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Assessment of multi-objective reservoir operation in the middle and lower Yangtze River based on a flow regime influenced by the Three Gorges Project

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ABSTRACT

The construction of multi-function reservoirs is important to guaranteeing the development and utilization of water and hydropower resources, but the construction of any hydrologic projects will inevitably affect the downstream flow regime that provides the driving force for riverine ecosystems. This paper therefore aims to propose a framework for assessing multi-objective reservoir operation models based on flow regime using the middle and lower Yangtze River as a case study. Using indicators of hydrologic alteration (IHA) and the histogram matching approach (HMA), critical influential factors for flow were investigated at the Yichang and Datong gauges, which are typical of the middle and lower Yangtze River. This found the magnitude of annual extreme minimum water flow rates to be the most dramatically changed indicator, with an overall degree of hydrologic alteration at the Yichang and Datong gauges of 41.98% and 34.58%, respectively. The monthly mean discharges of February and October at Yichang have been significantly changed as a result of the Three Gorges Reservoir (TGR) operation. Meanwhile, an improved range of variability approach (IRVA) was developed to obtain ideal target ranges for monthly average flow. A multi-objective ecological reservoir operations model was created for the TGR; the Non-dominated Sorting Genetic Algorithm II (NSGA-II) was applied to the model. Three typical years of wet, normal and dry years were selected, and the operation results with corresponding ideal target ranges were analyzed for the downstream Yichang and Datong cross sections. The results showed that there should be a reduction by 23.57%, 28.10% and 39.92% in the monthly mean flow of February and an increase by 34.48%, 112.36% and 52.12% in the monthly mean flow of October at Yichang cross section in wet, normal and dry years, respectively.
Close attention therefore needs to be given to integrating ecological objectives with appropriate flow regimes into multi-objective operation models.

1. Introduction

According to the Chinese National Committee on Large Dams (2012), ensuring comprehensive use of water resources requires the urgent construction of multi-function reservoirs that can provide a water supply, flood control, navigation, agriculture irrigation and hydropower generation. This is driven by the ever changing demands of economic and social development, as well as the need to provide effective disaster prevention and mitigation. However, the construction and flow regulation of such projects inevitably cause significant disturbances to natural river system (Arthington, 2012; Arthington et al., 2010), with changes in the spatial and temporal distribution of the natural flow (Richter and Thomas, 2007; World Commission on Dams, 2000; Zhang et al., 2015) altering the discontinuity of flow, the geomorphology of river channels and the accumulation of sediments (Costigan and Daniels, 2012; Graf, 2006; Zhang et al., 2012; Zhang et al., 2013). This, in turn, can lead to environmental deterioration and a loss of biodiversity in the downstream river ecosystem (Jager and Smith, 2008; Zhang et al., 2010).

Natural river flow regime has been adopted as a paradigm for ecological integrity conservation and restoration and is important in sustaining downstream river environments and aquatic ecosystems (Jiang et al., 2014). The concept of natural river flow regime was first proposed by Poff et al. (1997), which aimed to describe the characteristic pattern of a river's flow quantity, timing, and variability. Several studies have identified many ecologically relevant hydrological indicators which associated with the structure and function of riverine ecosystems and the distribution, composition, and diversity of aquatic organisms, to assess or describe such alterations of natural river flow

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regimes (Lytle and Poff, 2004; Olden and Poff, 2003; Richter et al., 1996; Yang et al., 2008b), from which indicators of hydrologic alteration (IHA) have been developed. The IHA consists of 32 hydrologic parameters that are considered to describe the full range of natural flow variability, including five groups of hydrologic features, that is, magnitude, frequency, timing, duration and the rate of change (Richter et al., 1996). These 32 parameters can be calculated from daily river flow rate. It is a popular tool for assessing the hydrologic changes induced by anthropogenic and natural processes (Shiau and Wu, 2008). The magnitude of changes of these 32 hydrologic parameters over time is defined as flow regime alteration.

The Three Gorges Dam (TGD) which is the biggest dam in the world was completed in 2003, after then it started its operation. The water level of TGD varies from 145 m to 175 m in its full capacity operation, corresponding reservoir storage capacities are 171.5×10^8 m^3 and 393×10^8 m^3, respectively. During the late May to early June in each year, the forebay of the TGD is lowered than the flood limit water level (145 m) to empty the flood control capacity. The water level is maintained on the flood limit water level in the flood season (from June to September) for flood control. The reservoir starts to store water since late October, and the let-down flow drops off with the water level increases to 175 m. During the dry season (from December to April), the water level is maintained on a higher water level to achieve the power production. The construction and operation of the TGD may significantly influence biodiversity in the downstream river ecosystem. Therefore, exploring the impact of TGD on the flow regime in the middle and lower reaches of the Yangtze River is necessary.

