Research on Optimal Operation of Reservoirs in Shule River Irrigation District Based on Dynamic Programming with Successive Approximation Method

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Abstract. Reservoir operation is an important means to realize optimal allocation of water resources. In order to reasonably distribute water resources in Shule River irrigation area and improve the utilization rate of water resources, according to the actual situation of Shule River irrigation area, taking the minimum annual water shortage and the highest irrigation guarantee rate of the whole irrigation area as the objective function, the deterministic long-term optimal operation model of reservoir group in the irrigation area is established, and the successive approximation dynamic programming (DPSA) is used to solve the problem, so as to realize the joint operation of Changma Reservoir, Shuangta Reservoir and Chijinxia Reservoir, and provide the basis and reference for the comprehensive management and scientific allocation of water resources in Shule River basin.

1. Introduction
Reservoir Operation can solve the contradiction between incoming water and water demand by regulating river runoff and redistributing water in time and space, so as to reduce flood disasters and increase profitability. It has an important supporting role in achieving sustainable development of water resources strategy [1]. Reservoir Operation is the central link of reservoir management and operation. Whether the engineering efficiency of the reservoir can be fully utilized and whether the water conservancy and hydropower resources can be used reasonably depends on the level of operation. In order to realize the reasonable allocation of water resources, optimization algorithms are introduced into the process of solving the reservoir operation problem. Dynamic programming method [2-5] is a recursive optimization method for studying multi-stage decision-making process, which is the most widely used method in reservoir operation. It reduces the dimension of complex optimization problems, but there is a dimension disaster problem. Genetic algorithm [6-9] is a method to search for the optimal solution by simulating the natural evolution process. It can converge to the global optimal solution, but it takes a long calculation time as the cost. Due to its strong data processing and mapping functions, BP neural network [10,11] can reflect the complex nonlinear relationship between the operating elements of the reservoir, but it is easy to fall into the local optimum when the initial value of weight is not set properly. Particle swarm optimization algorithm [12-15] is an intelligent optimization algorithm that mimics the swarm behavior of birds in a flock. It has achieved a lot in the application of reservoir dispatching, but there is a phenomenon of premature convergence. The above optimization algorithms have their own advantages and disadvantages in practical application, so the selection of the algorithms is still based on the actual engineering needs.
The Shule River irrigation area is short of water resources and has a fragile ecological environment. Reasonable utilization and optimal allocation of water resources have become an important way to realize the sustainable development of water resources in the irrigation area [16,17]. Based on the comprehensive analysis of various factors that affect the optimal dispatch of reservoirs in the irrigation area, this paper establishes a deterministic medium- and long-term optimal operation model for the reservoirs in the irrigation area, and uses the dynamic programming with successive approximation (DPSA) method to solve the optimal operation model. This provides a reference for the joint operation of Changma Reservoir, Shuangta Reservoir and Chijinxia Reservoir, so that the Shule River basin water conservancy project can give full play to its benefits and realize the sustainable utilization of water resources in the Shule River basin.

2. Research Background
Shule River basin, located at the western end of Hexi Corridor in Gansu Province, is one of the typical arid inland river basins. The trunk stream is 670 km long, the basin area is 41,300, the annual average precipitation is 40.2 ~ 57.5 mm, the annual evaporation is 2577.4 ~ 2653.2 mm, and the annual average temperature is 6.98 ~ 9.82°C [17]. There are three reservoirs in the irrigation area, namely Changma, Shuangta and Chijinxia, with a total storage capacity of 472.2 million. It is one of the large gravity irrigation districts covering over one million mu in Gansu Province [18].

