Postprint: Reservoir Optimal Operation for Multi-object Ecosystem Protection and Restoration

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Abstract

Over the past 20 years, with the implementation of integrated water resources planning and scheduling in the Tarim River (hereinafter referred to as the "Tarim River") basin, the ecological water conveyance target of "water flowing to Taitema Lake, with Daxihaizi Reservoir discharging 3.50\$×108m^{3}\$ annually on average" has been fundamentally achieved. However, vegetation is sparse and the ecological environment is fragile in the two-river area between the Qiwenkuoer River and the old Tarim River in the lower reaches of the Tarim River, and the ecological restoration effects over the years have not been significant. In view of this, this study established a medium- and long-term ecological optimal operation model for the reservoir, taking Daxihaizi Reservoir as the regulation entity and Daxihaizi' s discharged ecological water volume, in-stream ecological base flow, ecological water conveyance to Taitema Lake, and off-channel ecological water supply as ecological protection targets, and solved it using the particle swarm optimization algorithm. The results show that: (1) After optimal operation, the multi-year average discharge volume of Daxihaizi Reservoir is 5.23\$×108$m^{\{3\}, whichmeetsthewatervolumerequirementof 3.50\times 108m}$\{3\}\$ in the Phase I planning of the Tarim River, and the duration of continuous flow in the downstream river channel is significantly extended; (2) After optimal operation, the multi-year average inflow volume to Taitema Lake is 0.18\$×108$m^{\{3\}, whichrepresentsa 20.0\times 108m}$\{3\}\$, which lays the water volume foundation for the ecological restoration of desert riparian vegetation forests in the downstream two-river area. The research findings have important application value for the restoration and protection of desert riparian vegetation forests in the downstream two-river area of the Tarim River, maintaining the ecological health of the river channel and terminal lake, and constructing a subsurface ecological water bank, and also have important practical and promotional significance for constructing an ecological Tarim River basin.

Full Text

Abstract

Over the past two decades, the implementation of integrated water resources planning and scheduling in the Tarim River basin has largely achieved the ecological water delivery target of "flow reaching Taitema Lake with Daxihaizi Reservoir discharging an annual average of 3.50$×10^{8}$ m^3." However, vegetation remains sparse and the ecological environment fragile in the "two-river area" between the Qiwenkuoer River and the old Tarim River channel in the lower reaches, where multi-year ecological restoration efforts have shown limited success. This study establishes a medium- to long-term ecological optimization scheduling model for Daxihaizi Reservoir, using it as the primary regulation entity and considering multiple ecological protection objectives: the reservoir' s ecological discharge volume, in-stream ecological base flow, water delivery to Taitema Lake, and off-channel ecological water supply. The model is solved using particle swarm optimization. Results indicate: (1) Under optimized scheduling, Daxihaizi Reservoir' s multi-year average discharge reaches 5.23$×10^{8}$ m^3, satisfying the first-phase planning requirement of 3.50$×10^{8}$ m^3 while significantly extending the duration of continuous flow in the downstream channel; (2) The multi-year average inflow to Taitema Lake increases to 3.50$×10^{8}$ m^3, representing a 20.0% increase compared with measured data, with a more stable inflow process that benefits the consolidating lake ecosystem; (3) The guaranteed rate of ecological base flow in the lower Tarim River reaches 50.0%, with a 64.6% guarantee rate for uninterrupted flow, representing significant positive impacts on the ecosystem of China' s longest inland river that is heavily affected by human activities; (4) The multi-year average off-channel ecological water supply to the lower reaches reaches 1.67$×10^{8}$ m^3, establishing a hydrological foundation for ecological restoration of desert riparian vegetation in the two-river area. These findings hold important application value for the restoration and protection of desert riparian vegetation, maintenance of ecological health in river channels and terminal lakes, and construction of underground ecological water banks in the lower Tarim River, with broader significance for developing an ecologically sound river basin management approach.

