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Impact of floodgates operation on water environment using one-dimensional modelling system in river network of Wuxi city, China

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ABSTRACT

Floodgates operation is one of the major forms of river regulation in basin development and utilization, and have changed natural structures, processes of running water and associated environments. However, there are few analysis on the impacts of multiple floodgates integration on water environment. In this paper, a one- dimensional modelling system (MIKE 11) was established and applied to evaluate the impact of multiple floodgates integration on river flow regimes and water quality. Compared with the actual operation practice, the without floodgates scenario had been simultaneously assessed. The results showed that floodgate operation reduced water levels and river discharge and had opposite impacts on pollutant concentrations. The concentration of Chemical Oxygen Demand (COD) and Ammonia Nitrogen (NH_4-N) significantly increased due to floodgate operation. In addition, the floodgates are likely to threaten the water quality in Taihu Lake. The results provide a scientific basis for successful management of river regulation and serve as a valuable reference for future water environmental impact studies when new river floodgates are proposed.

1. Introduction

River regulation is a global phenomenon, and over half of the world's accessible surface water is already appropriated by humans (Tharme, 2003). Water project construction (e.g., dams and floodgates) is one of the major forms of river regulation in basin development and utilization (Zhang et al., 2010). Dams and floodgates were first constructed more than 5000 years ago, and the regulation of rivers for water security has been at the heart of the advancement of human civilizations (Petts and Gurnell, 2005). According to the World Commission on Dams (2000), over 48,000 large dams in over 140 countries have been constructed, and more than 800,000 small dams have been constructed worldwide (McCully, 1996; Tharme, 2003). In China, nearly 25,000 large dams are estimated to exist, accounting for approximately 50% of the total number of large dams in the world (WCD, 2000). However, dam and floodgates regulations give rise to significant impacts on the environment (Bombino et al., 2006; Benjankar et al., 2012; Zhai et al., 2010; Zhao et al., 2013). Floodgates construction and regulation not only cause river discontinuity and sediment deposition, resulting in riverbed elevation and significant changes of channel morphology (Dong, 2003; Suo, 2005), but change hydrological regimes, pollution migration and transform processes (Huang and Foo, 2002; Ahmet et al., 2006; Chung et al., 2008). Research on the impacts of floodgates regulation on flow regimes (FR) and water quality (WQ) in regulated rivers is a fundamental issue in water environmental research, and any findings will provide technical support for operation of water projects, flood control water quality management.

Numerical simulation is one of the main methodologies of assessing the impact of floodgates and dam on FR and WQ (Zuo et al., 2015). There are several existing numerical and analytical models for the processes, including the Solid and Water Assessment Tool (SWAT) (Hesse et al., 2008; Zhang et al., 2011), the River and Stream Water Quality Model (QUAL2) (Fang et al., 2008), the Water Quality Analysis Simulation Program (WASP) (Zuo et al., 2015). However, depending on various research objects, they all own inevitable limitations. SWAT processes a powerful capabil-

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ity for hydrologic process. QUAL2 concentrates on migration and transfer of many kinds of materials, such as chlorophyll, nutrients total nitrogen (TN), organic pollutants and heavy metals in natural rivers and WASP owns an advantage in lake water quality simulation. MIKE 11 is one of the most widely used water quality models in the world and applied in one- dimensional aquatic systems, such as lakes, streams, rivers, reservoirs, irrigation canals and other inland water systems (Danish Hydraulic Institute, 2007). It has been widely used for interpreting and predicting hydrodynamic process and water quality responses to natural phenomena and man-made pollution caused by various pollution management decisions (Le Ngo et al., 2008; Liang et al., 2015; Wang et al., 2011). However, the use of MIKE 11 in assessing the impact of floodgates on FR and WQ is rare.

The impacts of floodgates on FR and WQ often follow from two research strategies, spatial comparisons and temporal comparisons (Braatne et al., 2008). Spatial comparisons involve assessments of different reaches along a particular river or comparisons with nearby reaches of different rivers. It is based on the general assumption that adjacent river reaches will share similar hydrologic contexts and climatic regimes (Jansson et al., 2000). The focus of temporal comparisons is on analyzing historic time-series data before and after dams and sluice construction. However, each river is unique and there are also some differences in hydrology, geomorphology and aquatic environment (Naiman et al., 2010). Processes along river reaches reflect impacts of floodgates and characteristics of the upstream watershed that also vary across rivers. Meanwhile, river systems are naturally dynamic, with considerable seasonal and inter-annual variations in hydrology, including periodic disturbance, particularly from floods, that can produce major water environmental diversification (Rood et al., 2007). Thus, an effective comparison of with- versus without-floodgate scenarios in the same river during the same period is needed. However, there are few analysis on the research strategy.

