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Integrated approach of hydrological and water quality dynamic simulation for anthropogenic disturbance assessment in the Huai River Basin, China

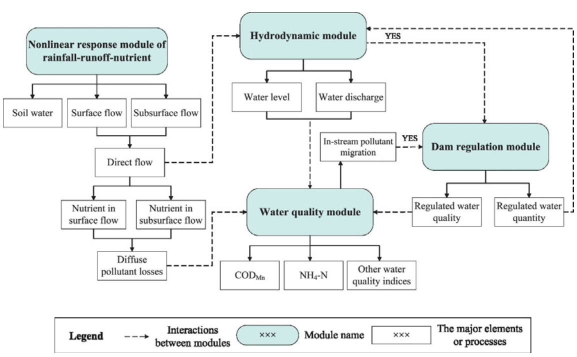
Xiaoyan Zhai [a,b], Jun Xia [c], Yongyong Zhang [c,*]

[a] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
[b] Research Center on Flood and Drought Disaster Reduction of the Ministry of Water Resources, Beijing 100038, China
[c] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Science and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

HIGHLIGHTS

- Integrated hydrological and water quality dynamic were simulated in regulated basin.
- Impacts of three anthropogenic activities were assessed for water quality-quantity.
- Dam regulation deteriorated downstream water quality with current pollutants.

GRAPHICAL ABSTRACT



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ABSTRACT

Detailed depiction of hydrological process and its associated pollution processes plays a critical role in environment improvement and management at basin scale. It also provides a useful tool to assess impact of potential factors on hydrological and water quality conditions. However, it was still difficult to well capture some typical characteristics of these complicated processes including built-in nonlinearity and time-variation, water infrastructure regulations, particularly for highly regulated basins. In this study, an integrated approach of hydrological and water quality dynamic simulation was proposed to solve these difficulties and assess the impacts of several anthropogenic disturbances. The Huai River Basin which was highly disturbed and seriously polluted, was selected as the study area. The main anthropogenic activities considered were point source pollution emissions, diffuse pollutant losses and dam regulations. Results showed that the integrated simulation could well capture the variations in water level, water discharge, concentrations of permanganate index (COD_{Mn}) and ammonia nitrogen (NH_4-N) in high (2007), normal (2008) and low (2004) flow years at 15 stations in the upper and middle streams of Huai River Basin. The regulation rules of downstream sluices played negative roles on water quality improvement if keeping current pollution sources, while those of middle stream sluices played positive roles on water quality improvement. However, the water quality deterioration was mainly attributed to emission of point source pollution (12%–43%), followed by diffuse pollutant loss (0–23%) and water quantity-oriented dam regulation (−29%–20%). The study was expected to provide technical supports for the implementation of water pollution control and sustainable water resources management in the Huai River Basin, and give a reference of integrated hydrological and hydrodynamic simulation.
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* Corresponding author.
E-mail address: zhangyy003@igsnrr.ac.cn (Y. Zhang).

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1. Introduction

Pollution has become an increasingly serious water issue in global river basins for decades, which has threatened drinking water safety and restricted global socio-economic development, especially in China. Huai River Basin is the most densely populated, highly polluted and regulated river basin in China. In 2014, 53.8% of river lengths were polluted (Huai River Water Resources Bulletin, 2014). The water shortage issue induced by water pollution has become increasingly serious, and so-called "cancer villages" have emerged along the riparian zone since the 1970s. Currently, most of the rivers are regulated by dams or sluices (Zhang et al., 2010), which has resulted in serious river fragmentation, aquatic ecosystem degradation, lakes and wetlands shrinkage and serious water quality deterioration (Zhang et al., 2012; Xia et al., 2015). Waste water emissions together with intensive dam regulations have dramatically aggravated water pollution, especially in the middle and lower reaches of the Huai River Basin (Zhang et al., 2010). It is urgent and critical to control water pollution and regulate the dams or sluices reasonably in the Huai River Basin.

The integrated simulation approach of water quality and quantity processes can provide insights into water pollution control and regulation of dams or sluices, and can facilitate the implementation of sustainable water resources management. Currently, two categories of models exist, i.e. watershed model and hydrodynamic model. The watershed model shows great superiority in describing the rainfall-runoff processes at basin scale, such as SWAT (Arnold et al., 1998), DTVGM (Xia, 1991, 2002a), HBV-N (Arheimer and Brandt, 1998) and HEQM (Zhang et al., 2016). However, model performance should still be improved for flow routing, transport and transformation of water quality, and dam regulation in river network. For example, the dynamic river flow routing can be accurately reproduced by a full Saint-Venant equation rather than a simplified water balance model commonly incorporated in a watershed model (Lian et al., 2007; Remo and Pinter, 2007; Paz et al., 2010; O'Sullivan et al., 2012; Paiva et al., 2013). The hydrodynamic model provides a widely-used approach because it is possible to derive detailed water quality and quantity processes with high spatial and temporal resolutions (Wu et al., 2004; Zhang et al., 2008; Cardona et al., 2011), such as EFDC (Hamrick, 1992), MIKE (Warren and Bach, 1992) and HEC-RAS (HEC, 1997). Whereas, enormous challenges still remain for their generalized applications, such as ambiguous land water and nutrient movement mechanisms (Yan and Kahawita, 2000; Gitis et al., 2007), flow regime and accompanying water quality processes disturbances by water infrastructure construction and regulation (Zhang et al., 2013).