Keywords: medium- and long-term ecological scheduling; multiple protection objects; off-channel ecological water supply; lake inflow volume; ecological base flow; Tarim River

Introduction

Water resources constitute an indispensable foundation for socioeconomic development and ecological conservation. Reservoirs play a critical role in water resources development and utilization, making reservoir scheduling research essential for unified management and efficient water use. Traditional reservoir scheduling models have focused on power generation, irrigation, and flood control objectives, solved using systems science approaches to guide reservoir operations. Internationally, ecological reservoir scheduling research began earlier than in China. Steinschneider et al. proposed a large-scale optimization scheduling model to explore the contribution of coordinated reservoir management to ecological benefits in multi-objective scheduling problems for large river basins. Sabo et al. published research on ecological scheduling for the Mekong River, coupling structural differences in river flow regimes through scheduling models to design flow patterns that satisfy both river ecological integrity and human economic needs.

To address premature convergence issues in conventional algorithms, researchers have proposed improved methods. Zhong et al. developed a simplex particle swarm algorithm successfully applied to cascade reservoir ecological scheduling. Xia et al. established a multi-objective optimization model for the Qingjiang cascade reservoir group considering ecological base flow and minimum ecological flow variations, solved using a cooperative particle swarm optimization algorithm. Zhong et al. introduced a gravitational search algorithm for ecological scheduling of the Wujiang reservoir group, demonstrating superior performance compared with conventional optimization algorithms and effectively reducing unsuitable ecological water volumes.

Research on ecological scheduling for the Tarim River basin began relatively late in China. Deng et al. studied ecological scheduling based on rational water resources allocation in the Tarim River basin, analyzing the relationship between ecological scheduling and water resources allocation and identifying key issues, objectives, and measures. Wang et al. reviewed water resources research progress in the Tarim River basin, identifying ecological scheduling, water rights allocation, ecological compensation, and inter-basin water transfer as key research directions. Xu et al. investigated the impacts of ecological water conveyance on vegetation community composition, diversity, and stability in the lower Tarim River, finding that while plant community stability has gradually improved since water conveyance began, it remains in an unstable state. Wang et al. evaluated the ecological and socioeconomic benefits of water conveyance projects in the lower Tarim River, showing that while water areas increased significantly, forest and grassland areas decreased. Li et al. analyzed vegetation dynamics and responses to ecological water conveyance from 2000-2018, noting that vegetation restoration effects remain limited.

The Tarim River, China’ s longest inland river, stretches 2,486 km from its source in the Yeerqiang River. Its basin, with an average elevation of approximately 1,000 m, features a typical continental climate and represents one of the world’ s most fragile ecosystems. Strong interference from climate change and human activities has significantly altered water resource spatiotemporal distribution patterns. Particularly after Daxihaizi Reservoir construction in 1972, downstream flow cessation caused 大面积衰退 of natural vegetation and drying of Taitema Lake. Desert riparian vegetation dominated by Populus euphratica, Tamarix ramosissima, and Haloxylon ammodendron forms ecological corridors in this extremely arid environment, playing vital roles in windbreak and sand fixation.

To protect ecological security and save the endangered "green corridor," the Tarim River Basin Management Committee and Authority were established in the 1990s. Since 2000, the Authority has implemented the "Tarim River Basin Recent Comprehensive Management Plan," organizing emergency ecological water conveyance to the lower reaches. Daxihaizi Reservoir has actively performed ecological functions, cumulatively discharging 8.161$\times10^{9}$ m^3 and achieving the target of 4.13$\times10^{8}$ m^3 annual average discharge, restoring Taitema Lake' s natural landscape. While the 3.50$\times10^{8}$ m^3 annual discharge target has been met, natural channel consumption using dual-channel conveyance reaches only 2.26$\times10^{8}$ m^3, with lake inflow of 3.50$\times10^{8}$ m^3. However, excessive lake area causes severe ineffective evaporation. The challenge remains how to make intermittent water conveyance functionally replace natural overflow to maximize riparian ecological restoration.