The Shule River irrigation district has two rivers, the main stream of the Shule River and the Shiyou River. At present, there are Changma Reservoir and Shuangta Reservoir on the main stream of the Shule River, and the Chijinxia Reservoir on the Shiyou River. Figure 1 shows the distribution relationship of the geographic locations of the three reservoirs. There is a close water conservancy connection between the three major reservoirs. Every year, the upstream Changma Reservoir transports water to the downstream Shuangta Reservoir and Chijinxia Reservoir. The process of transportation is extremely complicated. The water from Changma Reservoir is transferred to Shuangta Reservoir and Chijinxia Reservoir through the head of Changma Canal. When water is transferred to Shuangta Reservoir, there will be two water transfer routes. One is through natural river channels, and the other is to transfer water through artificial channels, which will take several days. When water is transported through natural channels, the water loss is very serious. Usually, the water loss can be as high as 80% on the first day of water transport. The lost water mainly seeps into the ground to supplement groundwater. The loss of water through artificial channels is slightly smaller. When transporting water to Shuangta Reservoir, it is possible to choose natural channels, artificial channels or two routes at the same time, no matter which method is adopted, the water loss and time during the whole process of water conveyance must be taken into account when building the model. When transporting water from the head of the Changma Canal to the Chijinxia Reservoir, it is mainly transported through the Shuhua main canal, and the process of transporting water also takes several days. In summary, the water transfer process of the three major reservoirs in the Shule River irrigation district is complicated, and many factors need to be considered. Taking the reservoir group in this irrigation district as the research object is very representative.

3. Establishment of Optimal Operation Model of Three Reservoirs

3.1. Objective Function
Reservoir operation is to determine the amount of water supply, water storage capacity and adjustment methods during the operation period of the reservoir. The operation mode, water supply and water storage within the year should be arranged first for the hydropower station reservoir with annual regulation performance. Based on the operating status of the reservoirs in the irrigation area, the data that has been mastered, and the actual scheduling needs, assuming that the reservoir's inflow runoff is known, the deterministic medium- and long-term optimal operation model for the reservoir group in the irrigation area is established.

For water-deficient areas such as the Shule River irrigation district, the minimum annual water shortage model for the entire irrigation district has strong practicability and is easily accepted by the public. The highest irrigation guarantee rate is one of the important standards to measure the level of
water resource operation in the irrigation area for the reservoir group dominated by irrigation. At the same time, it has strong operability. So the model with the highest irrigation guarantee rate is feasible for the optimal operation of reservoirs in the Shule River irrigation district. Therefore, in the joint operation model of the three reservoirs, the model of the minimum annual water shortage and the model of the highest irrigation guarantee rate are combined. Then the objective function of optimal operation of reservoirs in the irrigation area can be described as follows: under a certain water supply priority, the water shortage of each water department in the entire irrigated area during the operation period is the smallest, and the water supply is maximized.

![Figure 1. Reservoir project layout of Shule River irrigation district](image)

3.1.1. Model of minimum annual water shortage in the whole irrigation area. The role of reservoirs is mainly reflected in the reallocation of surface water resources in time and space. The minimum water shortage can well reflect the operation of reservoir. The minimum sum of squares of water shortage in the entire irrigation area at each time period is used as the objective function, and the form is as follows:

$$F = \min \sum_{r=1}^{R} \sum_{d=1}^{D} \sum_{t=1}^{T} (W_{r,dt} - D_{r,dt})^2$$

(1)

Where $D_{r,dt}$ represents the water demand of water department $d$ in time period $t$ of reservoir $r$ ($m^3$), $W_{r,dt}$ represents the actual water supply of water department $d$ in time period $t$ of reservoir $r$ ($m^3$).

$W_{r,dt}$ is calculated as follows:

$$W_{r,dt} = \begin{cases} D_{r,dt} & \text{if } D_{r,dt} \leq R_{r,dt} \\ R_{r,dt} & \text{if } D_{r,dt} > R_{r,dt} \end{cases}$$

(2)

Where $R_{r,dt}$ represents the available water supply of water department $d$ in time period $t$ of reservoir $r$ ($m^3$).
3.1.2. Model of the highest irrigation guarantee rate. The guarantee rate of irrigation water supply is the highest as far as possible under the condition of meeting the requirements of all water departments. The expression is as follows:

\[ r = \max P \]  

(3)

Where \( r \) represents the target value, that is, the highest guarantee rate. \( P \) represents the guarantee rate of irrigation water supply.

