Experimental ecological scheduling study on cascade hydropower station considering both fish spawning and hydropower generation

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ABSTRACT
In this study, a new ecological dispatching model for cascade hydropower stations considering fish reproduction is proposed by adding the ecological flow demand for fish spawning to the scheduling target of cascade hydropower stations. The study was conducted in the middle reaches of Jinsha River basin where Liyuan-Ahai cascade hydropower stations are located. By sorting out and analysing the habits and demands of aquatic organisms in the river along with the river water temperature and incoming water conditions, the hydrological and water temperature conditions suitable for experimental ecological regulation of the cascade section of the Jinsha River were obtained. Liyuan-Ahai cascade reservoirs were selected to carry out experimental ecological regulation simulations under different inflow scenarios. This study provides scientific basis and reference for cascade hydropower station dispatching, which can help restoration of the environment and satisfy optimal social and economic benefits.

Keywords: Aquatic life demand, Cascade hydropower stations, Experimental ecological regulation

The hydrological cycle of natural rivers undergo changes in wet and dry periods. These changes affect hydrological processes such as flow quantity, water stage and water temperature and transfer signals to the organisms in the ecosystem. The rhythmic changes of river hydrological conditions provide signals for fish spawning and reproduction and these activities have a certain response relationship with river ecological and hydrological indicators. In recent years, the impact of the operation of reservoirs on river ecological environment has received extensive attention from the government and the public. Reservoir operations are expected to meet not only the functions of flood control and power generation, but also consider the ecological needs of the river to a certain extent. As a major river ecological restoration measure, ecological regulation contributes to the development and improvement of traditional reservoir regulation methods. It mainly focuses on solving existing serious problems in the water environment, bringing the ecological factors into the current reservoir operation and controlling the ecological impact of reservoir operation while maintaining the benefit of flood control and water conservation. Compared with engineering measures, ecological regulation measures have low implementation cost, larger scope of effect on the downstream ecology and obvious ecological restoration effects.

Research on the ecological impact of reservoir operation started in the late 1970s, including the analysis of river hydrological regime changes caused by reservoir construction (Hueftle and Stevens, 2001; Field and Lund, 2006; Bednarek and Hart, 2005), the evolution mechanism of reservoir sedimentation and downstream river morphology and water quality changes. However, due to the lack of quantitative research on river ecological water demand, the practice of reservoir ecological operation has been restricted. In recent years, with the improvement of river eco-environmental water demand theory, more attention has been paid to reservoir ecological operation. Ecological regulation is to implement ecological compensation for rivers under flood control, power generation, water supply, irrigation, shipping and other objectives, so as to ensure the sustainable utilisation of water resources and promote the harmonious development of economy, society and environment in the basin. Some scholars have studied the ecological operation of the Three Gorges Reservoir based on the current regulation status (Cheng and Chen, 2007; Zou, 2008) and put forward a theoretical framework.
of ecological regulation (Cai, 2006). Dong et al. (2007) pointed out that ecological regulation should coordinate various benefit factors to achieve multi-objective equilibrium optimisation.

With the improvement of ecological regulation theory, many scholars have used it to formulate ecological goals of reservoir regulation in recent years. For example, in the ecological adaptive management of the Murray River in Australia, by increasing the discharge, peak discharge and duration during fish spawning and juvenile stages, the natural river hydrological pulse was restored to meet the spawning and reproduction requirements of downstream fish (King, et al., 2009). In the Connecticut River Basin of the United States, the large-scale optimal operation model is applied to ecological regulation (Steinschneider, et al., 2013). Researchers have established models of reservoir operation considering ecological water requirements (Wang, 2012; Yin et al., 2013) and proposed that ecological operation should be transformed into a comprehensive regulation process of the whole basin-large spatial scale, long series-large time scale and water cycle-large system scale (Deng et al., 2020). Buyukates and Roelke (2005) investigated the effect of two different inflow and nutrient loading regimes on zooplankton and phytoplankton biomass and diversity, i.e., continuous and pulsed inflows of 3-day frequency.

