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Research Article

Study of Water Resources Optimal Operation Model of Multireservoir: A Case Study of Kuitun River Basin in Northwestern China

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Aiming at the problems that need to be solved urgently in the current operation of a multireservoir in Kuitun River Basin, such as the uneven distribution of water resources in time and space, the large workload of manual operation calculation, and low coordination level, the paper takes the optimal operation of water resources in the basin as the main goal and carries out the research on the optimal operation model of the multireservoir in combination with the complex characteristics of local water resources system. Firstly, based on the generalization of hydraulic engineering in Kuitun River Basin, a water resources optimal operation model of the multireservoir is established and is solved by the graph theory. Then, the actual data of typical years were selected to test the model. The test results show that, compared with the actual water distribution, the water shortage rate of 2015 and 2016 in high flow years decreased by 98.57% and 100%, respectively; the water shortage rate of 2013 and 2014 in normal flow years decreased by 92.65% and 96.38%, respectively; and the water shortage rate of 2009 in a low flow year decreased by 87.78%. The model can provide the optimal operation scheme for the optimal operation of the multireservoir in the basin. And it can solve the problems such as the uneven distribution of water resources and the large workload of manual operation calculation and can provide technical support for the optimal operation of water resources of the multireservoir in Kuitun River Basin in the future.

1. Introduction

The function of reservoir operation is more and more prominent in the management of the multireservoir. How to maximize the function of reservoir has become one of the hot topics [1]. Formulating the optimal operation scheme of the multireservoir will become an effective method in operation and management of the multireservoir [2, 3]. At present, twelve reservoirs have been built in the Kuitun River Basin to solve various problems caused by the uneven distribution of water resources in time and space. However, the operation scheme of each reservoir was formulated only from the perspective of its own benefit, instead of the benefit of the whole multireservoir. The water resources of the multireservoir is always distributed according to the real-time situation and the experience, which is difficult to achieve optimal operation and resulted in unbalanced water supply and waste of water resources in the later stage. Therefore, in view of the present situation of the Kuitun River Basin, it is of great practical significance to study the optimal operation model of the multireservoir in this basin.

In recent years, scholars make a series of research and practices to study the optimal operation of the multireservoir. In general, connecting the scattered reservoirs into a whole: multireservoir, and comprehensively optimizing the multireservoir with different methods can improve the utilization rate of water resources and improve the overall regional benefit. Kumar et al. [4] used the simulation optimization method to optimize the operation of reservoirs in several basins of the Indian Peninsula. The study showed that the utilization efficiency of water resources was significantly improved when the reservoirs were united as one. Ye and He [5] put forward an optimal operation model of the multireservoir water supply based on particle swarm optimization. The results showed that the PSO algorithm and the new model could obtain reliable and efficient optimization results. Goor et al. [6] used the stochastic programming method to optimize the operation of the reservoir system in the east Nile River Basin. The optimized scheme increased the area of irrigation district by 5.5%. Yin et al. [7] put forward a general plan for the operation of large reservoirs in the Yangtze River Basin, which included the objectives, principles, and operation scheme of reservoir operation, and provided a comprehensive reference for the operation of large reservoirs in the future. Bai et al. [8] used the successive approximation method of dynamic programming to propose a synergistic benefit scheme for two key reservoirs in the Yellow River Basin during their operation in different situations. Li and Ouyang [9] proposed a generalized multiobjective flood control model (MOFCM) for joint optimal operation of cascade reservoirs in the lower reaches of the Jinsha River and the Three Gorges of Yangtze River, which realized the optimal operation of main and tributary reservoirs. Thechamani et al. [10] used nontime modeling methods to model and optimize the operation of the multireservoir in Chaoshan River Basin. Yekit [11] had formulated reservoir optimal operation strategies related to the Subak irrigation scheme water supply to support agricultural productivity at upstream, midstream, and downstream. Wang et al. [12] had carried out two sets of joint operation rules (JOR-I and JOR-II) for the multireservoir in Liaoning Province. The results showed that JOR-I was suitable for the operation of large reservoirs with large runoff and JOR-II was suitable for the operation of small reservoirs with small runoff, which provided guidance for the management of reservoir systems. At present, genetic algorithm, cuckoo algorithm, frog jump algorithm, and improved heuristic algorithm are the most popular optimization algorithms for the multireservoir, but the heuristic algorithm has many shortcomings such as low accuracy and instability. Zhou et al. [13] proposed a graph theory to solve the integration problem of the multireservoir and relationship; they applied it to the integration of the multireservoir flood forecasting and operation system, and it obtained good results. Based on the graph theory, the node graph is established, and the topological relationship among adjacency table, adjacency matrix, and correlation matrix can be used to effectively solve the water distribution problem between the multireservoir and irrigation districts.

2. Materials and Methods

2.1. Overview of the Study Area. The Kuitun River Basin is located in the southwestern margin of Junggar Basin on the northern slope of Tianshan Mountains, Xinjiang. It is bordered by Turgou and Bayingou River Basin in the east, Toto River Basin in the west, Kashi River Basin of Yili in the south, and the watershed of Mayierli Mountain and Zaire Mountain in the north [14]. Geographical coordinates are $83°22'00''$-$85°47'00''$ in the east longitude and $43°30'00''$-$45°04'00''$ in the north latitude. The main stream of Kuitun river is 360 km long, and the total area of the basin is $2.83 \times 10^4\,\text{km}^2$. The average temperature in this district is 7°C, the average temperature in January is -16°C, the average temperature in July is 26°C, the annual precipitation is 150~170 mm, and the annual evaporation is 1710~1930 mm.

The main stream of Kuitun River are composed of the Guertu river, Sikeshu river, and Kuitun river. The runoff of each river is greatly affected by seasons, and the interannual variation is small. The total annual runoff of the three rivers is about $1.256 \times 10^9\,\text{m}^3$, accounting for 80.9% of the total water in the Kuitun River Basin. At present, there are twelve both large and small reservoirs in the Kuitun River Basin, one large (2) type reservoir, six medium-sized reservoirs, and five small (2) type reservoirs (Figure 1).

2.2. Data Sources

2.2.1. Sources of Hydrological Data. All hydrological data used in this paper are from the Irrigation Management Department of Water Conservancy Project in Kuitun River Basin, Xinjiang.

2.2.2. Engineering Data Sources. All hydraulic engineering data used in this paper are from the Irrigation Management Department of Water Conservancy Project in Kuitun River Basin, Xinjiang, as shown in Table 1.

2.3. Model Construction. According to the actual situation of Kuitun River Basin, the multireservoir of Kuitun River Basin is generalized. On the premise of ensuring the ecological water use in the downstream of Kuitun River Basin, the optimal operation model of the multireservoir in Kuitun River Basin is established with the goal of minimizing the water shortage rate in the irrigation district by using the coordination decomposition theory of a large-scale system, and the physical model is transformed into mathematical model by graph theory and solved by computer.

2.3.1. General Thought of Model Construction. The hydraulic engineering in the study area is complex, and there are both series and parallel relationships between reservoirs. According to the relationship between supply and demand, it is divided into three subsystems, namely, subsystem 1, subsystem 2, and subsystem 3.

(i) Subsystem 1: the main water user is Liugou irrigation district. Its water supply sources are the Guertu river and Sikeshu river, and the upstream reservoir is Liugou reservoir.

(ii) Subsystem 2: the main water user is Chepaizi irrigation district. Its water supply sources are the Guertu river, Sikeshu river, and Kuitun river, and the upstream reservoirs are Liugou reservoir and Huanggou reservoir.

FIGURE 1: Schematic diagram of the multireservoir in Kuitun River Basin.

TABLE 1: The characteristic parameter of reservoirs.

Name of reservoir	L reservoir	K reservoir	C reservoir	H 1 reservoir	H 2 reservoir	Q reservoir
River	S river G river	K river	K river	K river	K river	K river
Normal water level (m)	373.10	318.00	308.68	344.50	362.00	417.50
Dead water level (m)	359.50	311.10	303.00	—	350.00	406.00
Total storage capacity (10^4 m^3)	10200	5000	4000	3220	2481	4000
Flood regulation storage capacity (10^4 m^3)	4900	1119	1000	200	500	721
Benefit storage capacity (10^4 m^3)	10200	5000	4000	1668	2481	4000
Dead storage capacity (10^4 m^3)	0	28	35	100	100	26

(iii) Subsystem 3: the main water user is Huanggou irrigation district. its water supply source is the Kuitun river, and the upstream reservoirs are Huanggou 1 reservoir and Huanggou 2 reservoir.

The subsystems are related to each other, and there is a feedback regulation relationship between the large-scale system and subsystems. So, the operation model of the whole system is established (Figure 2).

2.3.2. Multireservoir Combined Water Supply System. The series and parallel relationships between rivers and reservoirs in Kuitun River Basin are complex, by analyzing the hydraulic relationship between rivers and reservoirs, the characteristics of the water resources system in the basin are studied. The project is generalized by means of nodes and connections, and the relationship between various variables and parameters in the system is expressed by mathematical language and computer language to reflect the actual characteristics of the basin and the hydraulic relationship in the system. Finally, the reservoir is abstracted as a "point" element, and the water diversion and supply route are abstracted as a "line" element to form the joint commissioning node map of the multireservoir in Kuitun River Basin. The network simulation model of water distribution system is built, as shown in Figure 3.

According to water supply and demand, it is divided into three subsystems as shown in Figure 4.

