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Effects of ecological flow release patterns on water quality and ecological restoration of a large shallow lake

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ABSTRACT

Large shallow lakes play an important role in providing water for domestic supply and landscape irrigation, and maintaining a healthy ecosystem. A lake ecosystem possesses abundant aquatic plants and animals. Changes of the hydrological regime affect the water level, water quality, and species distribution. In this study, a two-dimensional hydrodynamic and water quality model is applied to a large shallow lake, Baiyangdian Lake. The model was established based on measured lake bed elevation, hydrological data, and water quality data. This model was validated for two water transfer events and wind-driven circulation in local areas was observed in the model results. Influences of water transfer and wind effects on water flow and distribution of ammonium and phosphate were then evaluated and discussed. A total of eighteen water transfer scenarios were simulated. The entire lake flow field and water transfer routes in the lake and nutrient distributions were analyzed under each water transfer scenario. The water transfer suggestions proposed in this paper are based on hydraulic characteristics of the lake and make up for deficiencies that previous did not consider the effects of flow transfers on the flow field of receiving. The environmental flow patterns and ecological restoration measures for Baiyangdian Lake are proposed based on the lake hydrodynamics and flow routes under different water transfer scenarios.

1. Introduction

In China shallow lakes are surrounded by densely populated areas, and the lakes provide food for humans and habitat for aquatic animals (Janssen et al., 2014). Animals, vegetation, and organisms living in a shallow lake form a regional ecosystem and maintain the stability of the ecosystem. Severe contamination has occurred in many lakes around the world, such as Taihu, Chaohu, Erhai, and Dianchi lakes in China and Lake Erie in the United States. Some of these lakes have experienced algal blooms, which have directly resulted in large areas with water supply difficulties (Guo, 2007; Kuiper et al., 2015; Michalak et al., 2013; Zhang et al., 2015). Non-point pollution from agriculture, domestic sewage, and industrial waste directly pollute lake water (Li et al., 2016; Wang et al., 2016). Continuous pollution leads to deterioration of water quality, and even death of aquatic animals and vegetation (Conley et al., 2009). Dams upstream prevent water from reaching downstream lakes, which indirectly intensifies lake pollution (Yang and Yang, 2013). Climate warming can indirectly change lake water quality and expand cyanobacterial blooms, especially for shallow lakes where the temperature is over °C 25 (Wu et al., 2015). Water level and nutrient loading are important stressors that degrade lake ecological stability, and reduction in rainfall and natural runoff also accelerate aquatic ecology degeneration (Kong et al., 2017).

Water transfer is regarded as an efficient way to (a) alleviate the contradiction between limited water quantity and increasing water demand, (b) decrease the pollution extent, and (c) recover lake or river ecological characteristics (Meador, 1992). The early water transfer projects mainly considered the water demands from a continuously expanding population and economy, but ignored environmental flows. For example, the California Water Project was constructed to transfer water from northern California's Feather River to southern California to meet water demands from its continuously growing population and economy (Kelley, 2011). However, fresh water was polluted and ecosystems were damaged under anthropogenic disturbances and climate influences.

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Domestic and industrial water are not the only reason for water transfer. Environmental flows for river and lake ecosystems also may require water transfer. Moses Lake in Washington, U.S., accepted dilution water and experienced an obvious decrease in the total phosphorous content and Chlorophyll-a (Welch and Patmont, 1980). Baiyangdian Lake in China, as an import freshwater wetland, has accepted inter-basin water transfer from the Yuecheng Reservoir (YCR) and the Yellow River to guarantee minimum environmental flows (Yang and Yang, 2014). In 2002, in order to avoid drought at Lake Nansihu in China, about 5.7 $\times$ 10^8 m^3 and 0.14 $\times$ 10^8 m^3 of water were transferred from the Yangtze and Huaihe rivers, respectively (Huang et al., 2003). Lake Taihu also has accepted water from the Yangtze River to improve the lake water quality (Hu et al., 2010). The Chinese Middle Route of the South to North Water Transfer Project (MRP) plans to transfer a portion of the water to Baiyangdian Lake as environmental flows every year, although the main purpose of this project is to provide domestic water for Beijing (Wang et al., 2016).

Ecological and environmental restoration after water transfer in the receiving water bodies is an important factor in assessing the influence of water transfer. Wang et al. (2016) assessed the effects of water transfer using a coupled model of cascade reservoirs operation schedule and water quantity-quality models, i.e. calculated stream-aquifer water exchange, irrigation return flow, and point and non-point pollution loads. A one-dimensional, long canal, water quality model was applied to simulate the water quality and predict the water pollution risk for the large MRP (Tang et al., 2014). Two-dimensional (2D) hydrodynamic and ecological models were developed to simulate the water levels and pollutant concentrations and calculate the appropriate environmental flows to reflect the effects of water transfer on water quality improvement in Baiyangdian Lake (Yang et al., 2016). The water age and residence time in Lake Chaohu were evaluated based on a 2D hydrodynamic model that was constructed using the Environmental Fluid Dynamics Code (EFDC), which revealed the influence of water transfer on water movement patterns in Lake Chaohu (Huang et al., 2016).

