Diverse responses of hydrodynamics, nutrients and algal biomass to water diversion in a eutrophic shallow lake

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Abstract

Water diversion has been increasingly applied to accelerate lake water exchange and alleviate urgent water crisis. However, effects of water diversion on water exchange and water quality for eutrophic lakes remain controversial. In this study, a three-dimensional hydrodynamic-water quality-sediment diagenesis model has been developed to assess effects of water diversion on hydrodynamics and water quality in eutrophic shallow Lake Wanghu. Results suggested that water diversion could dramatically promote water exchange and reduce residence time in most lake regions but its influence on water quality was diverse. A water transferring flow rate of 20~30 m^3/s could reduce water age to 40~58 days during regular water diversion operation, whereas a high transferring flow rate of 100 m^3/s was the best for emergency operation in late spring before the wet season. Moreover, nutrients and *Chlorophyll*-a exhibited notable spatial heterogeneity in improvement efficiency. Nutrients level in the donating system was a prerequisite to the relationship among water transport time scales, nutrients, and algal biomass in this eutrophic lake. During a clean water diversion, nutrients and algal biomass were positively associated with water age. However, when the donating system contained high level of nutrients, accumulated nutrients in the lake may still trigger algal bloom after a temporary relief due to flushing effect. Therefore, these water diversion strategies could be applied to guide a sustainable management of eutrophic Lake Wanghu in terms of transferring flow rate, wind fields, water quality in the donating system, transferring operation, and water diversion route.

Keywords: Water diversion; Nutrients; EFDC; Water age; Lake management

1. Introduction

Water quality deterioration is a ubiquitous issue caused by inappropriate anthropogenic activities and climate changes in freshwater bodies (Ho et al., 2019; Sinha et al., 2017; Smith and Schindler, 2009). Currently, water diversion project has been increasingly applied to accelerate water exchange and mitigate urgent water crisis (Hu et al., 2008; Yu et al., 2018). Theoretically, this technique could shorten renewal time and push nutrients out of the lakes to abate water pollution. In fact, it has been successfully applied to contain algal bloom amid a short term in Lake Taihu and Lake Chaohu, China (Hu et al., 2010; Xie et al., 2009), Moses and Green lakes in Washinton, USA (Hilt et al., 2011; Welch, 1981), Lake Tega and Lake Barato in Japan (Amano et al., 2010; Shinohara et al., 2008), etc. Nevertheless, this application is still controversial because it may not address nutrients over-enrichment and water quality degradation in lakes in the long run and even some detrimental effects have been reported in previous case studies (Khorasani et al., 2018; Qin et al., 2019; Yao et al., 2018).

In general, the role of water diversion project in the improvement of water quality can be determined by multiple factors, such as quantity and quality of water sources, receiving water conditions, transferring routes, and operation regulations (Gao et al., 2018). Nutrients in the transferred water may be even higher than those in the receiving waterbodies, which is caused by their own sources of pollution and self-purification capacity. Despite the shortened residence time and enhanced water exchanging rate through water diversion, the extra nutrients will be another critical concern. Due to an increased nutrients loading of 5%~10%, the water diversion from Yangtze River failed to curb algal blooms in Lake Taihu (Qin et al., 2019). On the other hand, although high flushing rate may relieve the bloom issue in confined lake regions to some extent (Li et al., 2013; Liu et al., 2014; Zhai et al., 2010), the entire efficiency of water diversion in small lakes was found to be much higher than that in large size lakes with greater spatial heterogeneity (Hu et al., 2010; Zeng et al., 2015). Furthermore, except the most vigorous flushing condition, a short residence time in major lake regions could not sufficiently impede the algal bloom because the growth rate of cyanobacteria can be doubled just within one day under appropriate conditions.

In order to evaluate the impact of water diversion project on hydrodynamics and water quality of lakes, field monitoring and numerical modeling are the most commonly used methods. However, comparison of water quality before and after implementation of water diversion is restricted to confined regions and monitoring periods due to a huge demand of long-term monitoring data (Hu et al., 2010; Nong et al., 2020; Roy et al., 2016). Thus, numerical method could be a useful alternative to assess hydrodynamics and water quality responses to water diversion project in terms of comprehensive water quality models and transport time calculations (Vinçon-Leite and Casenave, 2019). Nonetheless, acquisition sufficient data is a prerequisite to parameterize, calibrate, and validate the water quality model for impact analyses of water diversion project (Zou et al., 2014). In addition, biochemical processes could also lead to uncertainties during simulations and predictions. As a consequence, transport time could be employed as a compromised option to estimate the water exchange process and further characterize the fate of pollutants and variability of phytoplankton biomass (Gao et al., 2018; Huang et al., 2016; Shen et al., 2013; Wan et al., 2013). In fact, short transport time theoretically reduces aggregation of algal biomass and nutrients retention, thereby inhibiting eutrophication (Bargu et al., 2019; Janssen et al., 2019; Paerl and Huisman, 2008; Schmadel et al., 2018). Transport time scale could be described using water age, residence time, and flushing time (Gómez et al., 2014; Viero and Defina, 2016). At present, it is imperative to figure out the inherent relationship between transport time and nutrients or phytoplankton biomass. Usually, transport time may induce different fluctuations in water quality and dynamics of phytoplankton in lakes. Water age demonstrated a similar spatial pattern with *Chlorophyll*-a (*Chl*-a) in Poyang Lake (Qi et al., 2016), while it had a strong positive relationship with total phosphorus (TP) but was insensitive to total nitrogen (TN) and *Chl*-a during in Lake Dianchi (Zhang et al., 2016). Given these controversial findings, water quality responses to water diversion should be comprehensively evaluated.

In this study, a 3-D hydrodynamic-water quality-sediment diagenesis model will be introduced to evaluate the impact of water diversion on hydrodynamics and water quality in a eutrophic shallow lake in the middle of Yangtze River Delta (Lake Wanghu). Multiple factors will be comprehensively considered in this model, including quantity and quality of water sources, receiving water conditions (e.g., lake topography, water quality, etc.), and operation regulations. Specifically, the main objectives of existing research are to (1) investigate the spatiotemporal distribution of water age resulting from water diversion project in Lake Wanghu; (2) elucidate spatial responses of N and P concentrations and algal biomass to water diversion based on the aforementioned model; and (3) figure out the intrinsic relationship between water exchange and eutrophication in this lake. This work would gain novel insights into the dynamic response of water exchange, nutrients and algae growth to water diversion, which could in turn benefit the sustainable management of water diversion in eutrophic shallow lakes.