In subsystem 1, the upstream Liugou reservoir and the downstream Dazimiao reservoir are connected in series to provide water distribution for Liugou irrigation district, and the Dazimiao reservoir only regulates the water distribution in Liugou irrigation district, so Liugou reservoir is chosen as the key reservoir. In subsystem 2, the water of Quangou reservoir can only meet 40%~60% of the water demand of other water users in Huanggou irrigation district, and Quangou reservoir basically does not supply water to Huanggou irrigation district. Huanggou 1 reservoir and Huanggou 2 reservoir supply water to Huanggou irrigation district in series. Huanggou 1 reservoir and Huanggou 2 reservoir are generalized as Huanggou reservoir, which is regarded as a key reservoir; Quangou reservoir and other water users are not considered. In subsystem 3, the midstream Kuitun reservoir and the downstream Chepaizi reservoir are connected in series to supply water to Chepaizi irrigation district, and Chepaizi reservoir only regulates the

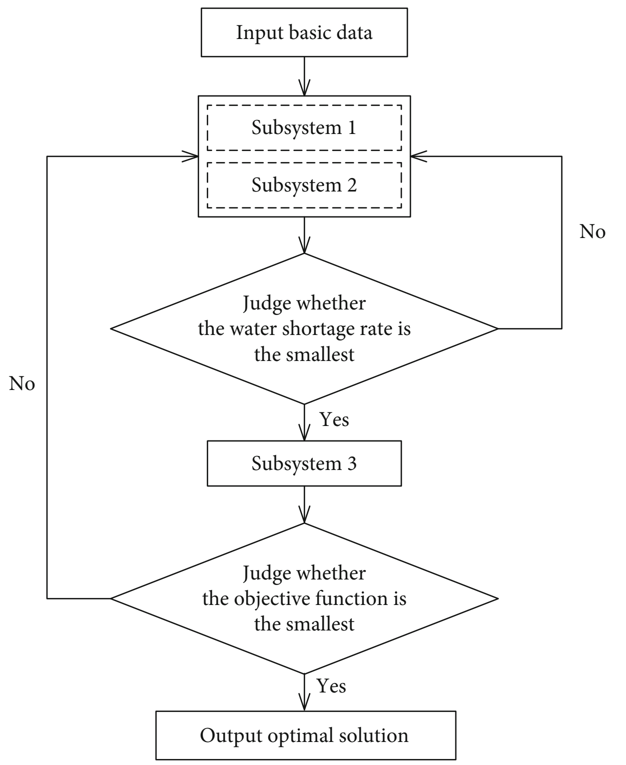

Figure 2: Flow chart for solving the model of optimal operation of reservoirs in Kuitun River Basin.

water distribution in Chepaizi irrigation district, so Kuitun reservoir is chosen as the key reservoir. The generalized node diagram of the multireservoir is shown in Figure 5.

2.3.3. Construction of Optimal Operation Model. Liugou reservoir and Kuitun reservoir in the multireservoir of Kuitun River Basin are river-blocking reservoirs, while the other reservoirs are plain reservoirs. There are special drainage channels for ecological water use near Liugou reservoir, so only Kuitun reservoir needs to consider the ecological base flow.

Dingwen Tian used the Tennant method to optimize the operation of a power station in Kuerle District of Xinjiang. The ecological base flow downstream of the dam was 10% of the average annual flow at the dam site [15]; Shuzhen Li put forward the rationality of discharging ecological base flow in different time periods under the condition that the total amount of ecological base flow remains unchanged and took Baiyanggou reservoir in Toudao as an example to illustrate its rationality [16]. According to the value of ecological base flow of many local reservoirs in Xinjiang and the situation of ecological water use in the downstream of Kuitun river, the ecological base flow is 10% of the average annual flow of the Kuitun reservoir.

(1) Water Supply Target of Irrigation District. Optimal operation of the multireservoir in Kuitun River Basin needs to meet the minimum requirements of agricultural water shortage in irrigation district, namely,

$$\min K_{ij} = \min \left\{ \frac{\mathrm{WD}_{ij} - \mathrm{WS}_{ij}}{\mathrm{WD}_{ij}} \right\}, \tag{1}$$

where K_{ij} represents the water distribution rate in the j month of the ith system, WS_{ij} represents the water supply in the j month of the ith system, and WD_{ij} represents the water demand in the j month of the ith system.

(2) Objective Function. Taking the minimum water shortage rate in the irrigation district of Kuitun River Basin as the objective function, it is divided into total objective function and subsystem objective function.

Total objective function:

$$\min f_m = \min \{\max (f_i)\}. \tag{2}$$

Among them, f_m represents the objective function and f_i represents the water shortage rate of the ith system.

In order to ensure that the water shortage rate of each irrigation district in the basin is the lowest and the whole water distribution is uniform, the total objective function is set as follows: In the same period, the largest water shortage rate of each irrigation district is the smallest, that is, the water shortage rate of each irrigation district is the smallest.

Subsystem objective function:

$$\min f_i(\mathrm{WS}_{ij}, \mathrm{WD}_{ij}) = \min \left\{ \frac{\mathrm{WD}_{ij} - \mathrm{WS}_{ij}}{\mathrm{WD}_{ij}} \right\}. \tag{3}$$

Among them, $i = 1, 2, 3$ are Liugou irrigation district, Huanggou irrigation district, and Chepaizi irrigation district, respectively.

(3) Constraint Conditions.

(1) Water balance constraint

$$V(t+1) = V(t) + (Q(m,t) - q(m,t)) \times \Delta t - S(m,t). \tag{4}$$

Among them, $S(m,t)$ is the loss of m reservoir in t period, $Q(m,t)$ is the reservoir inflow, $q(m,t)$ is the reservoir discharge flow, $Q(m,t) = I(m,t) + Y(m,t)$, $I(m,t)$ is the amount of water transferred from the upstream reservoir to m reservoir in t period, $Y(m,t)$ is the water intake of the river in t period, $q(m,t) = Q(m+1,t) + X(m,t)$, where $X(m,t)$ is the amount of water supply to m reservoir in t period.

(2) Storage constraint

$$V_{\min}(m,t) < V(m,t) < V_{\max}(m,t). \tag{5}$$

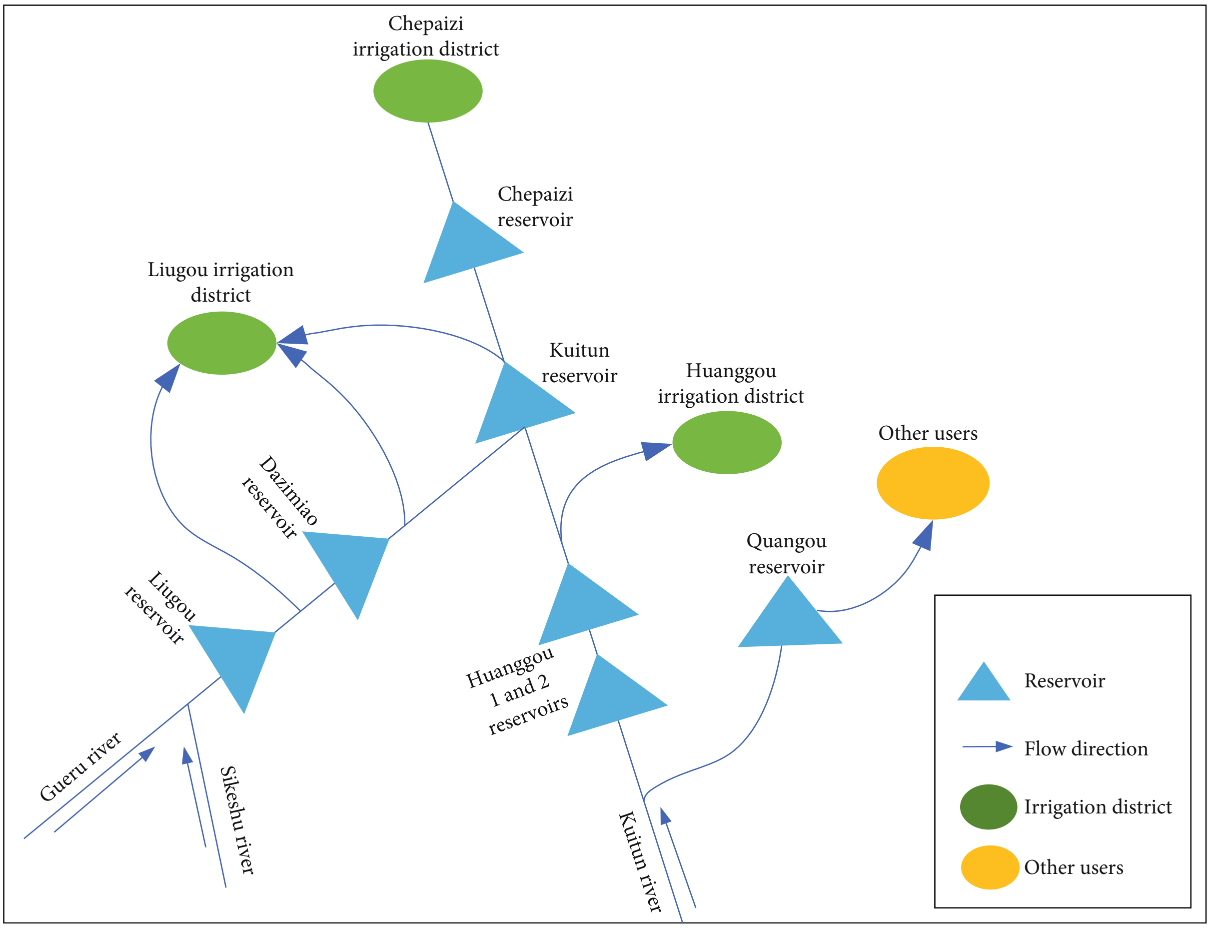

Figure 3: The reservoir regulation node graph.