Current research on ecological regulation of reservoirs has shifted from qualitative analysis to quantitative regulation practice, especially the ecological runoff process required downstream of the reservoir. Based on the reservoir water storage and discharge processes that consider the ecological demand of river water environment, the protection and restoration of downstream ecological system can be realised. The scope of ecological regulation is refined from the ecological water demand of the whole basin to the impact of specific ecological hydrological factors, which improves the theory and model of ecological regulation. However, according to the features of specific rivers, the ecological operation objectives and ecological factors of reservoirs are different. For further study, it is worthy to comprehensively consider the ecological needs of multiple aspects and construct the ecological operation model for cascade reservoirs. Therefore, in this study for the Jinsha River Basin, it was necessary to sort out and clarify the hydrological requirements of aquatic habitats and fishes, optimise the existing operation mode of cascade hydropower stations and carry out joint ecological operation research, so as to maximise the comprehensive benefits of cascade operation and establish the Green Ecological Protective Screen for the Yangtze River.

Based on the hydraulic connection between cascade hydropower stations and considering a series of constraints, the power generation of cascade hydropower stations and the pulse flow required for fish spawning were taken as targets and an ecological dispatch model of cascade hydropower stations for fish breeding was constructed.

Considering the existing dispatching methods of cascade hydropower stations in the Jinsha River and the dispatching sequence, the ecological scheduling principles were formulated as follows:

1. **Safety-first principle**: Ecological regulation experiments must obey the principle of safety first and the operation and application of various water conservation projects must be controlled within the designed or prescribed safety range.

2. **Flood control priority principle**: Reservoirs must ensure that the designed flood control storage capacity can be used for flood control, ecological regulation obeys flood control dispatching and the water levels of various reservoirs must be controlled within the designed or prescribed safety range.

3. **Near-natural principle**: Follow the basic guidelines of adapting to the natural flow situation and adapting measures to the local, time and species conditions, combining with the ecological problems arising from the operation of the reservoir and carrying out corresponding ecological regulation experiments according to the ecological needs of different protection objectives.

The objective function of the model is:

\[
W = E + F(Q_{i,t} - Q_{i,t}^*)
\]

subject to the following major constraints:

- **Water balance equation**:
  \[
  V_{i,t+1} = V_{i,t} + (Q_{i,t} - Q_{i,t}^*) \Delta t
  \]

- **Reservoir storage volumes limits**:
  \[
  V_{i,\text{min}} \leq V_{i,t} \leq V_{i,\text{max}}
  \]

- **Hydropower station power generation limits**:
  \[
  N_{i,\text{min}} \leq A_q H_{i,t} \leq N_{i,\text{max}}
  \]
where,
\[ W = \text{Target value} \]
\[ E = \text{maximum generation output of cascade hydropower stations, kW·h} \]
\[ F = \text{Intermediate variable} \]
\[ T = \text{Total ecological scheduling time, calculated in days} \]
\[ MM = \text{Infinite numbers} \]
\[ t = \text{Time, calculated in days} \]
\[ \Delta t = \text{time interval, calculated in days} \]
\[ M = \text{total number of reservoirs, among which i stands for a certain reservoir} \]
\[ A_i = \text{power generation coefficient of reservoir i} \]
\[ Q_{i,t} = \text{water discharge of reservoir i at time period t, m}^3/s \]
\[ Q_{i,t} = \text{reservoir inflow of reservoir i at time period t, m}^3/s \]
\[ q_{i,t} = \text{turbine release water discharge for power generation of reservoir i at time period t, m}^3/s \]
\[ H_{i,t} = \text{average head of reservoir i at time period, m} \]
\[ Q_{i,t}^*, Q_{i,t+1}^*, Q_{i,T}^*, Q_{i,1}^* = \text{ecological pulse flow of reservoir i at time period t, t + 1, T, 1, m}^3/s \]
\[ \Delta Q_{i,t}^* = \text{is the increased ecological pulse flow of reservoir i from time t to t + 1, m}^3/s \]
\[ \text{max}\Delta Q_i^* \text{ and Max}\Delta Q_i^* = \text{are the maximum permissible ecological pulse flow of reservoir i during time interval} \]
\[ \Delta t \text{ and during total time interval} T, \text{m}^3/s \]
\[ V_{i,0} \text{, } V_{i,t+1} = \text{volume of reservoir storages for reservoir i at the beginning of period t or t + 1, m}^3 \]
\[ V_{i,\text{min}} = \text{minimum consent water volume of reservoir i at the beginning of period t, m}^3 \]
\[ V_{i,\text{max}} = \text{maximum consent water volume of reservoir i at the beginning of period t, m}^3 \]
\[ N_{i,\text{min}} = \text{hydro plant minimum power generation constraint of reservoir i at time period t, kW} \]
\[ N_{i,\text{max}} = \text{installed plant capacity, kW} \]

