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An improved multi-objective optimization model for supporting reservoir operation of China's South-to-North Water Diversion Project

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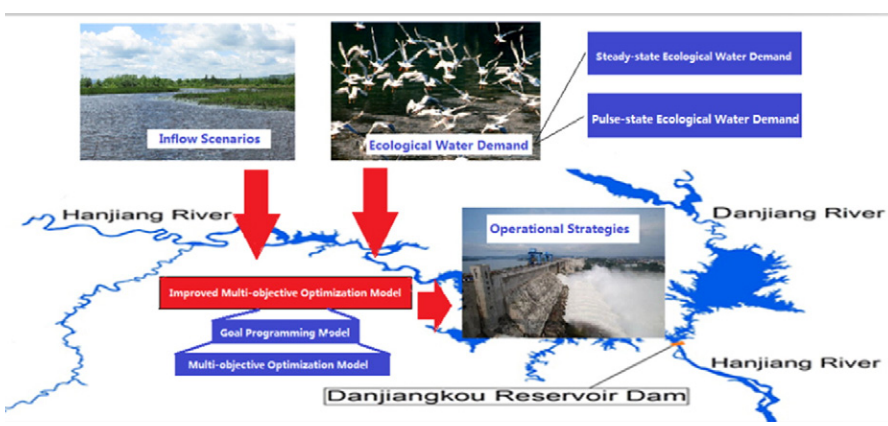
HIGHLIGHTS

- An improved multi-objective optimization model for reservoir operation was proposed.
- Ecological water demand was calculated combining those of steady- and pulse-states.
- The model was applied to the South-to-North Water Diversion Project in China.
- Both economic and ecological benefits were considered for reservoir operation.

GRAPHICAL ABSTRACT



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ABSTRACT

An improved multi-objective optimization model based on goal programming (GP) for supporting reservoir operation was developed under inflow senarios of multiple runoff guarantee rates (i.e., 25%, 75%, perennial mean, and 95%) and ecological goals with the combination of steady- and pulse-state ecological water demands. Under these four scenarios, discharge flows of Danjingkou Reservoir would be 358.40, 369.67, 268.91 and 98.14×10^8 m^3/a, and those at Taocha Canal headwork would be 104.61, 86.62, 95.08 and 64.00×10^8 m^3/a, respectively. The generated results for stream flows could successfully meet the predetermined operational goals for the project. Comparatively, under the scenario of 95% runoff guarantee rate, the obtained strategies could not satisfy the ecological water demands. The modeling results indicated that the capacity of water diversion and storage for Danjiangkou Reservoir would be enhanced due to the operation of the South-to-North Water Diversion Project. The results showed the risks associated with possible flooding would be comparatively low under those four runoff guarantee rates. This represents the current priority for flood control in Danjiangkou Reservoir needs to be changed into multiple ones including ecological water supply, water transfer, as well as downstream water security maintenance.

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1. Introduction

Freshwater is fundamental and integral to ecosystems and human society. It is of significance not only to provide food, energy, and many services for human beings, but also to maintain health conditions of ecosystems. Naturally, freshwater is unevenly distributed; resulting in potential conflicts in many regions where freshwater is required the most while the availability is comparatively the least (Gleick, 1993). For example, China's total water resource is approximately 2800 billion m^3, ranking the sixth in the world, but the per capita water resource is only 25% of the global average (The Ministry of Water Resources of the People's Republic of China, 2007; Wang et al., 2008). Moreover, the distribution of water resources is spatially and seasonally uneven in China (Piao et al., 2010). The uneven distribution of water in China has thus caused potential disparities in many regions. Potential water shortage is of great concerns in many areas that are scarce in water. To alleviate potential water shortages in such areas, China has made great efforts in implementing water transfer projects since the 1950s. Among them, the South-to-North Water Diversion Project, the largest one across the world is one of the most remarkable water related projects (Wang and Yang, 2005). The source water for this project is from Danjiangkou Reservoir of Hubei province. The operation of water transfer and the construction of engineering works have significantly changed eco-hydrological flow regimes in downstream of the reservoir (Wang et al., 2015). A number of impacts are associated with the water diversion in the source water areas. Therefore, it is of necessity to propose effective decision-support tools to realize multiple utilizing targets of water resources in the Danjiangkou Reservoir without causing too many adverse impacts on water, ecosystems and human beings. To minimize negative ecological impacts, it is a primary goal to optimize the current operation, for guaranteeing basic water use in water-receiving regions and reducing ecological effects in the water-source regions as well as middle and lower reaches of the Hanjiang River basin of central China.