Previous research strived to study the effects of water transfer on the changes of hydrological regimes, pollutant concentrations, and ecological improvement. While these studies qualitatively indicated the water quantity and water quality improvement, they only paid attention to individual points or sections (Yang and Yang, 2014; Yang et al., 2016). The transferred water allocations for downstream lakes were recommended based on the environmental flow without considering the lake flow field (Yang and Mao, 2011). The previous studies of water transfer projects mainly concentrated on the environmental flow and water level changes and did not consider the effects of flow transfers on the flow field of receiving lakes (Yang and Yang, 2014; Yang et al., 2016). Therefore, more studies are needed on the influence of water transfer on the lake flow field, water transfer routes, and nutrient distributions based on lake hydrodynamics.

This study explores the influence of different environmental flow patterns on the receiving water body, using a case study of Baiyangdian Lake in China. A 2D hydrodynamic and water quality model using MIKE 21 was applied to simulate the lake hydrodynamic characteristics of flow velocity and water level, and the spatial distributions of ammonium-nitrogen (NH_4-N) and phosphate-phosphorus (PO_4^{3-}). The water quantity and hydrodynamics processes were connected to analyze the water changes and lake hydraulic connectivity after water transfers. The flow field and water quality improvement were calculated and analyzed at lake-scale and regional-scale, respectively. Different flow routes and nutrient distributions were predicted based on different environmental flow release patterns. Based on the results from this study, an effective environmental flow pattern and lake restoration suggestions are proposed.

2. Materials and methods

2.1. Study area

Baiyangdian Lake (115°45′-116°07′ E, 38°43′-39°02′ N) is the largest shallow lake in northern China (Fig. 1). It is located in the downstream area of the Baiyangdian Basin and accepts runoff exceeding the storage capacity of upstream reservoirs, especially in the flood season. The total area of the lake is 366 km^2. The lake bed elevation gradually reduces from west to east with an average depth of approximately 2–3 m (Wang et al., 2014). In the 1950s, dam construction began on the upstream rivers. By the 1970s, a flood control system basically was established in the Baiyangdian Basin, consisting of the upstream reservoirs, main rivers, embankments, and Baiyangdian Lake downstream (Wu, 2009). However, several droughts have occurred in this lake since 1950, including a 5-year drought from 1984 - 1988 (Wang et al., 2014). Drought leads to shrinkage of the lake and intensifies lake pollution, which also leads to reduction in the aquatic animals and vegetation the lake can support (Yang and Yang, 2014). Severe lake ecological deterioration demands pollution control and ecological restoration for Baiyangdian Lake (Xie et al., 2010). Therefore, the Baoding City government has published a series of regulations to protect the ecological conditions of Baiyangdian Lake, i.e. the lake flood control level is set as 8.0–8.3 m and the flood warning water level is 9.0 m (Dagu datum) to avoid flood inundation; the lowest water level for meeting the requirements of the environmental function plan is 8.4 m (Dagu datum); and the water quality of at least 74% of the water area needs to meet the Grade III requirement of the national standards (GB 3838-2002), which is the minimum requirement for lake ecological water. To achieve this goal, Baiyangdian Lake accepted water transfers 33 times from the upstream Wangkuai Reservoir (WKR), Angezhuang Reservoir (AGZR), and Xidayang Reservoir (XDYR), and from the inter-basin YCR and the Yellow River from 1981 to 2012 (Fig. 1). The average rate of water transfer from WKR and XDYR to Baiyangdian Lake was between 0.78 and 24.9 m^3/s (Yang and Yang, 2014). Monthly water quality data at the eight water sampling locations shown in Fig. 1 from February 2012–July 2015 were provided by the Research Institute of Environmental Protection of Baoding City (China).

2.2. Governing equations

The MIKE 21 computer program was used to develop a 2D free-surface flow hydrodynamic model (DHI, 2010). The 2D model has been widely applied for water flow simulations in lakes, reservoirs, estuaries, and floodplains (Jiang et al., 2016; Li et al., 2014; Wen et al., 2013).

(1) Shallow water equations

Baiyangdian Lake is a typical shallow lake where the vertical acceleration can be ignored. Hydrostatic pressure was assumed in the vertical direction of the flow. A MIKE 21 hydrodynamic model was established to simulate the lake flow. The basic equations of motion derived from the incompressible Navier-Stokes equations are:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu_j)}{\partial x_j} = 0 \quad (1)$$