The study was carried out in the middle reaches of Jinsha River where the Liyuan hydropower station and Ahai hydropower station are located. The development tasks of these power stations are mainly power generation and flood control. According to the relevant research on the middle reaches of Jinsha River by the Institute of Water Engineering and Ecology, Chinese Academy of Sciences, Ministry of Water Resources, the demands for drifting-egg-fish spawning downstream of the reservoir dam site are as follows:

**Liyuan Reservoir:** when the water temperature in the lower reaches of dam site reaches above 18°C and the initial flow is greater than 1250 m³/s⁻¹, then the outflow can be gradually increased for 5 to 7 days (the daily average flow increases from 100 m³/s⁻¹ to 400 m³/s⁻¹). Finally, when the outflow increases to 2560 m³/s⁻¹ and the total increased water level downstream of the dam site is more than 4.29 m, the dispatch can be terminated.

**Ahai Reservoir:** when the water temperature in the lower reaches of dam site reaches above 18°C and the initial flow is greater than 1420 m³/s⁻¹, then the outflow can be gradually increased for 5 to 7 days (the daily average flow increases from 100 m³/s⁻¹ to 400 m³/s⁻¹). Finally, when the outflow increases to 3200 m³/s⁻¹ and the total increased water level downstream of the dam site is more than 4.29 m, the dispatch can be terminated.

According to the analysis of habitats for the main fishes, the period that meets the requirements for the reproduction and spawning of fishes in this river section is shown in Fig. 1.
mainly from May to July. Therefore, in order to carry out ecological regulation research, it is necessary to analyse the features of water temperature and runoff from May to July and combine the water temperature and water volume conditions to propose a preliminary suitable ecological regulation time.

The water temperature in the middle reaches of the Jinsha River increases from upstream to downstream. Based on statistics and analysis of the temperature at Shigu Hydrological Station and Panzhihua Hydrological Station during 2010-2018 (Figs. 2 and 3), it can be concluded that the suitable time for ecological regulation in the middle reaches of Jinsha River is after mid-May.

The target is the reproduction of drifting egg-producing fish in the middle reaches of Jinsha River and the long series of runoff from 1965 to 2018 are selected for simulation. This study assumed that ecological regulation will start on 1 June, 10 June and 20 June, respectively and the results indicated that:

(1) If the cascade hydropower station starts ecological dispatch on 1 June, there will be 3 years during which the water demand of each cascade after the dispatch could be met and the required inflow condition is that the average incoming water flow of Liyuan Reservoir in the next 15 days is greater than 1905 m$^3$ s$^{-1}$ and the amount of water saved in advance is greater than 166 million m$^3$.

(2) If the cascade hydropower station starts ecological dispatch on 10 June, there will be 12 years during which the water demand of each cascade after the dispatch could be met and the required inflow condition is that the average incoming water flow of Liyuan Reservoir in the next 15 days is greater than 1944 m$^3$ s$^{-1}$ and the amount of water saved in advance is greater than 192 million m$^3$.

(3) If the cascade hydropower station starts ecological dispatch on 20 June, there will be 31 years during which the water demand of each cascade after the dispatch, the average incoming water flow of Liyuan Reservoir in the next 15 days is greater than 1950 m$^3$ s$^{-1}$ and the amount of water saved in advance is greater than 321 million m$^3$.

Therefore, through simulation analysis, it can be concluded that when the hydrological and water temperature conditions of the incoming water in mid-June are met, it is easier to achieve ecological regulation.

