Optimal water allocation method for joint operation of a reservoir and pumping station under insufficient irrigation

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ABSTRACT

To address the problem of optimal allocation of water resources in water shortage areas, a reservoir and a pumping station water resource optimal scheduling model under the condition of insufficient irrigation is proposed. The model takes the maximum relative yield of crops as the objective function, the amount of water supplied, water spilled and water replenished as decision variables, the total amount of water supplied by the system, the water right of the pumping station and the operation criteria as constraints, and uses a dynamic programming method to solve the model. The optimal water supply and water spill process of the irrigation reservoir and the optimal water replenishment process of a pumping station during the entire growth period of dry crops were obtained. Moreover, under the conditions of 50 and 75% probability of exceedance, the optimized relative yields of crops increased by 17.1% and 19.6%, respectively. The results show that ensuring the optimal operation of joint water source projects can achieve the optimal allocation of limited water resources, and improve the relative yield of crops in irrigation areas, which has important guiding significance for the planning and management of water resources in similar irrigation areas.

Key words | dynamic programming, joint operation, pump station, reservoir, water right

INTRODUCTION

With the rapid depletion of freshwater resources worldwide, most irrigation areas are facing a major agricultural problem, which is the shortage of irrigation water supply. With the increasing demand for water resource for various purposes and the increasing cost of regional water resources development, the contradiction between supply and demand in agricultural irrigation is also increasing.

Reservoirs are important water source projects for the planning and utilization of water resources. To alleviate the water supply pressure of irrigation reservoirs, irrigation areas require various water diversion projects to replenish water for reservoirs or farmlands (Gong et al. 2019; Choi et al. 2020; Ma et al. 2020). At present, a large number of studies on the optimal allocation of water resources in...
irrigation areas only focus on the optimal allocation of existing water resources of irrigation reservoirs (Vedula & Kumar 1996; Ghahraman & Sepaskhah 2002; Georgiou et al. 2006; Janga Reddy & Nagesh Kumar 2007; Moradi-Jalal et al. 2007). However, research on the optimal allocation of water resources for the joint operation of reservoirs and water diversion projects is still lacking. Simultaneously, considering the gradual clarification of the right to use water resources (Molle 2004; Heikkila 2015), the impact of regional water rights restrictions must be considered in the water supply decision-making of irrigation systems.

The optimal operation of reservoir systems is an important method in the field of water resource management (Nandalal & Sakthivadivel 2002; Suiadee & Tingsanchali 2007; Console et al. 2008). The application of optimization technology to solve the problem of reservoir optimal operation is also one of the hot issues in this field. In the early stage, classical linear programming and dynamic programming methods (Bellman & Dreyfus 1964) can be used to solve a single reservoir optimal operation model. This type of traditional algorithm can be proved by strict theory to obtain a global optimal solution. However, the decision-making of reservoir irrigation water supply involves many factors, such as the type of irrigation crops, growth stage and the impact of water shortage on yield (Vedula & Mujumdar 1992; Vedula & Kumar 1996; Georgiou et al. 2006). When traditional methods deal with multiple-decision variable problems, the existence of the “curse of dimensionality” is its evident disadvantage.

A heuristic algorithm has significant advantages in dealing with nonlinear problems and solving multi-decision variable problems and has been widely used in different fields. Among them, intelligent algorithms represented by the genetic algorithm (Tegegne & Kim 2020), simulated annealing algorithm (Rouzegari et al. 2019), and particle swarm optimization algorithm (Al-Aqeeli & Mahmood 2020) have also been applied to the optimal operation of reservoirs (Jothiprakash & Shanthi 2006; Chen & Chang 2007; Yun et al. 2010; Scola et al. 2014). Considering the multiple constraints in a reservoir optimization model, a heuristic algorithm usually transforms a constrained problem into an unconstrained problem. The penalty function method (Samanipour & Jelovica 2020) is the most commonly used method to deal with constraints. When there are many complex constraints, the penalty function may affect the accuracy of the solution.

Based on regional water rights, this study considers an irrigation system composed of a reservoir and pumping station. The optimal allocation model of water resources for the joint operation of the reservoir and pumping station under the condition of insufficient irrigation is established and a dynamic programming method and genetic algorithm are used to solve the nonlinear model with multiple decision variables, to determine the optimal water supply and water spill process of the reservoir and water replenishment process of the pumping station during the entire growth period of dry crops. In addition, the applicability of the two algorithms in this type of model was verified.