2. Methods and materials

2.1 Study area

Lake Wanghu, located between 29°51′-29°54′ N and 115°20′-115°25′ E, belongs to a crucial wetland nature reserve in China (Fig. 1). It is a shallow lake with a surface area of 42.3 km^2 and a mean depth of 3.7 m. Lake Wanghu has been suffering from severe eutrophication issue, including P-enrichment and algal bloom. The main types of land use in the catchment include lakes, paddy field, forest land, swag, shrubland, dry land, etc. Lake

Wanghu has been suffering from severe eutrophication issue, including P-enrichment and algal bloom. Anthropogenic activities, such as agriculture operation, fish-farming, rural domestic sewage, etc., significantly contribute to water quality degradation of Lake Wanghu. Naturally high P background concentration in this watershed was another factor resulting in the fragile status of the lake (Zhu et al., 2019). Algal bloom in the lake usually occurred from June to August. During then, the average *Chl*-a concentration and algae density were around 45 μg/L and 4056 cell/mL, respectively. In 2018, the annual average TP and TN concentrations in Lake Wanghu were 0.27 and 0.88 mg/L according to monthly monitoring data, respectively. TP was nearly 4.2 times higher than the limit value (0.05 mg/L), while TN could meet the management requirement (1 mg/L) complying with administrative department of Lake Wanghu. Usually, higher nutrients concentrations were observed in wet season. In the long run, reduction of nutrients input is desired to mitigate eutrophication issue. Nonetheless, hydrodynamic flushing with water from nearby rivers has been regarded as a practical technique to physically flush nutrients and algae out of the lake for emergency cases. Thus, a short-distance water diversion has been designed to transfer water from River Fuhe to Lake Wanghu, and ultimately into the Yangtze River (Fig. 1). In order to obtain a holistic understanding on the impacts of water diversion on spatiotemporal variations of water age, nutrients, and *Chl*-a, Lake Wanghu was divided into five sub-areas (Zone I to V) according to its hydrological and ecological characteristics as shown in Fig. 1.

2.2 Model development

In this study, the impact of water diversion on hydrodynamics, water age, nutrient cycling, and biological processes in the lake was evaluated by three-dimensional (3-D) hydrodynamics-water quality-sediment diagenesis model (Fig. 2). Lake Wanghu Model was built up based on Environmental Fluid Dynamics Code (EFDC), which was initially developed by the United States Environmental Protection Agency and has been successfully applied to simulate the hydrodynamics, sediment transport, toxic contaminant transport, and water quality-eutrophication components in coastal regions, estuaries, lakes, reservoirs, rivers, and wetlands (Hamrick, 1992; Ji, 2008). The governing mass balance equation for each of the water quality state variables can be expressed as (Tetra Tech, 2007):

$$\begin{aligned}&\frac{\partial m_x m_y HC}{\partial t}+\frac{\partial (m_y HuC)}{\partial x}+\frac{\partial (m_x HvC)}{\partial y}+\frac{\partial (m_x m_y wC)}{\partial z}\\&=\frac{\partial}{\partial x}\left(\frac{m_y HA_x}{m_x}\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{m_x HA_y}{m_y}\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(m_x m_y \frac{A_z}{H}\frac{\partial C}{\partial z}\right)+m_x m_y HS_C\end{aligned}\qquad(1)$$

where C is concentration of a water quality state variable; u, v and w are velocity components in the curvilinear, sigma, x-, y- and z-directions, respectively; A_x, A_y and A_z are turbulent diffusivities in the x-, y- and z-directions, respectively; S_c is internal and external sources and sinks per unit volume; H is water column depth. m_x and m_y are horizontal curvilinear coordinate scale factors. In Eq. (1), the first term on the left-hand side represents the spatial and temporal dynamics of each state variable. The last three terms on the left-hand side account for the advective transport. The first three terms on the right-hand side account for the diffusive transport. The last term describes the kinetic processes and external loadings for each state variable.

In the Wanghu Model, 16 water column states variables were used to describe the algae dynamics and nutrients cycles. The modelling framework is shown in Fig. 2. *Chl*-a was used as an indirect measure of the overall algae population. The considered phytoplankton can be expressed as:

$$\left(\frac{\partial B}{\partial t}\right)=\left(P-BM-PR\right)B+\frac{\partial}{\partial H}\left(WS\cdot B\right)+\frac{WB}{V}\qquad(2)$$

where B is algal biomass (g C m^{-3}); t is time (d); P is production rate (d^{-1}); BM is basal metabolism rate (d^{-1}); PR is predation rate (d^{-1}); Z is water depth (m); WS is positive settling velocity (m d^{-1}); WB is external loadings (g C d^{-1}); V is cell volume (m^3).

Sediment nutrient fluxes across the sediment-water interface were simulated using a sediment diagenesis module which was internally coupled with water quality module. The module consists three basic processes, including depositional flux of particulate organic matter, their diagenesis and the resulting sediment flux. The governing equations in the sediment diagenesis model are detailed described in Park et al. (1995).

The concept of water age was used to describe the spatiotemporal hydrodynamic impact of the water transfer process in this study. Water age is defined as “the time that has elapsed since the particle under consideration left the region in which its age is prescribed as being zero” (Delhez et al., 1999; Shen and Wang, 2007). It is calculated as follows.

