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Runoff optimization and control for basin water allocation

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ABSTRACT

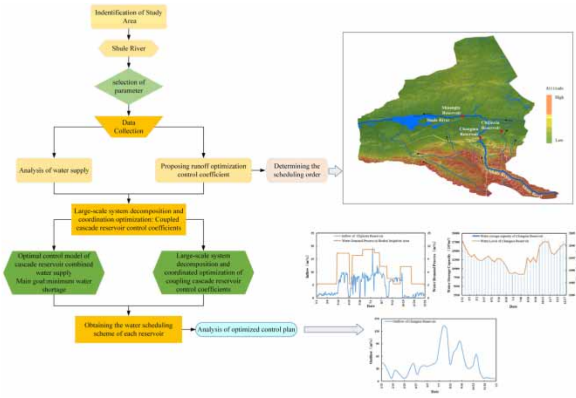
The water distribution plan for the three major irrigation districts (Changma, Shuangta, and Huahai) in the Shule River Basin in the planned year was analyzed in this study in an effort to resolve the insufficient natural endowment of water resources and contradiction between supply and demand throughout the basin. Based on this plan, and under the condition of satisfying the scheduling constraints of cascade reservoirs, the minimum total water supply shortage in the watershed was taken as the main goal coupled with the cascade reservoir runoff optimization control coefficient. An optimized dispatch model of the reservoir group was established accordingly. The large system coordination decomposition algorithm was called to solve the model and obtain the water scheduling scheme of each reservoir. After the optimal regulation of runoff, the water demand of the three major irrigation areas of Changma, Shuangta, and Huahai in the planned year is greater than the available water resources of the Shule River and the Petroleum River. The total surface runoff water shortage is 66.01 million m^3, which cannot be satisfied. Among the reservoirs, Shuangta has the highest water shortage quota of 43.503 million m^3, followed by Chijinxia with a water deficit quota of 22.18 million m^3, and finally by Changma with a minimum water shortage quota of 0.3277 million m^3. The results of this work may provide technical support for water resource allocation and regulations, as well as for the efficient usage of the Shule River Basin.

Key words: large system decomposition and coordination optimization algorithm, optimal dispatch model, runoff optimization control coefficient, water distribution

HIGHLIGHTS

- The cascade reservoir regulation coefficient γ is proposed.
- The water distribution plan is predicted for the three major irrigation districts (Changma, Shuangta, and Huahai) in the Shule River Basin in the planned year.
- The water scheduling scheme of the reservoirs Changma, Shuangta, and Chijinxia in the planned year is calculated and analyzed.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The natural endowment of water resources in the Shule River Basin is insufficient. There is an intense contradiction between supply and demand. Under the current water resource system, problems such as uneven water usage, unfavorable water distribution, low water use efficiency, and unreasonable water use structure persist (China Geological Survey 2004; Wang *et al.* 2011; Wang & Shi 2014). The optimization and control of water resources serve to adjust the industrial structure, build a water-saving society, and adjust the layout of productive forces on the demand side to suppress the increase in demand for water. Negotiating on the supply side with different competing water users, strengthening the control of water consumption, and constructing engineered facilities to achieve the natural spatial and temporal distribution of water resources can enhance a region's social and economic development. The optimal regulation of water resources can be understood as the scientific division of water resources with limited and different composition forms among different water users in different regions and basins, thus meeting goals of the whole system for the sake of sustainable development (Guo *et al.* 2015).

Many previous scholars have explored the joint optimal operation of reservoir groups. Constantly improving optimization algorithms and theories have been used to establish flood control, power generation, irrigation, water supply, sediment deposition, and ecology models for optimizing operation schemes under different objectives (Peng *et al.* 2003; Zhou *et al.* 2005; Tian 2007; Liu *et al.* 2008; Li *et al.* 2009; Liu *et al.* 2011; Ou *et al.* 2012; Chen *et al.* 2013; Bai *et al.* 2015; Jiang *et al.* 2016; Rashid *et al.* 2018; Ayenew *et al.* 2020; Azamipour *et al.* 2020). For instance, Chen *et al.* (2018) set the optimal dispatch model of reservoir groups for the three specific goals of power generation, water supply, and ecology to maximize power generation, minimize water shortage, and reduce deviation between the natural flow and post-dispatch flow at the Waizhou Hydrological Station on Ganjiang river. They used a multi-objective particle swarm optimization algorithm to solve the scheduling model, obtain the solution set of the three goals at each incoming water frequency, and analyze the competition between power generation, water supply, and ecological of large-scale controlled reservoirs in the Gan River Basin.

For the Xiaolangdi Reservoir, Tan *et al.* (2018) built a water-sediment multi-target model simulation calculation based on the reservoir area's silt reduction, power generation, and downstream river flow capacity. Tian, Lei, and Ma (Tian 2007; Lei 2011; Ma 2011) investigated the national economic water demand of the Shule River Basin across the three major reservoirs Changma, Shuangta, and Chijinxia to optimize the allocation of constrained water resources for the irrigation area. Guo *et al.* (2010) summarized the progress and prospects of optimal reservoir group dispatching to find that advanced technology can be used for the multi-objective, joint dispatch of reservoir groups. Schedules can be optimized based on rules, reservoir group dispatching decision support systems, and other aspects.

In summary, the social, economic, and ecological factors affecting water circulation have made maximizing comprehensive benefits the primary trend in water resource regulation and control. However, there is no standard multi-dimensional regulatory knowledge of water resource systems; existing evaluation criteria and mechanisms of water resource system regulation are incomplete and there is no effective connection between small-scale simulations of water resource system processes and large-scale, decision-level goals. When optimizing water resource system allocation plans, there are persistent problems with the mechanisms of water circulation processes (Wang & You 2016). Existing control methods are also relatively complex. Models are mainly dependent on water resource characteristics, which gives them limited universality.

The runoff regulation coefficients of cascade reservoirs were coupled in the present study with the resource water shortage problem of the Shule River Basin as the primary issue. The water shortage amount was defined as the main goal to build a runoff optimization regulation model, in an effort to balance the increase in water consumption for economic development with limited or insufficient water resources in the area.