The yield and transport processes of land water and nutrient are essentially nonlinear issues (Xia, 1991; Gomi et al., 2008; Tarquis et al., 2011; Tuset et al., 2016). Numerous existing studies have been conducted ranging from empirical to physical approaches (Rinaldo et al., 2005; Kim et al., 2012; Hallema and Moussa, 2014; Maxwell et al., 2014). Yan and Kahawita (2000) developed a physically based numerical model to simulate pollutant dissolution and transport in overland flow, while the proper validation of the complete model required further extensive experimentation. Cea et al. (2014) analyzed the performance of a two dimensional overland flow model using empirical laboratory data, but the application is limited to DEM and mesh resolution. The physical approaches try to demonstrate the role of underlying storage on runoff and nutrient processes based on hydrodynamics, while the elaborate depiction is still confined by observation availability, elaborate parameterization, computational efficiency and understanding of physical processes (Khu et al., 2008; Kim et al., 2012). Alternatively, systematic approach, which has gained popularity for decades, is highly efficient and applicable to depict the interactions between water and nutrients, and exhibits the inherent nonlinearity and time-variant nature in above processes. Specifically, functional series, which is unconditional to priori hypothesis and is suitable for complex systems with obscured physical mechanisms (Xia, 2002a), has been introduced into the nonlinear hydrological fields since the 1960s. Xia (1991) proposed a time variant gain model (TVGM) based on a nonlinear rainfall-runoff relationship with few parameters and limited inputs, and has been widely applied in many river basins of China. Thus, it will be an efficient way for water quantity and quality simulation to incorporate the nonlinear systematic theory into the river hydrodynamic model to efficiently and accurately reproduce the disturbed runoff and water quality processes at basin scale.

Furthermore, the impact of water infrastructure regulation should be considered, as flow regulation is a global phenomenon with rivers fragmented by water infrastructures, and significantly alters natural hydrological cycle (Zhang et al., 2013). The integrated water quality and quantity simulation considering water infrastructure regulations shows great superiority in representing unsteady flow and pollutants transportation, especially in dammed water systems. Zhang et al. (2011a) developed a dynamic numerical model through a laboratory experiment, and determined that water quantity and quality variations downstream of a sluice have nonlinear relationships with upstream flow, pollutant discharge and sluice regulation. Lopes et al. (2004) simulated the hydrodynamics and water quality processes integrating the ISIS FLOW and QUALITY modules and operational conditions of the Touvedo dam in the Lima river, North Portugal. Mateo et al. (2014) combined a water resources model, a river routing model and a reservoir operation module to simulate the floodplain inundation in the Chao Phraya River Basin, Thailand.

In the Huai River Basin, many studies on the integrated water quality and quantity modeling have been conducted to support sustainable water resources management (Zhang et al., 2013; Yang et al., 2016). Whereas, the challenges still existed on efficiently simulating the land movements of water and nutrient, accurately depicting the disturbed flow regime and accompanying water quality processes, and identifying impacts of various anthropogenic activities. The objectives of this study are to: (1) integrate nonlinear response module of rainfall-runoff-nutrient and specific operational rules of dams with river hydrodynamic and water quality modules to describe regulated runoff and water quality variables in the Huai River Basin; (2) assess the impacts of anthropogenic activities (dam regulation, point source pollutants and diffuse pollutant losses) on hydrodynamic and water quality variations and identify critical impacted areas.

2. Materials and methods

2.1. Study area

Located between Yangtze River Basin and Yellow River Basin, Huai River Basin (111°55′–121°25′E, 30°55′–36°36′N, Fig. 1), is the sixth largest river basin with high density of population in China. The drainage area is 274,657 km^2. Its climate belongs to the north-south climate transition straps, with northern warm temperate zone and southern subtropical zone. The annual average precipitation and runoff depths were 883 mm and 230 mm. Both precipitation and runoff gradually decreased from south to north, and were unevenly distributed throughout the year. Most of the precipitation fell between June and September (the flood season), and runoff in the flood season accounted for 55%–82% of total annual runoff. The main land uses were dry farmland (68%) and rice (15.4%).

This region confronted water disasters frequently, including droughts, floods, pollution and ecosystem degradation (Xia et al., 2011). Intensive anthropogenic activities significantly altered natural flow regimes and riverine environment (Zhang et al., 2011b; Zhai et al., 2014), such as industrial and municipal wastewater emissions, nutrient losses, excessive dam and sluice construction. The chemical oxygen demand (COD) and ammonium nitrogen (NH_4-N) loads discharged into rivers in 2014 were 1.08 and 1.39 times of those targeted emissions (Huai River Basin Comprehensive Planning 2012–2030, 2013). Diffuse pollution contributed 30% for water quality deterioration in 2000. Over 10 thousand dams and sluices were

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