### MODEL AND METHOD

#### Optimization model

**Objective function**

The contradiction between water supply and water demand and the relationship between water quantity and yield were considered. The Jensen model of the water production function was adopted (Jensen 1968), and an objective function was used to maximize the relative yield of crops in the irrigation district. To facilitate the calculation of the joint operation of the reservoir and supplementary pumping station, the ratio of the actual evapotranspiration and potential evapotranspiration in the water production function was transformed into the ratio of reservoir water supply and crop irrigation water demand (Wardlaw & Barnes 1999). The model is as follows:

\[
\max G = \prod_{i=1}^{N} \left( \frac{X_i}{Y_{SI}} \right)^{k_i} 
\]

where \( G \) is the relative yield of crops, \( i \) is the number of the growth period of the crop, \( N \) is the total number of crop growth periods, \( k_i \) is the sensitivity index of yield to water stress in period \( i \), \( X_i \) is the water supply of the reservoir under insufficient irrigation in period \( i \) (in \( \text{L}^3 \)), \( Y_{SI} \) is the irrigation water demand of the crop in period \( i \) (in \( \text{L}^3 \)).
Constraints

(1) Total quantity restriction of the water supply:

$$\sum_{i=1}^{N} X_i \leq SK + BZ$$

where $SK$ is the total amount of water available in the reservoir ($L^3$); $BZ$ is the water right of the pumping station, and the maximum amount of water extracted from the pump station ($L^3$).

(2) Operation-rule constraints:

$$V_{i}^{\text{min}} \leq V_i \leq V_{i}^{\text{max}}$$

where $V_i$ is determined according to the water balance equation:

$$V_i = V_{i-1} + LS_i + Y_i - X_i - EF_i - PS_i$$

where $V_i$ is the reservoir storage at the end of period $i$, ($L^3$); $LS_i$ is the incoming water in period $i$ of the reservoir, ($L^3$); $EF_i$ is the water lost in period $i$ of the reservoir, ($L^3$); $PS_i$ is the abandoned water quantity in period $i$ of the reservoir, ($L^3$).

According to the water balance equation of the system, the reservoir operation criteria are determined as follows:

(i) If $V_i \leq V_{i}^{\text{min}}$, the reservoir needs to be replenished through the pump station in the period $i$, and the replenishment amount of the pump station is:

$$Y_i = V_{i}^{\text{min}} - V_i$$

At this point, the water spilled is:

$$PS_i = 0$$

(ii) If $V_i \geq V_{i}^{\text{max}}$, the amount of water replenished from the pumping station is $Y_i = 0$, then the amount of water spilled is:

$$PS_i = V_i - V_{i}^{\text{max}}$$

(iii) If $V_{i}^{\text{min}} \leq V_i \leq V_{i}^{\text{max}}$, the reservoir does not need to be replenished or spilled, then:

$$Y_i = PS_i = 0$$

(3) Pump station constraints:

(i) Constraints on pumping capacity of pumping station:

$$Y_i \leq Y_{i}^{\text{max}}$$

(ii) Pumping station water rights constraints:

$$\sum_{i=1}^{N} Y_i \leq BZ$$

where $Y_i$ is the water replenishment of the pumping station in period $i$, ($L^3$); $Y_{i}^{\text{max}}$ is the maximum water replenishment of pumping station in period $i$, ($L^3$).

(4) Constraints on crop water demand:

$$Y_{Si}^{\text{min}} \leq X_i \leq Y_{Si}$$

where $Y_{Si}^{\text{min}}$ is the minimum irrigation water demand of the crop in period $i$, ($L^3$).

Solving method

Aiming at the nonlinear mathematical model established in this study, this study uses a dynamic programming method and genetic algorithm to solve the problem, and verifies the correctness of the results and the applicability of the algorithm by comparing the results of both algorithms.

Dynamic programming

Dynamic programming (DP), a branch of operations research, is a method based on the Bellman optimization principle (Bellman & Dreyfus 1964). When DP is used to solve the above model, the global optimal solution of the objective function can be obtained, and the complex constraints involved in the model can be transformed and
processed in the recursive process of DP, which is as follows:

(1) Phase \( i = 1 \):

\[ g_1(\lambda_1) = \max \left( \frac{X_1}{Y_S} \right)^{k_1} \]  \hspace{1cm} (12)

The state variables are discretized in the corresponding feasible domain \([0, SK + BZ]\) with step size \( d \), and \( m \) points discretized. Considering Equation (11), the feasible region of the decision variable (reservoir water supply \( X_1 \)) is \( Y_{i_{\text{min}}} \leq X_1 \leq \min \{Y_{S1}, \lambda_1\} \), and the decision variable is discretized in the feasible region with step size \( d \). Discrete \( X_1 \) is substituted into Equations (12) and (4), so the reservoir capacity at the end of phase 1 is \( V_1 = V_0 + L S_1 - E F_1 - X_1 \). At this time, pumping station water replenishment or reservoir water spill operation is taken into account, and dispatching criterion Equations (5)–(9) are adopted for testing:

(1) When the reservoir water capacity is greater than the upper limit of water storage, the resulting water spill is \( PS_1 = V_1 - V_{i_{\text{max}}} \), the reservoir volume is revised as \( V_1' = V_1 - PS_1 \).

