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Research papers

Is water age a reliable indicator for evaluating water quality effectiveness of water diversion projects in eutrophic lakes?

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ABSTRACT

Water diversion has been applied increasingly to promote the exchange of lake water and to control eutrophication of lakes. The accelerated water exchange and mass transport by water diversion can usually be represented by water age. But the responses of water quality after water diversion is still disputed. The reliability of using water age for evaluating the effectiveness of water diversion projects in eutrophic lakes should be thereby explored further. Lake Dianchi, a semi-closed plateau lake in China, has suffered severe eutrophication since the 1980s, and it is one of the three most eutrophic lakes in China. There was no significant improvement in water quality after an investment of approximately 7.7 billion USD and numerous project efforts from 1996 to 2015. After the approval of the Chinese State Council, water has been transferred to Lake Dianchi to alleviate eutrophication since December 2013. A three-dimensional hydrodynamic and water quality model and eight scenarios were developed in this study to quantity the influence of this water diversion project on water quality in Lake Dianchi. The model results showed that (a) Water quality (TP, TN, and Chl*a*) could be improved by 13.5–32.2%, much lower than the approximate 50% reduction in water age; (b) Water exchange had a strong positive relationship with mean TP, and mean Chl*a* had exactly the same response to water diversion as mean TN; (c) Water level was more beneficial for improving hydrodynamic and nutrient concentrations than variation in the diverted inflowing water volume; (d) The water diversion scenario of doubling the diverted inflow rate in the wet season with the water level of 1886.5 m and 1887 m in the remaining months was the best water diversion mode for mean hydrodynamics and TP, but the scenario of doubling the diverted inflow rate in the wet season with 1887 m throughout the year was optimum for mean TN and Chl*a*; (e) Water age influenced the effectiveness of water diversion on the improvement in TP, but not in TN and Chl*a*. Therefore, water age solely could not be used to evaluate the restoration of water quality in a eutrophic lake, because geobiochemical processes played a more important role in the growth of algae than did water exchange in Lake Dianchi.

1. Introduction

The challenge of restoring a eutrophic lake has been recognized widely since the 1960s (Davis, 1964; Forsberg, 1980; Conley et al., 2009; Paterson et al., 2011; Matthews et al., 2015; Pizarro et al., 2016). Many treatment technologies and management policies have thereby been proposed (i.e., waste water treatment plants (WWTPs) and use of riparian wetlands to intercept the pollutants). Compared with external and internal technologies to reduce nutrient loads, in-lake restoration measures have been applied less frequently (Özkundakci et al., 2010, 2011; Thevenon et al., 2011). The two types of in-lake restoration measures are biochemical and physical. The biochemical measures refer to adjusting the biological and chemical reaction rates to reduce the concentration of total nitrogen (TN), total phosphorus (TP), and algal biomass that is usually represented by chlorophyll *a*, Chl*a*, and include a biomanipulation application (Benndorf, 1995), hypolimnetic aeration technology (Jaeger, 1994), or a chemical precipitation method for phosphorus removal (Jaworska et al., 2009; Noyma et al., 2015). Physical measures improve lake water quality by accelerating hydrodynamic and mass transport processes, for example, through water diversion/dilution (Li et al., 2011, 2013). The lakes in China has long faced pressures from intensive watershed loads. For the plateau lakes in southwestern China, it is even worse because of

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the special watershed and physical characteristics of the lakes, such as slow rates of water flushing and the long hydraulic retention times (HRT) (Xie and Chen, 2001); therefore, biochemical processes play a dominant role in the control of eutrophication for lakes that have a high concentration of microorganisms and sufficient reaction time. In recent decades, water diversion has been used increasingly to promote the exchange of lake water and to dilute nutrient concentrations (Zeng et al., 2006; Brett and Benjamin, 2008; Li et al., 2013; Liu et al., 2014).

With clean diversion water, water exchange and mass transport can be enhanced for the receiving lake, and this is represented usually by the reduced age of the water (Li et al., 2011). Water age can be used as an indicator of the elapsed time that a dissolved substance has been transported from its source to a given location in the lake, and water age of the inflow inlets is zero where the dissolved substance is released (Delhez et al., 1999; Shen and Lin, 2006; Li et al., 2011). Li et al. (2011, 2013) have pointed out that the improvement of water age has spatial heterogeneity and the hydrodynamic processes in some areas of the lake can be accelerated preferentially. Despite an increasing implementation of water diversion projects, (e.g., the dilution of Lake Chaohu, China by the Yangzte River (Xie et al., 2009), dilution of water to eutrophic Lake Barato, Japan (Shinohara et al., 2008), Lake Laguna Alalay water transfer in Bolivia (Ayala et al., 2007), and the Qiantang River water transfer to Lake West, China (Jin et al., 2015), the responses in water quality by those bodies that receive water from diversions are still hotly debated. Some studies have shown that water quality can be improved effectively by water diversion (Amano et al., 2010; Hudak, 2011). The positive relationships of Chl$a$ and TP to water retention time (τ_w) can be deduced simply from the early steady-state phosphous budget model, such as $TP = \frac{L}{z\left(\frac{1}{\tau_w+\sigma}\right)}$, $TP = \frac{L(1-R)\tau_w}{z}$, and $\mathrm{Chl}a = 1866\left(\frac{L}{\frac{z}{\tau_w}+12.4}\right)^{1.449}$, where L is the areal phosphorus load, z is mean depth, σ is phosphorus decay rate, and R is the percentage of phosphorus that is intercepted in lakes (Vollenweider, 1969; Dillon and Rigler, 1975; Chapra and Tarapchak, 1976). The derived equations demonstrate that the smaller the water retention time is, the lower will be the TP concentrations and algal biomass. Water exchange rate or water age are, therefore, often used as indicators to evaluate effectiveness of water diversion projects for the control of eutrophication (Li et al., 2013; Liu et al., 2014). However, some studies have argued that water diversion only has a minimal impact on water quality and algal blooms, and that it sometimes shows spatial differences (Lepono et al., 2003; Hu et al., 2008; Xie et al., 2011; Li et al., 2013).