3.2. Constraints of Optimal Operation Model for The Three Major Reservoirs

3.2.1. Water balance equation.

\[ V_{r,t+1} = V_{r,t} + (I_{r,t} - O_{r,t}) \times \Delta t \]  

(4)

Where \( V_{r,t} \) represents the reservoir capacity of reservoir \( r \) in time period \( t \) (\( m^3 \)), \( I_{r,t} \) represents the average inflow of reservoir \( r \) in time period \( t \) (\( m^3/s \)), \( O_{r,t} \) represents the average outflow of reservoir \( r \) in time period \( t \) (\( m^3/s \)).

3.2.2. Flow continuity constraint. In the study of long-term optimal operation of reservoirs, the operation period is ten days or months, so the water retention time between upstream and downstream reservoirs is temporarily ignored. However, this factor must be taken into account when optimizing the operation of reservoir in real time. The flow continuity constraint equation is as follows:

\[ I_{r,t} = NI_{r,t} + DI_{r,t} \]

\[ O_{r,t} = qaw_{r,t} + qiw_{r,t} + qew_{r,t} + do_{r,t} \]  

(5)

Where \( I_{r,t} \) represents the average inflow of reservoir \( r \) in time period \( t \) (\( m^3/s \)), \( O_{r,t} \) represents the average outflow of reservoir \( r \) in time period \( t \) (\( m^3/s \)), \( NI_{r,t} \) represents the average natural inflow of reservoir \( r \) in time period \( t \) (\( m^3/s \)), \( DI_{r,t} \) represents the average flow of incoming water of reservoir \( r \) in time period \( t \) (\( m^3/s \)), \( qaw_{r,t} \) represents the average water diversion flow for irrigation of reservoir \( r \) in time period \( t \) (\( m^3/s \)), \( qiw_{r,t} \) represents the average industrial water diversion flow of reservoir \( r \) in time period \( t \) (\( m^3/s \)), \( qew_{r,t} \) represents the average ecological water diversion flow of reservoir \( r \) in time period \( t \) (\( m^3/s \)), \( do_{r,t} \) represents the average discharge of water discharged from reservoir \( r \) in time period \( t \) (\( m^3/s \)).

3.2.3. Upper limit of reservoir storage.

\[ V_{r,t} \leq VM_{r,t}, \quad t = 1,2,\ldots,T \]  

(6)

Where \( VM_{r,t} \) is the maximum allowable water storage of reservoir \( r \) in time period \( t \). In the flood season, it is the storage capacity corresponding to the flood limit water level of the reservoir, and in the non-flood season, it is the storage capacity corresponding to the normal storage level of the reservoir.

3.2.4. Lower limit of reservoir storage.

\[ V_{r,t} \geq VN_{r,t}, \quad t = 1,2,\ldots,T \]  

(7)
Where $VN_{r,t}$ is the storage capacity corresponding to the lowest allowable level of reservoir drawdown in time period $t$ of reservoir $r$, which generally is the dead storage capacity of the reservoir. However, other comprehensive utilization requirements of reservoirs must be considered, such as the realization of flood control and power generation of reservoirs.

3.2.5. Discharge flow restriction.

$$O_{r,t}^{\min} \leq O_{r,t} \leq O_{r,t}^{\max}$$

Where $O_{r,t}^{\min}$ is the lower limit of discharge flow of reservoir $r$ in time period $t$. Generally, it is determined by the water supply requirements and the river ecological environment requirements. $O_{r,t}^{\max}$ is the upper limit of the discharge flow of reservoir $r$, which is generally determined by the discharge capacity of hydropower stations and flood discharge facilities.