2. WATER DISTRIBUTION OF SHULE RIVER

2.1. Overview of Shule River main stream, three major irrigation areas, reservoirs

The Shule River is the second largest river in the inland river system of the Hexi Corridor in Gansu Province. It originates from the Shulenao Mountain between Tuolainan Mountain and Shule South Mountain in the western part of the Qilian Mountains. The total length of the main river is 670 km and the drainage area is 41,300 km^2, as shown in Figure 1. The water supply of Shule River is mainly recharged by precipitation, supplemented by ice and snow meltwater. The annual runoff changes are substantial. The annual runoff of the main channel of Shule River is 1.031 billion m^3; the annual runoff of Petroleum River is 51 million m^3 (National Water Resources Review Leading Group; Prepared by the Survey

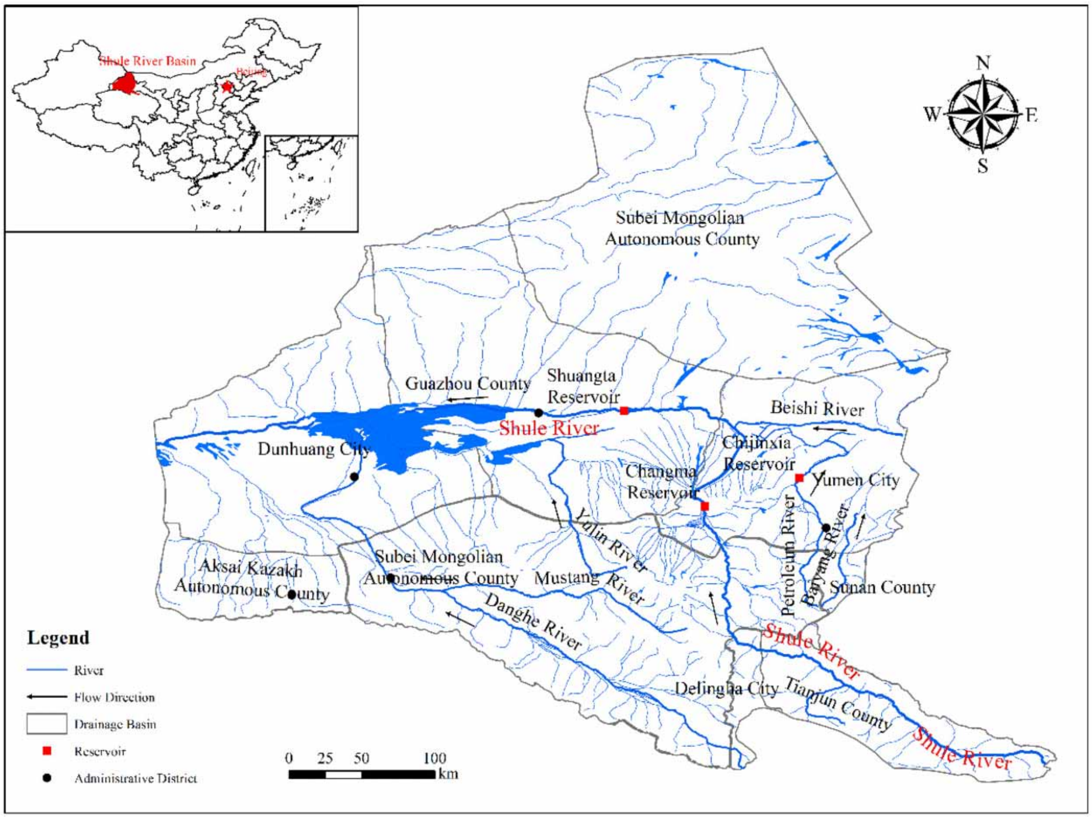


Figure 1 | Study area map of Shule River Basin.

Planning Design & Research Institute of the Yellow River Water Conservancy Commission of the Ministry of Water Resources 2004; Water Resources Bureau of Shule River Basin of Gansu Provincial Department of Water Resources).

Changma, Shuangta, and Huahai large-scale irrigation districts are responsible for agricultural irrigation water of 896.1 km^2 cultivated land across 22 towns and six state-owned farms in Yumen City and Guazhou County. They also provide industrial water supply, ecological water supply, and hydroelectric power supply, forming a relatively complete irrigation system. Changma Irrigation District is a national, large-scale artesian irrigation district. It is located in the middle and upper reaches of Shule River, spans the two counties and cities in Yumen and Guazhou, and has high terrain in the south and low terrain in the north. The total area is 3,380 km^2 and the total irrigation area is 464.5 km^2. Shuangta Irrigation District is located in the lower basin of Shule River in Guazhou County with an effective irrigation area of 309.5 km^2. The Shuangta Irrigation District uses the surface runoff of Shule River as the main replenishment of groundwater for necessary supplementation. Huahai Irrigation District is located in the lower reaches of the Petroleum River in Yumen City, with an irrigation area of 143.6 km^2 (Jiuquan City Water Conservancy Codification Committee; Li Y. 2016; Water Resources Bureau of Shule River Basin of Gansu Provincial Department of Water Resources).

After years of planning and construction in Shule River Basin, Changma, Shuangta, and Huaha initially formed a backbone engineering system facilitating the storage, diversion, adjustment, and drainage of water resources. The three reservoirs, Changma, Shuangta, and Chijinxia, have a total storage capacity of 472.2 million m^3 (Water Resources Bureau of Shule River Basin of Gansu Provincial Department of Water Resources). Changma is located 1.36 km from the entrance of Shule River Changma Gorge in Yumen City, with a total storage capacity of 193.4 million m^3 and an annual water transfer of 1.03 billion m^3. Changma is also a large type II reservoir for agricultural irrigation as well as comprehensive utilization of industrial water supply, hydropower generation, and flood control.

The Shuangta reservoir is located in Bulongji Township, Guazhou County, in the middle reaches of Shule River. It is a large type II reservoir with irrigation as its main function in addition to flood control, aquaculture, and tourism, with a total storage capacity of 240 million m^3. The Chijinxia reservoir is located in Chijinxia Gorge in the middle reaches of the Petroleum River in Chijin Town, Yumen City. Its main function is irrigation. It is a medium-sized reservoir that also provides flood control and power generation with a total storage capacity of 0.3878 billion m^3. The Chijinxia Reservoir regularly sends water to Huahai Irrigation Area by storing Chijin River water and Shule River water transferred through the Shuhua main canal (current status 40 million m^3/a, planned 70 million m^3/a); 60 million m^3 of water is transported to Huahai Irrigation District through Huahai Main Trunk Canal every year (Jiuquan City Water Conservancy Codification Committee; Li 2016; Water Resources Bureau of Shule River Basin of Gansu Provincial Department of Water Resources). The parameters of Changma, Shuangta, and Chijinxia reservoirs are shown in Table 1. The distribution of cascade reservoirs in the study area is shown in Figure 2.

2.2. Water distribution

2.2.1. Analysis of water supply

According to the existing water supply capacity of Shule River Basin, and considering residential, industrial, and agricultural requirements in the area, the water supply was analyzed with the goals of controlling water consumption and improving water use efficiency. The agricultural irrigation water in the irrigation area, combined with surface runoff data in the planning year (e.g., the multi-year average runoff), irrigated area, overall irrigation quota level, level of water-saving irrigation technology, and other factors were used to determine the available water. The total annual water resources of the main channel of Shule River total 1.134 billion m^3. The total surface water resource is 1.082 billion m^3 (multi-year average runoff of Shule River Main Channel is 1.031 billion m^3; multi-year average runoff of Petroleum River is 51 million m^3); the groundwater resources that do not overlap with surface water are 52 million m^3.