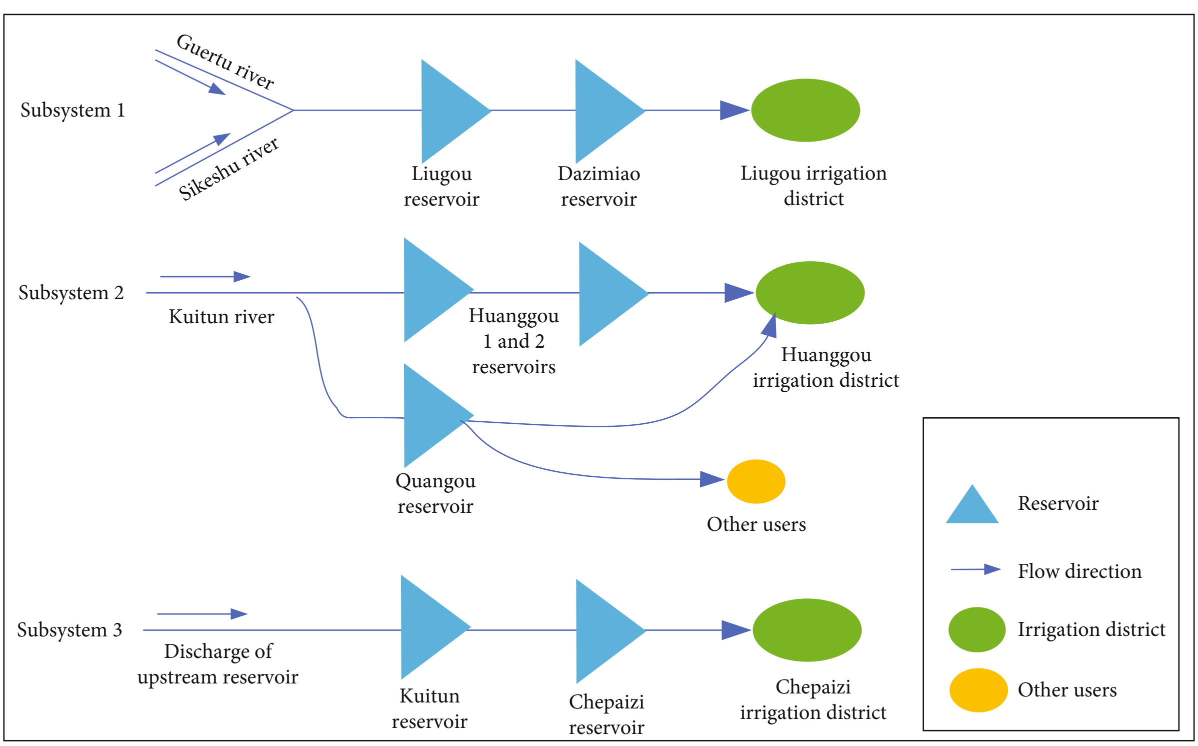

Figure 4: Summary schematic of subsystems.

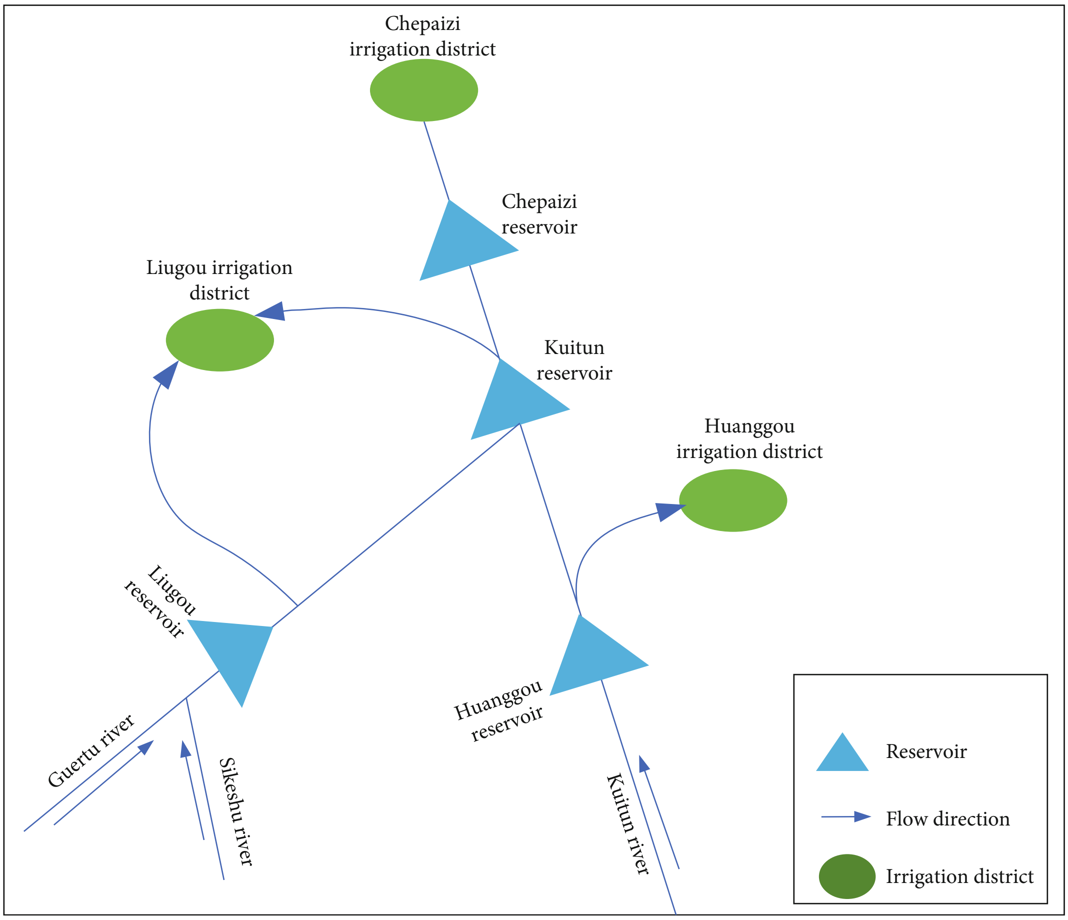

FIGURE 5: Summary diagram of joint operation nodes of the multireservoir.

Among them, $V(m, t)$, $V_{\max}(m, t)$, and $V_{\min}(m, t)$ are the storage capacity, the maximum allowable storage capacity, and the minimum allowable storage capacity of m reservoir in t period.

(3) Water level constraint

$$Z_{\min}(m, t) < Z(m, t) < Z_{\max}(m, t). \tag{6}$$

Among them, $Z(m, t)$, $Z_{\max}(m, t)$, and $Z_{\min}(m, t)$ are the water level of m reservoir in t period, normal water level, and dead water level.

(4) Channel diversion flow constraint

$$Q(m, t) < q. \tag{7}$$

Among them, $Q(m, t)$ represents inflow; q is the ability of the channel to divert water into the warehouse.

(5) Ecological base flow constraint

$$q(t) > Q_{\min}(t). \tag{8}$$

Among them, $q(t)$ is the discharge flow at the end of t period of Kuitun reservoir; $Q_{\min}(t)$ is the minimum discharge flow of Kuitun reservoir, which is the ecological base flow.

(6) Nonnegative constraint: all variables are not negative

2.4. Solution for Model

2.4.1. Solution Method. The basic idea of graph theory is that the whole multireservoir operation system is regarded as an organic whole connected by nodes with different attributes. The attributes of nodes are determined by the node type. There are two types of nodes: inflow and outflow.

(1) Node Graph Model. The inflow types of nodes including (1) runoff prediction, (2) diversion from upstream rivers, (3) depending on outflow of upstream nodes, (4) the superposition of multi-inflow (set this type to reduce data redundancy), and (5) other types (used to expand the attributes of nodes).

The outflow types of nodes including (1) reckoning from reservoir, (2) reckoning from reservoir operation, (3) reckoning from downstream water demand, and (4) other types (used to expand the attributes of nodes).

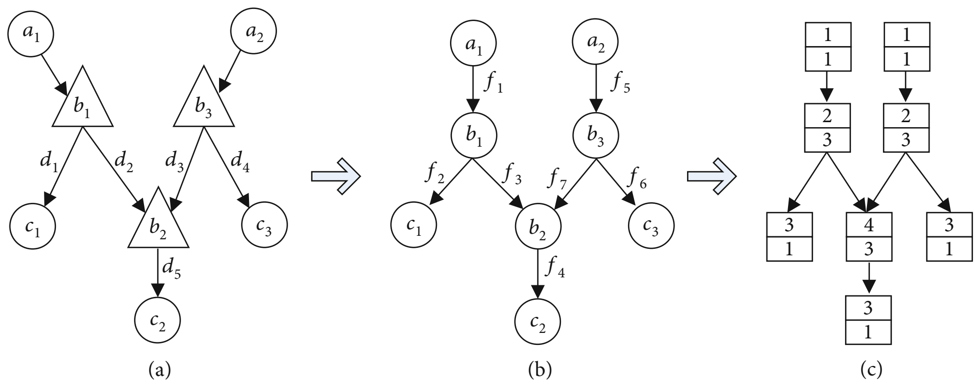

Figure 6: Optimal operation model of reservoirs in Kuitun River Basin based on graph theory.

The inflow types and outflow types of a node not only determines the attributes of the node itself but also the relationships between nodes, which forms the basis of system integration.

