoff effect has been achieved, and the proportion of runoff control in flood season in a wet year, a normal year and a dry year reaches 73.6%, 75.7% and 85.0% respectively.

In terms of water supply, although withdrawal of 100,000 m³/day has already been considered during the simulation, the water level of Gucheng Lake in wet, normal, dry years has always remained steady above the 8 m security level, which implies through optimized scheduling, the water distribution network can fully meet the demands of the urban and rural water supply of water and have the potential to be further expanded.

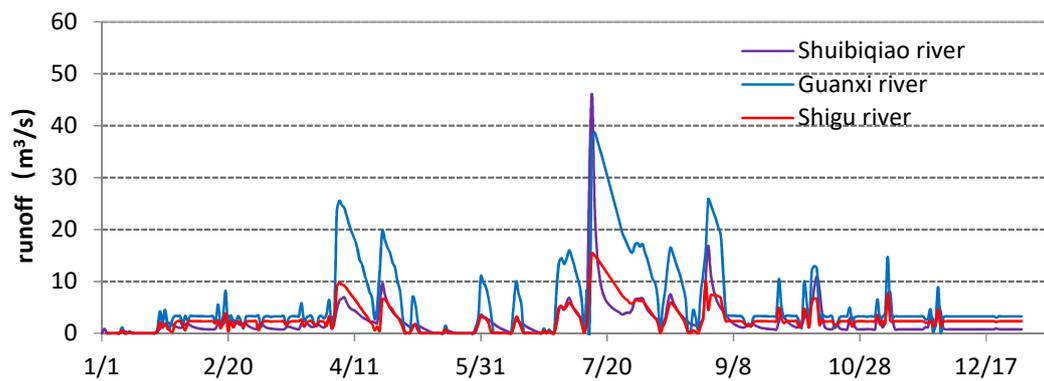


Figure 9. Runoff variation of river channels in a dry year (95%).

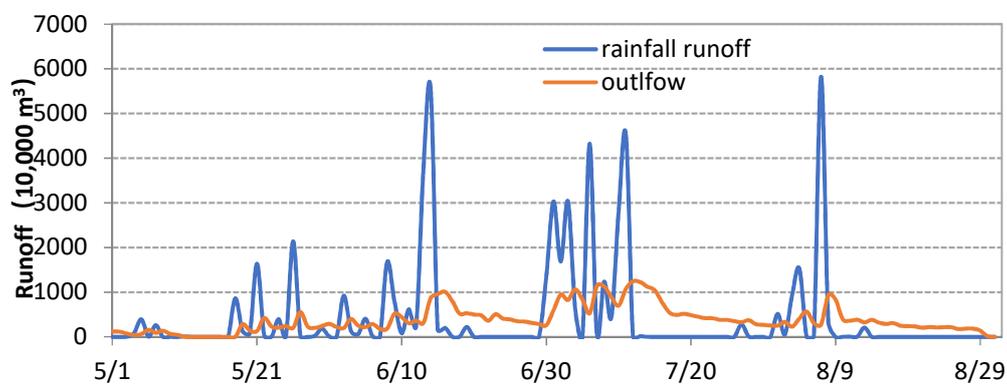


Figure 10. Comparison between daily rainfall runoff and outflow in the wet season (wet year, 5%).

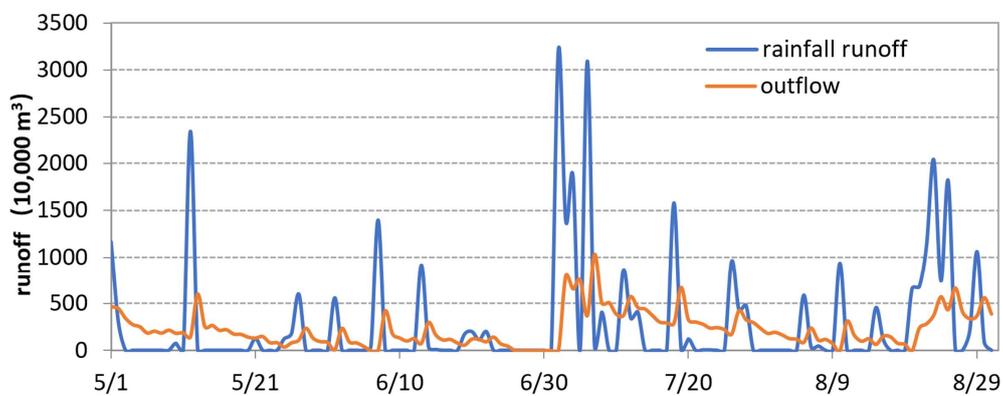


Figure 11. Comparison between daily rainfall runoff and outflow in the wet season (normal year, 50%).

