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A novel operation chart for cascade hydropower system to alleviate ecological degradation in hydrological extremes

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ABSTRACT

Incorporating limited ecological curves, a novel operation chart optimization method is proposed for the multipurpose hydropower systems, which is capable of improving power generation and overall ecological condition and alleviating ecological degradation under extreme dry or wet conditions. The method mainly includes: (1) determine the optimal ecological discharge using weighted usable area-discharge curve based on the physical habitat simulation model (PHABSIM); and (2) establish the operation chart optimization model aiming to maximizing power generation and overall ecological condition and solve the model with DPSA; then (3) derive the limited ecological curves and incorporate them in the operation chart. A case study is performed with Jasajiang (JS) and Madushan (MDS) reservoirs on the Yuan River in southwestern China. The results show that the optimized operation charts result in a 1.72% and 5.99% increase in hydropower generation and a 0.27% and 1.13% increase in ecological conservation degree for MDS reservoir, respectively. In addition, the frequency of ecological damage is reduced from 6.11% to 1.11% for JS reservoir and from 26.67% to 3.89% for JS and MDS reservoirs, respectively. A further discussion using a time series of random runoff generated by first-order Markov model has confirmed the adaptability of this operation chart. The feasibility and potential applications of this operation chart has been confirmed.

1. Introduction

In recent years, there have been increasing concerns over the ecological impacts of the extensive construction of cascade hydropower stations despite their high aquatic productivity and great hydropower potential (Wang, 2017). The construction of cascade reservoirs can dramatically alter the flow regime of rivers (Suen and Eheart, 2006), and thus ecological requirements should be incorporated into the operation chart of hydropower stations to balance ecological protection and other important functions.

Operation chart is a practical and widely used reservoir scheduling rule, it is usually derived by the reverse calculation method (Cheng et al., 2010). Specifically, a few typical hydrological years are selected based on historical runoff data, the water balance formula is used for the reverse calculation of the water level from the end of the dry season to the beginning of impounding, as shown in Fig. 1. The upper and lower envelopes of all indicator (water levels) lines are derived as the basic guiding curves (upper basic guiding curve and lower basic guiding curve). On the basis of that, increased and decreased output curve could be derived by increasing or decreasing the basic guiding curve at a certain ratio. Nevertheless, a potential problem is that the calculation is cumbersome and needs to be modified manually (Xie et al., 2015). Considerable attempts have been made to optimize reverse operation charts. As shown in Table 1.

However, it is noted that most previous studies on operation chart optimization have focused on water supply, power generation and flood control, with less attention to potential ecological impacts. Table 1 summarizes recent advancement in ecological operation and operation chart optimization of reservoirs. In particular, Zhou and Guo (2013) attempted to incorporate ecological requirements into the operating rule curves of multipurpose reservoirs for adaptation to climate changes, the objective of which was to maximize the ecological benefits. However, although this makes it possible to maximize overall ecological benefits, ecological deterioration cannot be totally avoided under hydrological extreme conditions. In addition, some ecological operation models just used the minimum ecological flow or ecological

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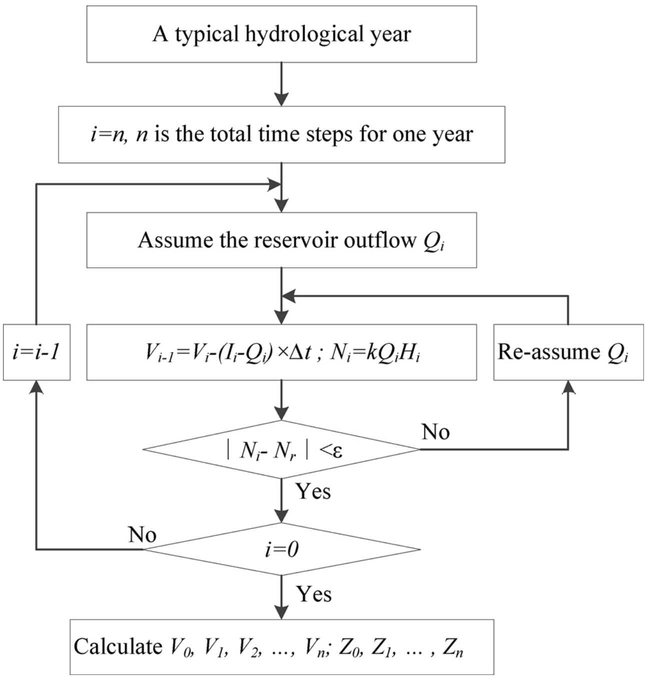

Fig. 1. The flowchart of conventional operation chart derivation.

guarantee rate as the constraint (Guo et al., 2018; Wen et al., 2018), which can effectively avoid dramatic ecological failure under hydrological extreme conditions. However, there is no technique to maximize the overall ecological condition of the basin, that is, it cannot effectively improve the overall ecological benefits.