(2) When the water storage of the reservoir is less than the lower limit of water storage, the pumping station should be used to replenish the reservoir, and the amount of supplementary water is \( Y_1 = V_{i_{\text{min}}} - V_1 \), according to Equation (9).

1. When \( Y_1 \leq V_{i_{\text{max}}} \), the filling capacity of the pump station is sufficient, and the storage capacity of the reservoir is revised as \( V_1' = V_1 + Y_1 \).
2. When \( Y_1 > V_{i_{\text{max}}} \), the filling capacity of the pump station is insufficient, and the water storage of the reservoir is revised as \( V_1' = V_1 + Y_1 \). At this time, the modified reservoir water storage is lower than the dead water level and does not meet the reservoir capacity constraint, and the corresponding function value of \( X_1 \) will be sifted out (the value is assigned to be negative).

Through steps (1)–(2), the discrete \( X_1 \) is tested by the constraint of the operation rule, combined with the value of the function for each discrete \( X_i \), then the optimal function value \( g_1(\lambda_1) \) corresponding to each discrete state variable \( \lambda_1 \) can be obtained, as well as the optimal function value corresponding to the optimal reservoir water supply \( X_1^* \), water replenishment \( Y_1^* \), and water spill \( PS_1^* \).

(2) Phase \( i = 2, \ldots, N-1 \):

\[ g_i(\lambda_i) = \max \left[ \left( \frac{X_i}{YS_i} \right)^{k_i} \cdot g_{i-1}(\lambda_{i-1}) \right] \]  \hspace{1cm} (13)

State transfer equation:

\[ \lambda_{i-1} = \lambda_i - X_i \]  \hspace{1cm} (14)

According to the state transfer equation (Equation (14)), the function value \( g_{i-1}(\lambda_{i-1}) \) that meets the requirements in the \( i-1 \) phase can be found and the process of step (1) repeated for each discrete state variable \( \lambda_i \), the optimal value of the function \( g_i(\lambda_i) \), and the optimal function value corresponding to the optimal reservoir water supply \( X_i^* \), water requirements \( Y_i \), and water spills \( PS_i^* \).

(3) Phase \( i = N \):

\[ g_N(\lambda_N) = \max \left[ \left( \frac{X_N}{YS_N} \right)^{k_N} \cdot g_{N-1}(\lambda_{N-1}) + p(x) \right] \]  \hspace{1cm} (15)

A penalty term is introduced at the last stage of the recursive process to test the water rights constraint of the pumping station (Equation 10), and the expression is as follows:

\[ p(x) = \begin{cases} \mu & \text{if } \sum_{i=1}^{N} Y_i > BZ \\ 0 & \text{otherwise} \end{cases} \]  \hspace{1cm} (16)

where \( \mu \) is the penalty factor, which is a sufficiently small negative number.

The state transfer equation is given by:

\[ \lambda_{N-1} = \lambda_N - X_N \]  \hspace{1cm} (17)

So far, all the constraints involved in the model have been transformed and processed. Substituting Equation (17) into Equation (15), the process of step (2) can be repeated to obtain the global optimal function value \( G^* = \max g_N(\lambda_N) \), and its corresponding optimal reservoir water supply process \( (X_1, X_2, \ldots, X_N)^* \), optimal water replenishment process of
pumping station \((Y_1, Y_2, \ldots, Y_N)^*\), and reservoir water spill process \((PS_1, PS_2, \ldots, PS_N)^*\).

The optimization flow chart of the system is shown in Figure 1.

Genetic algorithm

A genetic algorithm (GA) is an optimization algorithm developed by imitating the evolution mechanism of nature. The advantages of this algorithm are simple, general and robust, and it is suitable for parallel processing (Samanipour & Jelovica 2020); therefore, it is often used to solve the planning problem in the field of optimal reservoir operation (Jothiprakash & Shanthi 2006; Chen & Chang 2007; Yun et al. 2010).