Agricultural irrigation in Shule River Basin does not essentially rely on precipitation, so in a moderate drought year (where the guaranteed rate of incoming water in the mountains is 75%), the irrigation area is smaller compared to a normal water year (where the guaranteed rate of incoming water in the mountains is 50%). There is no change in irrigation quota, so the irrigation quota of Shule River Basin in a normal water year is equal to that in a moderate drought year (Gansu Provincial Department of Water Resources 2017). The average runoff of the main stream was used to calculate the water supply of the main stream of Shule River in this study accordingly. In accordance with the thematic study report (Gansu Provincial Department of Water Resources 2019), the utilization rate of surface water resources in the basin is 80% in the planned year and the available surface water of Shule River and Petroleum River in the planned year is 0.8656 billion m^3. The actual overall runoff of Shule River Irrigation District can be comprehensively adjusted using Changma, Shuangta, and Chijinxia reservoirs. The regulation structure of Shule River Cascade Reservoir is shown in Figure 3.

2.2.2. Water distribution plan

Based on the current status of annual water use in 2018, water quotas were used as indicators to predict the planned annual water use scale in 2030. On the basis of the current supply and demand status of the main stream of Shule River, annual residential plans, production, and ecological water use at the planning level were integrated into the forecast of water supply and demand. A supply and demand balance analysis of water resources was conducted to obtain a water allocation plan for the Shule River irrigation area.

The balance of supply and demand takes place in three stages. The first stage centers on population growth, socio-economic development, urbanization, and similar factors; if there is still a gap in the first stage, then the second stage incorporates the construction of water source projects to increase the available water. If the water demand is still not met, then measures such

Table 1 | Cascade reservoir parameters in main stream of Shule River

Reservoir	**Changma**	**Shuangta**	**Chijinxia**
Controlled watershed area (10^4 km^2)	1.325	3.44	0.344
Multi-year average runoff (10^8 m^3)	10.3	2.97	0.354
Beneficial reservoir capacity (10^8 m^3)	1	1.2	0.21185
Total storage capacity (10^8 m^3)	1.934	2.4	0.3878
Regulate capability	Incomplete annual adjustment	Years of adjustment	Annual adjustment
Construction process	Completed	Completed	Completed

Note: Original data are from the sources listed here (National Water Resources Review Leading Group; Northwest Survey & Design Institute Gansu Provincial Water Resources & Hydropower Survey & Design Institute 2004; Tian 2007; Lei 2009; Yang 2014).

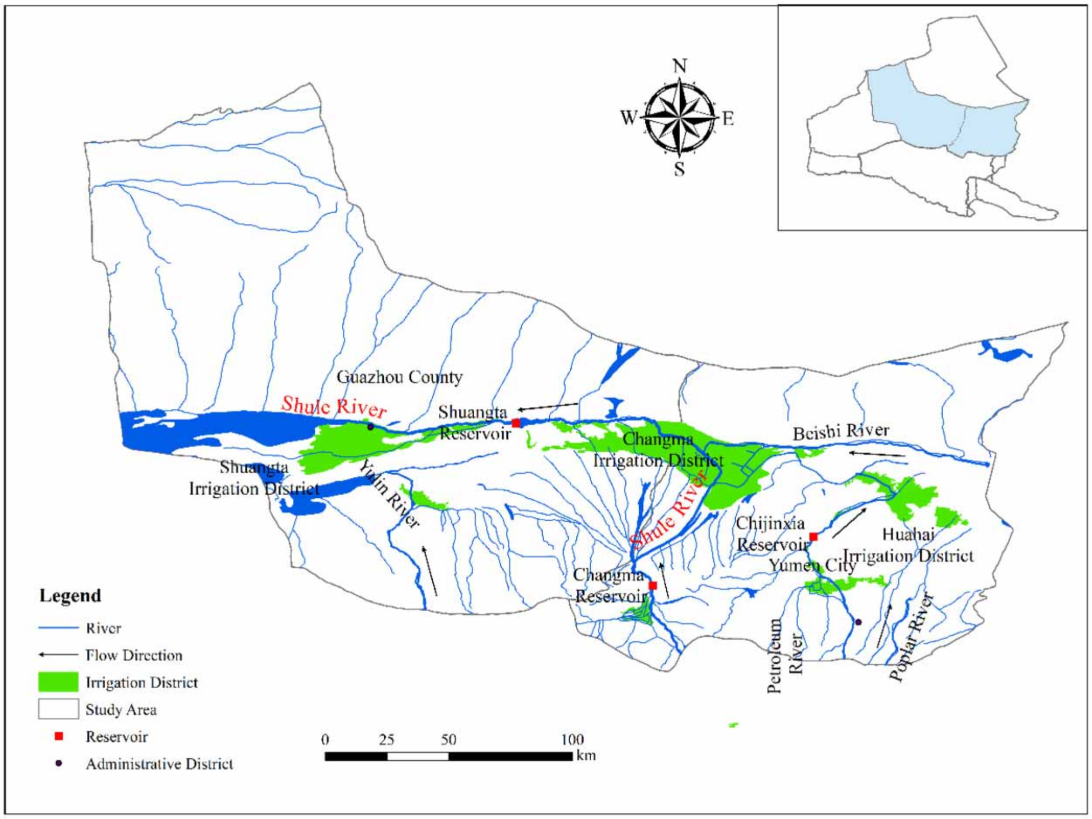


Figure 2 | Distribution of water systems, irrigation areas, and reservoirs in study area.