In the optimal operation model of the multireservoir of Kuitun River Basin based on graph theory (Figure 6): a_1 represents the total amount of water from the Guertu river and the Sikeshu river, and a_2 represents the total amount of water from the Kuitun river. b_1, b_2, and b_3 represent Liugou reservoir, Kuitun reservoir, and Huanggou reservoir, respectively. c_1, c_2, and c_3 represent Liugou irrigation district, Chepaizi irrigation district, and Huanggou irrigation district, respectively. In Figure 6(c), the number above the square is the inflow type, and the number below the square is the outflow type. The model of the subsystem $1\sim3$ based on the graph theory are shown in Figures 7–9.

Subsystem 1: Liugou irrigation district.

Subsystem 2: Huanggou irrigation district.

Subsystem 3: Chepaizi irrigation district.

(2) Digital Connotation of Node Graph. The 2-tuple consisted of the point set $P=\{p_1, p_2, \cdots, p_n\}$ and the unordered edge set $F=\{f_1, f_2, \cdots, f_m\}$ are denoted as $G=(P, F)$. The p_i element in P is called the vertex and the f_j element in F is called the edge. If p_i to p_j is directed, it is called the directed graph, and the directed edge is denoted as $<p_i, p_j>$; otherwise, it is an undirected graph and an undirected edge is denoted as (p_i, p_j).

It is particularly important for computer to describe geometric figures with graph $G=(P, F)$. There are three main ways of representing the graph: adjacency table, adjacency matrix, and correlation matrix. The adjacency table is more convenient and faster for the database to save operation data.

(1) Adjacency table

The results of Figures 6(b)–9(b) denoted by the adjacency table are shown in Table 2.

(2) Adjacency matrix

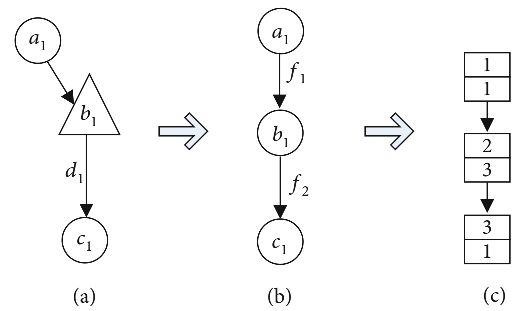

Figure 7: Model of subsystem 1 based on graph theory.

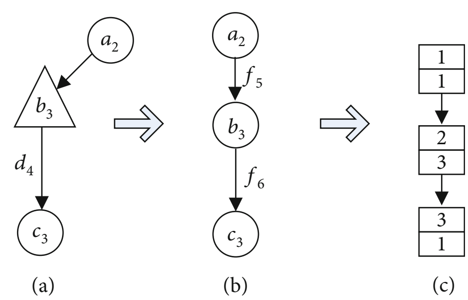

Figure 8: Model of subsystem 2 based on graph theory.

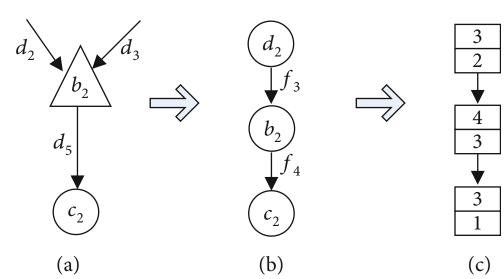

Figure 9: Model of subsystem 3 based on the graph theory.

Figure 7(b) is denoted by adjacency matrix A. Figure 8(b) is denoted by adjacency matrix B. Figure 9(b) is denoted by the adjacency matrix C. The adjacency matrices A, B, and C are as follows:

Table 2: Adjacency table of the system node graph.

Object	Subsystem 1		Subsystem 2		Subsystem 3		Whole system						
Line	f_1	f_2	f_5	f_6	f_3	f_4	f_1	f_2	f_3	f_4	f_5	f_6	f_7
Upstream node	a_1	b_1	a_2	b_3	d_2	b_2	a_1	b_1	b_1	b_2	a_2	b_3	b_3
Downstream node	b_1	c_1	b_3	c_3	b_2	c_2	b_1	c_1	b_2	c_2	b_3	c_3	b_2

$$A=\begin{array}{c} \\ a_1 \\ b_1 \\ c_1 \end{array}\begin{array}{c} \begin{array}{ccc} a_1 & b_1 & c_1 \end{array} \\ \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \end{array}, B=\begin{array}{c} \\ a_2 \\ b_3 \\ c_3 \end{array}\begin{array}{c} \begin{array}{ccc} a_2 & b_3 & c_3 \end{array} \\ \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \end{array}, C=\begin{array}{c} \\ d_2 \\ b_2 \\ c_2 \end{array}\begin{array}{c} \begin{array}{ccc} d_2 & b_2 & c_2 \end{array} \\ \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \end{array}. \tag{9}$$

(3) Correlation matrix

Figure 7(b) is denoted by the correlation matrix D. Figure 8(b) is denoted by correlation matrix E. Figure 9(b) is denoted by the correlation matrix F. The correlation matrices D, E, and F are as follows:

$$D=\begin{array}{c} \\ a_1 \\ b_1 \\ c_1 \end{array}\begin{array}{c} \begin{array}{cc} f_1 & f_2 \end{array} \\ \begin{bmatrix} 1 & 0 \\ -1 & 1 \\ 0 & -1 \end{bmatrix} \end{array}, E=\begin{array}{c} \\ a_2 \\ b_3 \\ c_3 \end{array}\begin{array}{c} \begin{array}{cc} f_5 & f_6 \end{array} \\ \begin{bmatrix} 1 & 0 \\ -1 & 1 \\ 0 & -1 \end{bmatrix} \end{array}, F=\begin{array}{c} \\ d_2 \\ b_2 \\ c_2 \end{array}\begin{array}{c} \begin{array}{cc} f_3 & f_4 \end{array} \\ \begin{bmatrix} 1 & 0 \\ -1 & 1 \\ 0 & -1 \end{bmatrix} \end{array}. \tag{10}$$

2.4.2. Typical Year Selection and Optimal Operation Criteria

(1) Determination of the Typical Year. It has to consider that the optimal operation model of the multireservoir in Kuitun River Basin should be in line with the current situation of water conservancy projects in the basin as far as possible. Therefore, the typical year is selected only in recent years. The selected results are as follows: three high flow years, 2015, 2016, and 2017; two normal flow years, 2013 and 2014; and one low flow year, 2009.

(2) Optimal Operation Criteria. The reservoir water supply in Kuitun River Basin is mainly used for irrigation in every irrigation district, the irrigation period is from April to November every year; April, May, and June are spring irrigation; July and August are summer irrigation; September, October, and November are autumn and winter irrigation.

(1) Crop water requirement: based on the annual temperature, precipitation, and crop water requirement characteristics, in order to improve crop yield, the water supply of the basin in June, July, and August should be guaranteed to the greatest extent.

(2) Reservoirs regulation and storage period: the water supply period of reservoirs is from April to November, and the water storage period of reservoirs is from December to March of the next year.

(3) Starting and regulating capacity of reservoir operation: according to the starting and regulating capacity of reservoirs over the years, in combination with the water inflow from December to March of the next year to comprehensively consider, the Liugou reservoir starting and regulating capacity is 9.324×10^4 m^3, the Kuitun river reservoir starting and regulating capacity is 5.417×10^4 m^3, and the Huanggou reservoir starting and regulating capacity is 3.549×10^4 m^3.

2.4.3. Model Test. The optimal operation calculation of the multireservoir in Kuitun River Basin can be carried out by using the adjacency table representation with the nonforward vertex-first topological ordering method. The main idea of this method is as follows: define a stack T to hold the sequence of nodes and select the most upstream node from the node adjacency table, as shown in Figure 7(a) with nodes b_1 and a_1. The node p_i is put into the stack T, and all edges of p_i and p_i are deleted from G_{z0}. The above selection and deletion are repeated until there are no nodes. Finally, stack T saves the topological sequence of subgraph G_{z0}. When c_1 is selected as the working node in Figure 7(b), the calculation sequence of nodes is a_1, b_1, and c_1. When c_3 is selected as the working node in Figure 8(b), the calculation sequence of nodes is a_2, b_3, and c_3. When c_2 is selected as the working node in Figure 9(b), the calculation sequence of nodes is d_2, d_3, b_2, and c_2.

According to the inflow type and outflow type of each node and the parameter settings of each node set in advance, the system chooses the corresponding calculation model for calculation. The subsystems feedback to each other, and the node sequence that meets the objective function is determined; finally, it is recorded in the water resources optimal operation database of the multireservoir in Kuitun River Basin in turn and output the optimal operation scheme. We take 2017 as an example, see Table 3.

3. Results

According to the principles of water diversion and irrigation district water supply, the annual water demand of each irrigation district can be maximized, and the water supply in June, July, and August can be guaranteed.

Table 3: Results of optimal operation of the multireservoir in Kuitun River Basin in 2017.

Node	4	5	6	7	8	9	10	11
a_1	1472.00	2513.00	5121.00	4684.00	6526.00	6024.00	1477.00	877.00
b_1	684.00	682.00	3590.65	12488.96	8903.94	999.00	48.00	35.00
c_1	684.00	842.00	2507.00	4336.00	3266.00	999.00	48.00	35.00
a_2	379.00	2126.00	3125.00	4928.00	4398.00	2600.00	509.00	420.00
b_3	1246.00	659.00	3125.00	4928.00	4398.00	2600.00	509.00	420.00
c_3	1246.00	499.00	2589.00	4110.00	3120.00	93.00	290.00	187.00
b_2	2073.32	1192.88	4798.33	9417.66	6915.94	746.05	580.72	61.94
c_2	2022.00	1140.00	4768.00	9385.00	6886.00	725.00	550.00	9.00

Table 4: Results of annual water shortage in each irrigation district in high flow years.