In this study, the GA adopts a real-coded method, in which the reservoir water supply \(X_i\) is generated randomly in the feasible region \([Y_{S_i}^{min}, Y_{S_i}^{max}]\), the pumping station's water replenishment \(Y_i\) is generated randomly in the feasible region \([0, Y_i^{max}]\), and the water spill \(PS_i\) is determined according to the water balance equation. Considering that the model involves many constraints, a penalty function is constructed to deal with the constraints in the process of solving the genetic algorithm. The function expressions are as follows:

\[
P_1(x) = \begin{cases} 
\mu_1 & \text{if } V_i > V_i^{max} \\
0 & \text{otherwise}
\end{cases}
\]  
\( (18) \)

\[
P_2(x) = \begin{cases} 
\mu_2 & \text{if } V_i > V_i^{min} \\
0 & \text{otherwise}
\end{cases}
\]  
\( (19) \)

\[
P_3(x) = \begin{cases} 
\mu_3 & \text{if } \sum_{i=1}^{N} Y_i > BZ \\
0 & \text{otherwise}
\end{cases}
\]  
\( (20) \)

\[
P_4(x) = \begin{cases} 
\mu_4 & \text{if } V_{end} \neq V_{0} \\
0 & \text{otherwise}
\end{cases}
\]  
\( (21) \)

The optimization flow chart of the system is shown in Figure 1.
where $P_1$, $P_2$, $P_3$, and $P_4$ are penalty functions of the upper and lower limits of storage capacity, water right of the pumping station, and boundary conditions of storage capacity, respectively; $\mu_1$, $\mu_2$, $\mu_3$, and $\mu_4$ are penalty factors respectively. The penalty factor is $-10,000$ in the actual solution process.

The fitness function of the GA is constructed by integrating the objective and penalty functions of the model:

$$F = G + P_1 + P_2 + P_3 + P_4 \quad (22)$$

where $F$ is the value of the fitness function.

**CASE STUDY**

The Yibei (YB) irrigation district is located in the eastern mountainous area of Xinyi, Jiangsu Province, China (Figure 2). There are many low hills in the study area that affect its topography. The main crops are winter wheat and another cash crop, and the area of the main wheat winter crop in the irrigation district is $1270 \, \text{hm}^2$. The climate is warm and monsoonal and the climate varies markedly from year to year, with a multyear mean rainfall of $891.5 \, \text{mm}$ and an average evaporation rate of $968.0 \, \text{mm}$. The main source of irrigation water in the irrigated area is the Shadun (SD) Reservoir (Figure 2), and the coefficient of irrigation water use is 0.48, with a designed storage capacity of $7.5 \times 10^6 \, \text{m}^3$ and a lower limit of $2 \times 10^6 \, \text{m}^3$.

The YB irrigation district is located in a hilly area, and relying only on reservoir water storage cannot guarantee the normal agricultural water use in the irrigation district, so the surface water should be intercepted and external water should be simultaneously diverted for replenishment. Based on the local ‘Xinyi Water Source Project Planning’ data, and considering the division of regional water rights, the total allowable water replenishment of the pumping station is $3 \times 10^6 \, \text{m}^3$. In this study, winter wheat is considered as the research object, and its growth period spans from October to June of the following year. According to the division of growth stages of winter wheat, the entire water resources scheduling process was divided into six periods. The parameters of the crop experiment in the irrigation area are shown in Table 1, and the parameters of the pumping station are listed in Table 2.

With a probability of exceedance of 50 and 75%, the water in flow and irrigation water demand of each stage of the system were obtained according to the planning data of the water source project in the YB irrigation area. See Tables 3 and 4 for details.

Evaporation loss is a function of evaporation depth and average free water surface of a reservoir in each period. Evaporation depth ($E_i$) was obtained from evaporation data acquired by the coefficient of correction using an $E_{601}$ evaporator (Table 5), and the data required correction.
by the coefficient \( k \). The average free water surface of each reservoir in a specific period is determined by the surface-volume relationship, which was provided by the Xinan Water Authority. Finally, the reservoir evaporation for a specific period can be computed using Equation (23):

\[
EF_i = 0.1 \times w_i \times E_i \times (\alpha V_i + \beta)
\]  

where \( EF_i \) (10\(^4\) m\(^3\)) is the evaporation loss of a reservoir in period \( i \), \( E_i \) (mm) is the evaporation depth of the \( E_{601} \) evaporator in period \( i \), \( w_i \) is the correction coefficient for period \( i \), \( V_i \) (10\(^4\) m\(^3\)) is the average water storage in period \( i \), and \( \alpha \) and \( \beta \) are the reservoir coefficients. For the SD reservoir, \( \alpha = 2.117 \times 10^{-3} \), \( \beta = 1.863 \).

