Multi-objective model of irrigation water distribution based on particle swarm optimization

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Abstract. Developing the high-efficiency agriculture is the strategy of agricultural sustainable development, and rational allocation of irrigation water resources is an important way in improving the efficiency of agricultural resources utilization. In this paper, the particle swarm optimization algorithm is used to optimize the irrigation water distribution schedule. This model focuses on decreasing the leakage loss and increasing allocation efficiency of irrigation water distribution. The transition process verified the rationality of the water distribution scheme and effectively satisfied the actual demand.

1. Introduction

As an agricultural powerhouse, ensuring agricultural water use is not only the basis of guaranteeing the national economy, but also the sustainable development of the economy in China [1]. It exists 959 million mu irrigated area in China, and agricultural water use accounts for 62.4% of all [2]. Therefore, it is so necessary to adopt water-saving measures to cope with the water crisis and provide reliable basis for irrigation water distribution and management [3].

Considering various constraints in the water distribution process, naturally, multi-objective and simultaneous optimization is needed to optimize the distribution of water in canal system. However, there is a salient feature of the multi-objective optimization problem, which the improvement of one sub-goal may cause the performance of another to be reduced. That is, it is difficult for multiple sub-goals to achieve optimality at the same time. And that situation is explained by Pareto non-inferior solution set theory that the ideal result of the multi-objective optimization problem is to make the sub-objectives as optimal as possible [4]. However, for the same multi-objective optimization problem, there may be many non-inferior solutions, so it is necessary to select the most suitable one as the optimal solution according to the specific needs in the actual situation. With the rapid development of computer science, the method of optimizing the water distribution of canal system by mathematical model came into being. Many ways to solve the optimal irrigation system are as following: linear programming (LP), nonlinear programming (NLP), dynamic programming (DP), stochastic dynamic programming (SDP), chaotic algorithm (CA) and model coupling, etc.

In the early stage of the study, many methods of manual management were mainly used. Aiming at maximizing economic benefits, dynamic programming was proposed, Hall et al [5], to make optimal water allocation decisions for water use departments. Suryavanshi and Reddy [6] firstly assumed that the superior irrigation water distribution channel was a group of equal-flow flow tubes, whose flow...
rate was equal to the sum of the lower-level channel flows. In order to reduce the investment of the canal project, a linear model was established to optimize it. And Juan [7] also established an optimal water resource allocation model under non-sufficient irrigation. However, manual management not only lacked a unified standard, that was to say, it doped some subjective factors of planners to some extent, but also the existence of dynamic models may lead to serious problems on the dimension scale. These shortcomings lead to low efficiency. In the near future, the rise of intelligent algorithms provided a new idea for solving complex models of irrigated water resources optimization. Wardlaw et al [8] applied genetic algorithm to the distribution of irrigation water among different crops. Taking into account the economic, social and ecological benefits of sustainable agricultural development, Tang et al [9] adopted entropy weight coefficient to establish an optimization model of multi-index comprehensive evaluation of water resources optimal allocation in irrigation areas. In order to maximize the total benefit, total crop yield, ecological benefit and water productivity in irrigation area, Wang [10] established a multi-objective crop planting structure optimization model, which was solved by multi-objective chaotic particle swarm optimization algorithm. A multi-objective model about optimization water allocation was established by Zhang et al [11] to acquire the highest increased yield benefit and water income of the irrigation district under the basic of soil moisture and the water production function. The information of land use and soil moisture in irrigation area was gained easily by RS technology and the optimization water allocation in each branch under the condition of multi-objective could be obtained by the model solution with ant colony algorithm in GIS system of each the image pixeles. Zhao et al [12] introduced dynamic penalty function processing constraints and proposed simulated annealing algorithm to solve the problem of water distribution in canal system. Zhang et al [13] through the construction of fitness function and efficient processing of constraints, the free water search algorithm was applied to solve the channel water distribution model. Zhou et al [14] took the minimum difference between the diversion flow and the diversion time as the objective function, and combined with the improved genetic algorithm to solve the optimal irrigation group combination in the irrigation area. Hu et al [15] applied the cat swarm optimization algorithm to solve the optimal water distribution model of irrigation canal rotation irrigation and compared it with the particle swarm optimization algorithm. Kong [16] used the improved multi-objective ant colony algorithm to optimize the distribution of water in an irrigation area in central Liaoning Province. Chen et al [17] optimized the water resources of irrigation area through the robust optimization model, and obtained the water distribution targets under the multi-water source, multi-crop and different robustness coefficients in the irrigation area. Although the intelligent algorithm was efficient, but if the water distribution problem wasn’t based on reasonable algorithms, precise optimization targets, and appropriate parameters, it would produce low iteration accuracy, achieve local optimum, and run time in solving the water distribution problem of the canal system.