The Taihu Lake Basin, the seventh largest river basin in China, is a highly regulated river system with numerous floodgates. The Wuxi, a city along Taihu Lake, the number of floodgates and dams has reached 1200 (TBA, 2008). However, majority of previous studies focused on a single dam or floodgate whereas have not investigated the impacts of multiple floodgates integration on water environment (Hu et al., 2008; Zhai et al., 2010). This work aimed, therefore, to estimate the impacts of floodgates, particularly the effects of multiple floodgate operation, on FR and WQ based on a one- dimensional modeling system. This information is fundamental for successful management of the entire river basin. Given the importance of floodgates as a primary form of river regulation in many river basins worldwide, our study can be used as a basis for future environmental impact studies when new floodgates are proposed in other similar river basin.

2. Materials and methods

2.1. Study area

As one of the most economically developed cities in China, Wuxi (31°7′–32°2′N and 119°33′–120°38′E) is located on the north shore of Taihu Lake in the Yangtze River Delta in east China (Fig. 1). Characterized by high population density and well-developed industries, Wuxi has an average population density of approximately 10 times more than the national average. Water resources per capita in Wuxi is less than one-sixth of the national average, although the average annual precipitation is 1048 mm and the water resource quantity is 1.7 billion m^3. During the last two decades, the water supply in Wuxi has been heavily polluted because of rapid industrialization and urbanization. In June 2007, a regional water supply crisis occurred in Wuxi. The crisis was triggered by an algae bloom in Taihu Lake (Yang et al., 2008).

Simultaneously, Wuxi are subject to periodic, but not continuous, flooding and year-round high water tables. This is attributed to the specific geographical position and the local climatological characteristics: (1) The river network is highly complicated with a density of 3–4 km/km^2. (2) The low-lying topography, and numerous double-flow rivers exist in the network with limited draining and self-purification capacity. (3) The average annual precipitation is 674.70 mm during May to September, accounting for 64.38% of the annual rainfall. The Wuxi government launched large-scale flood control projects, and more than 700 floodgates of different sizes have been built to control flooding.

In this study, we chose 16 main internal rivers in the river network of Wuxi, namely, Beijing–Hangzhou Grand Canal, Wangyu River, Xingou River, Beixingtang River, Xicheng Canal, Baiqugang River, Zhihugang River, Li River, Daxigang River, Bodugang River, Jiuli River, Xibei Canal, Liangxi River, Caowangjing River, Yangxi River, and Ancient Canal, totalling 291.34 km in length (Fig. 1). The water quality objectives of Wuxi were set in accordance with China Environmental Quality Standards for Surface Water (GB3838-2002) (MEP, 2002). The water quality of the Wangyu River, Baiqugang River, Zhihugang River, Li River, Daxigang River, Bodugang River, Jiuli River, Xibei Canal, Liangxi River, and Caowangjing River are required to satisfy the Class III of Water Quality Standards of China (Chemical Oxygen Demand, COD $\leq$ 20 mg/L; Ammonia Nitrogen, NH_4-N $\leq$ 1.0 mg/L). The water quality of the Beijing–Hangzhou Grand Canal, Xicheng Canal, Xingou River, Beixingtang River, Yangxi River, and Ancient Canal are required to conform the Class IV of Water Quality Standards (COD $\leq$ 30 mg/L, NH_4-N $\leq$ 1.5 mg/L).

2.2. Floodgate operation

Wuxi is an archetypal example of China flooding area. According to historical records, 13 large floods have occurred in Wuxi from 1983 to 2006. In 2004, Wuxi launched a new flood control project that was fully completed at the end of 2008. An area of 136 km^2 was protected by the project, and the total drainage design flow was 415 m^3/s. The flood control project included a total of seven flood control stations with 14 floodgates, namely, Yandaigang station, Xianli Bridge station, Jiangjian station, Limin Bridge station, Beixingtang station, Jiuli River station, and Bodugang station (Fig. 1). Flooding management for nature conservation objectives in the river network that is predominantly concerned with the maintenance of appropriate hydrological regimes, particularly the control of water levels at certain periods of the year. In Wuxi, numerous tributary rivers in the suburbs function as back-up reservoirs. Before the rainy season, these tributary rivers must be kept below a certain water level to reserve space for floodwaters.

The following key parameters are applied in the floodgate operation:

(1) Water level (WL) at Beijing–Hangzhou Grand Canal. The canal is located in the upper reaches of Wuxi and is the most important site for flood control in the whole Taihu Lake Basin. It's also a representative characteristic for the river network in Wuxi. (2) WL at Ancient Canal, Bodugang River, Jiuli River and Beixingtang River. These rivers are situated in the middle and lower reaches of Wuxi and the water levels at these rivers are significant indicators to measure the safety level of the flood control system in Wuxi. (3) WL at tributary rivers. It is regulated to ensure storage of floods.

The flood season in Wuxi lasts from May to September each year, the pre-flood season is from January to April and the post-flood season lasts from October to December. The target water levels in Wuxi for flood control are shown in Fig. 2. In the pre-flood season a lower warning level of 3.2 m is defined. In the flood season the flood control capacity is augmented and a upper warning level of