Previous studies have been limited and time-constrained, focusing on analyzing existing measures or effects. This study utilizes 20 years of inflow data from the lower reaches, using Daxihaizi Reservoir as the regulation entity to construct a medium- to long-term ecological optimization scheduling model for multiple ecosystem protection objects. The objective is to fully exploit reservoir ecological scheduling potential, guarantee off-channel ecological water supply to the two-river area, address rational allocation of ecological water in the lower basin, provide water support for ecological restoration in arid inland river basins, and offer theoretical and practical value for ecological protection and restoration in the lower Tarim River.

1.1 Study Area Overview

The lower Tarim River extends from Daxihaizi Reservoir to Taitema Lake, situated between the Taklamakan and Kumtag deserts, with a total length of 350 km. Daxihaizi Reservoir is located in the desert plain area of the lower Tarim River main stream, 210 km from the 2nd Division and 155 km from Korla City. The region features a typical continental arid climate with annual precipitation of only 17.4-42.0 mm and evaporation of 2,500-3,000 mm, resulting in an extremely fragile ecological environment with poor resistance.

The lower reach can be divided into upper and lower segments. The upper segment from Daxihaizi to Alagan (the two-river area) has a complex water system with numerous branches. The main channel splits into eastern and western branches 4.2 km below the reservoir: the eastern Qiwenkuoer River (204.5 km) and western old Tarim River (143.8 km), converging at Alagan before turning south. The lower segment from Alagan to Taitema Lake (153.1 km) forms a narrow north-south belt.

Daxihaizi Reservoir, originally constructed in 1972 as a large-scale reservoir for agriculture, irrigation, flood control, and ecological supply, was repurposed in

2012 as a medium-sized reservoir dedicated exclusively to ecological water supply for the lower Tarim River. By the end of 2014, agricultural irrigation functions were completely removed. Due to long upstream conveyance distances, unstable surface water, and intermittent flow characteristics, this study positions the reservoir as an ecological-only facility using stored water to centrally regulate downstream conveyance, maximizing ecological benefits for vegetation restoration through medium- to long-term scheduling. Reservoir characteristic water levels and capacities are shown in Table 1.

Table 1 Reservoir characteristic water level and capacity

Water Level Type	Elevation (m)	Capacity (10^8 m^3)
Dead water level	846.00	0.15
Normal pool level	848.60	0.25
Design flood level	849.30	0.28
Check flood level	849.60	0.30

Due to limited inflow data for Daxihaizi Reservoir, the river channel attenuation rate from the Aral hydrological station to the Qiala station was applied to estimate inflow at Daxihaizi using collected Qiala data:

$$W = W' \times (1 - \eta)^L$$

where W is the inflow at Daxihaizi Reservoir (10^8 m^3), W' is the inflow at Qiala section (10^8 m^3), η is the unit length attenuation rate (0.18%), and L is the channel length from Qiala to Daxihaizi (km).

Based on current water resources development in the lower Tarim River basin, a scheduling network node diagram was developed encompassing reservoirs, hydrological stations, control sections, and lakes. The ecological scheduling nodes for Daxihaizi Reservoir are shown in Figure 2.

Figure 2 Ecological dispatch node of Daxihaizi Reservoir in the lower reaches of Tarim River

2 Ecological Scheduling Model Establishment and Solution

The model utilizes engineering data (reservoir characteristic parameters, water level-capacity curves) and inflow data (20 years of measured data from 100 km upstream). The scheduling period is monthly scale from May to November, covering the critical ecological period.

2.1 Model Establishment

The first-phase Tarim River comprehensive management plan established the target of "Daxihaizi Reservoir discharging 3.50$×10^{8}$ m^3 annually with water reaching Taitema Lake." Ecological protection objects include in-stream ecological base flow, multi-year average discharge volume, and critical off-channel ecological water for the two-river area. Therefore, the ecological scheduling system involves multiple protection objects: total ecological discharge, in-stream base flow, off-channel habitat water demand, and Taitema Lake inflow.