3.2.6. Channel over-current capacity constraint. When transferring water from upstream reservoirs to downstream reservoirs, water may be transferred through artificial channels. As the over-current capacity of channels is limited, constraints on the over-current capacity of channels should be considered. In addition, for the northern irrigation area, the time of water conveyance is also limited, and water conveyance may be restricted during winter and spring to prevent the channel from freezing and cracking.

4. DPSA Algorithm of Optimal Operation Model for Three Major Reservoirs

For the above reservoir group optimization operation model, each reservoir is faced with discrete problem of storage capacity and decision variables, which finally constitutes a multi-dimensional state, multi-dimensional decision and multi-objective problem. If the conventional dynamic programming method is adopted, it is easy to cause the dimensional disaster, so that the solution process is too long and even the optimal solution cannot be obtained. Therefore, the dynamic programming with successive approximation method is adopted to solve the optimal operation model.

4.1. Dynamic Programming Model for Optimal Operation of Reservoir Groups

4.1.1. Model variables. (a) Stage variables. The process of the given problem is properly divided into several interrelated stages so that it can be solved in a certain order. Such variables describing the stages are called stage variables. In this study, the scheduling period is divided into several periods (the length of the period is self-defined), and the sequence number $t$ ($t = 1, 2, 3, ... n$) of each period is used as the stage variable.

(b) State variables. State represents the natural or objective condition at the beginning of each stage. It describes the state of the process of studying the problem. The variables that describe the state of this process are called state variables. In reservoir operation, the reservoir water level $Zt$ or the storage volume $Vt$ at the end of the period is often used as the state variable. This study uses the storage volume $Vt$ as the state variable. As it is assumed that the inflow process of the reservoir is known, the operation process of the reservoir described by this state variable has no aftereffect.

(c) Decision variables. Decision-making means that when the process is in a certain state in a certain stage, different decisions can be made to determine the state of the next stage. This kind of decision is called a decision, and the variables describing the decision are called decision variables. In this study, the outgoing flow of the reservoir (including the average water diversion flow of irrigation, industry, ecology, and the average water transfer flow) is used as the decision variable.

4.1.2. State transition equation. The state transition equation is the evolution process of determining the process from one state to another. In the joint dispatching model with the goal of minimizing water shortage, according to the water balance principle, the state equation can be expressed as:
\[ V_{r,t+1} = V_{r,t} + (N_{r,t} + DI_{r,t} - qaw_{r,t} - qi_{r,t} - qew_{r,t} - do_{r,t}) \times \Delta t \] (9)

Where \( V_{r,t} \) represents the water storage capacity of reservoir \( r \) at the end of \( t \) period (m³), \( N_{r,t} \) represents the average inflow of natural water into the reservoir during period \( t \) of reservoir \( r \) (m³/s), \( DI_{r,t} \) represents the average flow of incoming water of reservoir \( r \) in time period \( t \) (m³/s), \( qaw_{r,t} \) represents the average water diversion flow for irrigation of reservoir \( r \) in time period \( t \) (m³/s), \( qi_{r,t} \) represents the average industrial water diversion flow of reservoir \( r \) in time period \( t \) (m³/s), \( qew_{r,t} \) represents the average ecological water diversion flow of reservoir \( r \) in time period \( t \) (m³/s), \( do_{r,t} \) represents the average discharge of water discharged from reservoir \( r \) in time period \( t \) (m³/s). \( \Delta t \) represents the length of the period (s).

If the reservoir has no transfer water, \( N_{r,t} \) is zero, such as Changma Reservoir. Similarly, if the reservoir has no water output, \( do_{r,t} \) is zero, such as Shuangta Reservoir and Chijinxia Reservoir.

