

# MULTI-OBJECTIVE OPTIMAL OPERATION OF CASCADE HYDROPOWER PLANTS BASED ON WATER-ENERGY NEXUS: A WATER FOOTPRINT APPROACH

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#### ABSTRACT

Hydropower is the key component of the water-energy nexus, which can meet the energy demand and mitigate the greenhouse effect. This paper constructs an optimal operation model for cascade hydropower plants considering water footprint, quantifies the tradeoff relationship between power generation and water consumption (reservoir water footprint). The preliminary application in the Yalong River case has shown that (1) there are clear tradeoffs between hydropower generation and water consumption and (2) scheme 2 is the optimal scheme from the water-energy nexus for both two scenarios in a normal year.

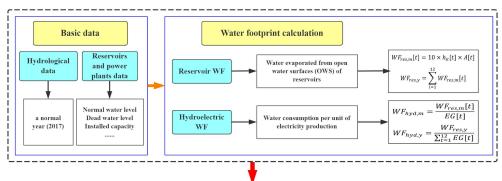
Keywords: Multi-objective operation, Cascade hydropower plants, Water footprint, Benefit tradeoffs, Yalong River.

## **1** INTRODUCTION

The nexus is an advanced concept, which can improve system efficiency and performance through holistic understanding and coordination allocation of resources, and it also is the current research hotspot(Dai et al. 2018). Hydropower has the dual attributes of water-energy, on the one hand, hydropower generates clean and renewable energy to meet the energy demand and mitigate the greenhouse effect; on the other hand, the storage of water in reservoirs generates a lot of water consumption through the evaporation from open water surfaces (OWS) of reservoirs(Zhang et al. 2018). Therefore, how to balance these two attributes is a research problem. At present, most researches on the optimal operation of cascade hydropower plants (HHPs) focus on flood control and power generation benefits and ignore the impact on the ecological environment and water consumption. The water footprint is an indicator used to quantify the water consumption caused by human activities, which can be better applied to hydropower research(Hoekstra 2003). However, most of the available literature concerns only static the water footprint of hydropower, ignoring its temporal characteristics. To do so, based on the water-energy nexus, this paper takes the water footprint as an objective function, constructs an optimal operation model for cascade HHPs, and takes the lower reach of the Yalong River (China) as a research case-study, guantifies the tradeoffs relationship between power generation and water consumption (reservoir water footprint), and analyses the temporal variation characteristics of the water footprint. The present research results can provide scientific evidence for the sustainable development of hydropower and the improvement of resource utilization efficiency.

#### 2 METHODS

This study employs the reservoir WF (water evaporated from OWS of reservoirs) and hydroelectric WF (the water consumption per unit of electricity production) to evaluate the consumption of water by hydropower for cascade HHPs (Mekonnen and Hoekstra 2012). Also, this paper constructs an optimal operation model for cascade HHPs and uses NSGA-II(Deb et al. 2002) algorithm to solve it. Finally, a sensitivity index is used to analyze the sensitivity of the hydroelectric WF. The flow chart through the methods used in this study is shown in Figure 1.



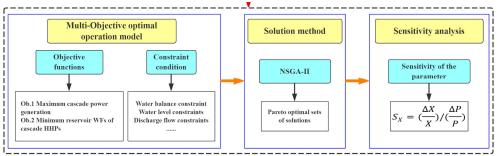
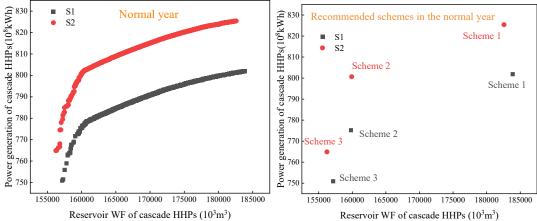


Figure 1. The flow chart through the methods used in this study.

# 3 RESULTS AND DISCUSSION

In this paper, a normal year is analyzed as a representative, and two scenarios are set: S1 (with the ecological flow) and S2 (without the ecological flow).

The Pareto optimal solution set of two scenarios is shown in Figure 2(a), and three schemes are selected as the recommended programs: scheme 1 (maximum cascade power generation), scheme 2 (minimum hydroelectric reservoir WFs of cascade HHPs), and scheme 3 (minimum reservoir WFs of cascade HHPs), as shown in Figure 2(b). We find that a clear tradeoff between hydropower generation and water consumption and the scheme with the maximum cascade power generation (Scheme 1) has the largest reservoir water footprint at some time. This is mainly because reservoirs usually operate at high water levels to pursue power generation benefits, which leads to a larger OWS. Therefore, scheme 2 is the optimal scheme from the water-energy nexus based on water footprint approach. And for scenario S1, the power generation and the reservoir WFs of the cascade HHPs of scheme 2 are 775.23×10<sup>8</sup> kWh and 159803.61×10<sup>3</sup> m<sup>3</sup>, respectively; for scenario S2, they are 800.65×10<sup>8</sup> kWh and 159922.22×10<sup>3</sup> m<sup>3</sup>, respectively.



**Figure 2.** The Pareto optimal set of solutions under scenarios S1 and S2 in the normal year. **ICLUSIONS** 

# 4 CONCLUSIONS

The following conclusions are drawn from this study:(1) there are clear tradeoffs between hydropower generation and water consumption and (2) scheme 2 is the optimal scheme from the water-energy nexus for both two scenarios in a normal year.

## ACKNOWLEDGEMENTS

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