Ecological Engineering 95 (2016) 271–279

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Modeling the impacts of water transfer on water transport pattern in Lake Chao, China

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ARTICLE INFO

Article history:
Received 10 January 2016
Received in revised form 4 June 2016
Accepted 18 June 2016
Available online 2 July 2016

Keywords:
Water age
Residence time
Water transfer
Hydrological model
Hydrodynamic model

ABSTRACT

Water transport pattern plays an important role in determining water and pollution transport, and is worth our investigation. In this study, a hydrological model (Xinanjiang) and a hydrodynamic model (Environmental Fluid Dynamics Code, EFDC) were coupled to investigate the impacts of a water transfer project on the water transport pattern of Lake Chao, China. The Xinanjiang model simulated the inflow discharges for the EFDC model. The validation results were acceptable with a Nash–Sutcliffe coefficient of 0.74 and 0.84 for the Xinanjiang and EFDC models. Based on the calibrated models, four simulations were implemented and compared to evaluate the impacts of the water transfer project on the water transport pattern, described by water age and residence time. The simulation results revealed that the water transfer project had the potential to shorten water age and residence time of the lake, however, should be carried out by considering the influences of wind conditions and water transfer route. This study demonstrated a successful adaption of water age and residence time for describing water transport pattern, and highlighted the importance of model coupling approach in addressing multidisciplinary questions from the complex natural ecosystem.

Software availability

Model name: Xinanjiang Model
Model download: http://www.escience.cn/people/elake/index.html
Programming language: Python
Model name: Environmental Fluid Dynamics Code
Model download: http://sourceforge.net/projects/snl-efdc/
Programming language: FORTRAN

1. Introduction

Learning water transport pattern in a large lake is challenging, however, helpful for our understanding of water quality dynamics (Shen and Haas, 2004). Several indicators (e.g., turnover time, flushing time, water age and residence time) have been widely used to evaluate water transport in aquatic systems (Monsen et al., 2002; Pilotti et al., 2014; Shen and Haas, 2004). Among these indicators, water age was originally used to describe the processes of water exchange and nutrient transport processes of rivers, estuaries and oceans with intensive water exchange induced by tide and wind, and was successfully adapted in large shallow lakes with poor water movement (Li et al., 2011). The indicator of water age described the length of a dissolved substance staying in a lake since it was transported from inlets into the lake (or a specific area of the lake). However, the water managers may want to know how long a dissolved substance would be transported out of the lake (or a specific area of the lake). Residence time could be an optional solution to this question even it was so far mostly used in estuary areas (Ascione Kenov et al., 2012; Wan et al., 2013).

During the last decade, severe algal blooms occurred in Lake Chao (a large shallow lake in China) due to the excessive nutrient loading of the inflow rivers (Kong et al., 2016). To improve water quality and alleviate severe algal blooms in Lake Chao, a water transfer project was proposed to transfer water from the Yangtze River into Lake Chao. Such water transfer project was widely demonstrated worldwide to have complex impacts on both the sending and receiving ecosystems (Fornarelli and Antenucci, 2011; Fornarelli et al., 2013; Gohari et al., 2013; Hu et al., 2010; Tang et al., 2016; Zhai et al., 2010). Many approaches were thus proposed and used to evaluate various impacts of a water transfer project on water quality, phytoplankton dynamics, algal bloom, etc.

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http://dx.doi.org/10.1016/j.ecoleng.2016.06.074
0925-8574/

(Fornarelli and Antenucci, 2011; Fornarelli et al., 2013; Huang et al., 2015b). However, the impacts of a water transfer project on the water transport pattern of Lake Chao were not adequately evaluated due to the limited data of inflow discharges for hydrodynamic modeling of the lake. Lake Chao includes six large inflows without hydrological stations located at their outlets. Inspired by the "holistic systems thinking" proposed by Laniak et al. (2013), this ungauged challenge could be partly alleviated based on the existing hydrological models to estimate the inflow discharges of Lake Chao (Cole and Moore, 2009; Yao et al., 2014).

Given the important role of the Yangtze River water transfer project for the Lake Chao ecosystem, this study aimed to investigate its impacts on water transport of Lake Chao. Two indicators (water age and residence time), originally used in marine systems, were adapted to represent the water transport pattern of Lake Chao based on the fundamental definitions. Their spatial heterogeneity (pattern) of water age and residence time in the lake was calculated based on a three-dimensional hydrodynamic model. The inflow discharges for the hydrodynamic model were estimated based on a two-dimensional hydrological model.

