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Optimized reservoir operation to balance human and environmental requirements: A case study for the Three Gorges and Gezhouba Dams, Yangtze River basin, China

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ABSTRACT

After the construction and operation of the Three Gorges and Gezhouba dams, their impacts on hydrologic alterations in the middle and lower reach of Yangtze River are under high attention worldwide, of which the balance between the human and environmental flow requirements is one of the most important issues. This study uses an optimization model for the operation of reservoirs to compare the different environmental flow requirements of river ecosystems. Based on the different environmental flow requirements, four scenarios were established: (1) the no environmental flow case; (2) the minimum environmental flow (MEF) case; (3) the appropriate environmental flow (AEF) case; and (4) the environmental design flow (EDF) case. The EDF case is first proposed in this paper, which considers the reservoir adjustment ability and comprehensively balances the economic, social and ecological benefits. The Range of Variability Approach (RVA) is used to evaluate the potential hydrological alterations of each of the four scenarios. The comparison results of the power production and the degree of hydrological alteration in the four different scenarios, indicate that the system operation under the EDF case imposes the least hydrological alteration while providing adequate power production. The encouraging results demonstrate that this method will be a robust tool for practitioners to better perform reservoir operations in balancing the human and environmental requirements.

1. Introduction

Reservoirs facilitate the access to water supplies and the generation of electricity. However, the operation of reservoirs influences the downstream ecology, hydrology, and geomorphology (Ligon et al., 1995; Magilligan and Nislow, 2005; Van Steeter and Pitlick, 1998). Due to the construction and operation of reservoirs, many of the original physical and ecological features of natural systems have been significantly altered (Choi et al., 2005; Petts, 1979, 1980; Poff et al., 1997). The regulation of reservoirs, which modulates the natural water flow downstream of these dams, has often been a major cause of ecological impacts (Bunn and Arthington, 2002).

The operation of reservoirs inevitably leads to changes of the natural water flow by reducing the flows of the downstream river, which play a critical role in sustaining the ecological system of a river (Poff et al., 1997). To avoid or mitigate ecological degradation, the consensus among scientists and river managers is to manage water releases from the reservoirs (Arthington et al., 2006) to protect the ecological system and to maintain the ecological condition of rivers. The concept of environmental flow was developed to define the volume of water that should remain in a river, and the environmental flow varies over time to sustain specified ecosystem conditions (King et al., 2003).

It is essential to study the methods of protecting environmental integrity while meeting the human needs for water resources (Yin et al., 2010). The environmental flow regime approach, as a new paradigm for multi-objective water resource management, provides a strategy for decision makers to producing compromises between human needs and environmental flow requirements (Marchetti and Moyle, 2001; Shiau and Wu, 2006; Suen and Eheart, 2006; Tisdell, 2010; Wang and Lu, 2009; Xia et al., 2009). Over the past decades, researchers have attempted to balance human needs and environmental flow requirements to develop optimal reservoir facility operating schemes. Most of these attempts target the minimum environmental flow (MEF), thereby assigning a minimum water quantity constraint to the reservoir water release (Homa et al., 2005; Jager and Smith, 2008). The MEF describes the minimum channel flow necessary to satisfy the ecological requirements of the current situation in a river under the influence of human activity (Yu and Xia, 2004). This method implicitly gives lower priority to ecosystems than to human needs (Yin and Yang, 2011). The MEF conditions are unfavorable hydrological conditions for ecological systems. The appropriate environmental flow (AEF), in contrast, is more effective in maintaining the health of a

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river ecosystem and the population structure of biological species. The target of the AEF is the most suitable flow that enables ecological system stability and species diversity (Chen et al., 2007). However, this method emphasizes the environmental requirements, to a certain extent, it underestimates the human need.

Unfortunately, both of the two methods mentioned above cannot simultaneously address the environmental flow requirements and human water needs. To address these issues simultaneously, this paper proposes the concept of the environmental design flow (EDF). The EDF, bounded by the MEF and AEF, balances the reservoir function of power generation and the responsibility of ecosystem protection. The EDF considers the reservoir adjustment ability and comprehensively balances the economic, social and ecological benefits.

The Yangtze River is one of the most important rivers in the world. The Yangtze River is the third longest river, represents the ninth largest in drainage area, and has the third largest annual runoff (Xia et al., 2006). With the construction of the Three Gorges Dam (TGD), the worldwide prominence of the Yangtze River has significantly increased. The major purposes of the TGD are electricity generation and flood control. To achieve these purposes, the operating strategy for the dam is to store part of the water from the wet season to maintain the hydroelectric power generation during the dry season. The operation of the TGD is reflected in the changes of the seasonal flow distribution downstream of the dam (Gao et al., in press; Yuan et al., 2012). The Gezhouba Dam (GD) is 38 km downstream from the TGD. These two dams can be considered as a whole regarding their influence on the hydrological regime because the GD was constructed primarily for power generation and rarely stores water (http://www.233.com/jzs1/gcsw/fudao/20080806/081618644.html). After the construction and operation of the TGD and the GD, a number of studies have focused on their influence on the mid-lower reaches of the Yangtze River (Li et al., 2011; Sun et al., 2012; Yang et al., 2006; Yi et al., 2010; Zhang et al., 2012). However, reservoir operation methods that effectively balance the human and environmental flow requirements have been seldom reported in literature. In addition, to consider the downstream hydrological alterations, the effects of reservoir operations on human needs and environmental flow requirements must be considered.