$$\frac{\partial c(t,\vec{x})}{\partial t}+\nabla\left(uc(t,\vec{x})-K\nabla c(t,\vec{x})\right)=0 \tag{3}$$

$$\frac{\partial \alpha(t,\vec{x})}{\partial t}+\nabla\left(u\alpha(t,\vec{x})-K\nabla \alpha(t,\vec{x})\right)=c(t,\vec{x}) \tag{4}$$

where c is the tracer concentration; α is the age concentration; u is the velocity field; K is the diffusivity tensor; t is time; $\vec{x}$ is coordinate. The mean water age “a” then can be calculated as follows:

$$a(t,\vec{x})=\frac{\alpha(t,\vec{x})}{c(t,\vec{x})} \tag{5}$$

Lake Wanghu Model consisted rectangular grids with 3,878 active cells with a uniform cell size 100 m in both x and y directions. Three evenly distributed sigma layers were adopted in the vertical dimension. The bottom topography data were measured and interpolated into the model grids. The model was driven by atmospheric forcing, tributary inflow/outflow, and interaction with sediment flux. The flow rate and water quality data of 11 primary rivers including water temperature (WT), dissolved oxygen (DO), TP, phosphate (PO_4^{3-}), TN, ammonia (NH_4^{+}), chemical oxygen demand (COD), and *Chl*-a were monthly monitored from November 2018 to July 2019 as the model flow boundary inputs (Fig. 1). Water samples were manually collected at 50 cm below the surface water. WT and DO were measured in situ by YSI. Other water quality concentrations were analyzed in the laboratory (Tang et al., 2020). TP and TN concentrations in unfiltered water were determined by spectrophotometry after digestion with alkaline potassium persulfate. PO_4^{3-} and NH_4^+ concentrations were analyzed by spectrophotometric method and Nessler's reagent colorimetric method after filtered. COD was analyzed by the standard dichromate method. *Chl*-a concentrations were determined by spectrophotometry at wavelengths of 665 nm and 750 nm, following extraction with hot 90% ethanol. The daily meteorological data including atmospheric pressure, surface air temperature, relative humidity, precipitation, evaporation, solar radiation, and fractional cloud cover were sourced from the weather station near the lake. The 10 water quality monitoring sites shown in Fig. 1 was used for model calibration.

2.3 Scenario definitions

Transferred water quantity and quality in the donating system (River Fuhe), wind field, and operation timing are considered as crucial factors affecting the efficiency of water diversion. In Table 1, seven scenarios based on the combinations of these factors were defined to investigate the response of water exchange, N and P concentration, and algal biomass to water diversion in Lake Wanghu. More specifically, Scenario 1 was in the absence of water diversion and used as the baseline case for reference. Water diversion included two operation rules, i.e., regular and emergency water diversion. Fresh water was transferred with a relatively low flow rate throughout the year in regular cases (Scenarios 2-5), while large quantity fresh water was transferred within a short period under emergency cases (Scenarios 6 and 7). Under regular cases, Scenarios 2 and 3 were applied to examine the effect of transferring flow rate (i.e., 5 to 100 m^3/s) and various wind fields on hydrodynamics, respectively. In addition, two different water quality conditions in the donating system have been investigated in Scenarios 4 and 5, which corresponded to monitoring data (average concentration of TP 0.077 mg/L, and TN 1.63 mg/L) and administrative standard suggested by the local government (TP 0.2 mg/L and TN 1 mg/L). In emergency cases, Scenario 6 aimed to determine the role of flowrate and transferring period in hydrodynamics, whereas Scenario 7 was applied to elucidate the influence of water quality in the donating system on water quality in Lake Wanghu. The model configurations and parameters, excluding driving factors shown in Table 1, were identical for all cases as aforementioned.

The improvement percentages of water exchange η (WA) and water quality η (WQ) caused by different water diversion scenarios are calculated as follows.

$$\eta\left(WA\right)=\frac{\left(WA_1-WA_i\right)}{WA_1}\times 100\% \tag{6}$$

$$\eta\left(WQ\right)=\frac{\left(WQ_i-WQ_1\right)}{WQ_1}\times 100\% \tag{7}$$

where WA_1 and WA_i is the water age (day) for the baseline Scenario 1 and water diversion Scenarios 2-7 in Table 1, respectively; WQ_1 and WQ_i is the concentrations of water quality variables (mg/L) for the baseline Scenario 1 and water diversion Scenarios 2-7, respectively.

3. Results and discussion

3.1 Model performance

This study performed multi-sites (10 sites in Fig. 1) and multi-variables (i.e., water depth (WD), WT, DO, TP, TN, NH_4^+, COD and *Chl*-a) calibration for the Lake Wanghu Model. The parameters were calibrated by trial-and-error method to make the modelling results best match the observed data. The key calibrated parameters for Lake Wanghu Model are listed in Table S1. Results showed that the model had an acceptable performance to reproduce the changes of hydrodynamics and water quality. Statistical results of model calibration at 10 monitoring sites are summarized in Table 2 and the comparison of time series between simulated and observed data for site #5 in the central lake is depicted in Fig. 3.

The hydrodynamic module exhibited good agreement between the simulated and observed water depth with an averaged relative error (RE) and absolute error (AE) of 11.25% and 0.27 m, respectively. This indicated the module reproduced a good water balance related to inflow/outflow, precipitation, and evaporation. Besides, water temperature accurately followed the spatiotemporal trend of observed data with an averaged RE of 9.58%, suggesting that the model had reached a reasonable representation of thermal dynamic processes and provided a basis for verifying water quality dynamic processes. Different from the changing trend of water temperature, the module demonstrated a lower DO concentration in summer with the RE of DO concentration ranging from 16.61% to 26.93%. Despite some missing peak points, various spatial distributions of RE values for nutrient concentrations in Table 2 also depicted acceptable mean RE for TP, TN, NH_4^+ and COD of 33.16%, 28.20%, 26.64%, and 18.01%, respectively. Although algal concentration in spring-summer was slightly overestimated, the model could capture the spatial heterogeneity and seasonal changes with RE for *Ch*l-a varying from 20.81% to 55.36%. Overall, Lake Wanghu model could be applied for further analyses of water diversion scenarios.

3.2 Improvement of water exchange through water diversion

Water exchange characteristics could be described by spatiotemporal changes of water age (Li et al., 2011). In the baseline Scenario 1, the initial average water age in Lake Wanghu was 141 days but it may exhibit spatial heterogeneity resulting from tributary locations, flow rates and wind fields. The influence of water diversion on water exchange was comprehensively assessed in terms of various transferred flow rates (Scenario 2), operation durations (Scenario 6), and wind field conditions (Scenario 3).