Month		L irrigation district			C irrigation district			H irrigation district		
		2015	2016	2017	2015	2016	2017	2015	2016	2017
Sp irrigation	4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	6	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Su irrigation	7	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	8	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
A and W irrigation	9	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	10	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	0.01%	0.00%	0.00%	0.01%	0.00%	0.00%	0.01%	0.00%	0.00%

Table 5: Minimum discharge of reservoirs in high flow years (unit: 10^4 m^3).

Month		4	5	6	7	8	9	10	11
2015	L reservoir	866.42	827.88	9045.62	13393.90	9683.25	2382.52	5199.94	3285.30
	H reservoir	1448.32	1028.62	3706.40	5438.57	7324.12	331.61	2413.88	2108.88
	K reservoir	2244.90	1586.35	7066.42	9809.10	9077.79	1463.95	3926.88	3030.39
2016	L reservoir	1011.75	322.64	4926.43	6718.60	4646.96	1657.31	1360.37	1896.18
	H reservoir	1306.25	138.24	3721.20	3293.95	2590.14	537.23	1143.15	1731.93
	K reservoir	2290.47	313.28	3751.53	7132.96	5840.14	1807.62	1667.94	1512.79
2017	L reservoir	684.00	682.00	3590.65	12488.96	8903.94	999.00	48.00	35.00
	H reservoir	1246.00	659.00	3125.00	4928.00	4398.00	2600.00	509.00	420.00
	K reservoir	2073.32	1192.88	4798.33	9417.66	6915.94	746.05	580.72	61.94

Table 6: Minimum inflow of Kuitun reservoir in high flow years (unit: 10^4 m^3).

Month	4	5	6	7	8	9	10	11
2015	0.00	0.00	6304.47	9809.10	9077.79	1463.95	3926.88	2994.95
2016	0.00	61.74	2367.93	3499.98	2534.30	558.28	1173.87	1784.87
2017	0.00	1903.00	2066.35	8970.96	6915.94	2507.00	219.00	233.00

3.1. Optimal Results of High Flow Year

3.1.1. Water Shortage Rate of Each Irrigation District after Optimization. After the optimal operation calculation of the optimal model, the water shortage rate of each irrigation district decreases significantly in high flow years of 2015, 2016, and 2017. The specific results are shown in Table 4.

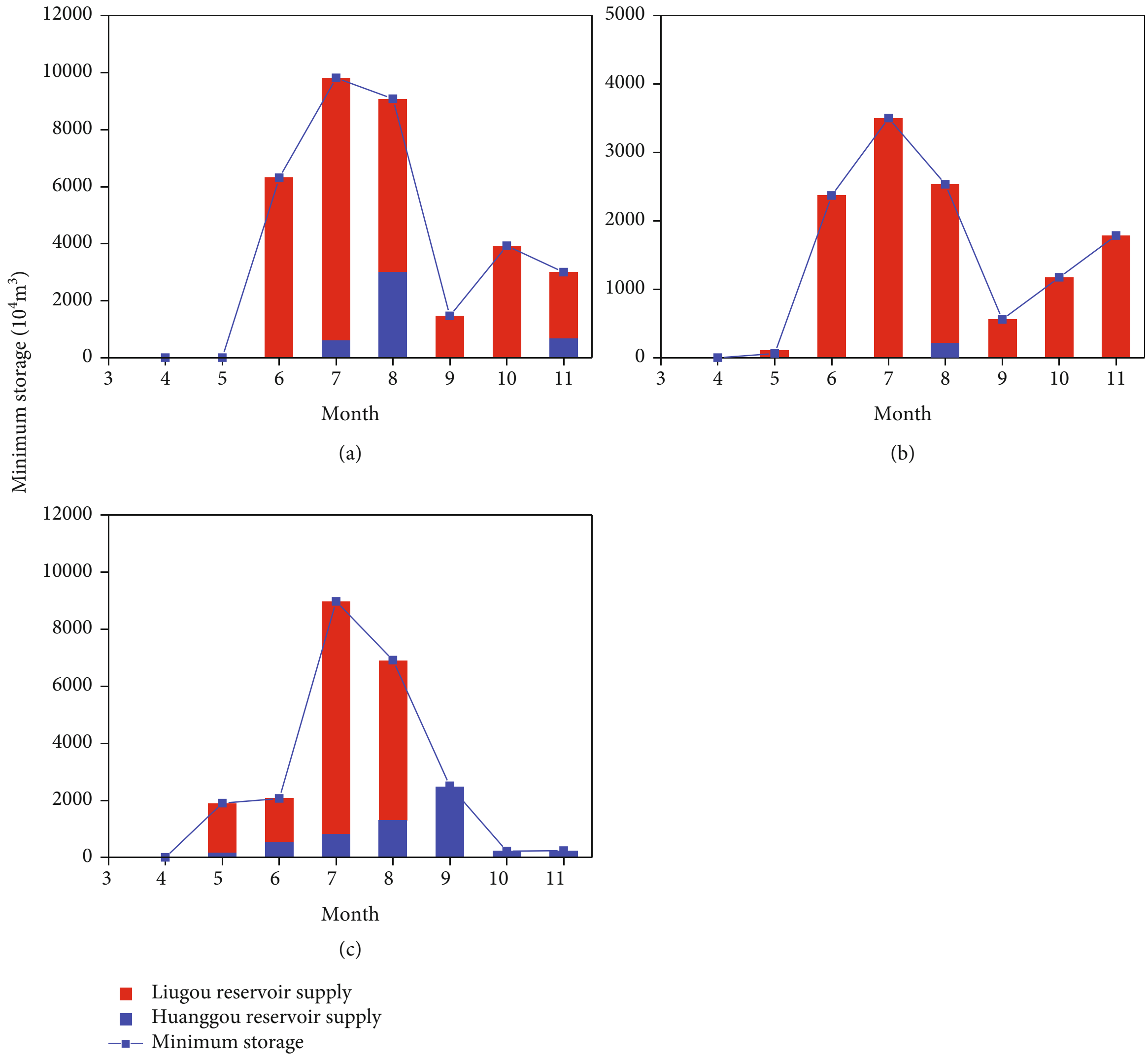

Figure 10: Minimum inflow and supply distribution diagram of Kuitun reservoir: (a) 2015, (b) 2016, and (c) 2017.

3.1.2. Regulation and Storage Process under the Upstream Reservoir Discharges according to the Minimum Discharge Flow (Taking Huanggou Reservoir as an Example)

(1) Minimum discharge is shown in Table 5

(2) The minimum inflow of Kuitun reservoir is shown in Table 6

It can be seen from the change of minimum inflow and supply distribution diagram of Kuitun reservoir in Figure 10, when Huanggou reservoir discharges according to the minimum discharge flow: The minimum inflow of Kuitun reservoir in high flow years of 2015, 2016, and 2017 is the largest in July, followed by August and the smallest in April. In July, August, and November 2015, Huanggou reservoir and Liugou reservoir jointly provide water supply for Kuitun reservoir. In August 2016, Huanggou reservoir independently provide water supply for Kuitun reservoir. From May to November 2017, Kuitun reservoir needed Huanggou reservoir and Liugou reservoir to jointly provide water supply.

(3) Storage capacity change curve of the multireservoir operation

It can be seen from the storage capacity change curve of the multireservoir operation in Figure 11, when Huanggou reservoir supply water with minimum discharge: From July to August in high flow years of 2015, 2016, and 2017, the irrigation district has the largest water demand, and the regulation capacity of Liugou reservoir and Kuitun reservoir is basically close to the dead storage capacity; after September, the water supply decreases and the upstream reservoir begins to store water; Huanggou irrigation district only needs Huanggou reservoir for water supply, and the reservoir capacity is the lowest in August and November.

3.2. Optimal Results of Normal Flow Year

3.2.1. Water Shortage Rate of Each Irrigation District after Optimization. After the optimal operation calculation of the optimal model, the water shortage rate of each irrigation

