Indian J. Fish., 68(3): 137-142, 2021
DOI: 10.21077/ijf.2021.68.3.113583-19

Note

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

GUO WEI[1], YAO LIQIANG[2], WU GUANG DONG[2], CUI FU NING[3], SHAO JUN[1], OU YANG SHUO[1], DU TAO[1], WANG KUN[1] AND CAO JUN[4]

[1]*Bureau of Hydrology, Changjiang Water Resources Commission, Wuhan city, Hubei province, China*

[2]*Changjiang River Scientific Research Institute, Changjiang Water Resources Commission of the Ministry of Water Resources of China, Wuhan, Hubei, China*

[3]*Yunnan Jinsha River Midstream Hydropower Development Corporation Limited, Kunming city, Yunnan province, China*

[4]*Institute of Hydroecology, MWR and CAS, Wuhan City, Hubei province, China*

e-mail: bounob12345@163.com

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 needs 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:

$$W = E + F\,(Q_{i,t} - Q^*_{i,t}) \quad \text{(1)}$$

$$E = \mathrm{Max} \sum_{t=1} \sum_{i=1} A_i\, q_{i,t}\, H_{i,t}\, \Delta t \quad \text{(2)}$$

$$F = \begin{cases} MM, \text{ if } Q_{i,t} < Q^*_{i,t} \\ 0, \text{ if } Q_{i,t} \geq Q^*_{i,t} \end{cases} \quad \text{(3)}$$

$$Q^*_{i,\,t+1} = Q^*_{i,t} + \Delta\, Q^*_{i,t} \quad \text{(4)}$$

$$0 \leq \Delta Q^*_{i,t} \leq \max \Delta Q^*_i \quad \text{(5)}$$

$$Q_{i,T} - Q^*_{i,1} \geq \mathrm{Max} \Delta Q^*_i \quad \text{(6)}$$

Subject to the following major constraints - Water balance equation:

$$V_{i,t+1} = V_{i,t} + (Q_{\lambda i,t} - Q_{i,t}) - \Delta t \quad \text{(7)}$$

Reservoir storage volumes limits:

$$V_{it.\,min} \leq V_{it} + \leq V_{it.max} \quad \text{(8)}$$

Hydropower station power generation limits.

$$N_{it.\,min} \leq Aq_{it} H_{it} \leq N_{it.\,max} \quad \text{(9)}$$

where,

W = Target value

E = maximum generation output of cascade hydropower stations, kW·h

F = Intermediate variable

T = Total ecological scheduling time, calculated in days

MM = Infinite numbers

t = Time, calculated in days

Δt = time interval, calculated in days

M = total number of reservoirs, among which i stands for a certain reservoir

A_i = power generation coefficient of reservoir i

$Q_{i,t}$ = water discharge of reservoir i at time period t, m^3/s

$Q_{\lambda i,t}$ = reservoir inflow of reservoir i at time period t, m^3/s

$q_{i,t}$ = turbine release water discharge for power generation of reservoir i at time period t, m^3/s

$H_{i,t}$ = average head of reservoir at time period, m

$Q_{i,t}^*$, $Q^*_{i,t+1}$, $Q^*_{i,T}$, $Q^*_{i,1}$, = ecological pulse flow of reservoir i at time period t, t + 1, Tor1, m^3/s

$\Delta Q^*_{i,t}$ = is the increased ecological pulse flow of reservoir t from time t, t to time t + 1, m^3/s

$\max\Delta Q_i^*$ and $\mathrm{Max}\Delta Q_i^*$ = are the maximum permissible ecological pulse flow of reservoir i during time interval Δt and during total time interval T, m^3/s

$V_{i,t}$, $V_{i,t+1}$ = volume of reservoir storages for reservoir i at the beginning of period t or t, m^3

$V_{it.min}$ = minimum consent water volume of reservoir i at the beginning of period t, m^3

$V_{it.max}$ = maximum consent water volume of reservoir i at the beginning of period t, m^3

$N_{it.min}$ = hydro plant minimum power generation constraint of reservoir i at time period t, kW

$N_{it.max}$ = 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, some of the major species of fishes that lay drifting eggs in the river section of Liyuan-Ahai cascade hydropower system are *Coreius guichenoti*, *Rhinogobio ventralis* and *Schizothorax dolichonem*. The distribution of main fish spawning grounds in the Liyuan-Ahai river section is shown in Fig. 1.

