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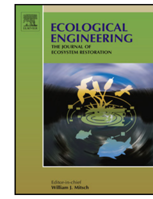

Assessing and modeling impacts of different inter-basin water transfer routes on Lake Taihu and the Yangtze River, China

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ABSTRACT

To enhance water exchange and alleviate eutrophication in Lake Taihu, the third largest freshwater lake in China, four different inter-basin water diversion named Route One to Four, have been implemented or planned to flush pollutants out of Lake Taihu by transporting freshwater from Yangtze River. Due to the shallowness and large size of Lake Taihu, it is quite complex to set the optimal transferred inflow rate for each route or the combination of routes to maximize the benefits for improving the lake's water exchange with minimum economical cost and environmental impact. In this study, the appropriate transferred inflow rates and environmental impacts of the different water transfer routes on both Lake Taihu ("receiver") and the Yangtze River ("supplier") were assessed using the concept of water age and Lagrangian particle tracking based on a three-dimensional Environmental Fluid Dynamic Code (EFDC) model. The results showed that the appropriate flow rates were quite different from the single route diversion to the combination of routes, depending on priorities such as lowest economical cost and highest water quality improvement for specific lake regions or the entire lake. Two optimal combinations of routes to achieve specific results in different seasons were determined to improve the water exchange of the lake. During the algal bloom seasons, the objective of the combination focused on enhancing water exchange in the specified lake regions such as Meiliang Bay and Zhushan Bay. The optimal flow rates for Route One to Route Four were 80, −70 ("−" means outflow), 100 and 20 m^3/s, respectively. In the non-algal bloom seasons, the combination concentrated on lowering water ages in the entire lake. The optimal flow rates for Route One to Route Four were 90, −40, 70 and 20 m^3/s, respectively. The results suggested that the Yangtze River Diversion, as an emergency stopgap measure, played important roles on enhancing water exchange in the lake, but had minimal impact on the Yangtze River. The findings of this study provide useful information for the local government and decision-makers to better understand the physical and hydrological processes of water transfer projects and to assist in managing the water transfer projects.

1. Introduction

Eutrophication has become ubiquitous in many lakes, reservoirs and other freshwater bodies affected by anthropogenic nutrient inputs over the past few decades (Paerl and Huisman, 2008; Qin et al., 2010; Schindler and Vallentyne, 2008; Smith and Schindler, 2009). Water transfer engineering, an important method for lake restoration, has been successfully used in many water bodies for accelerating water exchange, diluting polluted water, improving water quality and mitigating eutrophication issues by transferring

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large volumes of water from a relatively clean source to a severely polluted water body. There are currently over 160 large-scale inter-basin water transfer projects in 24 countries (Ghassemi and White, 2007; Wang, 2004), including the famous Snowy Mountain Scheme in Canada (Pigram, 2000), the California State Water Project in the United States (Davies et al., 1992), the Northern Siberian Rivers Diversion in the former Soviet Union (Voropaev and Velikanov, 1985) and the Ganges Water Diversion in India (Mirza, 2004). In China, major inter-basin water transfer projects include the man-made Great Canal from Beijing to Hangzhou city (Yao, 1998), the South-to-North Water Diversion Project transferring water from southern China to northern China by three different transfer routes (Liu and Zheng, 2002) and the water transfer project from the Yangtze River to Chaohu Lake (Xie et al., 2009).

The Yangtze River Water Diversion, transporting water from the Yangtze River to Lake Taihu, is another example of inter-basin water transfer engineering in China. Lake Taihu, the third largest freshwater lake in China, is suffering from severe eutrophication problems, threatening the water supply for the surrounding cities (Hu et al., 2008; Yang and Wang, 2003). In order to relieve eutrophication by enhancing water exchange in Lake Taihu, the Yangtze River Water Diversions have been built (Qin et al., 2010). Up to now, four different routes of this project have been implemented or planned (Fig. 1). Route One (the original route), implemented in 2002, transfers freshwater from the Yangtze River into Lake Taihu via the Wangyu River and discharges water through the Taipu River. Previous literature showed that Route One, as an emergency measure, could temporarily improve water quality and mitigate algal bloom in some lake regions excluding the most polluted area in Lake Taihu (i.e., Meiliang Bay, Zhushan Bay, Northwest and Southwest Zones) (Hu et al., 2008, 2010; Li et al., 2011a; Zhai et al., 2010). Route Two (the improved route) was applied in 2004 to improve the water exchange in Meiliang Bay in the northern lake region by adding two additional pump stations named Meiliang and Xingou around Meiliang Bay (Fig. 1) (JWRA, 2006). Li et al. (2013) showed that Route Two played a supplementary role for Route One in enhancing water exchange directly in Meiliang Bay. The optimal flow rate from the Wangyu River (Route One) was predicted to be 120 m^3/s, and the corresponding appropriate outflow rate from the Meiliang pump station (Route Two) was about 15–20 m^3/s based on the multi-objective optimization method. However, both Route One and Route Two did not significantly enhance water exchange in the northwest and western regions, the heavily polluted areas of Lake Taihu. Hence, Routes Three and Four have been recently designed to enhance water exchange in those polluted lake regions. Route Three is planned to bring fresh water from the Yangtze River to the northwest region via the Xinmeng River. Route Four is planned to take fresh water via the Changxing River to the southwest lake region. The design concept is to transfer water from the clean source into the specified hyper-eutrophic areas directly and flush the pollutants out of Lake Taihu. However, whether these diversions will work or not is difficult to predict due to the complex hydrodynamics of Lake Taihu.