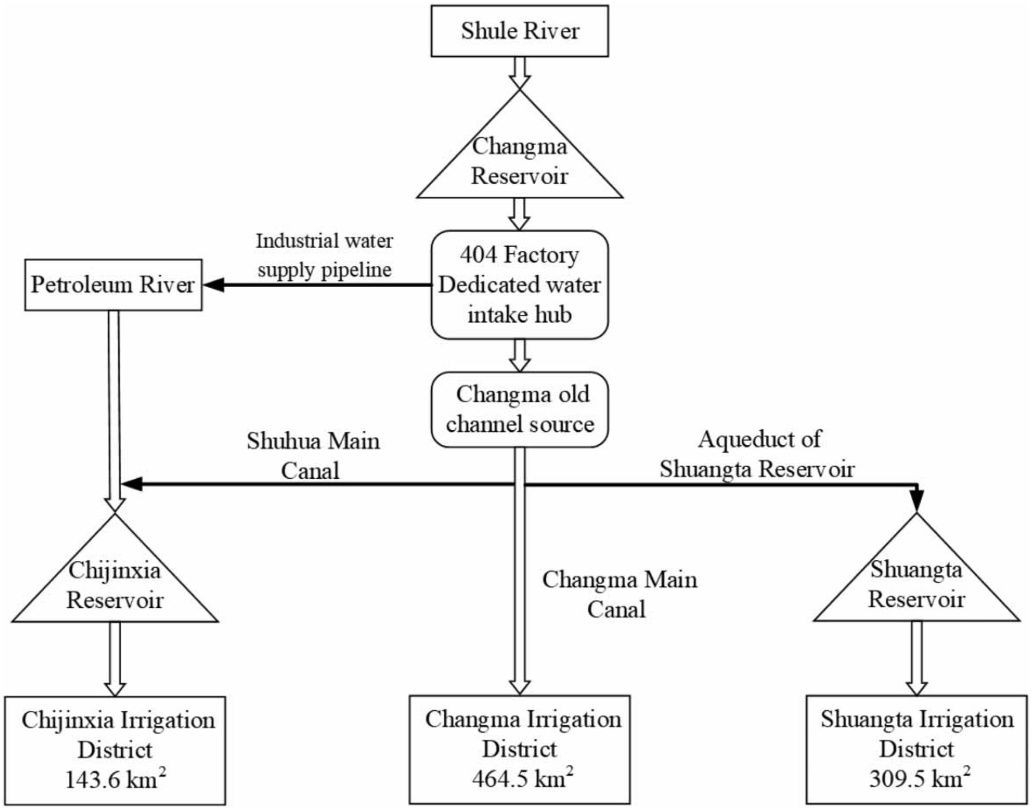


Figure 3 | Regulation structure of Shule River Cascade Reservoir.

as water conservation, reclaimed water utilization, and adjusting the water structure to meet water requirements are considered. Analysis of the supply and demand balance of water resources outside the river channel is based on the water supply of various engineering facilities and demand for agricultural, industrial, and rural/urban residential water.

The total water resources in Shule River Basin are relatively scant. There is a dramatic contradiction between water supply and demand. As the economic situation in the watershed improves, the total population grows, and industrialization continues to progress, the demand for water resources in various water departments will continually increase and will further intensify the contradiction between the sustainable use of water resources and the current environmental situation. A 2030 water distribution plan under the multi-year average flow was obtained with the goal of balancing supply and demand (Table 2).

3. RUNOFF OPTIMIZATION CONTROL COEFFICIENT

The planning, development, and operation of watershed reservoirs are conducted in accordance with 'basin-cascade-rolling-synthesis' mode as large-scale water conservancy projects are constructed. Regardless of whether there are leading reservoirs, the regulation and control capacity of rivers based on the regulation reservoir capacity of each cascade reservoir is higher than that of a single reservoir (Li 2014). The magnitude of this value is determined by the magnitude of the runoff of each watershed and the cumulative storage capacity of each cascade reservoir. An existing single-stage reservoir is not consistent with a newly constructed cascade reservoir in the basin. Reservoir parameters must be adjusted considering the location and function. The number of reservoirs planned and constructed in the river basin may increase to the point at which the storage capacity adjustment factor no longer represents the entire cascade control factor. In this study, the cascade reservoir regulation coefficient and water resource regulation information were combined to analyze the water resource management mode under the influence of the cumulative impact of runoff.

3.1. Single reservoir capacity adjustment coefficient

The storage capacity adjustment coefficient (β^*) is the ratio of the Beneficial reservoir capacity (V) of this grade of reservoir to the multi-year average annual runoff ($\bar{W}$) at the dam site. The size of the storage capacity adjustment coefficient (β^*) is independent of the storage capacity adjustment coefficients of upstream cascade reservoirs. The calculation formula is as follows:

$$\beta^* = \frac{V}{\bar{W}} \tag{1}$$

where (β^*) is the reservoir capacity adjustment coefficient; (V) is the Beneficial reservoir capacity, m^3; ($\bar{W}$) is the annual runoff at the reservoir dam site, m^3.

Table 2 | Annual water allocation plan of Shule River Basin

	Irrigation area (10^8 m^3)			
/	Changma	Shuangta	Huahai	Total
Resident water requirement	0.0259	0.0127	0.0158	0.0543
Residential water supply	0.0215	0.0105	0.0131	0.0451
Agricultural water requirement	5.0116	3.3394	1.5492	9.6687
Agricultural water supply	4.1611	2.7727	1.2863	8.0279
Industrial water demand	0.1762	0.1174	0.0545	0.3481
Industrial water supply	0.0360	0.0240	0.0111	0.0711
Ecological water requirement	0.1449	0.0961	0.0419	0.2829
Ecological water supply	0.1203	0.0798	0.0348	0.2349
Multi-year average water supply	4.4791	2.9803	1.3887	8.6560
Total water demand	5.3946	3.5895	1.6725	10.4251
Total water shortage	0.9155	0.6091	0.2838	1.7691
Ratio of total water shortage to total water demand (%)	16.97%	16.97%	16.97%	16.97%

3.2. Regulation coefficient of series cascade reservoirs

Regardless of the impact of tributary influxes, the reservoirs of the independent river were taken here as the research object for one-way analysis of top-to-bottom ability. The cascade control coefficient (γ) of each cascade reservoir refers to the adjustment capacity of the cascade reservoir to the multi-year average runoff at the dam site based on deduction of cumulative regulation of runoff from upstream cascade reservoirs. The multi-year average runoff at this dam site is the sum of the discharge volume from the upstream reservoir and the natural water flow between upper-level reservoirs. The calculation formula is as follows:

$$\gamma_i = \begin{cases} \beta_1 = \dfrac{V_1}{W_1}, i = 1 \\ \dfrac{\beta_i}{1 - \dfrac{\sum_{i=1}^{n-1} V_i}{W_i}}, i > 1 \end{cases} \tag{2}$$

3.3. Regulation coefficient of mixed cascade reservoirs

The runoff regulation coefficient (γ) of the mixed cascade reservoirs should combine the cascade reservoirs connected in series on each tributary into the main stream. The cascade reservoirs in the river basin can then be integrated across their top-down geographical relationship. Under the influence of cumulative regulation, each cascade reservoir can regulate the multi-year average runoff. The mixed reservoir is Y-shaped in this case. The calculation formula is:

$$\gamma_i = \begin{cases} \beta_1 = \dfrac{V_1}{W_1} \quad , i = 1 \\ \dfrac{\beta_i}{1 - \dfrac{\sum_{i=1}^{n-1} V_i + \sum_{j=1}^{n-1} V_j}{W_i}}, i > 1 \end{cases} \tag{3}$$

where (γ_i) is the (i)-th reservoir cascade regulation coefficient; (i) $= 1, 2\ldots$, n; (V_i) is the beneficial reservoir capacity of the i-th cascade reservoir on the main stream, 100 million m^3; (V_j) is the beneficial reservoir capacity of the j-th cascade reservoir on the tributary, 100 million m^3; (W_i) is the multi-year average runoff at the dam site, 100 million m^3.