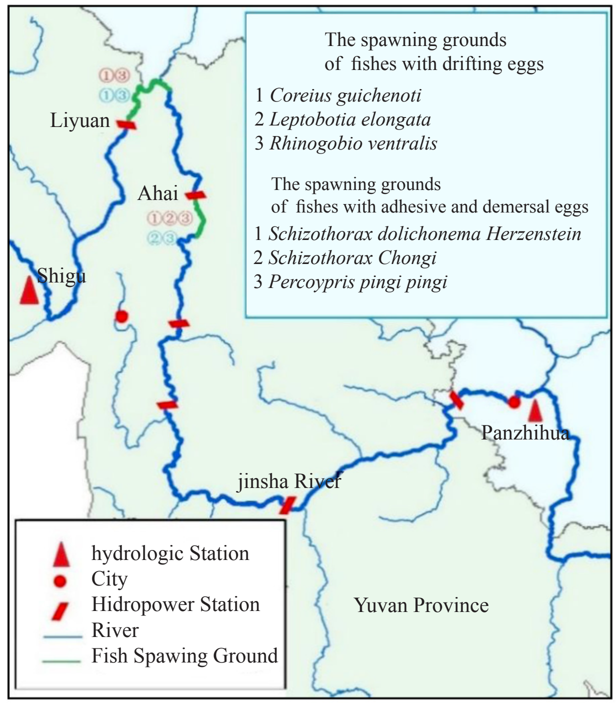


Fig. 1. Distribution map of main fish spawning sites in the Liyuan-Ahai river section of Jinsha River

Combining results of previous research done by Bureau of Hydrology, Changjiang Water Resources Commission and 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 $m^3 s^{-1}$, then the outflow can be gradually increased for 5 to 7 days (the daily average flow increases from 100 $m^3 s^{-1}$ to 400 $m^3 s^{-1}$). Finally, when the outflow increases to 2560 $m^3 s^{-1}$ 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 $m^3 s^{-1}$, then the outflow can be gradually increased for 5 to 7 days (the daily average flow increases from 100 $m^3 s^{-1}$ to 400 $m^3 s^{-1}$). Finally, when the outflow increases to 3200 $m^3 s^{-1}$ 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 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:

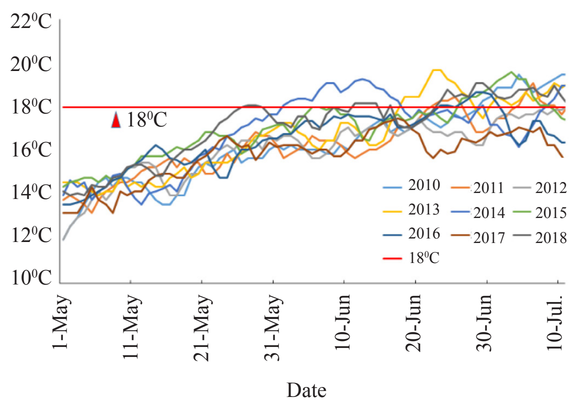


Fig. 2. Daily average water temperature of Shigu hydrologic station from May to July, 2010 to 2018

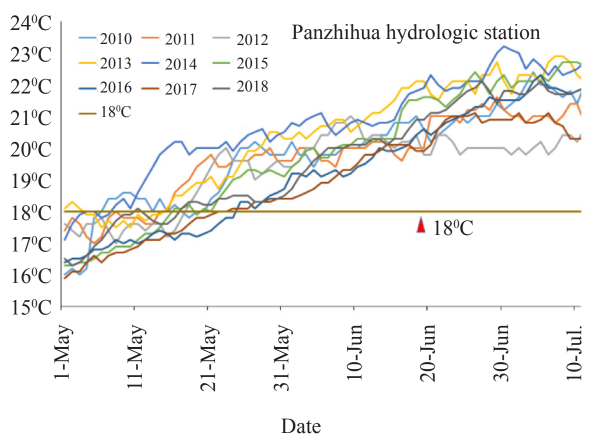


Fig. 3. Daily average water temperature of Panzhihua station from May to July, 2010 to 2018

(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.