Although previous papers have evaluated the effect of Routes One and Two on accelerating water exchange in Lake Taihu and obtained the optimal transferred flow rates for them (Li et al., 2011a, 2013), it still remains unclear about the effects of Routes Three and Four. For example, how will the new-planned Routes Three or Four work for enhancing water exchange in the lake? How to set the optimal transferred flow rate for the single route or combination of the four routes to improve the lake's water exchange with a minimal economical cost? Additionally, the impact of water transfer diversions should focus on both the "receiver" (Lake Taihu) and "donator" (Yangtze River). However, previous research only assessed the impacts on the receiving system (Hu et al., 2008, 2010; Li et al., 2011a, 2013; Zhai et al., 2010), ignoring the donating systems.

Thus, the hydrodynamic and hydrological impacts on both Lake Taihu and the Yangtze River and appropriate flow rates of different inter-basin water transfer routes will be assessed using the concept of water age and particle tracking based on a three-dimensional Environmental Fluid Dynamic Code (EFDC) model in this paper. The detailed objectives of this study were to: (1) understand the effect of single route of inter-basin water transfer on the hydrodynamic process of Lake Taihu and its appropriate transferred flow rate based on a multi-objective optimization program; (2) identify the optimal combinations and the corresponding flow rates for Lake Taihu in the algal bloom seasons and the non-algal bloom seasons, respectively; (3) assess the impact of water diversions on the hydrodynamic processes of the Yangtze River. This study aimed to help the local government and other decision-makers to better understand the effect of water transfer projects on the physical and hydrodynamic processes in Lake Taihu and the Yangtze River.

2. Study area

Lake Taihu, a well-known large shallow lake, is located in the lower Yangtze River delta between 30°56′–31°33′ N and 119°53′–120°36′ E, with an area of 2338 km^2 and a mean depth of 1.9 m (Fig. 1, Qin et al., 2010). The lake retention time was about 181 days during the period from 1951 to 1988 and 309 days after the 1990s (Qin, 2008). Wind is a key driving force in the hydrodynamic processes of Lake Taihu. Wind direction around the lake changes with the seasons, with southeasterly winds prevailing in the summer and northwesterly winds prevailing during the winter, while the average wind speeds are 3.5–5 m/s (Hu et al., 2006). Lake Taihu is divided into eight sub-areas according to its hydrological and ecological characteristics: Zhushan Bay, Meiliang Bay, Gonghu Bay, Northwest Zone, Southwest Zone, Central Zone, East Epigeal Zone and Dongtaihu Bay (Fig. 1, Hu et al., 2008). The southeast part of the lake has a significantly better water quality compared to the northwest section due to the special locations of the influent and effluent rivers (Hu et al., 2010; Li et al., 2011b). The northwest parts of Lake Taihu, including Meiliang Bay, Zhushan Bay, Northwest Zone and Southwest Zone, suffer from frequent algal blooms and serious eutrophication problems.

The section of the lower Yangtze River related to this water transfer project extends from the Wufeng Mountain to the Xuliujing River (Fig. 1). The length of the main stem is about 221 km in the water transfer study area. The averaged flow discharge from 1950 to 2005 of the Yangtze River in Jiangsu Province was about 28,700 m^3/s (Chen et al., 2001). All water transfer routes are related to the Yangtze River, either withdrawing water from it or returning water to it.

Route One takes water to Gonghu Bay through the Wangyu River and flows out via the Taipu River in Dongtaihu Bay (Fig. 1). The actual inflow rate in operation from the Wangyu River ranges from 20 to 240 m^3/s (Jia et al., 2008). Route Two, built in March 2004 and first tested in 2006, takes polluted water out of Meiliang Bay to the Yangtze River by using two new pump stations named Meiliang and Xingou around Meiliang Bay. The designed maximal operation flow rate for each pump station is 50 m^3/s (JWRA, 2006). Route Three was planned to bring water from the Yangtze River to the Xinmeng River, and go though Lake Gehu, the Taige River and the Caoqiao River, and eventually flow into Zhushan Bay (Fig. 1). The designed maximal inflow rate of Route Three is about 100 m^3/s. Route Four was designed to transfer water into Lake Taihu through the Changxing River near the Southwest Zone, with a predicted inflow rate in the range of 0–50 m^3/s.