2. Material

2.1. Study area

Lake Chao watershed, covering an area of 13,555 km^2, is located in central Anhui province, China (Fig. 1). The watershed mainly includes five land use types, i.e., water surface, residential area, forest, paddy and dry lands, with an area ratio of 8.4%, 7.0%, 19.2%, 63.4% and 2.0%. A large (surface area, 768 km^2), shallow (mean depth, 2.7 m) lake (Lake Chao) is located in the center of the watershed. Annual precipitation of the watershed is approximately 1072 mm. Lake Chao include six inflows (Hangbu River, Baishitian River, Zhao River, Zhegao River, Nanfei River and Pai River) and one outflow (Yuxi River) connecting with Yangtze River. The mean hydraulic retention time of Lake Chao is 207 days. During the last few decades, excessive nutrient loading deteriorated the water quality of Lake Chao, and resulted in severe algal blooms (Deng et al., 2008). Total phosphorus and nitrogen in western Lake Chao (0.66 and 7.63 mg/L) were higher than those in eastern Lake Chao with a value of 0.34 and 5.29 mg/L, respectively (Jiang et al., 2014). The high nutrient conditions in western Lake Chao was mainly due to the large nutrient loading from Nanfei River with a large city (Hefei) in its watershed (Fig. 1).

2.2. Water transfer project

A water transfer project has been planned to transfer water from Yangtze River to Lake Chao. This water transfer project has two optional routes (Routes 1–2) in Fig. 1 (Wang and Chen, 2011). In Routes 1–2, the water in Yangteze River will be transferred to Lake Chao through Zhao River and Baishitian River. In Route 1, the transfer water will flow out of Lake Chao through Yuxi River. In Route 2, the transfer water will flow out of Lake Chao through Pai River, and flow into Huai River (Fig. 1). Route 2 required intensive pumping project. Because Pai River is an inflow river, implying that its water would not flow into Huai River without pumping project. The water transfer project was expected to have a transfer capacity of more than 1 billion m^3 water annually from Yangtze River into Lake Chao. However, the actual water transport amount will be determined by the degree of drought in Lake Chao watershed. This water transfer project aimed to improve the water quality and alleviate water resource shortages in Lake Chao. Because the nutrient concentration (except nitrate) in Yangtze River is significantly lower than those in Lake Chao and its surrounding rivers (Table 1).

2.3. Data

The hydrological and hydrodynamic models required the inputs of land use, meteorological and hydrological data. The simulation (calibration and validation) period was from 1980 to 1986. Meteorological data in another period (2010–2013) were collected to simulate the inflow discharges of Lake Chao. Brief information of these collected data was listed in Table 2.

The land use of Lake Chao watershed in 1980s and 2007 was interpreted using the method of supervised classification based on the satellite image by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. Five land use types (water surface, residential area, forest, paddy and dry lands) were included.

The meteorological data included the factors of daily maximum, minimum and average of air temperature (T_{Max}, T_{Min} and T_{Ave}, °C), daily average of relative humidity (Wet, %) wind speed (WS, m/s), wind direction (WD, °), daily sunshine hours (H_{Sun}, h) and precipitation (Pr, mm). These data were collected from nine weather stations (Fig. 1).

The daily hydrological data included discharge (Q, m^3/s) and water level (WL, m). Discharge data were recorded at the hydrological stations H1-H2. Water level data were recorded at the outlet area of Lake Chao (hydrological station H2 in Fig. 1).

3. Methods

3.1. Model description

A hydrological model and a hydrodynamic model were coupled together to simulate the changes of water age and residence time in Lake Chao due to Yangtze River water transfer. Their reliability was improved and evaluated based on model calibration and validation.

3.1.1. Hydrological model

The two-dimensional Xinanjiang model was used to simulate daily flow discharge. This model was originally developed by Zhao (1992), and has been widely applied and improved for hydrological modeling in the humid and sub-humid areas (Yao et al., 2014; Zhao et al., 2011). The Xinanjiang model included four modules, i.e., evapotranspiration module, runoff generation module, runoff separation module and runoff routing module. Water evaporation was calculated based on the Penman-Monteith method proposed by Allen et al. (1998). A parabolic curve of tension water capacity was used to describe the watershed heterogeneity in runoff generation module. Runoff separation module divided the total runoff into three components, including surface runoff, interflow and groundwater runoffs. Runoff routing module described the overland and channel flow by the one-dimensional kinematic wave function with Manning's equation. Further details about the Xinanjiang model could be found in Zhao (1992).

The Xinanjiang model aimed to simulate six inflow discharges for the boundary conditions of a hydrodynamic model described in the following section. A spatial resolution of 500 × 500 m was used in this case study. The simulated period of the hydrological model was from 1980 to 1986 with a daily time step. The warm-up period was 1980, and the calibration and validation periods were 1981–1983 and 1984–1986, respectively.

All the parameters in Xinanjiang model were firstly initialized from literatures. Sensitive parameters were identified using a one-at-a-time sensitivity analysis method (Cariboni et al., 2007; Huang et al., 2014). The sensitivity analysis method calculated sensitivity value for each parameter by implementing two simulations with the parameter value increased or decreased by 10%. A higher sensitivity value of a parameter implies that the flow discharges of Lake