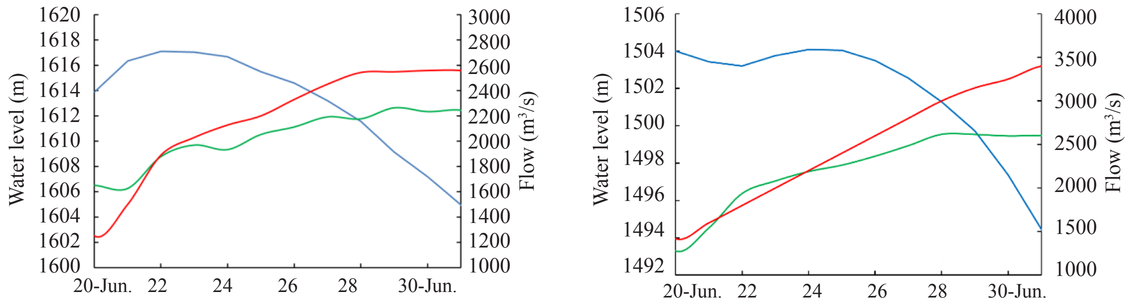
(2) If the cascade hydropower station starts ecological dispatch on 10 June, there will be 12 years during which the water demand of each cascade after the dispatch could be met and the required inflow condition is that the average incoming water flow of Liyuan Reservoir in the next 15 days is greater 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.

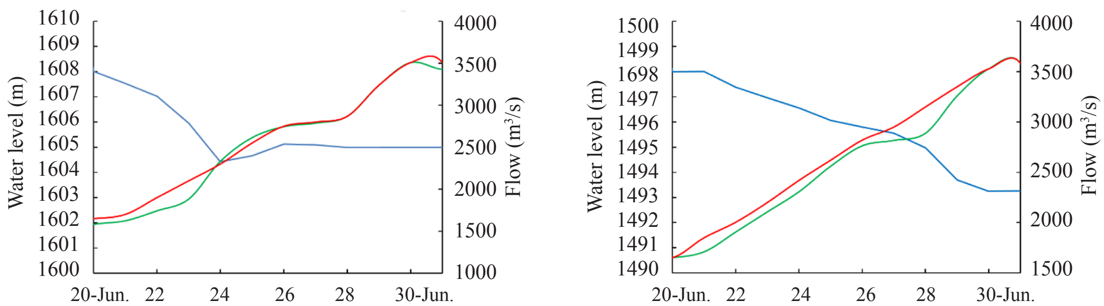
Therefore, through simulation analysis, it can be concluded that when the hydrological and water temperature conditions of the incoming water in mid-June are met, it is easier to achieve ecological regulation.

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.

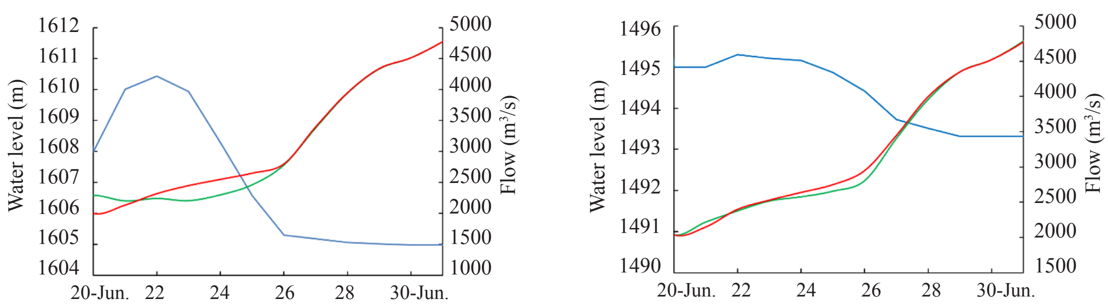
After comparative analysis, the power generation comparison of the schemes during the dispatch period, with and without ecological dispatch is shown in Table 1. From Table 1, it can be concluded that, after the ecological dispatch is carried out, the cascade power generation is reduced compared with 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