This paper focuses on balancing the human needs and the ecological requirements. Based on the different environmental flow requirements, four scenarios have been established for the TGD and the GD: 1) no consideration of the environmental flow, 2) consideration of the MEF, 3) consideration of the AEF, and 4) consideration of the EDF. A comparison of the simulated operations of TGD and GD for these alternative scenarios is presented. The Range of Variability Approach (RVA) is used to evaluate the potential hydrological alterations in the four scenarios. The hydrological alterations, as well as the power production of the scenarios, are compared to present the visual impact of maintaining the environmental flow regime on the power production. The results demonstrate that the EDF imposes the least hydrological alteration while providing adequate power production. The results of the comparison highlight a more reasonable approach for balancing the environmental flow and the power generation in the operation of a reservoir.

2. Study area

The Yangtze River is the longest river in Asia, which is about 6300 km in length and flows into the East China Sea (Yi et al., 2010). The entire basin has an elevation ranging from 0 m to 5000 m and covers a latitudinal range of about 25°N to 35°N. The climate in the Yangtze River basin is strongly controlled by the subtropical monsoon climate in the southeast Pacific Ocean and Indian Ocean. The average rainfall for the entire basin is 1000 mm/year to 1400 mm/year (Li et al., 2011) while the mean annual discharge is about 9.20×10^{11} m^3/year (Milliman and Syvitski, 1992).

Two major dams, the TGD and the GD (Fig. 1), are considered in this study to investigate the influences of dam construction on the Yangtze River. The TGD, which locates in the main stream, has the largest storage capacity (3.93×10^{10} m^3, approximately 4.5% of the annual total discharge) in the Yangtze River. It began to impound water on June 1, 2003 and started full operation in 2009 with the function of flood control, navigation and power generation. Partially activated in 1981, the GD, with a capacity of 1.58×10^9 m^3, is located in the main stream of the Yangtze River, 38 km downstream from the TGD (Li et al., 2011). The GD was constructed mainly for power generation, so it rarely stores water. In fact, the GD releases a flow similar to the reservoir inflow, and it basically does not regulate the inflow (http://www.233.com/jzs1/gcsw/fudao/20080806/081618644.html).

Yichang hydrological station, which is the outlet of the upper Yangtze River basin (Li et al., 2011) and is 44 km away from the downstream of TGD and is 6 km away from the downstream of GD, was chosen in this study to evaluate the dam impacts on the streamflow. Results showed that the forebay of the TGD is lowered than the flood limit water level to empty the flood control capacity during the late May to early June in each year. During the flood season (June to September), the water level is maintained on the flood limit level (145 m) whereas the let-down flow of the reservoir is remained the same as the inflow and consequently the competition for flood control, power production and ecology is nonexistent. At the end of October, the reservoir begins to store water, and the let-down flow drops off with the level increases to 175 m. From December to April, the reservoir maintains a higher water level to achieve the power benefit of the reservoir despite this is drought period.

3. Data and methodology

3.1. Data

3.1.1. Daily flow data

The flow regimes of the Yangtze River have been altered significantly for the operation of the TGD since 2003. However, the study of Zhang et al. (2012) indicated that there were no significant streamflow changes due to the construction of the GD before the TGD operation. On the whole, the operation of the TGD is the most important reason for runoff change. As a result, the year of 2003 has been used as a changing point to divide the pre- and post-dam periods. The daily mean flow data for 109 years (1900–2008) was recorded at the downstream point, that is, the Yichang hydrological station, and was analyzed during the pre-dam period (1900–2002) and the post-dam period (2003–2008).

3.1.2. The minimum environmental flow

The MEF indicates the minimum channel flow necessary to satisfy the ecological requirements of the current environmental situation in a river under the influence of human activity. The MEF may be defined as the channel flow of the driest hydrological condition in the natural state because it is regarded as the drought limitation for the ecosystem (Yu and Xia, 2004).

The MEF used in this study was calculated using the monthly frequency minimum environmental flow method (Li et al., 2007). Using the long historical series of natural flows, the monthly minimum flow values determined the MEF. Table 1 describes the MEF at the Yichang hydrological station.

3.1.3. The appropriate environmental flow

The AEF represents the most suitable flow process for the stability and species diversity of an ecological system. The AEF is more effective than the MEF in maintaining the health of the river ecosystem and the population structure of the biological species (Chen et al., 2007).

The AEF was calculated by the monthly average frequency method (Li et al., 2007). The AEF is defined as 50% of the historical flow during