Combined with the previous scheduling simulation conclusions, it is assumed that the simulations will be carried out under three scenarios of inflow from 20 June (the inflow of Liyuan Reservoir in the next 15 days is greater than 2000 m$^3$ s$^{-1}$, 2500 m$^3$ s$^{-1}$ and 3000 m$^3$ s$^{-1}$ respectively). The simulation results of the Liyuan-Ahai reservoirs proposed in the previous paragraph are used to provide a reference for the development of experimental ecological scheduling of cascade hydropower stations. The detailed dispatching process is shown in Fig. 4.

After comparative analysis, the power generation comparison of the schemes during the dispatch period, with and without ecological dispatch is shown in Table 1. From Table 1, it can be concluded that, after the ecological dispatch is carried out, the cascade power generation is reduced compared with that when the ecological dispatch is not carried out and the reduction rate is about 2%. When the incoming water flow increases from 2000 m$^3$ s$^{-1}$ to 3000 m$^3$ s$^{-1}$, since the chances of the cascade generators being fully utilised increase, the reduction of the cascade power generation is reduced, which also shows that when the incoming water conditions are close to the natural
flood process that is conducive to fish spawning, it is ideal to carry out ecological dispatch under the condition of less power loss of cascade hydropower stations. It provides opportunities and conditions for the interactive win-win of cascade economic benefits and ecological environment, which can provide reference and expertise for other river basins and other cascade hydropower stations to carry out experimental dispatch.

Based on the prediction of different inflow for Liyuan and Ahai reservoirs, this study carried out an experimental ecological operation for cascade reservoirs in the middle reaches of the Jinsha River in 2020. Results show that Liyuan and Ahai reservoirs can simultaneously carry out ecological regulation experiment combined with pre-flood water level drawdown process. While meeting the hydrological conditions required for the natural

Table 1. Power generation with / without ecological dispatch (unit: 10^8 billion kWh)

<table>
<thead>
<tr>
<th>Scene</th>
<th>Without ecological dispatch</th>
<th>With ecological dispatch</th>
<th>Percentage of battery reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q_p&gt;2000 m^3 s^-1</td>
<td>10.08</td>
<td>9.85</td>
<td>-2.28%</td>
</tr>
<tr>
<td>Q_p&gt;2500 m^3 s^-1</td>
<td>9.91</td>
<td>9.74</td>
<td>-1.72%</td>
</tr>
<tr>
<td>Q_p&gt;3000 m^3 s^-1</td>
<td>10.44</td>
<td>10.31</td>
<td>-1.25%</td>
</tr>
</tbody>
</table>

Q_p refers to the incoming water flow of Liyuan Reservoir
reproduction of fishes that lay drifting eggs, it will have a minor impact on the pre-flooding water level drawdown process.

By coupling the needs of river ecosystems and existing dispatching methods, this research carried out the practice of ecological regulation oriented to the demand of aquatic organisms. Through the simulation of experimental ecological operation of Liyuan and Ahai cascade reservoirs under different inflow scenarios, it can be concluded that cascade hydropower stations can carry out experimental ecological operation in June when the water temperature and water quantity are satisfied. Specifically, the Liyuan Reservoir need to reserve part of the water volume in the early stage and carry out water volume dispatching by considering inflow prediction in the late stage, so the pulse flow and water level required for downstream fish spawning can be satisfied. This study can improve the joint operation rules of flood control, power generation and ecological demand in the middle reaches of Jinsha River and provide a reference for the most comprehensive benefits of cascade hydropower stations in the development and optimal dispatch of water resources. In actual dispatch, considering that the time for the experimental ecological dispatch in the middle reaches of the Jinsha River is close to the flood season, it is necessary to flexibly select the appropriate working conditions according to the real-time water and rain conditions, reservoir operation and power system demand.

Acknowledgments

This work was financially supported by the CRSRI Open Research Program (Program SN:CKWV2019766/KY), National Public Research Institutes for Basic R&D Operating Expenses Special Project (Program SN:CKSF2017061/SZ) and National Natural Science Foundation of China (Program SN:52009006) and the Second Tibetan Plateau Scientific Expedition and Research Program (STEP) (Grant No. 2019QZKK0203).

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