4. LARGE-SCALE SYSTEM DECOMPOSITION AND COORDINATION OPTIMIZATION: COUPLED CASCADE RESERVOIR CONTROL COEFFICIENTS

4.1. Optimal control model of cascade reservoir combined water supply

The main goal is to minimize the total water supply deficit of Shule River Basin according to the water allocation scheme under the conditions of cascading reservoir scheduling constraints. The objective function of the optimal reservoir group operation model, based on the regulation capacity of cascade reservoirs, can be described as follow:

The minimum water shortage is expressed as:

$$obj = \min \sum_{i=1}^{M} \sum_{j=1}^{T} \Delta Q_{i,j} \Delta t = \min \sum_{i=1}^{M} \sum_{j=1}^{T} (|Q_{i,j}^{x} - Q_{i,j}^{l}|\Delta t) \tag{4}$$

where ($\Delta Q_{i,j}$), ($Q_{i,j}^{x}$), ($Q_{i,j}^{l}$) are the water shortage, water demand, and water supply of the (i)-th reservoir ((j) period), respectively; (M) is the number of reservoirs; (i) is the reservoir number; (T) is the number of periods.

The following constraints must also be met:

(1) Hydraulic connection between cascade reservoirs:

$$D_{i,j} = Q_{i-1,j} + S_{i-1,j} + R_{i,j} - G_{i,j} \tag{5}$$

(2) Water balance constraints:

$$V_{i,j} = V_{i,j-1} + (D_{i,j} - Q_{i,j} - S_{i,j} - G_{i,j})\Delta t \tag{6}$$

(3) Storage capacity constraints:

$$V^L_{i,j} \leq V_{i,j} \leq V^U_{i,j} \tag{7}$$

(4) Flow constraints:

$$\begin{gathered} Q^L_{i,j} \leq (Q_{i,j} + S_{i,j}) \leq Q^U_{i,j} \\ Z_{i,start} \\ Z_{i,end} \end{gathered} \tag{8}$$

(5) Initial water level:

$$Z_{i,0} = Z_{i,start} \quad Z_{i,0} = Z_{i,end} \tag{9}$$

where $(D_{i,j})$ is the inflow of the (i)-th reservoir at (j) period; $(Q_{i,j})$ is the discharge flow of the (i)-th reservoir at (j) period; $(S_{i,j})$ is the waste water discharge of the (i)-th hydropower station at (j) period; $(R_{i,j})$ is the inflow between $(i - 1)$ and (i) reservoirs at (j) period; $G_{i,j}$ is the water supply flow in the (i) reservoir in (j) period; $(V_{i,j})$, $(V^L_{i,j})$, $(V^U_{i,j})$ are the water storage, minimum, and maximum water storage capacity of the (i)-th reservoir at the end of (j) period, respectively; $(Q^L_{i,j})$, $(Q^U_{i,j})$ are the lower limit and upper limit of the discharge flow of the (i)-th hydropower station at (j) period, respectively; $(Z_{i,start})$, $(Z_{i,end})$ are the water storage level at the beginning and the end of the (i)-th reservoir operation, respectively.

4.2. Large-scale system decomposition and coordinated optimization of coupling cascade reservoir control coefficients

The large system decomposition and coordination optimization algorithm divides the system into several independent subsystems according to their respective characteristics, ultimately producing a model for each subsystem that can be optimized one-by-one. The coupling variables are used to connect the subsystem to the second or higher level for adjustment to optimize the entire system. During the joint optimization of cascade reservoirs, the optimization sequence of each reservoir subsystem must be carefully designed for proper adjustments in the upper floors. The various reservoirs of the cascade reservoir group were sorted based on their individual regulation coefficients. The connections between subsystems were determined followed by decomposition, coordination, and optimization (Gao 2007).

For the optimal operation of the combined water supply of cascade reservoirs, the coupling constraint vector between reservoir groups was determined according to the cascade reservoir control coefficients. A Lagrangian multiplier vector was introduced to construct a system-optimized Lagrangian function. Different river sections were decoupled to form a series of subsystems, making each subsystem independent of each other and singularizing the model variables.

The optimal control sequence was determined according to the cascade reservoir control coefficients. Each subsystem was optimized to obtain an initial solution. The differential optimization coordination variables and objective functions of each sub-model were then adjusted to iteratively derive the global optimal solution of the entire system:

$$\begin{aligned} L = {} & \sum_{i=1}^{M}\sum_{j=1}^{T} x_{ij} + \sum_{i=1}^{M}\sum_{j=1}^{T} u_{ij}[(Q_{ij} + (1-\alpha_i)x_{ij} - I_{ij})\Delta t + V_{i\,j+1} - \mathrm{V}_j] \\ & + \sum_{i=1}^{M-1}\sum_{j=1}^{T} \lambda_{ij}\left(Q_{ij} + \sum_{i=1}^{R_{i+1}-1} Q_{ij} + B_{i+1j} - I_{i+1j}\right) \end{aligned} \tag{10}$$

When the inflow (I_{ij}) and interval runoff (B_{ij}) are known, the Lagrange function (L) can be decomposed to obtain:

$$L_i = \sum_{j=1}^{T} (x_{ij} + \lambda_{ij} Q_{ij}) \quad \lambda_{Mj} = 0 \tag{11}$$

In this study, the calculation process and steps of large system decomposition coordination were divided into two layers. The cascade reservoirs in the basin were used as the second layer and operated separately; the cascade joint operation of the basin was used as the first layer. The operation sequence of each cascade reservoir determined by the regulation coefficient of the cascade reservoir was used to determine the order of individual operations. After each operation, the Lagrange multiplier variable (λ_{ij}) was fed back to the whole system. The optimal operation value of cascade reservoir was finally obtained via the coordination factor.

An infeasible solution can be transformed into a feasible solution via constraint processing, thus allowing the intelligent optimization algorithm to continually evolve. The constraint treatment methods incorporated into this model are as follows:

- When the discharge flow of the reservoir is below the minimum discharge flow constraint, the discharge flow is revised to the minimum discharge flow. The reservoir water balance is recalculated to determine the new end water level.
- When the final water level is lower than the minimum water level constraint of the reservoir in the current period, the minimum discharge flow constraint is ignored and the final water level of the reservoir is corrected to the minimum water level constraint value of the reservoir. The reservoir water balance calculation is carried out again and the new reservoir discharge flow is obtained.
- When the final water level is above the maximum water level restriction of the reservoir in the current period, the minimum discharge flow restriction is ignored and the final water level of the reservoir is corrected to the maximum water level constraint value of the reservoir. The reservoir water balance calculation is recalculated to obtain the new discharge flow of the reservoir.
- When the discharge flow of the reservoir exceeds the minimum discharge flow constraint, the discharge flow is revised to the maximum discharge flow and the reservoir water balance is recalculated to obtain the new end water level. When the final water level is below the minimum water level constraint of the reservoir in the current period, the minimum discharge flow constraint is ignored and the final water level of the reservoir is modified to the minimum water level constraint value of the reservoir. The water balance calculation of the reservoir is carried out again to obtain the new discharge flow of the reservoir.