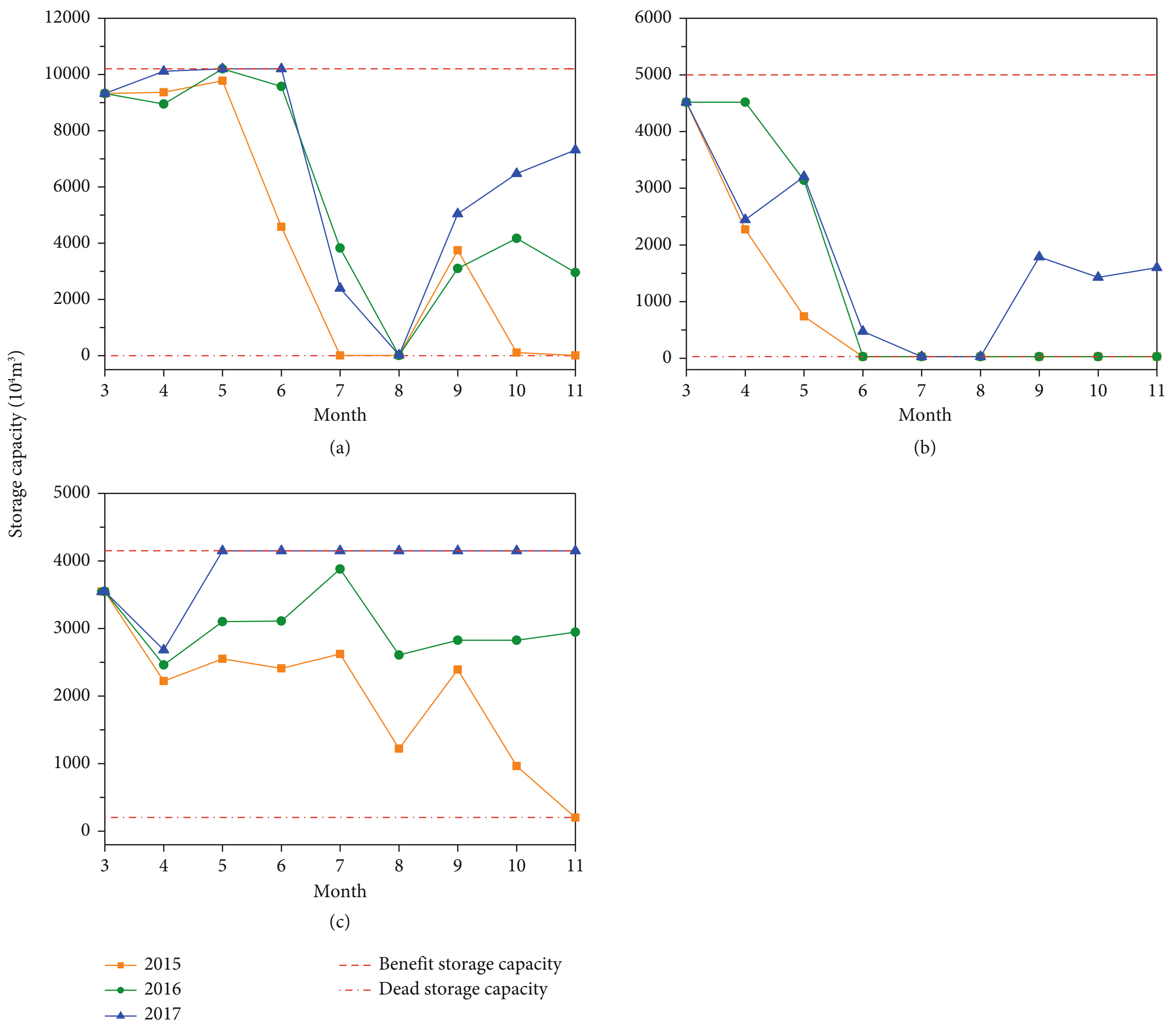

Figure 11: Storage capacity change curve of the multireservoir: (a) L reservoir, (b) K reservoir, and (c) H reservoir.

district decreases significantly in the normal flow years in 2013 and 2014. The specific results are shown in Table 7.

3.2.2. Regulation and Storage Process under the Upstream Reservoir Discharges according to the Minimum Discharge Flow (Taking Huanggou Reservoir as an Example)

(1) Minimum discharge is shown in Table 8

(2) The minimum inflow of Kuitun reservoir is shown in Table 9

It can be seen from the change of minimum inflow and supply distribution diagram of Kuitun reservoir in Figure 12, when Huanggou reservoir discharges according to the minimum discharge flow: In the normal flow year 2013, the minimum inflow of Kuitun reservoir is the largest in July, followed by September, slightly lower in August than in September, and the minimum is 0 in April and May. In the normal flow year 2014, the minimum inflow of Kuitun reservoir is the largest in July, followed by August, and the minimum in April and May was 0. In the normal flow year 2013, Liugou reservoir independently provide water supply for Kuitun reservoir. In the normal flow year 2014, Huanggou reservoir and Liugou reservoir jointly provide water supply for Kuitun reservoir in August, September, and October.

(3) Storage capacity change curve of the multireservoir operation

It can be seen from the storage capacity change curve of the multireservoir operation in Figure 13, when Huanggou reservoir supply water with minimum discharge: In July in the normal flow year 2013, Liugou reservoir, Kuitun reservoir, and Huanggou reservoir have the smallest reservoir capacity. In August in the normal flow year 2014, Liugou reservoir, Kuitun reservoir, and Huanggou reservoir have

Table 7: Results of annual water shortage in each irrigation district in normal flow years.

Month		L irrigation district 2013	L irrigation district 2014	C irrigation district 2013	C irrigation district 2014	H irrigation district 2013	H irrigation district 2014
Sp irrigation	4	0.00%	2.50%	0.00%	2.50%	0.00%	2.50%
	5	0.00%	4.00%	0.00%	4.00%	0.00%	4.00%
	6	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Su irrigation	7	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	8	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
A and W irrigation	9	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	10	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	11	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 8: Minimum discharge of reservoirs in normal flow years (unit: $10^4\,m^3$).

Month		4	5	6	7	8	9	10	11
2013	L reservoir	848.17	572.47	2138.13	7941.54	6770.27	3871.19	3011.00	1985.00
	H reservoir	1415.18	375.77	2950.91	4296.61	3447.70	11.55	1042.19	675.22
	K reservoir	1393.24	437.06	3267.19	7861.53	6857.91	3653.17	3204.22	2911.99
2014	L reservoir	606.36	1018.41	2297.28	8569.55	4300.87	1515.62	759.08	1828.69
	H reservoir	1199.93	839.42	2660.37	4095.62	5637.73	1789.19	1711.28	796.28
	K reservoir	1402.95	957.37	2913.69	4607.40	3452.97	1204.62	1740.77	1237.68

Table 9: Minimum inflow of Kuitun reservoir in normal flow years (unit: $10^4\,m^3$).

Month	4	5	6	7	8	9	10	11
2013	0.00	0.00	434.06	3748.85	3428.95	3591.70	2169.40	1249.91
2014	0.00	0.00	680.81	4607.40	3452.97	1204.62	1740.77	1237.68

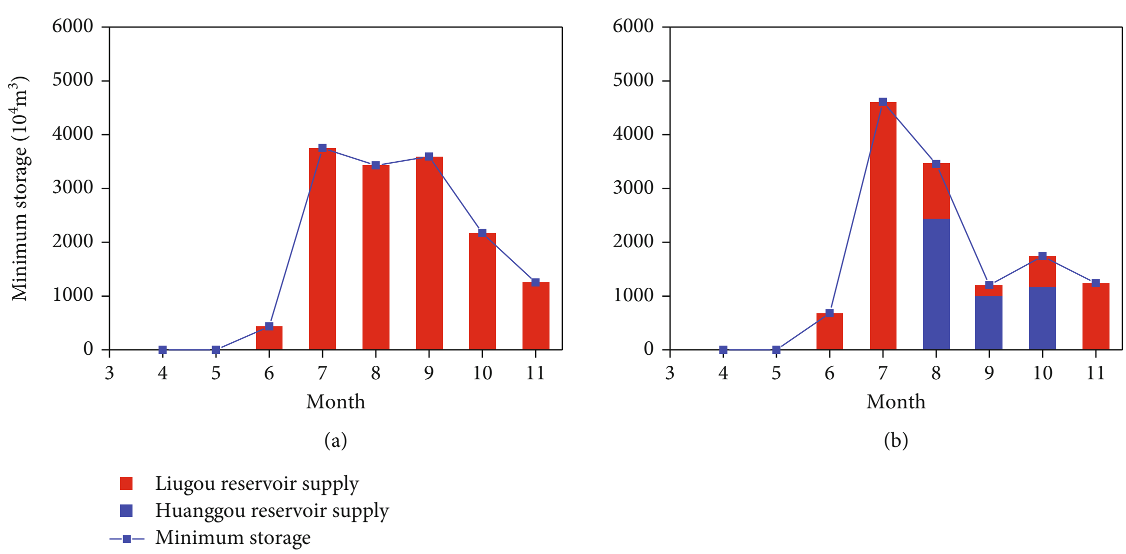

Figure 12: Minimum inflow and supply distribution diagram of the Kuitun reservoir: (a) 2013 and (b) 2014.

the smallest reservoir capacity; Liugou reservoir is close to dead storage capacity from July to November; and Kuitun reservoir is dead water level from June to November; The storage capacity of Liugou reservoir, Kuitun reservoir, and Huanggou reservoir in November in normal flow years 2013 and 2014 are the maximum.