### RESULTS

In the conventional operation of the irrigation system, the initial boundary of the reservoir water storage is \( 3.18 \times 10^6 \) m\(^3\) and \( 2.86 \times 10^6 \) m\(^3\) when the water probability of exceedance is 50 and 75%, respectively. The optimal operation results of irrigation system are listed in Table 6.

Using the DP method to solve the model, the optimal values of the function under 50 and 75% probabilities are 0.637 and 0.373, respectively. Compared with the standard operation policy (SOP) results, the relative yield of winter wheat is increased by 17.1% and 19.6%, respectively. At the same time, using a genetic algorithm to solve the model, the optimal values of the function at 50 and 75% probabilities were 0.628 and 0.364, respectively. The comparison of the final solution results shows that the optimal function values of DP and GA are close, which indicates that the solution results of the two methods are more reliable.

### COMPARISON AND DISCUSSION

#### Comparison of scheduling results

Figure 3(a)–3(d) show that the operation curves obtained by DP and GA are between the upper and lower limits of the reservoir capacity, indicating that the operation process of the system is reasonable. However, it can still be found that the reservoir capacity curve generated by DP is
generally under the capacity curve generated by SOP and GA, which means that the operation process generated by DP maintains the average storage capacity of the reservoir at a small level and reduces the evaporation loss of the reservoir to the greatest extent. Therefore, Table 6 reveals that at 50% probability of exceedance, the system evaporation of DP is 3000 m$^3$ less than that of GA, and at 75% probability of exceedance, it is 8000 m$^3$ less than that of SOP and GA. Therefore, the optimal planning and management of local runoff resources and regional water rights can be achieved using DP to solve the optimal scheduling model of an irrigation system.

Figure 4(a) and 4(b) show that the water replenishment decision of the pumping station generated by GA is affected...
by randomness, and there are water replenishment operations in all stages of the system, which is also the main reason for the increase in average reservoir storage and evaporation loss. When DP is used to solve the problem, the joint operation criterion of the irrigation reservoir and pumping station can be coupled into the recursive process, which can clearly dictate when and how much water should be replenished. This also makes the quantity of make-up water generated by DP less than SOP and GA. In addition, the reduction in the number of water replenishments also means a reduction of the number of start-ups at the pump station, which is convenient for the staff to maintain and manage the pump unit.

Algorithm performance comparison

Considering that the solution results of GA may be affected by changes in internal parameters, the crossover rate and mutation rate of GA were analyzed first. The variation range of the crossover rate is 0.5 to 0.8, the variation range of the mutation rate is 0.05 to 0.15, and the population is 200. The optimal solution of the objective function under different GA parameter combinations is presented in Table 7.

However, as shown in Table 7, using the GA solution model, different parameter combinations in the algorithm significantly impact the final solution results. Moreover, GA is affected by the random search characteristics; even if the parameters are the same, the optimal value obtained after several runs is slightly different. When the DP method is used, the analysis of redundant parameters is not required, and the result is always unique and reliable.

CONCLUSION

In this study, the optimal allocation model of water resources for the joint operation of a reservoir and the pumping station under insufficient irrigation conditions was established considering regional water rights. The results of the joint operation of different water source

![Figure 4](image-url)

**Figure 4** | (a) the water replenishment process of the pump station at 50% probability; (b) the water replenishment process of the pump station at 75% probability.

| Parameter analysis of crossover rate and mutation rate (GA) |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Crossover rate | Mutation rate | Objective function | Crossover rate | Mutation rate | Objective function |
|----------------|-------------|------------------|----------------|-------------|------------------|
| 0.5            | 0.05        | 0.589            | 0.7            | 0.05        | 0.609            |
| 0.1            | 0.621       | 0.355            | 0.1            | 0.628       | 0.321            |
| 0.15           | 0.602       | 0.348            | 0.15           | 0.562       | 0.337            |
| 0.6            | 0.05        | 0.597            | 0.8            | 0.05        | 0.598            |
| 0.1            | 0.562       | 0.351            | 0.1            | 0.612       | 0.363            |
| 0.15           | 0.586       | 0.322            | 0.15           | 0.606       | 0.364            |

The above results are the optimal values obtained by running 10 times.
projects in the irrigation system were discussed. In addition, the optimal water supply and water spill process of the irrigation reservoir and the optimal water replenishment process of the pumping station in the whole growth period of dry crops were determined. The optimal allocation of local runoff and regional water resources was achieved which has a certain guiding significance for decision-makers in irrigation areas. In addition, the classical dynamic programming method was used to solve the mathematical model involving three decision variables, which also enriches the application of the traditional algorithm in practical problems.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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