2.2 Constraint Conditions

The model converts three protection objects into constraints:

1) **Total ecological discharge constraint**: Daxihaizi Reservoir' s multi-year average total discharge must be ≥ 3.50\$×10^{8}\$ m^3.
2) **Taitema Lake inflow constraint**: While the first-phase plan only required water to reach the lake, faster water arrival and excessive inflow (3.59\$×10^{8}\$ m^3 in 2017, creating the largest water area since 1972) cause severe ineffective evaporation. Based on Fan Zili' s research on Taitema Lake area, the multi-year average inflow is constrained to ≥ 0.15\$×10^{8}\$ m^3.
3) **In-stream ecological base flow constraint**: As an inland dissipative river with highly unstable inflow, the base flow guarantee rate is set at 50.0%.

For off-channel ecological water demand, the critical period is May-June when Populus euphratica seeds disperse and germinate. The objective function maximizes the multi-year average off-channel ecological water supply to the two-river area:

$$F = \max \frac{1}{N} \sum_{i=1}^{N} W_i^{\text{off}}$$

where F is the multi-year average off-channel ecological water supply (10^8 m^3), W_i^{off} is the off-channel supply in year i, and N is the total number of years in the scheduling period.

Additional constraints:

1) **Water balance**: $V_t = V_{t-1} + (I_t - q_t) \times \Delta t$
2) **Storage capacity**: $V_t^{\min} \le V_t \le V_t^{\max}$
3) **Water level**: $Z_t^{\min} \le Z_t \le Z_t^{\max}$
4) **Discharge capacity**: $0 \le q_t \le q_t^{\max}$
5) **Total discharge**: $\frac{1}{N \times T} \sum_{i=1}^{N} \sum_{j=1}^{T} q_{i,j} \ge W_e$
6) **Base flow guarantee**: $P_i = \frac{\text{Number of months meeting base flow}}{T} \ge P_{\min}$

7) **Lake inflow**: $\frac{1}{N\times T}\sum_{i=1}^{N}\sum_{j=1}^{T} q_{i,j}^{\text{lake}} \geq W_l$
8) **Initial condition**: $Z_0 = Z_{\text{begin}}$
9) **Non-negativity**: All variables ≥ 0

2.3 Model Solution

The off-channel maximum ecological water supply problem is a single-objective optimization solved using the mature and efficient Particle Swarm Optimization (PSO) algorithm. PSO abstracts birds in a swarm as massless "particles" that share information and cooperate, with each particle' s velocity influenced by its own and the swarm' s historical best positions.

In n-dimensional solution space with m particles, at iteration k:

- Particle positions: $X^k = (x_1^k, x_2^k, \cdots, x_m^k)$
- Particle velocities: $V^k = (v_1^k, v_2^k, \cdots, v_m^k)$
- Individual best positions: $P_{\text{best}}^k = (p_1^k, p_2^k, \cdots, p_m^k)$
- Global best position: $G_{\text{best}}^k = (g_1^k, g_2^k, \cdots, g_n^k)$

Velocity and position updates:

$$v_{i,j}^{k+1} = W \cdot v_{i,j}^k + c_1 r_1 (p_{i,j}^k - x_{i,j}^k) + c_2 r_2 (g_j^k - x_{i,j}^k)$$

$$x_{i,j}^{k+1} = x_{i,j}^k + v_{i,j}^{k+1}$$

where W is the inertia weight, c_1 and c_2 are learning factors, and r_1, r_2 are random numbers uniformly distributed in [0,1].

For this study, Daxihaizi Reservoir discharge flow is the decision variable across 7 monthly periods (May-November). Particle dimension is set to 7, with position corresponding to discharge flow and velocity to flow changes. Parameters: population size = 50, maximum iterations = 500, learning factors = 2.0, inertia weight = 0.8.

3 Results Analysis

3.1 Reservoir Ecological Discharge Analysis

The optimized discharge process is shown in Figure 3. After processing the runoff data, the multi-year average inflow at Daxihaizi is 5.25$×10^{8}$ m^3, with optimized discharge of 5.23$×10^{8}$ m^3, satisfying water balance and verifying feasibility.

