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Original Research

Impact of the Three Gorges Project operation on the water exchange between Dongting Lake and the Yangtze River

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ABSTRACT

The Three Gorges Project (TGP) is a world known project to utilize and manage the water resources of the Yangtze River. The reservoir stores water at the end of the flood season, and replenishes downstream reaches with water in dry seasons. In addition to such benefits, the TGP has irreversibly changed the hydrological process and the river-lake relation of the middle and lower reaches. In this paper, a hydrodynamic model was established to quantify the impact of the TGP's operation on the water exchange between Dongting Lake and the Yangtze River during 2009–2013. The results indicated that: the operation of the TGP has considerably reduced the peak discharge and the flood volume of the main stream and the Dongting Lake area. The inflow volume from the Yangtze River to Dongting Lake via three outlets decreased by 1.9–3.5 billion m^3/yr, while the outflow volume from Dongting Lake to the Yangtze River at Chenglingji increased by 0.3–1.6 billion m^3 in September and 0.4–0.6 billion m^3 in October, respectively. This research provides valuable information for flood control, irrigation, and water allocation in the middle and lower reaches of the Yangtze River, and serves as a typical case for investigating the impact of other hydropower projects around the world.

1. Introduction

Economic development, industrialization, and urbanization have driven up the demands on water resources and hydropower, which can be met by building more dams and reservoirs. Approximately 50,000 large dams (> 15 m high) and millions of small reservoirs have been constructed to meet the needs of social and economic development throughout the world (World Commission on Dams, 2000). The global gross reservoir capacity is 10,000 km^3, almost 5 times the aggregated river flow. More than half of the 300 biggest river systems around the world are controlled by or under the impact of dams. The relation between the main stream and tributaries as well as the aquatic ecological environment downstream are in the process of irreversible change (Nilsson & Berggren, 2000). There has been growing concern about the impact of dams on the aquatic ecological environment of drainage basins. Various studies show that large dams not only altered river flows but also resulted in negative ecological impacts, including the loss of biodiversity in aquatic and wetland ecosystems (Benjankar et al., 2012; Cappellen & Maavara, 2016; Grill et al., 2015; Pelicice et al., 2015). Therefore, dam construction is usually accompanied by disputes about the benefits of the dam and the costs of negative ecological impacts.

The Three Gorges Project (TGP) is a key water resources project intended for the management and development of the Yangtze River. It has comprehensive benefits including flood control, power generation, navigation, etc. The TGP has many benefits, however, it has inevitably changed the natural hydrological situation of the downstream reaches. Sediment trapping and release of clear water cause scouring of the river channel in the lower reaches, which also makes the supplementary tributary flow for the main stream unsteady, and results in complicated changes to the runoff and water level of the Yangtze River main stream (Fang & Rodi, 2003; Fang & Wang, 2000). After the TGP was put into operation, the scouring of the river channel decreased the medium and low water levels, and reduced the water volume diverting from the main stream into the Dongting Lake area via the three outlets (namely Songzi, Hudu, and Ouchi). Since the operation of the TGP in 2003, water levels close to the historical lowest levels in the middle and lower Yangtze River were frequently observed in 2006, 2007, 2009, and 2011 (Min & Zhan, 2012). The three outlets river system continued to shrink while the water area of Dongting Lake decreased (Chang et al., 2010; Ou et al., 2014). The drop of water level in the main stream downstream

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from the TGP during the storage period of the TGP accelerated the outflow from Dongting Lake, and made the dry season in the lake area come earlier (Lai et al., 2014; Wu et al., 2015).

The hydrological situation of the Yangtze River influenced by the TGP needs to be clarified for the sake of providing better guidance to water administrative departments for water allocation and risk management. Fang et al. (2012) used a one-dimensional mathematical model to simulate flow and fluvial processes based on the field data of hydrology and sediment transport for forecasting the erosion and deposition in the middle and lower reaches of the Yangtze River over the next two decades. Lai et al. (2013) presented a coupled hydrodynamic analysis model designed for simulating the large-scale water system in the middle Yangtze River Basin considering seasonal wetting and drying controlled by complex river-lake interactions. They concluded that the hydrological situation in the middle and lower reaches of the Yangtze River would experience new changes in post TGP era.

This study aims to determine the impact of the TGP's operation on the water exchange between Dongting Lake and the Yangtze River by comparing two scenarios, with and without the TGP operation. A description of the study area and river network is presented, followed by an introduction of the 1-D hydrodynamic model capable of simulating the flow processes in the study area. By comparing the results of the hydrodynamic outputs of two scenarios, the influence of the TGP on the water exchange between Dongting Lake and the Yangtze River is quantified, and finally conclusions are drawn after discussion.