In Scenario 2, eight flow rates ranging from 5 to 100 m^3/s were designed to investigate the relationship between water exchange and transferring flow rate. Fig. 4 demonstrates spatial distribution of water age under different transferring flow rates. As the transferring flow rate was increased from 5 to 50 m^3/s, water age decreased from 153 to 25 days, implying that water exchange could be enhanced through water diversion. Transferring water footprint was gradually diffused from Zone IV to other subzones, leading to heterogeneous spatial distribution of water age. Specifically, water division could promote water exchange in Zone IV near the inlet, but had limited effect on water movement in bays (Zone I and II) which were away from the diversion route. In fact, due to lake size and complex shoreline, many previous studies have also found that the improvement of water exchange may not involve the entire lake during the water diversion (Huang et al., 2016; Qi et al., 2016). Furthermore, Fig. 5a depicts the detailed relationship between water age and transferring flow rate using the function of $WA = 669.86Q^{-0.841}$ (R^2=0.9914). Initially, water age decreased dramatically with elevated transferring flow rate but tended to be stable after the flow rate reached 30 m^3/s. Hence, an economical water transferring flow rate of 20~30 m^3/s would be recommended to improve water exchange (water age of 40~58 days) when water diversion project is regularly operated.

Water diversion project has been widely deployed as an emergency technique to alleviate water pollution crisis. In Scenario 6, two high transferring flow rates (50 and 100 m^3/s) with various operation durations (1~30 days) were selected to determine their influences on water exchange in Lake Wanghu. Fig. 6 demonstrates the effective transferring areas under different transferring flow rates with varying water diversion durations. As shown in Fig. 6, when the operation duration was within 7 days, the effective exchange area corresponding to transferring flow rate of 100 m^3/s was almost two times larger than that under 50 m^3/s. When the operation duration of emergency diversion was extended to 30 days, the effective exchange area reached 81.91% and 90.31% for transferring flow rate of 50 and 100 m^3/s, respectively. In addition, half of the lake area could be effectively exchanged within 10 days under a transferring flow rate of 50 m^3/s, but it only took 5 days to achieve a similar area for transferring flow rate of 100 m^3/s. Hence, it could be concluded that a higher transferring flow rate may significantly improve water exchange in a short term but two different flow rates would ultimately achieve comparable effective exchange area with operation duration more than one week.

Wind field is another driving factor affecting water dynamics (Li et al., 2013), especially for the shallow lake. In Scenario 3, eight different wind directions under transferring flow rate of 30 m^3/s were designed to investigate the effect of wind field on waster exchange. Fig. 5b describes the spatial distribution of water age under different wind field conditions. In the whole lake, the minimum water age of 23 days was found the southwest wind condition, while the east wind could cause a water age high up to 58 days. Interestingly, water age in bay areas was more sensitive to the wind field than that in the open water areas. For instance, water age in Zone I (bay area) was 138 days under southeast wind but 39 days for west wind. However, water age in Zone IV (open water area) varied in the range of 15~45 days under all wind fields. Therefore, in order to improve water exchange, a southwest wind was suggested for the entire lake, while west and northwest wind fields may be beneficial for polluted bay areas.

3.3 Impact of water diversion on water quality

3.3.1 Impact of regular water diversion operation on water quality

Two different water quality conditions in the donating system have been applied to investigate the role of water diversion in the improvement of water quality. Actual monitoring data and administrative standard suggested by the local government were used in Scenario 4 and 5, respectively.

As compared with the baseline Scenario 1, average TN, TP and *Chl*-a in the whole lake after water diversion Scenario 4 was decreased by 3.7%, 10.35% and 5.99% to 1.44 mg/L, 0.094 mg/L and 26.38 μg/L, respectively. This implied that regular water diversion could improve lake water quality to some extent. Fig. 7 depicts comparative temporal patterns of nutrients and *Chl*-a in site #1 (bay area) and site #5 (central area) with and without water diversion. Particularly, water quality in site #1 had no direct and distinct response to water diversion. In contrast to the baseline scenario, TN, TP and *Chl*-a was only decreased by 1.35%, 0.22% and 0.89%, respectively. In site #5, however, the average TN, TP and *Chl*-a showed a notable decrease by 5.73%, 20.14% and 10.00% to 1.41 mg/L, 0.11 mg/L and 26.83 μg/L, respectively. This suggested that responses of nutrients and *Chl*-a were more sensitive to water diversion in central area than those in the bay area.

As water quality in source water is dynamically changing, water quality standard in River Fuhe suggested by government in Scenario 5 was also adopted to predict the influence of water diversion. After water diversion, average TN and *Chl*-a in the whole lake were decreased by 13.97% and 1.67% to 1.29 mg/L and 27.67 μg/L, respectively. Unfortunately, an average increase of 11.12% for TP implied the increasing deterioration of TP in the majority areas in the lake. Thus, more stringent TP in the donating system should be executed. In addition, the influence of water diversion presented spatial heterogeneity. Due to various water exchange ability and nutrients levels in the donating system (Fig. 7), response of nutrients concentrations in the central zone (Site #5) to water diversion was more sensitive than that in the bay area (Site #1). Higher reduction of TN was observed in Scenario 5, while distinct TP decreased was found in Scenario 4, which may be associated with different initial nutrients levels in the source water. Moreover, regardless of nutrients level in the inflow, nutrients and *Chl*-a showed negligible fluctuations in Site #1, revealing that regular water diversion operation could not improve water quality in the bay areas.

3.3.2 Impact of emergency water diversion operation on water quality

According to the long-term water quality monitoring data in Lake Wanghu, non-point source pollution during wet season (June to August) would result in poor water quality. In addition, water diversion project should avoid wet season to ensure the safety of flood control. Thus, in emergency operation of Scenario 7, a high flowrate of 100 m^3/s was used to flush the lake for seven days starting from early May. The water quality of source water was assumed to meet the standard proposed by the administrative department. Variations of water quality were evaluated after water diversion for seven days.