In reality, the responses of water quality and aquatic ecosystems to water exchange are far more complicated than described by the phosphous budget model: (a) The diverted water nutrient loads can affect directly the water quality by mass conservation. Lake water quality can be diluted effectively if TN and TP concentrations of the diverted inflow are lower than the recipient lake, otherwise, it will be polluted further; (b) The diverted water volume can shorten the renewal time of lake water and accelerate the flushing of nutrients out of the lake; (c) The quickened water exchange can disturb the water-sediment interface, which can cause the resuspension of particulate phosphorus and nitrogen and an increase in sediment release fluxes of dissolved phosphorus and nitrogen. The rising nutrient concentrations can further contribute to the growth of algae; (d) The accelerated flushing rate can impact floating algae and the increased suspended solids (SS) can impair the available light for algal photosynthesis; (e) In addition, the hydrodynamic response to water diversion can be influenced by topographic, boundary, and wind conditions, which further generate spatial differences in water quality. It is, therefore, necessary to explore the influence of water diversion on hydrodynamics and water quality, as well as the relationship of water exchange (expressed as water age) with water quality (TN, TP and Chl$a$) for any water diversion project from a physical perspective.

In past decades, numerical water quality modeling has been developed most frequently to evaluate and to predict the effectiveness of eutrophication restoration measures and decision policies, e.g., the dynamic PCLOOS model (Janse et al., 1992), DELWAQ-BLOOM-SWITCH model (Van der Molen et al., 1994), EFDC model (Deleersnijder et al., 2001), DYRESM-CAEDYM model (Trolle et al., 2008) and WASP model (Yenilmez and Aksoy, 2013). Thus, a three-dimensional hydrodynamic and water quality model was applied in this study to quantify the influence of water diversion on water quality, because of the detailed description of its mechanism and cost-savings for engineering construction in real-world applications. Inflow water volumes and lake water level are two principal factors that affect the quality of lake water due to water diversion (Alexander et al., 2007; Xie et al., 2011; Liu et al., 2014; Li and Shen, 2015). Using various combinations of impact factors, water diversion scenarios were developed in our study after the verification and calibration of a water quality model to explore fully the responses of eutrophication to different water diversion alternatives.

For Lake Dianchi, one of the three major entrophic lakes that have been given priority by the Chinese Central Government, approximately 7.7 billion USD was invested during 1996–2015 for lake restoration. However, no significant improvement (e.g., TP of about 0.20 mg/L, TN of 2.20 mg/L, and Chl$a$ of 67.00 μg/L) has been observed after this significant financial investment and numerous project efforts. The Chinese State Council approved the transfer of clean water from the Deze Reservoir to Lake Dianchi through the Panlongjiang River in 2008. The Niulanjiang Water Diversion Project (NLJWDP) cost about 1.2 billion USD and it has been under normal operation since December 29, 2013. In our previous study (Liu et al., 2014), we proposed a three-dimensional hydrodynamic, nutrient fate and transport model, as well as an algae dynamics model, to analyze the effects of watershed nutrient loading, variations in diverted inflow water, and lake water level on water quality; the influence of water exchange on lake water quality hasn't yet to be analyzed. The remaining important questions that need to be answered include: (a) Can NLJWDP accelerate hydrodynamic and mass transport processes of Lake Dianchi? (b) For lakes with serious eutrophication, can increasing water exchange improve water quality accordingly? and (c) What are the best water diversion modes for improving water quality and aquatic ecosystems? Finally, we want to demonstrate the reliability of water age as an indicator for evaluating effectiveness of water diversion projects.

2. Materials and methodology

2.1. Study area

Lake Dianchi, a semi-closed plateau lake in China's Yunnan Province (latitude 24°28′–25°28′N, longitude 102°30′–103°00′E), has the surface area of approximately 306.3 km^2, mean depth of 5.0 m and watershed area of 2920 km^2 (Fig. 1). Its water source is supplemented mainly by urban drainage and rainfall runoff. It has a long water retention time (about 3.5 years) and poor capacity for water self-purification. Since the 1980s, Lake Dianchi has suffered a dramatic deterioration in water quality and severe eutrophication due to rapid socioeconomic growth and urban expansion in the watershed (Yang et al., 2010). To dilute nutrient concentrations (TN and TP) effectively and to try to achieve the target Chl$a$ concentration of 35 μg/L (Zou et al., 2011), 0.58 billion m^3 water has been transferred annually a distance of 116 km to Lake Dianchi