In view of the common problems of the above intelligent algorithms, this paper proposes a water distribution optimization model based on particle swarm optimization algorithm, and combines the canal hydrodynamic model to verify the water distribution scheme, and obtains the optimal solution based on actual operational requirements.

2. Canal-based optimal water allocation algorithm and model based on particle swarm optimization

2.1. Fundamental principles of particle swarm optimization

Independent variables are represented by the positions of particles with initial constraints. The number of initial particles is N and the position "x" of each particle is determined by the number of independent variables and the range of values. The change speed is also determined by the number N and the velocity v. The expressions of position and velocity are as follows:

\[ x_i = \{ x_{i1}, x_{i2}, \ldots, x_{iN} \} \]  

(1)
\[ v_i = \{v_1, v_2, \ldots, v_N\} \]  

(2)

Considering the inertia weight, individual learning factor, group learning factor and based on historical location and speed, the location and speed of the next process are determined synthetically. The specific process of single iteration is as follows:

\[
v_{id}^{n+1} = \omega \cdot v_{id}^n + c_1 \cdot \gamma_1 \cdot (p_{id}^n - x_{id}^n) + c_2 \cdot \gamma_2 \cdot (p_{gd}^n - x_{id}^n)
\]

(3)

\[ x_{id}^{n+1} = x_{id}^n + v_{id}^{n+1} \]

(4)

In the formula, "\(v_{id}^n\)" and "\(v_{id}^{n+1}\)" respectively for single particle velocity value after i and i+1 iterations, "\(x_{id}^n\)" and "\(x_{id}^{n+1}\)" respectively for the position of a single particle numerical i, after i+1 iterations, "\(\omega\)" inertia weight, "\(\gamma_1, \gamma_2\)" difference adjusting inertia weight (in this paper in order to reduce the error, the value reduced to 0-1 ), "\(c_1, c_2\)" respectively for individual learning and group learning factor, "\(p_{id}^n\)" and "\(p_{gd}^n\)" respectively for single and group size The history of the best position.

The MOPSO is based on the original PSO. It applies the particle swarm that can only be solved on a single target to the multi-objective optimization problem. MOPSO can find non-inferior solutions to multi-objective optimization problems in the global scope in a shorter time under actual corresponding constraints.

2.2. Multi-objective and multi-variable irrigation water optimizing model

The correlation functions of the water distribution optimization model are as follows.

\[
\min S = \frac{1}{T} \sum_{t=1}^{T} (q_{ui} \cdot q_{ave})^2
\]

(5)

\[
\min P = \frac{1}{100} \sum_{i=1}^{T} \beta_u A_u L q_{ui}^{(1-m_u)} + \frac{1}{100} \sum_{j=1}^{l} \beta_j A_j L q_{j}^{(1-m_j)} (t_i' - t_j)
\]

(6)

\[
q_{ui} = \sum_{j=1}^{l} q_j \cdot f(t)
\]

(7)

\[
q_j = q_j + \frac{1}{100} \beta_j A_j L q_j^{(1-m_j)}
\]

(8)

The two optimization targets correspond to equations (5) and (6) respectively, wherein the water flow smooth optimization target corresponds to the standard deviation "\(S\)" of the upper channel water delivery flow for different round periods; The minimum leakage optimization target corresponds to the total amount of water seepage in the distribution channel of unit "\(m^3\)". "\(j\)" is the lower water distribution channel number; "\(i\)" is the different time period during the rotation period.