Although water diversion could reduce the average TN by 11.65% to 1.23 mg/L, average TP was increased by 54.21% to 0.17 mg/L. Obviously, this high TP concentration could not meet the desired water quality standard. Different from regular water diversion, both of water quality in the bay and central area could respond immediately to emergency water diversion (Fig. 8). Specifically, both of TP in Site #1 and #5 increased to a high level, which may be ascribed to high P concentration in the donating system and facilitated internal P release by intensive disturbance (Zhang et al., 2016). TN in Site #5 showed a distinct decrease of 32.85% but less reduction of 7.55% was found for TN in Site #1. In spite of apparent initial decrease, *Chl*-a in Site #5 returned back to normal level shortly. Actually, phytoplankton biomass was dramatically diluted by input water with low *Chl*-a and subsequently flushed out of the lake within a short water age effect (Wan et al., 2013; Welch et al., 1972). Nonetheless, high phosphorus after the water diversion could lead to accumulated phytoplankton biomass rapidly. Hence, under emergency water diversion, fluctuations of nutrients primarily resulted from water quality and quantity in the donating system and intensive release from sediments, whereas short time flushing effect was responsible for *Chl*-a.

3.4 Relationship between water exchange and water quality

Fig. 9 compares the improvement efficiency of water exchange and water quality variables in different regions of Lake Wanghu under regular water diversion Scenario 4 and 5. On the whole, improvement efficiency of water exchange was not in proportion to those of nutrients and *Chl*-a with notable spatial heterogeneity in both scenarios. Specifically, the average improvement efficiency of 53.89% for water age in the entire lake was significantly higher than that of TP (10.34% and -11.12% in Scenario 4 and 5, respectively), TN (3.70% and 13.97% in Scenario 4 and 5, respectively) and *Chl*-a (5.99% and 1.67% in Scenario 4 and 5, respectively). This revealed the more remarkable improvement of hydrodynamic process was induced by water diversion as compared with that for various water quality variables. Both water exchange and water quality were slightly improved in the bay area. As compared with Scenario 1, water age in Zone I and II for Scenario 4 and 5 was decreased by 14.79% and 19.90% to 123 and 104 days, respectively. TN concentration was decreased by 1.13~7.83%, however, higher phosphorus input from the source water had negligible improvement for the average TP in bay area. Extended water residence time and high nutrients levels resulted in less than 1.21% reduction of *Chl*-a concentration in the bay area. Interestingly, water age in Zone IV and V was decreased by 73.07% and 65.32% to 38 and 57 days, respectively. TN, TP and *Chl*-a were decreased by 24.88%, 4.06% and 11.21% in Zone IV for Scenario 4. These high improvement efficiencies for hydrodynamics and water quality in Zone IV and V may be related to their locations which were close to inlet and outlet of water transfer route, respectively.

Previously, it is well known that long water age could facilitate the eutrophication process through improved nutrients uptake, transformation, and sink (Bargu et al., 2019), and promote the growth and accumulation of algal biomass (Paerl and Huisman, 2008). Nonetheless, improvement efficiency of nutrients and *Chl*-a after water diversion can be influenced by characteristics of donating water system (e.g., nutrients level), receiving water system (e.g., hydrodynamics, lake topography and nutrients level), and water diversion operation (e.g., transferring flow rate, timing, and duration). Interactions between physicochemical and biological processes will determine variations of nutrients and phytoplankton biomass at different spatial and temporal scales. Thus, it is inadequate to speculate variation of algal biomass based on renewal timescale alone in eutrophic lakes.

In fact, diverse relationships (e.g., positive, insensitive, non-monotonic or spatiotemporal variable) may exist among water transport time scales, nutrients, and algal biomass in various water systems (Bargu et al., 2019; Lucas et al., 2009). Phytoplankton biomass accumulation and productivity rates were probably correlated with the water residence time in a wet-dry tropical estuary (Burford et al., 2012). After a three-year study of water residence time and cyanobacteria dynamics in a shallow lake (Lake Albufera, East Spain), algal biomass was stimulated by 1-2 orders of magnitude with an increased water residence time of 45% and thus flushing was recommended to minimize toxic cyanobacterial blooms (Romo et al., 2013). Furthermore, since *Chl*-a was found to achieve a maximal value when flushing time was approximately four days in eutrophic New River Estuary, this non-monotonic response of phytoplankton biomass to flushing time reflected a balance between nutrient stimulation of phytoplankton biomass and advective losses associated with inflow (Hall et al., 2013). Asynchronous response was also found between response variables (N retention rate) and explanatory variables (water residence time and *Chl*-a) in Königshütte Reservoir, a highly flushed system (Kong et al., 2019). Lucas et al. (2009) ascribed fuzzy relationship between transport time and algal biomass to phytoplankton growth-loss balance using a simplified concept model in a steady-state system. Thus, the various limiting factors of algal growth (e.g., nutrients and hydrodynamics) could be responsible for these diverse relationships in different aquatic systems. In this study, the nutrients level in the donating system was a prerequisite to the relationship among water transport time scales, nutrients, and algal biomass in the eutrophic lake. Albeit disproportionate changing rates, nutrients and algal biomass were positively related with water age during clean water diversion. In contrast, when the donating system was under the condition of high nutrients, nutrients in the lake further accumulate and algal bloom would revive after temporary relief owing to flushing effect.

3.5 Implication for water diversion management in eutrophic lake

In order to achieve sustainable management of the lake, reduction of external and internal nutrients loadings is an essential prerequisite (Huang et al., 2019; Khorasani et al., 2018). Appropriate manipulation of water diversion should be employed to mediate hydrodynamic process and water quality in certain lake regions to some extent. Although water diversion project could remarkably enhance water exchange and shorten retention time in most lake regions, its influence on water quality may be ambiguous because of covariation of different driving factors. Therefore, some crucial strategies for water diversion of Lake Wanghu have been proposed in terms of hydrodynamics and water quality as follows.

(1) Optimal transferring flow rate and wind condition

Transferring flow rate and wind condition during water diversion could physically accelerate water exchange, thereby disturbing the biochemical process. Under regular operation in Lake Wanghu, water age followed a power function of the transferring flow rate with optimal water transferring flow rate ranging from 20 to 30 m^3/s. Regarding emergency operation, larger transferring flow rate of 100 m^3/s could provide more satisfactory results in short-term operation of about seven days. Besides, southwest wind was a relatively suitable condition for the entire lake, whereas west and northwest benefited highly polluted bay areas.