Figure 3 Multi-year monthly average water volume variation in Daxihaizi Reservoir

Comparing measured and optimized discharge (Figure 4), during 2002-2020 the measured average discharge was 4.61$\times10^{8}$ m^3 (2002-2011) and 6.76$\times10^{8}$ m^3 (2012-2020), with flow months accounting for 33.3% and 41.7% of the year respectively. After optimization, discharge reaches 6.49$\times10^{8}$ m^3 and 8.07$\times10^{8}$ m^3, with flow months increasing to 41.7% and 50.0%. The multi-year average discharge of 5.23$\times10^{8}$ m^3 exceeds the 3.50$\times10^{8}$ m^3 target, extending flow duration by 1-2 months and providing a solid foundation for vegetation restoration.

Figure 4 Measured and optimized discharge process

3.2 Taitema Lake Inflow Analysis

During the first-phase project, various conveyance methods created highly unstable inflow, with 3.59$\times10^{8}$ m^3 entering the lake in 2017, creating the largest water area since 1972 (449 km^2). Such unstable, sharply fluctuating inflow provides no significant ecological benefit. After optimization, constraining inflow to 0.15×10^{8} m^3 yields a multi-year average of 0.18$\times10^{8}$ m^3 (Figure 5), a 20.0% increase with reduced variability (0-0.55$\times10^{8}$ m^3 range). This stable inflow better consolidates the lake ecosystem and provides habitat for wildlife.

Figure 5 Optimization process of water inflow into Taitema Lake

3.3 In-Stream Ecological Base Flow Analysis

While the first-phase plan lacked base flow requirements, optimization achieves a 50.0% guarantee rate for meeting the 5 m^3/s ecological base flow, with 64.6% guarantee rate for uninterrupted flow (Figure 6). This significantly promotes growth of desert riparian forest vegetation, particularly Populus euphratica, curbing ecological degradation and enhancing community stability.

Figure 6 Downstream discharge and ecological base flow

3.4 Off-Channel Ecological Water Supply Analysis

Given excessive lake inflow, controlling it to reasonable levels while allocating saved water to the two-river area better meets ecological restoration needs. Figure 7 shows October water supply outside the channel. Maximum supply reaches 2.95$\times10^{8}$ m^3 (2010), minimum 0.25$\times10^{8}$ m^3 (2015), with a multi-year average of 1.67$\times10^{8}$ m^3. This volume can expand the watered area of desert riparian vegetation, raise groundwater levels, increase plant diversity, and provide effective guarantees for growth of key species, yielding significant ecological benefits.

Figure 7 Reservoir water supply outside the river channel each October during the operation period

4 Conclusions

1) Optimized scheduling yields a multi-year average discharge of 5.23$\times10^{8}$ m^3 from Daxihaizi Reservoir, meeting the first-phase target of 3.50$\times10^{8}$ m^3 and extending downstream flow duration, indicating potential for further improvement in desert riparian forest restoration.

2) Optimized multi-year average inflow to Taitema Lake is 0.18$\times10^{8}$ m^3, a 20.0% increase that stabilizes inflow within 0-0.55$\times10^{8}$ m^3, crucial for consolidating the lake ecosystem and protecting wildlife habitats.

3) The optimized scheme achieves a 50.0% guarantee rate for ecological base flow and 64.6% for continuous flow, providing important positive impacts on the lower Tarim River ecosystem.

4) The multi-year average off-channel ecological water supply of 1.67$\times10^{8}$ m^3 establishes a hydrological foundation for restoring desert riparian vegetation in the two-river area.

As an inland river heavily impacted by human activities, the Tarim River' s lower reaches exhibit highly unstable inflow. This study focused on maximizing available ecological water for the two-river area without considering vegetation water demand processes. Future research should develop real-time ecological optimization scheduling based on critical period water demand processes to maximize ecological benefits from limited water resources and secure the "green corridor" ecosystem.

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