(a) Liyuan hydropower station Q_{15}>2000 M³/s



(b) Liyuan hydropower station Q_{15}>2500 M³/s



Experimental ecological operation for Liyuan reservoir

Experimental ecological operation for Ahai reservoir

(b) Liyuan hydropower station Q_{15}>3000 M³/s

— Water level, — Inflow, — Outflow

Fig. 4. Experimental ecological regulation process

Table 1. Power generation with / without ecological dispatch (unit: 10*billion kwh)

Scene	Without ecological dispatch	With ecological dispatch	Percentage of battery reduction
Qp>2000 m³ s⁻¹	10.08	9.85	-2.28%
Qp>2500 m³ s⁻¹	9.91	9.74	-1.72%
Qp>300 0m³ s⁻¹	10.44	10.31	-1.25%

Qp referes to the incoming water flow of Liyuan Reservoir

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 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).

References

Bednarek, A. T. and Hart, D. D. 2005. Modifying dam operations to restore rivers: Ecological responses to Tennessee River Dam mitigation. *Ecol. Appl.*, 15(3) : 997-1008. https://doi.org/10.1890/04-0586.

Buyukates, Y. and Roelke, D. 2005. Influence of pulsed inflows and nutrient loading on zooplankton and phytoplankton community structure and biomass in microcosm experiments using estuarine assemblages. *Hydrobiologia*, 548(1): 233-249. https://doi.org/10.1007/s10750-005-5195-x.

Cai, Q. H. 2006. Explore the implementation of ecological regulation and give full play to the ecological functions of the reservoir. *Proceedings of the International Conference on Hydropower*, 23 October 2006, Kunming City, Yunnan Province, China.

Cheng, G. W. and Chen, G. R. 2007. Ecological operating experiment for Three-Gorge Reservoir, creating healthy stream environment for Changejiang River. *J. Hydraul. Eng.*, S1: 526-530.

Deng, M. J., Huang, Q., Chang, J. X. and Huang, S. Z. 2020. Large-scale ecological operation research and practice. *J. Hydraul. Eng.*, 51(07): 757-773.

Dong, Z. R., Sun, D. Y. and Zhao, Ji. Y. 2007. Water resources and hydropower engineering, Multi-objective ecological operation of reservoirs. *Water Conservancy and Hydropower Technology*, 1: 28-32. https://doi.org/10.3969/j.issn.1000-0860.2007.01.005.

Field, R. and Lund, J. R. 2006. Multi-objective optimisation of Folsom Reservoir operation. *Proceedings of the Operations Management Conference* 2006, p. 205-214.

Hueftle, S. J. and Stevens, L. E. 2001. Experimental flood effects on the limnology of Lake Powell Reservoir, South-western USA. *Ecol. Appl.*, 11(3): 644-656. https://doi.org/10.1890/1051-0761.

King, A. J., Ward, K. A., O'Connor, P., Green, D., Tonkin, Z. and Mahoney, J. 2009. Adaptive management of an environmental watering event to enhance native fish spawning and recruitment. *Freshw. Biol.*, 55(1): 1-15. https://doi.org/10.1111/j.1365-2427.2009.02178.x.

Steinschneider, S., Bernstein, A., Palmer, R. and Polebitski, A. 2013. Reservoir management optimization for basin-wide ecological restoration in the Connecticut River. *J. Water Res. Pl.*, 140(9): 4014023. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000399.

Wang, J. Q. 2012. *The research and application of reservoir operation model of stochastically dynamic programming facing for ecological water demand*. Zhengzhou University, Zhengzhou City, Henan Province, China.

Yin, Z. J., Yang, C. H. and Xu, J. J. 2013. Ecological regulation of cascade dams in the lower Jinsha River under different ecological flow constraints. *J. Hydroelectric Eng.*, 32(03): 66-70+81.

Zou, Z. H. 2008. *Research on ecological operation of Three Gorges Reservoir*. Hohai University, Nanjing City, Jiuangsu Province, China.

Date of Receipt : 06.08.2021
Date of Acceptance : 16.09.2021