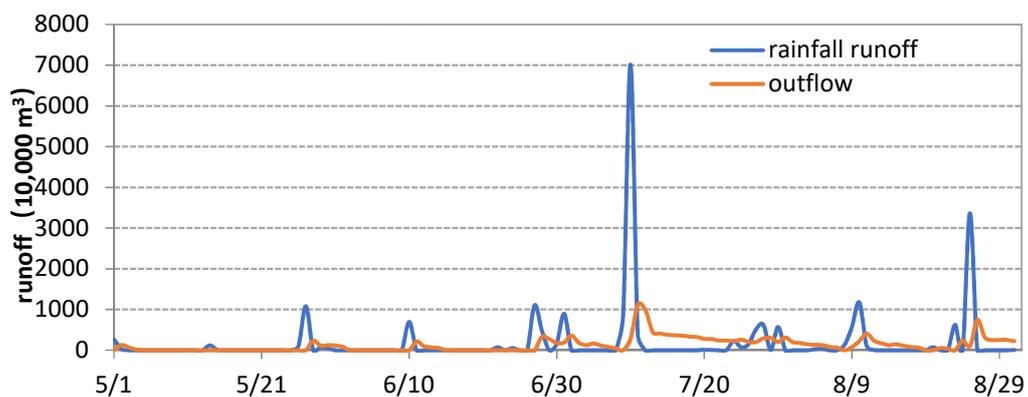


Figure 12. Comparison between daily rainfall runoff and outflow in the wet season (dry year, 95%).

From the perspective of ecological environment protection, the guaranteed rate of ecological flow in Guanxi River, Shigu River and Shuibiqiao River can be significantly improved by optimizing scheduling. By comparing and analyzing the water security of natural state and water distribution network, the guaranteed ecological flow rate of the Shuibiqiao River, Guanxi River and Shigu River in a normal year (50%) can be increased by 28.93%, 63.64% and 68.60%, respectively (Table 6).

Table 6. Ecological flow assurance rate comparative analysis table.

Status	Dry year (95%)			Wet Year (5%)			Normal Year (50%)		
	Shuibiqiao River	Guanxi River	Shigu River	Shuibiqiao River	Guanxi River	Shigu River	Shuibiqiao River	Guanxi River	Shigu River
Natural status	30.17%	21.90%	19.01%	31.82%	21.49%	18.18%	28.93%	19.42%	15.29%
After regulation	37.95%	40.00%	75.62%	40.41%	89.04%	82.19%	48.22%	98.63%	99.73%
Increment	7.78%	18.10%	56.61%	8.59%	67.55%	64.01%	19.29%	79.21%	84.44%

4. Conclusions and Suggestion

The water system of Gucheng Lake in Gaochun District is rich in water resources. However, due to urbanization construction and unreasonable water resource regulation, flooding in the new district cannot be effectively controlled, which not only causes the threat of floods, but also causes most of the rain–flood resources to be lost needlessly; meanwhile, the urban and rural water supply, ecological river and lake water are facing water resource shortages.

According to the simulation research, better regulation rules can bring more benefits, and a LWL of 9 m and a HWL of 12 m is the best combination in the field for flood control and ecological water demands. The utilizable potential of the annual average rain–flood resources of the Gucheng Lake catchment area reached 57 million m³. Through the construction of a water distribution network, taking Gucheng Lake as the core, the rain–flood resources in the flood season have been effectively controlled. The controlled rates of runoff in the flood season from May to August in a wet year, a normal year and a dry year reached 73.6%, 75.7% and 85.0% respectively. The guaranteed rate of ecological environment water in the Shuibiqiao River, Guanxi River and Shigu River can be improved by nearly 50%, on average. The demand for 100,000 m³/day for the urban and rural water supply is also effectively ensured.

It is recommended that the comprehensive utilization of water resources for an urban water distribution network can be achieved by taking rain–flood control and utilization into consideration, as suggested by this research, and should be further applied in other regions, which would be helpful to enhance the water-use efficiency in water-stressed cities.

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