The formula includes: the channel's water flow rate "\(q_{ui}\)" in the i-th time period, unit "\(m^3/s\)"; the average flow rate of the upper channel in the whole period "\(q_{ave}\)", unit "\(m^3/s\)"; lower channel "\(j\)" with water hair flow "\(Q_j\)". unit "\(m^3/s\)"; the lower channel "\(j\)" is equipped with the net flow "\(Q_j\)", unit "\(m^3/s\)"; the 0-1 variable f(t) controlling whether irrigation is used; the rotation period "\(T\)" is in days; the lower channel The length of "\(j\)" is "\(l_j\)", the unit is "\(Km\)"; the length of the superior channel is "\(L\)", the unit is "\(Km\)"; the leakage reduction factor "\(\beta_j\)" after the channel adopts the leakage prevention measures; the sub-channel j-bed soil permeable Coefficient "\(A_j\)"; soil permeability coefficient "\(m_j\)" of the lower channel "\(j\)" channel; leakage reduction coefficient "\(\beta_u\)" after the upper channel adopts anti-seepage measures; superior channel bed Soil permeability coefficient "\(A_u\)"; soil permeability
index "m_u" of superior channel canal bed; lower channel "j" starts irrigation time "t_j" and ending irrigation time "t_j'", unit "day".

The constraints are as follows:

- **Traffic constraints:**
  \[ \alpha_{dj} Q_{dj} \leq Q_j \leq \alpha_{uj} Q_{dj} \]
  where \( \alpha_{dj} \) and \( \alpha_{uj} \) are the traffic constraint coefficients for the superior and lower channels, respectively.

- **Time constraints:**
  \[ 0 \leq t_j \leq t_j' \leq T \]

- **Water quantity constraint:**
  \[ \sum_{j=1}^{n} Q_j (t_j' - t_j) \leq W_{max} \]
  \[ Q_j (t_j' - t_j) \geq M_j \cdot S_j \]

The formula includes: Allowable water quantity \( W_{max} \), unit "m³". The crop irrigation quota \( M_j \) under the lower channel control area, unit "m³/m²". The sub-channel control area crop area \( S_j \), unit "hm²".

- **0-1 constraint:**
  \[ f(t) = \begin{cases} 1, & t_j \leq t \leq t_j' \\ 0, & \text{others} \end{cases} \]

The empirical formula is used to calculate the canal leakage in the model. The constraint coefficients for minimum and increased flow of the channel are generally derived from empirical coefficients. And the formulas and coefficients above are obtained by reference to Farmland Hydraulics [18].

### 3. Solution of water distribution in XiDong Irrigation District based on unsteady flow simulation of irrigation canal

#### 3.1. Study area background and model parameter determination

In this paper, the XiDong Canal system is used as the simulation object. This area belongs to XiJun irrigation district, which is one of the large irrigation districts in the middle reaches of HeiHe River. The extreme shortage of water resources is a typical feature of this area. The canal system is mainly composed of XiDong branch canal, the MaoJiaWan branch canal and nine direct distribution canals. Currently, the channel water utilization coefficient is 0.556 and the irrigation water utilization coefficient is 0.484. It is proposed to use the irrigation data of the three rounds of summer irrigation in the GanZhou District Water Distribution Plan in 2007, with a rotation period of 25d and a comprehensive irrigation quota of 1200 m³/hm². The volume of the incoming flow is 2.805 million m³. The specific distribution of the canal system is shown in figure 1, and the channel-related design parameters are shown in table 1.
Figure 1. XiDong canal system layout.