5. CASE ANALYSIS

5.1. Reservoir topology in irrigation area

The capacity adjustment coefficient (β^*) of the reservoirs Changma, Shuangta, and Chijinxiain can be calculated using Equation (1). The runoff regulation coefficient (γ) of the cascade reservoirs Changma, Shuangta, and Chijinxiain in Table 3 can be calculated using Equations (2) and (3). The scheduling order of Changma, Shuangta, and Chijinxia was determined by the series cascade reservoirs of the main stream of Shule River first, then by the cascade reservoirs of the tributaries of the mixed stream. According to the large-scale system decomposition and coordination optimization structure diagram of coupled cascade control coefficients (Figure 4), the three reservoirs of the system were decomposed into two layers. In the second layer, the Lagrange multiplier variable (λ_{ij}) obtained after the individual scheduling was fed back to the whole watershed of the system. The joint scheduling of the three cascade reservoirs was used as the first layer for coordination. The optimal values for runoff optimization control of Changma, Shuangta, and Chijinxia were then calculated.

5.2. Analysis of optimized control plan

The large system decomposition and coordination algorithm coupled with cascade control coefficients were used to run the optimal Shule River scheduling model. The target value is water supply shortage. The input conditions of the model are incoming water from each catchment area (multi-year average runoff data in 10-day intervals) and the water consumption of each water unit based on the current year, taking into account economic and social development, population growth

Table 3 | Runoff regulation coefficient of the three cascade reservoirs, Shule River main and tributaries

Reservoir	Multi-year average runoff (10^8 m^3)	Beneficial reservoir capacity (10^8 m^3)	Capacity adjustment coefficient β^*(%)	Runoff control coefficient γ
Changma	10.3	1	9.7%	0.097087379
Shuangta	2.97	1.2	40.4%	0.598446328
Chijinxia	0.354	0.21185	59.8%	0.68253562

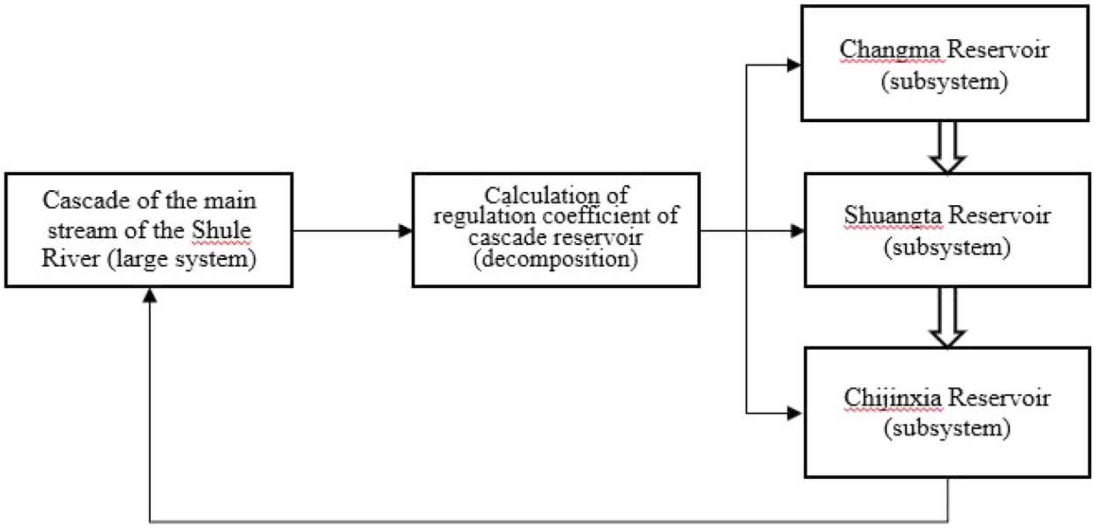


Figure 4 | Decomposition and coordination optimization of large-scale system coupled with cascade control coefficients.

rate, water-saving measures, water conservancy project planning and other relevant factors. The water demand of each irrigation district in 2030 was predicted and a water allocation plan was obtained accordingly. The Changma, Shuangta, and Chijinxia reservoirs are jointly operated. Among them, Changma operates in the form of smooth discharge during the flood season in July, while Shuangta and Chijinxia operate according to the flood control level. Changma Reservoir begins storing water in August. The transfer of water from Changma to Shuangta and Chijinxia occurs from November to March of the following year subject to the double constraints of water volume and time.

The problem-solving dimension is three reservoirs multiplied by 36 [108]. The optimal decision-making space is 36 ten-day water level thresholds. The highest water level in the normal period is the normal water storage level, the lowest water level is