4.1.3. Dynamic programming recursive equation. After determining the objective function, model variables and state transition equation, the recursive equation of dynamic programming adopts the inverse time series recursive equation, which is in the form of:

\[ f_{r,t}(V_{r,t}) = \min[L_{r,t}(V_{r,t}, N_{r,t}, DI_{r,t}, qaw_{r,t}, qi_{r,t}, qew_{r,t}, do_{r,t}) + f_{r,T+1}(V_{r,T+1})] \] (10)

\[ f_{r,T+1}(V_{r,T+1}) = E_{r,0} \] (11)

Where \( L_{r,t} \) represents the benefits obtained by taking decisions \( qaw_{r,t}, qi_{r,t}, \) and \( qew_{r,t} \) under state \( V_{r,t} \) at stage \( t \) of the \( r \) reservoir. \( f_{r,t}(V_{r,t}) \) represents the optimal benefit of the remaining process of the \( r \) reservoir from the initial storage capacity \( V_{r,t} \). \( E_{r,0} \) represents the termination status of reservoir \( r \).

4.2. DPSA Algorithm and Solution Steps

DPSA decomposes the reservoir group system containing \( R \) reservoirs into \( R \) single reservoir subsystems, and calculates the optimized operation strategy of each reservoir according to the single reservoir optimization method for each reservoir, which is used as the initial solution for the joint operation of the reservoir group. Then the operation strategy of each reservoir is improved in turn by considering the joint operation conditions of the reservoir group.

In the optimization of any reservoir \( r \), the strategy of the rest reservoirs is temporarily fixed. And the steady-state operation strategy of reservoir \( r \) can be obtained by using the iterative method of value, which replaces the initial operation strategy of reservoir \( r \). The above calculation is carried out for \( r=1,2,\ldots,R \) reservoirs one by one. After the first round of calculation is completed, the second round is carried out until the operation strategies of all reservoirs meet the convergence conditions. Finally, the approximate optimal solution of the library group can be obtained.

If it is a series reservoir group, it should be optimized from the first upstream reservoir to the downstream one by one. If it is a mixed reservoir group, the optimization should start from the reservoirs with poor regulation performance and small storage capacity one by one reservoir and one by one river. The successive approximation method only optimizes one reservoir at a time, and even if there are two state variables, it is not difficult to solve. The algorithm flow is shown in figure 2.

5. Implementation of Joint Optimization Operation of Three Reservoirs

According to the actual situation of irrigation area, industrial water supply should be guaranteed first, irrigation water supply should be provided second, and ecological water supply should be considered
last. In terms of the priority of water transfer, according to the layout of water conservancy projects in the irrigation area, the discharge water from The Changma Reservoir flows through more than 20 kilometers of natural channel and then is transferred at the head of the Changma Canal. Since Changma irrigation district does not have water conservancy regulation engineering facilities, it is usually necessary to ensure the water demand of Changma irrigation district first, and then consider water transfer to Shuangta Reservoir and Chijinxia Reservoir. Then, according to the water demand of each water department in the irrigation area in the year of operation. The optimal operation strategy of the three reservoirs in the irrigation area and the water transfer strategy in the basin can be obtained by comprehensively considering the various factors of the combined operation of reservoirs and solving the optimal operation model of the reservoir group. The calculation period is ten days. The operation scheduling strategy of reservoir refers to indicators such as the water discharge in each period, the storage capacity and reservoir water level at the end of each period. The specific operation process of joint optimal reservoir operation is shown in figure 3. The step of reading the reservoir operation rules is to obtain the start time, end time and limit water level of the Changma Reservoir, Shuangta Reservoir, Chijinxia Reservoir in the early flood period, main flood period and final flood period. The setting of water transfer parameters among the three reservoirs mainly includes setting of water transfer route, setting of water loss and setting of water transfer priority.