(2) Prerequisites for water quality in the donating system

In Scenario 5, it has been found that higher nutrients levels in the transferring water can pose threat to water quality in receiving water system, which was in good agreement with previous studies (Davies et al., 1992; Zeng et al., 2015). Moreover, in Lake Taihu water diversion project, Qin et al. (2019) also reported that water diverted from the nearby nutrient-enriched Yangtze River actually led to increased nutrient loadings to Taihu by 5%-10%. So they concluded that some detrimental effects would still exist, e.g., nutrient-enrichment and cyanobacteria bloom in the receiving water system. Hence, it is necessary to assess the potential impacts of water diversion project on the eutrophication of the receiving system, especially for eutrophic lakes. Relatively low nutrients concentration in the donating system is a prerequisite for water diversion. The critical nutrients level shall be proposed earlier before water diversion implementation. In water diversion project of Lake Wanghu, TP in the source water shall keep a lower concentration or at least keep the current status, instead of merely meeting the standard required by the administration department. Eventually, more stringent P monitoring and management in River Fuhe should be carried out to ensure the effectiveness of water diversion, especially for emergency operation with a large amount of inflows.

(3) Transferring operation options (timing and duration)

Under regular water diversion operation, a constant low inflow rate around 20 to 30 m^3/s was advised to accelerate water exchange in most regions of the lake. However, late spring before the wet season was a more ideal time to perform emergency operation and a high transferring flow rate of 100 m^3/s could be helpful to prevent algal bloom.

(4) Deployment of a reliable water diversion route

Due to different lake shape or topography (Schmadel et al., 2018) and water diversion routes (Li et al., 2011), it is very common to observe spatial heterogeneity of water exchange and water quality improvement during water diversion. Usually, a reliable water diversion route shall be carefully deployed before water diversion. Transferring routes with multiple inlets were adopted to improve the water diversion performance in Lake Taihu and Lake Poyang (Li et al., 2013; Qi et al., 2016). Nevertheless, because of very limited water sources near the basin in this study, existing water diversion route with sole inlet can only improve the water exchange and water quality in some lake regions adjacent to water transfer route, excluding the heavily polluted bay areas. Therefore, apart from water diversion, reinforced interconnection with other nearby lakes with desirable water quality may be a supplementary measure.

4. Conclusions

A reliable 3-D hydrodynamic-water quality-sediment diagenesis model was developed to evaluate influences of water diversion on hydrodynamics and water quality in eutrophic shallow Lake Wanghu. This water diversion project could remarkably enhance water exchange and shorten residence time in most lake regions, yet its influence on water quality could be diverse because of covariation of different driving factors. In the regular water diversion operation, a water transferring flow rate of 20~30 m^3/s was recommended to enhance water exchange. However, in a short-term emergency operation, a high transferring flow rate of 100 m^3/s was proved to be the best option to mitigate algal bloom in late spring before the wet season. Although southwest wind significantly facilitated water exchange in the entire lake, west and northwest wind fields were only beneficial for heavily polluted bay areas. Furthermore, nutrients and *Chl*-a exhibited notable spatial heterogeneity in improvement efficiency. During a clean water diversion, nutrients and algal biomass were positively associated with water age. Nevertheless, accumulated nutrients in the lake may trigger algal bloom after a temporary relief due to flushing effect under a circumstance of high nutrients level in the donating system. More importantly, P concentration in the source water shall be lower than existing administrative level. Therefore, these fundamental strategies for water diversion could shed lights on sustainable management of eutrophic Lake Wanghu.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table 1 Water diversion scenarios.

Scenario groups		Transferred flowrate (m^3/s)	Transferred duration (days)	Transferred water quality	Wind field
1	No water transfer	/	/	Monitoring data	Monitoring data
2	Regular water transfer	5, 10, 20, 30, 40, 50, 80, 100	365	/	/
3		30	365	/	2 m/s, eight wind directions
4		20	365	Actual monitoring data	Monitoring data
5		20	365	Government management criterion	Monitoring data
6	Emergency water transfer	50, 100	1~30	/	/
7		100	7	Government management criterion	Monitoring data

Notes:

Water quality in River Fuhe (donating water system) includes two types, i.e., monitoring data (averaged concentration of TP 0.077 mg/L, and TN 1.63 mg/L) and meet the local government management criterion (TP 0.20 mg/L, and TN 1.00 mg/L).

Table 2. Error statistical analysis of multi-sites and multi-variables calibration.

Lake Region	Station ID	WD		WT		DO		TP		TN		NH_4^+		COD		*Chl*-a	
		MAE (m)	RE (%)	MAE (°C)	RE (%)	MAE (mg/L)	RE (%)	MAE (mg/L)	RE (%)	MAE (mg/L)	RE (%)	MAE (mg/L)	RE (%)	MAE (mg/L)	RE (%)	MAE (µg/L)	RE (%)
Zone I	#1	0.22	11.91	1.76	9.32	1.75	16.61	0.08	30.84	0.43	28.15	0.14	31.43	2.28	11.21	5.49	24.43
	#2	0.22	8.72	0.89	5.54	1.44	19.33	0.07	33.60	0.34	27.48	0.10	25.64	2.46	9.05	8.81	30.82
Zone II	#6	0.21	10.14	2.64	15.92	1.98	23.25	0.08	36.45	0.39	32.79	0.10	25.56	5.49	21.43	7.67	27.54
Zone III	#3	0.36	12.71	1.53	6.03	1.97	24.13	0.05	42.12	0.26	17.54	0.08	17.62	5.29	21.36	10.66	34.25
Zone IV	#4	0.23	8.32	1.54	6.33	1.87	22.93	0.03	23.34	0.37	30.63	0.11	23.62	4.77	18.36	8.35	24.18
	#5	0.27	10.14	1.49	7.89	1.43	19.90	0.05	30.78	0.32	30.27	0.17	38.10	3.49	24.93	21.45	55.36
Zone V	#7	0.34	14.15	1.89	10.92	2.17	25.36	0.03	29.55	0.31	36.75	0.15	38.94	3.92	21.59	8.84	44.16
	#8	0.31	10.65	2.00	15.13	1.70	23.18	0.29	29.89	0.36	38.78	0.25	21.82	2.57	13.05	9.23	32.45
	#9	0.17	8.67	1.73	8.61	2.39	26.93	0.07	39.27	0.17	16.55	0.13	29.81	4.46	23.73	9.05	28.14
	#10	0.38	17.11	1.91	10.14	1.69	21.79	0.07	35.79	0.21	23.06	0.05	13.85	3.31	15.43	3.58	20.81

Notes:

Mean Absolute Error (MAE) is calculated as $MAE = \frac{\sum_{i=1}^{N}\left|O_i - X_i\right|}{N}$.