To assess flow regime alteration using IHA, Richter et al. (1998) established the range of variability approach (RVA), which has since been used in a series of water resources management studies into flow regime alteration caused by the construction or operation of reservoirs. The RVA employs the natural (pre-impact) flow series at a 50% frequency (the interval between 25% and 75%) to obtain the IHA target ranges. An implication of the RVA presumes that 50% of the pre-impact years would have the values of the hydrologic parameter within the target range. Yang et al. (2008a) used this method to investigate the spatial variability of hydrologic alteration caused by dam construction along the middle and lower Yellow River. In exploring environmental flows below the Tanghe Reservoir, Yin et al. (2011) employed the RVA using hydrologic indicators related to high-flow events (floods and high flow pulses) to quantify the flow regime alteration caused by reservoir operation. RVA has been proven to be a practical and effective means of assessing hydrologic alteration and obtaining target ranges of hydrologic parameters without complicated computations, but the variations of hydrologic parameters which falling beyond the target range are not taken into account (Shiau and Wu, 2008).

Shiau and Wu (2004) also used RVA to investigate the hydrological impacts of a diversion weir in Taiwan, with RVA-based reservoir operation models aimed at protecting the natural flow regime having widely attracted the attention of reservoir managers. For example, Koel and Sparks (2002) compared historical hydrologic alteration based on the RVA and fish abundance in the Illinois River, and then used their relationships as criteria for dam operation. Yang et al. (2012a) have also constructed a reservoir operation model based on RVA that maximizes the natural flow regime, and applied this to the Xiangyang section of the Han River downstream of the Danjiangkou reservoir. Similarly, Yin et al. (2012) constructed reservoir operation objectives for minimizing downstream hydrological alteration as a possible method for evaluating environmental flows below dams. All these studies agree that the closer a hydrologic parameter is to its natural or pre-impact value which calculated in the period before the impact of the dam, the degree of downstream flow regime alteration is smaller, immediately the less environmental deterioration or a loss of biodiversity in the downstream river ecosystem. Though we agree with this view, it is inappropriate to determine the target range of a natural statistic or pre-impact value of a hydrologic parameter as the interval between the first quartile to the third quartile of a parameter series. This is because the distribution of a pre-impact hydrologic parameter time series exhibits regular fluctuation, meaning that the range between the first and third quartile cannot represent the overall trend. Instead, the pre-impact reference value needs to be defined as concentrated, repeated hydrologic parameter values recorded before the water project was constructed. To this end, Shiau and Wu (2008) proposed a novel histogram matching approach (HMA) with a dissimilarity metric, which is based on the quadratic-form of the distance between the frequency vectors of the pre-impact and post-impact histograms and weighted by a specified similarity matrix.

To alleviate the environmental deterioration or a loss of biodiversity of water withdrawal, damming and weirs on downstream ecosystem, ecological targets or constraints should be incorporated into modern reservoir operation, which is defined as multi-objective reservoir operation model (Castelletti et al., 2014; Steinschneider et al., 2014). In order to restore river flow and return it to the value before the impact of the dam, it is necessary to construct an optimal operation objective function to minimize alteration of hydrological indicators which are most greatly affected by the construction of a dam. However, as the IHA values affected by dam operation are calculated using daily discharge data which is the outflow from the dam to the downstream, it is difficult to develop a multi-objective operation model that considers simultaneously the social demands, economic benefits and ecological objectives for an optimal flow regime. In this study, we aim to develop a framework for assessing a multi-objective reservoir operation model based on the flow regime of the middle and lower Yangtze River as a case study. The steps involved in this are: 1) analyze and evaluate the main hydrological indicators for the flow regime after TGD operation and obtain the ideal threshold for monthly water flow rates; 2) investigate the comprehensive influence of TGD construction on the flow regime at two large-scale hydrological gauges; 3) build a multi-objective reservoir operation model to protect the Qingcaosha water source and a spawning ground for four major species of Chinese carp; 4) using the results of the operation model, calculate the corresponding monthly average flows of the Yichang and Datong gauges under three typical hydrologic years, and then compare and assess these with their ideal threshold. All this is intended to provide guidance and advice for the ecological operation of the TGD based on the flow regime of the middle and lower Yangtze River.

2. Study area and data

2.1. Study area

Originating in the Tanggula Mountains of the Qinghai-Tibet plateau, the Yangtze River stretches over a distance of >6300 km before reaching the East China Sea, with a drainage area of >1.8 million km^2. The TGR located at the upper end of the Yangtze is the largest hydroelectric power station in the world, with minimum and maximum releases of 1580 and 98,800 m^3/s, respectively. Located downstream, the middle and lower Yangtze River has a drainage area of 0.8 million km^2. The Yichang gauge located 44 km downstream of the TGD controls river discharge into the middle reach of the Yangtze River. Similarly, discharge of the lower reaches into the East China Sea is controlled by the Datong gauge, which represents the last major hydrological station in the main channel (Fig. 1). The Yichang and Datong gauges were therefore selected as study sites to assess any change in the flow regime of the Yangtze generated by operation of the TGR.

2.2. Data

The daily stream flow at the Yichang and Datong hydrological gauges (Fig. 1) over the period between 1950 and 2013 was collected from the Changjiang Water Resources Commission of China. For the purposes of analysis, the data at each station was divided into two