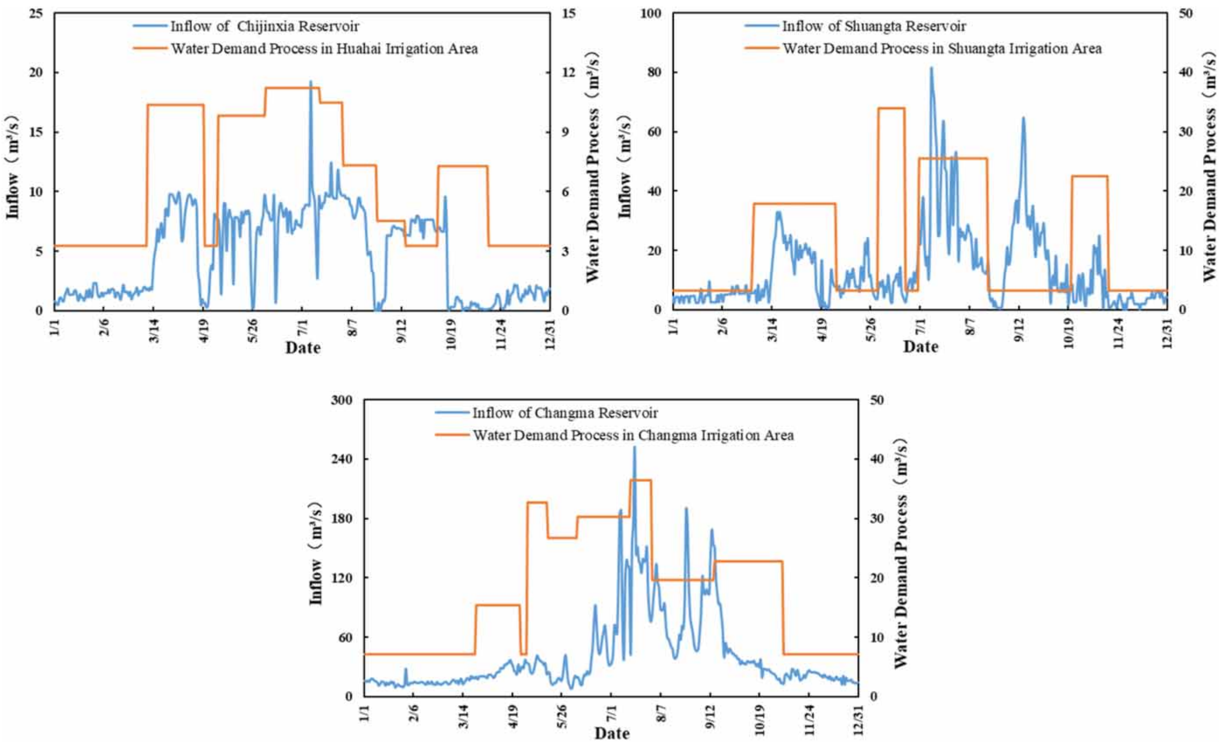


Figure 5 | Inflow of Changma, Shuangta, and Chijinxia; water demand process in irrigation area.

the dead water level, the highest water level in the flood season is the limited water level in the flood season, and the lowest water level is the dead water level. The discharge flow is characterized by the Changma, Shuangta, and Chijinxia reservoirs. The algorithm's population size is 200 and the number of iterations is 2,500. The inflow flow process of Changma, Shuangta, and Chijinxia, as well as the water demand process of Changma Irrigation District, Shuangta Irrigation District, and Huahai Irrigation District, are shown in Figure 5.

According to the model input conditions and algorithm parameters of the Shule River optimal dispatch model, the large system decomposition coordination algorithm was called to solve the model to determine a water dispatch plan for each reservoir as shown in Figures 6–8.

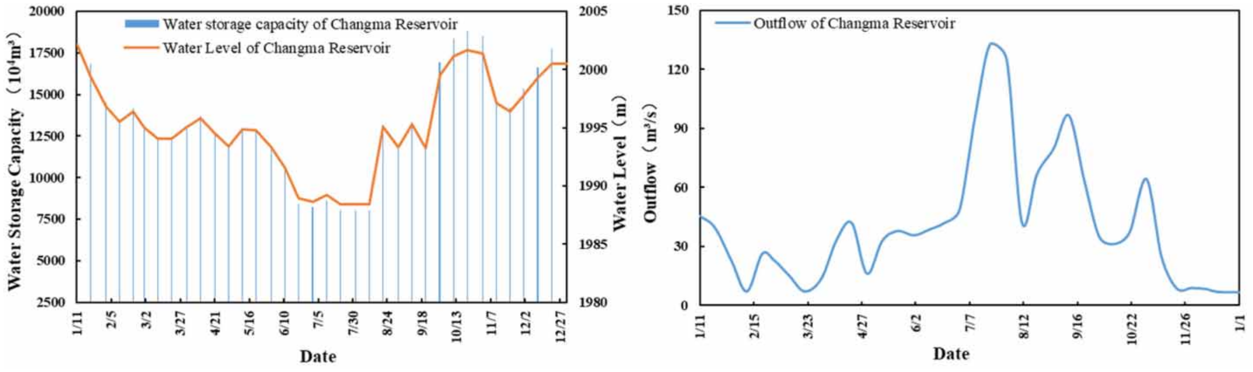


Figure 6 | Changma Reservoir water storage capacity, reservoir water level, and outflow simulations.

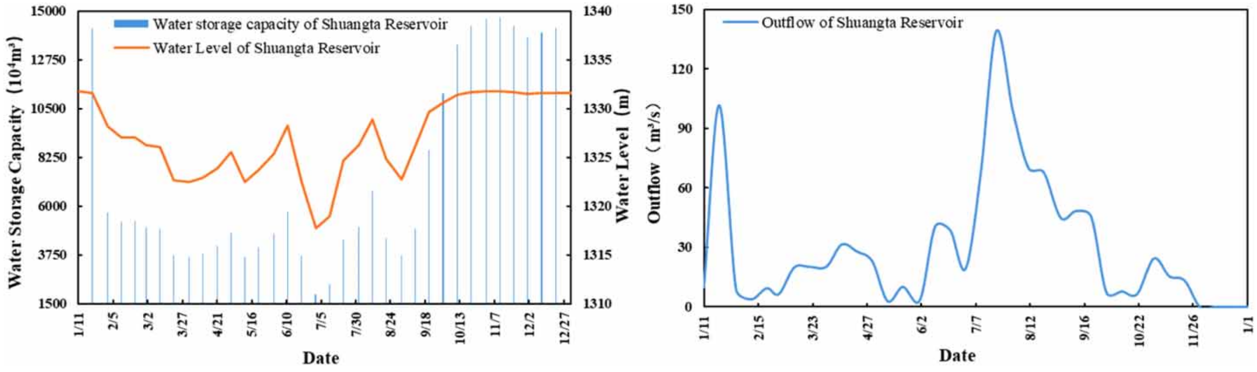


Figure 7 | Shuangta Reservoir water storage capacity, reservoir water level, and outflow simulations.

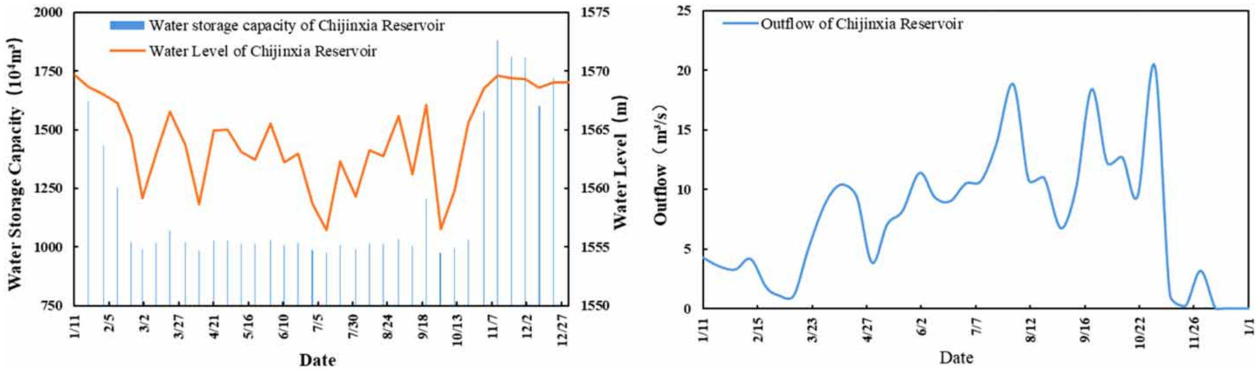


Figure 8 | Chijinxia reservoir water storage capacity, reservoir water level, and outflow simulations.