Relative Error (RE) is calculated as $RE = \frac{\sum_{i=1}^{N}\left|O_i - X_i\right|}{\sum_{i=1}^{N} O_i} \times 100\%$.

O_i and X_i means observed and Simulated data, respectively.

Figure captions

Fig. 1. Study area and water diversion route.

Fig. 2. Modelling framework of water transfer in Lake Wanghu.

Fig. 3. Comparisons of simulated and observed data for multi-variables at site #5 from Nov 1, 2018 to Jul 31, 2019.

Fig. 4. WA distribution caused by different transferring flow rate.

Fig. 5. Impact of transferring flow rate (a) and wind field (b) on water age.

Fig. 6. Effective exchange areas along with time (a) transferring flow rate=50 m^3/s; (b) transferred flow rate=100 m^3/s.

Fig. 7. Impact on water quality in the bay area (Site #1) and central area (Site #5) through regular water diversion operation, respectively.

Fig. 8. Impact on water quality in the bay area (Site #1) and central area (Site #5) through emergency water diversion operation, respectively.

Fig. 9. Improvement efficiency of water exchange and water quality variables through regular water diversion operations. (a) Water diversion Scenario 4; (b) Water diversion Scenario 5.

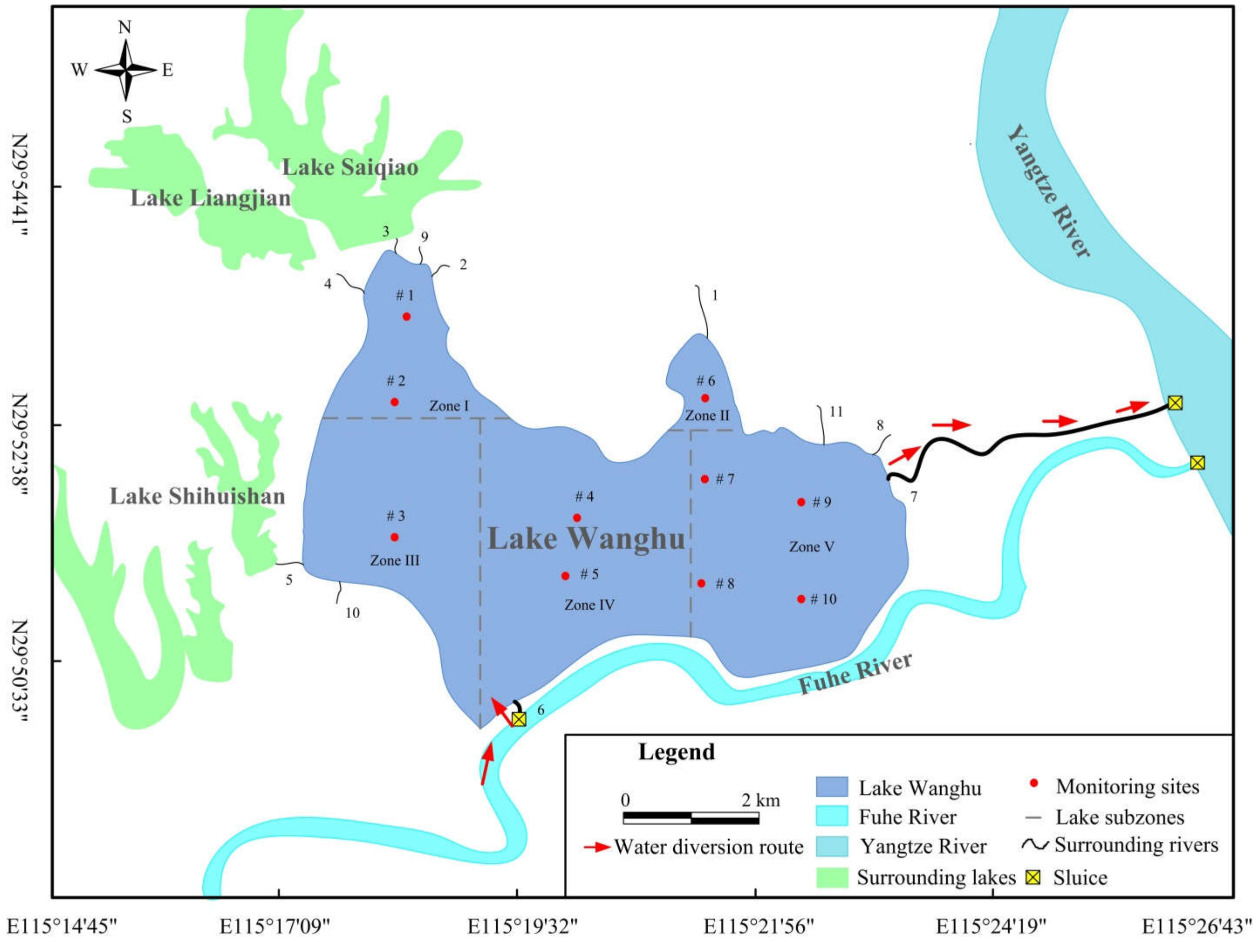
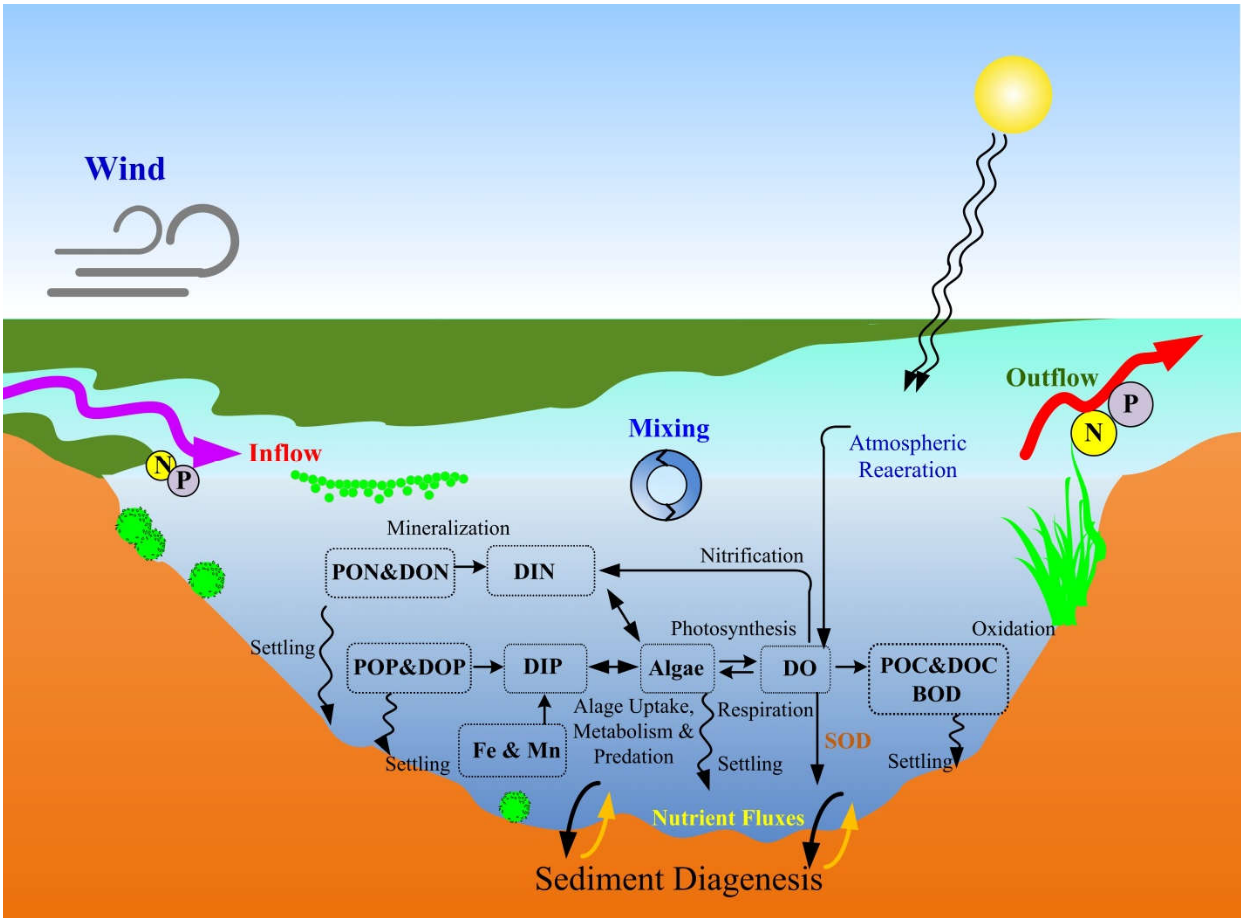