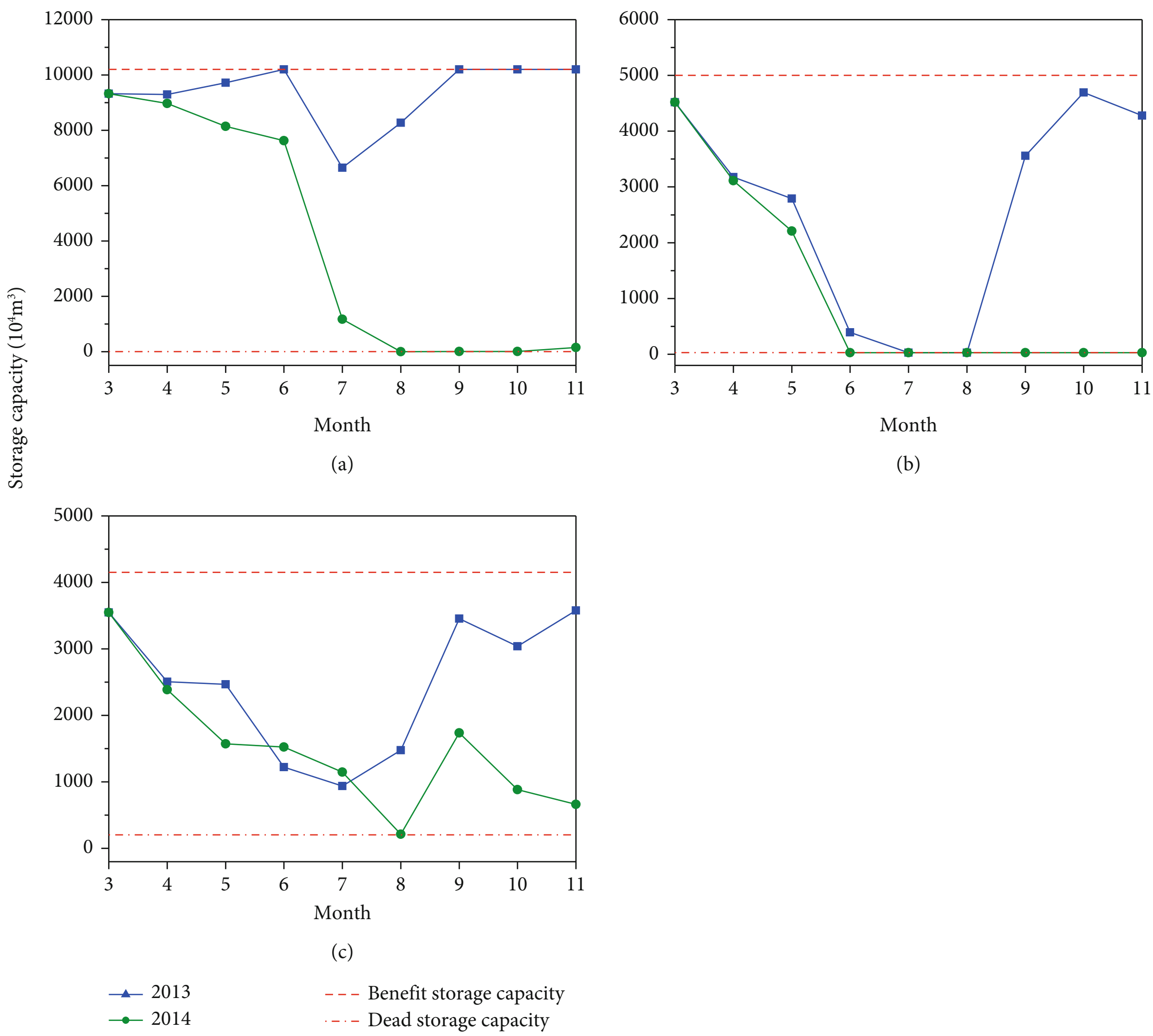

FIGURE 13: Storage capacity change curve of the multireservoir: (a) L reservoir, (b) K reservoir, and (c) H reservoir.

3.3. Optimal Results of Low Flow Year

3.3.1. Water Shortage Rate of Each Irrigation District after Optimization. After the optimal operation calculation of the optimal model, the water shortage rate of each irrigation district decreases significantly in the low flow year in 2009. The specific results are shown in Table 10.

TABLE 10: Results of annual water shortage in each irrigation district in the low flow year.

Month		L irrigation district	C irrigation district	H irrigation district
Sp irrigation	4	0.00%	0.00%	58.50%
	5	0.00%	0.00%	58.50%
	6	0.00%	0.00%	40.00%
Su irrigation	7	0.00%	0.00%	15.42%
	8	0.00%	0.00%	0.00%
A and W irrigation	9	0.00%	0.00%	1.00%
	10	0.00%	0.00%	12.00%
	11	0.00%	0.00%	1.50%

3.3.2. Regulation and Storage Process under the Upstream Reservoir Discharges according to the Minimum Discharge Flow (Taking Huanggou Reservoir as an Example)

(1) Minimum discharge is shown in Table 11

(2) The minimum inflow of Kuitun reservoir is shown in Table 12

(3) Storage capacity change curve of the multireservoir operation

It can be seen from the storage capacity change curve of the multireservoir operation in Figure 14, when Huanggou reservoir supply water with minimum discharge: Liugou reservoir has the lowest storage capacity in June and July, and the storage capacity rises at the end of August; Kuitun reservoir is close to the dead storage capacity at the end of May;

Table 11: Minimum discharge of reservoirs in the low flow year (unit: 10^4 m^3).

Month	4	5	6	7	8	9	10	11
L reservoir	2376.50	3211.38	3582.78	3637.99	3635.27	1927.38	1937.05	1959.27
H reservoir	2027.69	2027.69	2113.40	2979.19	3522.33	1667.49	1482.21	1659.07
K reservoir	2686.82	3523.25	3992.44	4049.99	4044.54	2154.09	2173.43	2217.88

Table 12: Minimum inflow of Kuitun reservoir in the low flow year (unit: 10^4 m^3).

Month	4	5	6	7	8	9	10	11
Minimum storage capacity	0.00	834.88	1969.78	2024.99	2022.27	1077.05	1086.72	1108.94

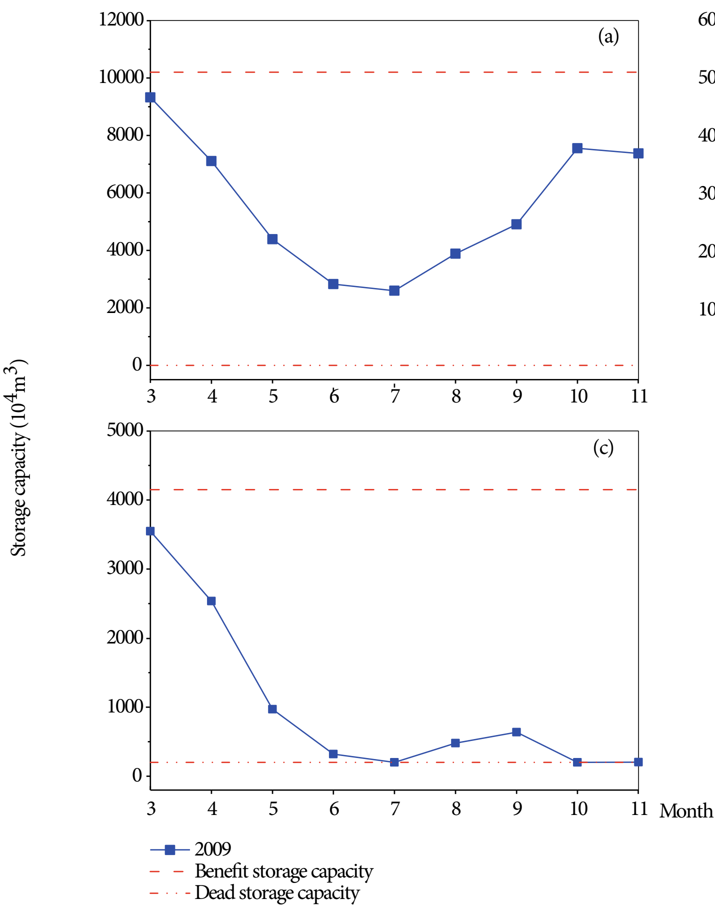

Figure 14: Storage capacity change curve of the multireservoir: (a) L reservoir, (b) K reservoir, and (c) H reservoir.

Huanggou reservoir is close to dead storage capacity at the end of June.

4. Countermeasures and Suggestions

4.1. Optimal Operation Scheme. When Liugou reservoir and Huanggou reservoir supply water within the allowable water supply range of storage capacity in each period, the goal of minimum water shortage rate and minimum discharge of upstream reservoirs in Kuitun River Basin can be achieved (Figures 14–16). Therefore, the above optimization results can be obtained when the reservoir supply water within the allowable water supply range of storage capacity; otherwise, the water shortage rate will be higher than the current results.

(1) Reservoirs operation diagram in upstream in high flow year.

(2) Reservoir operation diagram in upstream in normal flow year.

(3) Reservoir operation diagram in upstream in low flow year.

Reservoirs operation diagram in upstream in the low flow year is seen in Figure 14 in Section 3.3.2.