As shown above, the three reservoirs appear to return to the initial water storage process after the discharge and storage process is complete under the condition of multi-year average runoff. Chijinxia has a relatively small storage capacity, so the water storage capacity changes rapidly and stores fill quickly in October. Changma and Shuangta begin storing water in August and

Table 4 | Regulation process of Changma, Shuangta, and Chijinxia reservoirs

	Changma Reservoir Regulation			**Shuangta Reservoir Regulation**			**Chijinxia Reservoir Regulation**		
10-day interval	**Water supply quantity 10^4 m^3**	**Water shortage quantity 10^4 m^3**	**Water diversion discharge m^3/s**	**Water supply quantity 10^4 m^3**	**Water shortage quantity 10^4 m^3**	**Water diversion discharge m^3/s**	**Water supply quantity 10^4 m^3**	**Water shortage quantity 10^4 m^3**	**Water diversion discharge m^3/s**
1	612.21	0	7.09	282.18	0	3.27	282.18	0	3.27
2	612.21	0	7.09	282.18	0	3.27	282.18	0	3.27
3	673.43	0	7.09	310.40	0	3.27	310.40	0	3.27
4	612.21	0	7.09	282.18	0	3.27	282.18	0	3.27
5	612.21	0	7.09	160.11	122.07	1.85	282.18	0	3.27
6	489.76	0	7.09	79.69	146.06	1.15	225.75	0	3.27
7	612.21	0	7.09	94.71	248.79	1.10	1,546.28	0	17.90
8	612.21	0	7.09	448.91	446.50	5.20	1,546.28	0	17.90
9	1,244.89	0	13.10	847.65	137.30	8.92	1,700.91	0	17.90
10	1,326.54	0	15.35	811.26	84.15	9.39	1,546.28	0	17.90
11	1,326.54	0	15.35	715.98	179.43	8.29	1,546.28	0	17.90
12	969.37	0	11.22	282.18	0	3.27	1,546.28	0	17.90
13	2,820.92	3.50	32.65	611.67	236.23	7.08	246.77	35.41	2.86
14	2,566.00	0	29.70	709.13	138.77	8.21	282.18	0.00	3.27
15	2,538.34	0	26.71	662.42	270.27	6.97	308.74	1.66	3.25
16	2,431.03	0	28.14	805.60	115.19	9.32	2,886.46	45.72	33.41
17	2,616.21	0	30.28	778.91	190.48	9.02	2,932.18	0	33.94
18	2,616.21	0	30.28	729.93	239.46	8.45	282.18	0	3.27
19	2,616.21	0	30.28	925.66	43.73	10.71	2,204.03	0	25.51
20	2,882.81	0	33.37	930.94	0	10.77	2,204.03	0	25.51
21	3,464.36	0	36.45	995.84	0	10.48	2,424.44	0	25.51
22	1,694.95	0	19.62	632.18	0	7.32	2,204.03	0	25.51
23	1,694.95	0	19.62	632.18	0	7.32	2,204.03	0	25.51
24	1,864.45	0	19.62	550.61	0	5.79	310.40	0	3.27
25	1,694.95	0	19.62	390.86	0	4.52	0	282.18	0
26	1,830.12	0	21.18	336.52	0	3.89	282.18	0	3.27
27	1,965.28	0	22.75	282.18	0	3.27	282.18	0	3.27
28	1,965.28	0	22.75	316.88	0	3.67	282.18	0	3.27
29	1,965.28	0	22.75	629.13	0	7.28	282.18	0	3.27
30	2,161.81	0	22.75	692.04	0	7.28	1,972.26	0	20.75
31	1,288.74	0	14.92	101.33	527.80	1.17	1,333.37	610.68	15.43
32	612.21	0	7.09	21.53	434.12	0.25	1,150.78	294.70	13.32
33	612.21	0	7.09	275.07	7.11	3.18	0	282.18	0
34	612.21	0	7.09	0	282.18	0	4.03	278.15	0.05
35	582.94	29.27	6.75	4.17	278.01	0.05	0	282.18	0
36	673.43	0	7.09	87.71	222.69	0.92	205.22	105.18	2.16

reach their highest levels in October, then return to the normal storage level thereafter. Changma discharges in July, at which point its outflow reaches 132 m^3/s. Similarly, Shuangta shows its largest outflow in July at 139.1 m^3/s; the amount of water it contains at this time is also largest. In October, the outflow of Chijinxia reaches a maximum of 20.3 m^3/s. The outflow of the cascade reservoirs Changma, Shuangta, and Chijinxia can be calculated by Equation (4) under the constraint of satisfying Equations (5)–(9). Table 4 shows the runoff control process of the three reservoirs. The overall runoff is less than the water demand, so under the condition of maximum water intake, the maximum water shortage of Shuangta under reservoir regulation is 43.503 million m^3, followed by Chijinxia with a water shortage of 22.18 million m^3. The minimum water shortage of Changma Reservoir is 327,700 m^3 and the surface water shortage for the three major irrigation areas is 66.01 million m^3. Under Shule River Basin Irrigation District management regulations, well water and spring water can continue to be used for irrigation. The water supply quantity, water shortage quantity, water diversion discharge, and total water shortage of the Changma, Shuangta, and Chijinxiain cascade reservoirs can be calculated using Equations (10) or (11).

6. CONCLUSIONS

This study was conducted to investigate the runoff optimal dispatch plan of Shule River Basin coupled with the regulation coefficient of its cascade reservoirs. We considered the multi-year average runoff at the dam site based on deduction of cumulative runoff from upstream cascade reservoirs and the beneficial reservoir capacity, then established the cascade reservoir regulation coefficient (γ). From upstream to downstream, first the main stream and then the tributaries, the dispatching order of the Changma, Shuangta, and Chijinxia reservoirs was determined by using the proposed cascade reservoir regulation coefficient (γ). Based on the water allocation scheme of Shule River Basin, the scheduling scheme of the three cascade reservoirs for the planning year was obtained by model calculation.

Our calculations indicate that under the multi-year average incoming runoff, all three reservoirs return to the initial storage process after the completion of water release and storage through optimal scheduling. However, the amount of water available for surface runoff is less than the amount of water demanded. Under the condition that the water intake process is maximized, the water shortage quota of Shuangta Reservoir is the highest at 43.503 million m^3, followed by that of Chijinxia Reservoir; the water shortage quota is 22.18 million m^3. The minimum water shortage of Changma Reservoir is 327,700 m^3 and the amount of surface water shortage across the three irrigation areas is 66.01 million m^3.

We solved the runoff optimization regulation model according to the model input conditions and algorithm parameters using a large system coordinated decomposition algorithm. In operating this method, obtaining the water scheduling scheme of each reservoir should be prioritized to resolve problems with water consumption for economic development under water resource constraints.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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