In recent years, the effects of reservoir construction and operation on ecological environment have drawn much attention. In many developed countries, reducing the effects of dams on aquatic ecosystems and ensuring ecosystem safety have been prioritized among the related policies and regulations (Cai et al., 2011). For example, in Japan, the amended River Act of 1997 clearly stated that people should protect and preserve the aquatic environment when utilizing water resources (Soda and Yuhora, 2012). In the United States, since 1986, hydropower stations have been required to propose operational schemes considering the impacts on the ecological environment and conduct environmental assessments upon applications for operating licenses from the Federal Energy Regulatory Commission (Howells et al., 2014). To realize the harmonious development of nature, society and economy, reservoir operation considering ecological water demand has received increased attention. Such operations can greatly affect satisfaction of water demands by downstream ecosystems and socioeconomic development in water-source areas (Rupérez-Moreno et al., 2015). Large-scale water diversion projects like the South-to-North Water Diversion Project usually have multiple functions, including flood control, power generation, water supply, irrigation and ecological protection. Reservoir operation is a multi-objective decision-making problem with a series of complex constraints (Porse et al., 2015). A certain amount of water needs to be maintained under each individual function which leads to a series of potential water conflicts. Multi-objective optimization methods can provide desired results through tradeoff analysis among such competing objectives (Asadzadeh et al., 2014).

In the field of reservoir operation optimization, a number of programming methods were adopted such as multi-objective weighting method (Hao and Chen, 2010), non-linear programming (Higgins et al., 2008), dynamic programming (Bizzi et al., 2012), stochastic programming (Dong et al., 2015), compromise programming (Shiau and Wu, 1992), and intelligent optimization (Chaves and Chang, 2008). For instance, Yang et al. (2015) combined reservoir operation function and operating rule curves to develop an adaptive multi-objective operational model for the Danjiangkou Reservoir of China aiming at deriving multi-objective operating rules to adapt to climate change and alleviate conflicts. Luo et al. (2011) proposed a multi-objective optimal operation model with an iterative algorithm, in which gray correlation and entropy weighting ideal point methods were combined for cascaded hydropower systems such as Three Gorges cascaded hydropower, for China to coordinate different operation objectives. In Luo's study, the model was extended from a single-objective fuzzy dynamic programming model to the multi-objective one which was more convenient and efficient than ordinary dynamic programming did. Although progress has been made in the field of multi-objective optimization research, multi-objective decision methods for reservoir operation still have multiple disadvantages (Cai et al., 2009). For example, the weights can largely influence the results and the non-linearity in locating global optima and destroy the optimization techniques (Zhang and Shen, 2014). Above all, both the model and algorithm must be improved. For large-scale water control project systems in particular, such as the South-to-North Water Diversion Project, a practical and easily operating model considering water demands by ecosystems is desired.

Among many optimization modeling approaches, goal programming (GP) is adopted by many decision makers for its high efficiency. It is a multi-objective programming method that has been used in many fields including reservoir operation optimization. After being introduced in 1961, it has been extensively used and considered as a robust modeling technique (Mamun et al., 2015). It has been proven as a practical and effective way to solve multi-objective optimization operational models, where a number of sub-objectives are transferred into constrains and conveniently solved. Verma et al. (2010) applied goal programming in combination with three approaches, Min–Max Goal Programming (MMGP), Weighted Goal Programming (WGP) and Preemptive Goal Programming (PGP) to develop an improved optimal operation model for the Mahanadi Reservoir Project system. Mamun et al. (2015) presented a GP optimization algorithm to reflect terms and conditions of the Supplemental Operating Agreements of the Columbia River Treaty between British Columbia Hydropower Limited Corporation and "United States Entities". Comparing with other optimization algorithm such as the non-dominated sorting genetic algorithm II (NSGA-II) (Chang et al., 2016; Tsai et al., 2015) and the particle swarm optimization algorithm (PSO) (Bai et al., 2015), GP is a useful meso-scopic method with less requirements for data and is widely used in reservoir operation, especially for issues with two goals. It is of particularly use for reflecting decision makers' judgments. Also, it had a clear mechanism and a user-friendly form which can be applied by decision makers easily. This method is expected to be applied in solving multi-objective optimization operation models for complex reservoir operational projects, such as China's South-to-North Water Diversion Project.

The objective of this research is to develop an improved multi-objective optimization model (IMOOM) based on goal programming (GP) for supporting the operation of Danjiangkou Reservoir, in the source area of the South-to-North Water Diversion Project in China. Also, multiple ecological goals with the combination of steady- and pulse-state ecological water demands will be incorporated into IMOOM. This objective entails the following tasks: 1) establishment of inflow scenarios to calculate ecological water demands under steady and pulse states, 2) construction of the proposed IMOOM considering ecological water demands under multiple hydrologic runoff guarantee rates, setting the maximum of core ecosystem service function values as the operational target, and 3) adoption of GP method with the minimization of deviation to develop an optimal reservoir operational programming. This research will improve the existing optimization models for reservoir operation through enhanced comprehensiveness in reflecting the major modeling factor for eco-environment protection. At the same time, both steady- and pulse-state water demands will be introduced to the model by improving the Tennant method (Tennant, 1976). The