2. Study area and river network

The Yangtze River is the third longest river of the world with a catchment area of 1.8×10^6 km^2. It is a golden waterway that links eastern, central, and western parts of China providing a lifeline of sustainable economic and social development. The TGP is located at Sandouping town, Yichang City, Hubei Province. The normal water level of the reservoir is 175 m, with a total capacity of 39.3 billion m^3. Total length of the reservoir is more than 600 km with a water area about 1084 km^2. The primary operation of the TGP began in June 2003 with the operation levels of 135 m in the flood season and 139 m in the dry season, respectively. In 2006, the operational water level became 144–145 m in the flood season and was raised to 156 m after the flood season. On October 26, 2010, the water level reached 175 m, making it possible to deliver the comprehensive benefits of flood control, power generation, navigation, etc, for which the TGP was designed.

Dongting Lake is the second largest freshwater lake in China and an important part of flood control system of the middle and lower reaches of the Yangtze River. The natural water area of Dongting Lake is 2625 km^2 with a capacity of 16.7 billion m^3 and the annual average outflow is nearly 300 billion m^3. Normally, Dongting Lake is divided into three sub-lakes, i.e. East Dongting Lake, West Dongting Lake, and South Dongting Lake. The entire lake has a very complex terrain and morphology. The bathymetry of most of the bottomlands ranges from 22 to 27 m in East Dongting Lake, 24 to 29 m in South Dongting Lake, and 27 to 30 m in West Dongting Lake (Lai et al., 2013). There are many traverse rivers with uncertain flow directions in the river network in the Dongting Lake area. All these tributaries form a complicated river network system with very perplexing hydraulic relation.

After being regulated by the TGP, the water from the upper reaches of the Yangtze River flows through Zhicheng Station, and a portion enters Dongting Lake via the three outlets joining with the water from Xiangjiang, Zishui, Yuanjiang, and Lishui rivers, and finally drains into the Yangtze River again at Chenglingji running through Luoshan Station on the main stream.

The research region of this study is shown in the red boundary zone in Fig. 1. Information on the hydrological stations considered in this paper are listed in Table 1.

3. Model building and calibration

3.1. Model introduction

The MIKE-11 modelling system (DHI, 2003) was applied in the study by using the 1-D hydrodynamic module (HD) and the Nedbør Affstrømnings Model (NAM) module (Singh et al., 2014). The NAM module is a lumped conceptual modelling tool for simulating rainfall-runoff processes. It accounts for the moisture content in four different and mutually interrelated storages that represent physical elements of the catchment. The four storages are: snow storage (optional), surface storage, lower zone storage, and ground water storage. These storages are connected by equations that simulate the land phase hydrological cycle (Solomatine & Torres, 1996). The HD module is the core of MIKE-11. An implicit finite-difference, 6-point Abbott-Ionescu scheme (Abbott & Ionescu, 1967) is implemented to solve the De Saint-Venant equations. The HD module receives the runoff hydrographs from the NAM module and treats them as boundary conditions for computation of water levels and discharges along the river system. Bed resistance can be described by Manning's roughness coefficients (DHI, 2003; Solomatine & Torres, 1996). In this study, The HD module was used for the flow calculations in the river network of the study area, while receiving runoff hydrographs from the uncontrolled sub-basins computed using the NAM module.

3.2. Model setting

3.2.1. River system generalization

The river network for simulating the water exchange between Dongting Lake and the Yangtze River is generalized as shown in Fig. 2. Apart from the main stream between the TGP and Luoshan Station, the Qingjiang, Xiangjiang, Zishui, Yuanjiang, Lishui, Songzi, Hudu, Ouchi rivers, Dongting Lake area, and other diversion channels and secondary tributaries were included in the simulated network as well.

3.2.2. Sub-basins division and boundary conditions

In this model, the Yichang hydrological station is the upper boundary on the main stream of the Yangtze River, while Luoshan Station is the outlet boundary. The study area can be divided into seven sub basins, i.e. Qingjiang Basin, Xiangjiang Basin, Yuanjiang Basin, Zishui Basin, Lishui Basin, Dongting Lake area, and Yichang-Luoshan area. The locations of these sub-basins are shown in Fig. 1 while detailed information on the sub-basins is listed in Table 2. Five of the sub-basins were measured by an individual hydrological station. For two of the sub-basins no measured data are available, and thus the NAM module was applied to simulate the hydrograph. The daily areal average precipitation data and the monthly potential evapotranspiration data for the same period were used as the input to the NAM module, and the calculated runoff was input to the HD module as surface source lateral inflow.

3.2.3. Profile data

The river section measurements of the study area in 2012 were used in the simulations. The interval between measurements on the main stream of the Yangtze River between Yichang Station and Luoshan Station was about 2 km, while at least three

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