Given the complexity of operation chart optimization, the ecological discharge is usually taken as a constant estimated by the Tennant method or other simple methods (Tharme, 2003). However, the demand of fish species for ecological discharge can vary dynamically depending on their growth cycles. There have been extensive studies on the ecological discharge regimes, which can be categorized into four groups, namely hydrological, hydraulics, habitat simulation and holistic methodologies. Hydrological methods and hydraulics methods mainly focus on hydrological and hydraulic characteristics of rivers, while neglecting aquatic organisms' demands for habitats. In comparison, the habitat simulation and holistic methods are proposed based on field investigation and experiments, which reflects the more realistic preferences of aquatic species. In particular, the habitat simulation method is more suitable for micro-habitat simulation while the integrated method is more appropriate for macro-habitat simulation (Spence and Hickley, 2000). The Physical Habitat Simulation Model (PHABSIM) (Bovee and Milhous, 1978) is one of the classical models proposed in the early 1970 s which can simulate habitat area for aquatic creatures. It is also widely used in ecological flow determination (Booker and Dunbar, 2004; Johnson et al., 2017), since it can provide insights into how the hydraulic habitat of fish species changes in response to the alteration of flow regime, and thus determine the optimal ecological streamflow based on habitat–flow curves. For example, Gibbins et al. (2001) determined the ecologically acceptable river flow regimes of Kielder reservoir and water transfer system using PHABSIM. Wen et al. (2016) quantified the ecological demand using PHABSIM, which was then incorporated into the cascade reservoir operating schemes.

Based on the quantification of ecological requirements by Wen et al. (2016), we derived the limited ecological curves and incorporated them into optimal operation charts for multipurpose hydropower systems, which was capable of improving power generation and ecological conservation and alleviating ecological degradation as much as possible under hydrological extreme conditions. A case study was then performed with the Jiasajiang (JS) and Madushan (MDS) cascade hydropower stations in the Yuan River basin in southwestern China, and *Cyprinus rubrofuscus Lacépède* and *B. rutilus* were selected as the representative fish of the downstream reach of JS reservoir and MDS reservoir, respectively. PHABSIM was initially used to simulate the relationship between the stream flow and physical habitat of fish species and determine the optimal ecological discharge range for a given river reach. The operation chart optimization model with the goal of maximizing power generation and ecological conservation was established and resolved by Dynamic Programming Successive Approximation (DPSA) algorithm, then the limited ecological curve, a new guiding curve which reflects basic ecological demand in practical operation was derived and incorporated into the operation chart.

2. Research area and data

The Yuan River is located in southwestern China, with a total length of 692 km and a drainage area of 34,629 km^2. Two main tributaries - Lishe River and Lvzhi River join at the Sanjiangkou to form the Yuan River (Fig. 2), and then it flows through the southwestern China and Vietnam before emptying into the sea. The Yuan River basin has high aquatic productivity and hydropower potential. However, the utilization of water resources is restricted to the main reach of the river, while most branches and the upper reach of the river are essentially

Table 1
Recent advancements in reservoir operation charts optimization and reservoir ecological operation.

Types	Researchers	Context
Operation charts optimization	Zahraie and Hossein (2009)	Proposed optimal reservoir operation policies considering variable agricultural water demands
	Jiang et al. (2014)	Proposed a new total output operation chart optimization model and a new optimal output distribution model with the goal of maximizing power generation
	Taghian et al.(2014)	Proposed optimal operational policies to achieve the optimal water allocation and the target storage water levels for multi-objective reservoirs
	Wang et al.(2014)	Proposed new discriminant coefficient method-based drawing models with the goal of maximizing the guaranteed output and annual average power generation.
Reservoir ecological operation	Sale et al. (1982)	Used the optimal ecological flow corresponding to the optimal fish habitat area as the optimal ecological flow and established the optimal operation model.
	Homa et al. (2005)	Minimized the disparity between the natural and reservoir ecological release to improve the satisfaction of ecological flow requirements.
	Castelletti et al. (2008)	Added the minimum ecological flow constraint to the optimal operation model to realize the ecological protection of the river
	Szemis et al. (2014)	Included an objective function to minimize the difference in environmental flow operations between time steps accounting for updated environmental allocation forecast information.
	Rossel and de la Fuente, (2015)	Added an ecological constraint to the multi-objective optimization model of reservoir operation to improve the water quality. Moreover, some scholars regard the ecological element as an objective for research rather than as a constraint