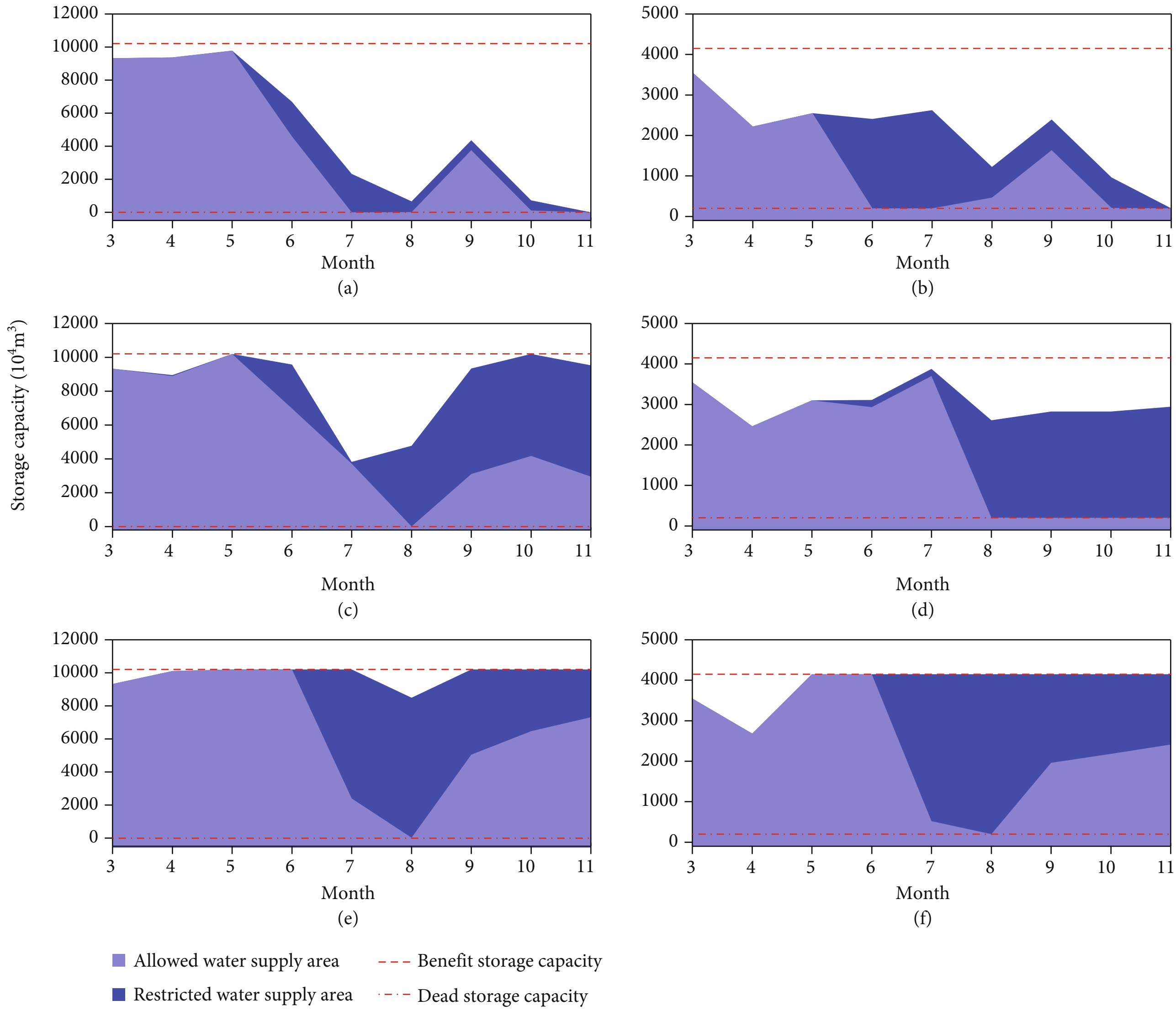

Figure 15: Reservoirs operation diagram in upstream in high flow years: (a) L reservoir in 2015, (b) H reservoir in 2015, (c) L reservoir in 2016, (d) H reservoir in 2016, (e) L reservoir in 2017, and (f) H reservoir in 2017.

4.2. Suggestions on Optimal Operation of the Multireservoir

4.2.1. Suggestions on Optimal Operation of Kuitun River Multireservoir. At present, the multireservoir operation in Kuitun River Basin is mainly based on artificial experience. The time and space of water demand in each crop are not uniform. In most cases, for the crop that firstly applies for the water distribution, the actual water supply can not only meet the water demand plan but also even exceed the quota of water supply, which leads to the high water shortage rate of the crop that later applies for water distribution.

In view of the phenomenon of uneven distribution of water resources in time and space in operation of the multireservoir, the water distribution plan for the multireservoir operation in that year should be formulated in advance. The optimal operation of the multireservoir is simulated according to the predicted inflow of the year and the water use plan of each irrigation district, to alleviate the contradiction between water supply and demand in the basin caused by the uneven distribution of water resources in time and space in operation of the multireservoir to the greatest extent.

4.2.2. Suggestions for the Independent Water Distribution District of Quangou Reservoir. For many years, the water distribution of Quangou reservoir in Kuitun River Basin can only meet 40%~60% of its independent water allocation area. According to the reservoir optimal operation results in high flow years and normal flow years mentioned above, there are more water in the reservoir at the end of November. The following suggestions are made for less available water:

(1) Improving the prediction accuracy of upstream inflow and increasing the water diversion from Quangou reservoir to the river channel according to the water use plan of each unit.

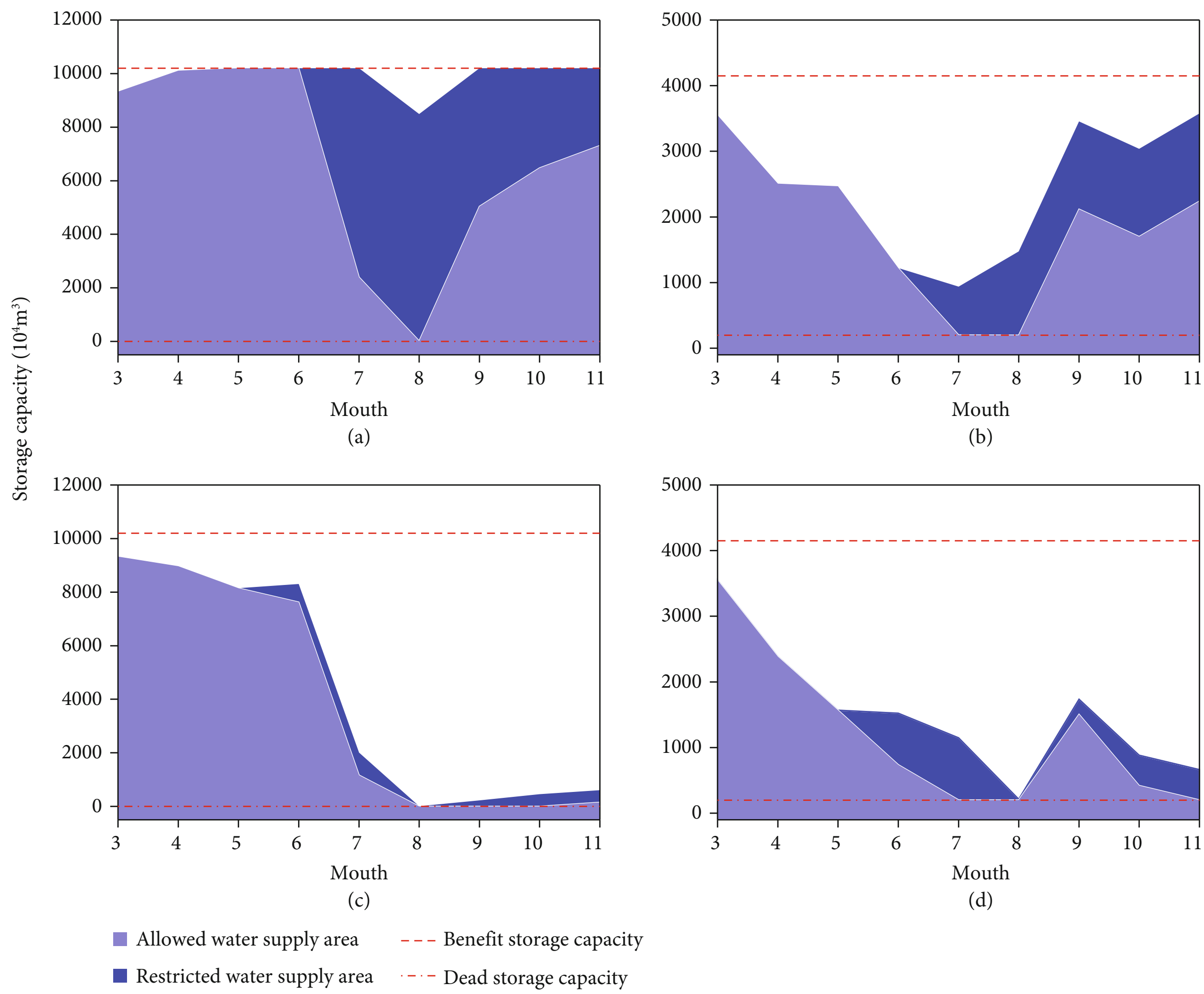

FIGURE 16: Reservoir operation diagram in upstream in normal flow years: (a) L reservoir in 2013, (b) H reservoir in 2013, (c) L reservoir in 2014, and (d) H reservoir in 2014.

(2) Users in other upstream districts should consider establishing links with Huanggou reservoir, such as diverting water to Quangou reservoir and constructing channels and other measures.

(3) Users in other downstream districts should consider establishing links with the Kuitun reservoir and Chepaizi reservoir, such as constructing channels to increase the available water supply from the Guertu river and the Sikeshu river to users in other downstream districts through the Liugou reservoir and the Kuitun reservoir.

5. Conclusion

Aiming at the problems that need to be solved urgently in the current operation of the multireservoir in Kuitun River Basin, such as the uneven distribution of water resources in time and space, the time cost of massive manual calculation, and low coordination level, a water resources optimal operation model of the multireservoir is established, and the actual data of typical years are selected to test the model. The test results show that the water shortage rate of 2015 and 2016 in high flow years decreased by 98.57% and 100%, respectively, compared with the actual water distribution; the water shortage rate of 2013 and 2014 in normal flow years decreased by 92.65% and 96.38%, respectively, compared with the actual water distribution; and the water shortage rate of 2009 in the low flow year decreased by 87.78% compared with the actual water distribution.

Abbreviations

L reservoir:	Liugou reservoir
K reservoir:	Kuitun reservoir
C reservoir:	Chepaizi reservoir
H reservoir:	Huanggou reservoir
Q reservoir:	Quangou reservoir
S river:	Sikeshu river
G river:	Guertu river
K river:	Kuitun river
Sp irrigation:	Spring irrigation
Su irrigation:	Summer irrigation
A and W irrigation:	Autumn and winter irrigation

L irrigation district: Liugou irrigation district
C irrigation district: Chepaizi irrigation district
H irrigation district: Huanggou irrigation district.

Data Availability

The data used to support the conclusions of this study are available from the corresponding authors upon request.

Conflicts of Interest

The authors declare no competing interests.

Authors' Contributions

Changlu Qiao made the formulation of overarching research goals and aims and establishment of the model. Yan Wang made solution method for the model and did data analysis and preparation of the original draft. Yanxue Liu did the data curation and writing of the initial draft. Junfeng Li performed the analysis with constructive discussions and did the review and editing of the manuscript. Heping Zhang and Jiangang Lu made the model test and diagramming.

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