Figure 2. Flow of DPSA algorithm

Figure 3. The joint operation process of the reservoir

Figure 4 shows the beneficial operation diagram of the reservoir generated according to the operation plan (taking Changma Reservoir as an example), which is a tool to guide the operation of reservoir regulation. With the ten-day period as the abscissa and the water storage as the ordinate, the reservoir operation diagram contains three indicating lines, including the damage prevention line, the restricted water supply line and the flood control and dispatch line, as well as the graphs of four indicating areas, including the normal water supply area, the reduced water supply area, the increased water supply area and the flood control area. According to the water storage of each period on the reservoir operation diagram, the supply and storage of the reservoir are determined. With a reservoir operation diagram, it is possible to decide whether to supply water normally, increase or decrease it, minimize useless water discharges, and avoid interruption of the water supply, depending on the area where the water storage capacity of the reservoir is located at that time. Figure 4 shows the dispatching
line in three-dimensional form, so as to show the relationship between each indicator line more intuitively.

![Changma Reservoir beneficial operation diagram](image)

**Figure 4.** The beneficial operation diagram of the reservoir

According to the calculation results of the optimal operation system of the three reservoirs, the storage and discharge methods of Changma Reservoir are basically "two storage periods and two discharge periods" -- the storage period is August in flood season and November to March in winter non-irrigation season, and the discharge period is From April to June and From September to October. The incoming water in flood season and remaining water in winter should be regulated, stored and utilized as much as possible. In order to prolong the service life of the Changma Reservoir, in July, when the river water contains the largest amount of sediment in the flood season, the reservoir is open without water storage to facilitate sand flushing and desilting, reducing the amount of silt accumulation in the reservoir, that is, adopting the "Storing clean water and draining muddy water" mode. The sediment content of the river in August is second only to that in July during the flood season. If the water level can also be lowered to flush and discharge the sediment, the sedimentation volume of the reservoir can be greatly reduced. However, due to the large amount of water in the first and middle of August, if the reservoir is opened without impoundment, it will be difficult to fill the reservoir before the end of August, and it will not be able to meet the demand for irrigation water in autumn and winter in September and October. Therefore, the reservoir must be stored from early August, as much water as possible until the reservoir is full. For Shuangta Reservoir and Chijinxia Reservoir, the annual operation process of the reservoir is obviously divided into multiple operation stages, which are basically the repeated operation process of "water storage-water discharge-water storage-water discharge". After the Shuangta irrigation district and the Huahai irrigation district start to irrigate, the Shuangta Reservoir and the Chijinxia Reservoir both need to transfer water from the upstream Changma Reservoir.

### 6. Conclusion

With the rapid development of economy and society, the contradiction between supply and demand of water resources is becoming increasingly serious. Realizing the optimal operation of reservoirs has become an important means for the optimal allocation of water resources in the irrigation area.

(1) Based on comprehensive analysis of various factors affecting optimal operation of reservoirs, this paper establishes a deterministic medium- and long-term optimal operation model for the
reservoirs in irrigation district. Under the condition of certain water supply priority and water transfer priority, the objective function of the model is to minimize the water shortage and maximize the water supply satisfaction of each water department in the whole irrigation area during the dispatching period. The constraints of the model include water balance, flow continuity constraint, the upper and lower limits of reservoir storage, discharge flow restriction, channel over-current capacity constraint, etc.

(2) The optimal operation system of reservoir group in irrigation area is generally a mixed reservoir group system with many decision variables and many factors to be considered comprehensively. Therefore, the DPSA method is adopted to solve the model. The combined optimal operation model of the three reservoirs can adjust and control the incoming water and impounding water in time and space, giving full play to the role of reservoirs in regulating and storing water, and improving the utilization rate of water resources in each irrigation area.

(3) For Shule River irrigation district, the optimal operation of the three reservoirs provides scientific basis for agricultural irrigation in Changma irrigation district, Shuangta irrigation district and Huhai irrigation district, and has important theoretical value and practical significance for guiding industrial and ecological water use in each irrigation area and each department. However, in order to realize the rational use of regional water resources and sustainable development of water resources, the joint management of surface water and groundwater must be considered in the areas of water resources shortage such as the Shule River irrigation area in Hexi Corridor. Much more needs to be done in this regard.

7. References
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