| Table 1. Channel distribution model coefficient table. |
|-----------------------------------------------|
| Parameters                                    | Value |
| Sub-channel minimum flow coefficient $\alpha_{ij}$ | 0.6   |
| Sub-channel auxetic flow coefficient $\alpha_{ij}$ | 1.2   |
| Sup-channel minimum flow coefficient $J_i$     | 0.4   |
| Sup-channel auxetic flow coefficient $J_i$     | 1.2   |
| The reduction coefficient of anti-seepage measures $\beta_j$ | 0.5   |
| Canal bed soil permeability coefficient $A_j$  | 3.4   |
| Drainage bed soil permeability index $m_j$     | 0.5   |

3.2. Particle swarm optimization algorithm results

Solving the canal optimization model and generating the canal time-sharing results are shown in figure 2. Figure 2 shows that the water distribution time is shortened to about 11 days. At the same time, considering the delay of manual opening, the result is not the flow distribution of water at the beginning of the round period reflects the relative rationality of the results.

According to the water distribution time schedule, combined with the water demand of each branch channel, the flow of each channel after optimization is shown in figure 3: the model optimizes the flow to meet the requirement of no flushing and no silt constraint, and can be close to the design flow size; and the second and fifth branch channels. The flow rate is almost the same as the design flow, and the flow of the other channels is slightly lower than the design flow, which indirectly reflects the conservative nature of the branch channel irrigation.
3.3. Simulation of unsteady flow distribution process in open channel based on optimized water distribution model

The MIKE11 model is used to validate and simulate the optimized water distribution scheme. The results are shown in figures 4 and 5, taking the first direct bucket and the ninth bucket for example directly.

Figure 4. (a) Transition process of water level in front of a bucket gate and (b) Transition process of water level after a bucket gate.

Figure 5. (a) Water level transition process in front of Jiudou sluice and (b) Water level transition process after Jiudou sluice.
Most of the previous studies have split the relationship between optimal water distribution scheme and practical application. In this paper, channel simulation is introduced into the follow-up work of optimization, and the water level transition situation before the gate is obtained: the water level before irrigation directly belongs to Bucket one and it can reach 0.82 m; the water level before the gate directly belongs to Bucket nine can also reach 0.70 m. That means the feasibility of the water distribution scheme, given by PSO in practical operation, is preliminarily verified.

4. Conclusion
- In this paper, 11 channels of XiDong canal system are taken as the research object. Based on the optimization objectives of smooth flow transition and minimal water loss, a multi-objective optimization model of canal system is established by particle swarm optimization (PSO). The results show that the allocation time of irrigation area is reduced from 25 days to 13 days, which greatly optimizes the allocation time of canal system and improves the allocation efficiency.
- On the premise of achieving steady flow and minimum seepage of canal system, the total amount of water distribution is optimized based on the flow optimization of each branch canal, so that the flow of main canal is increased from 1.298 m$^3$/s to 2.31 m$^3$/s. Meanwhile and the total amount of water distribution of canal system is 2.0507 million m$^3$, which is about 36% higher than the plan. This reflects the efficiency of the water distribution scheme obtained by the model.
- Based on the optimization results obtained by particle swarm optimization and the hydrodynamic numerical model of irrigation area, the water level and flow transition process of XiDong trunk canal and some branch canals in the simulation period is determined. Whether the optimized water distribution scheme meets the relevant requirements of irrigation water distribution is discussed, and the feasibility of the water distribution scheme is proved.

Acknowledgements
The authors express gratitude for the financial support from the National Key R&D Program of China (Grant Nos. 2016YFC0400207, 2017YFC0403203, 2017YFD0701000 and 2016YFD200700), National Natural Science Foundation of China (Grant No. 51509248), Jilin Province Key R&D Plan Project (20180201036SF), Chinese Universities Scientific Fund (Grant No. 2019TC108), Open Fund of Synergistic Innovation Center of Jiangsu Modern Agricultural Equipment and Technology, Jiangsu University (Grant No. 4091600002), Open Fund of State Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University (Grant No. 19R06).

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