N
W
E
S
Lake Saiqiao
Lake Liangjian
Lake Shihuishan
Lake Wanghu
Yangtze River
Fuhe River
Zone I
Zone II
Zone III
Zone IV
Zone V
1
2
3
4
5
6
7
8
9
10
1
2
3
4
5
6
7
8
9
10
11
N29°54'41"
N29°52'38"
N29°50'33"
E115°14'45"
E115°17'09"
E115°19'32"
E115°21'56"
E115°24'19"
E115°26'43"
Legend
0
2 km
Water diversion route
Lake Wanghu
Fuhe River
Yangtze River
Surrounding lakes
Monitoring sites
Lake subzones
Surrounding rivers
Sluice

Fig. 1.

636 
Wind
Inflow
N
P
Mixing
Atmospheric Reaeration
Outflow
P
N
Mineralization
PON&DON
DIN
Nitrification
Settling
POP&DOP
DIP
Algae
DO
POC&DOC BOD
Photosynthesis
Oxidation
Alage Uptake, Metabolism & Predation
Respiration
SOD
Fe & Mn
Settling
Settling
Settling
Nutrient Fluxes
Sediment Diagenesis

637 Fig. 2.

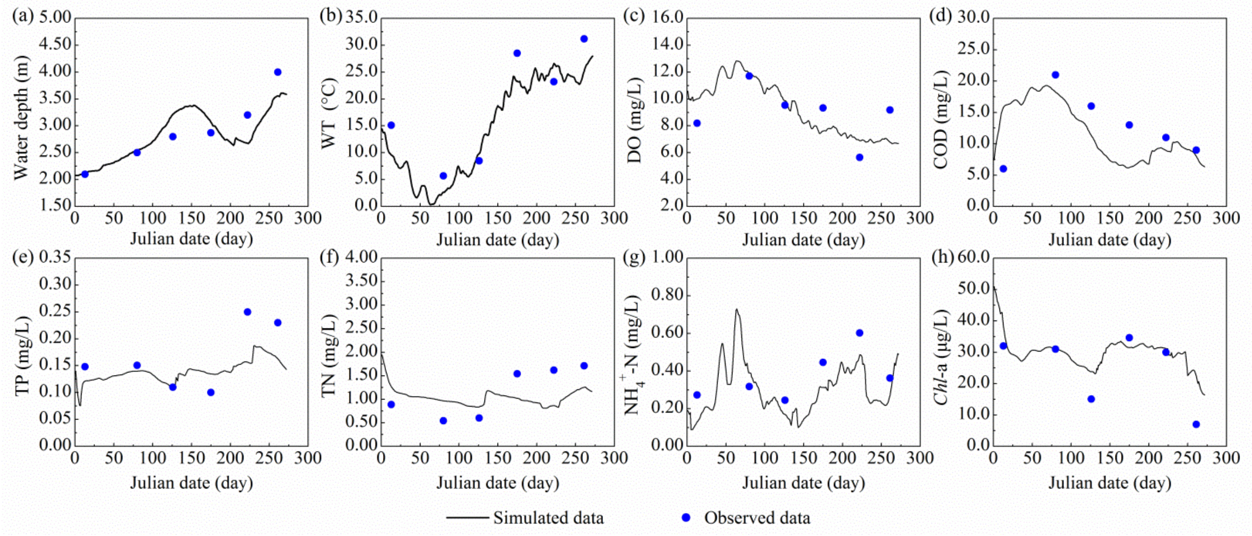

(a)
Water depth (m)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
(b)
WT (°C)
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
(c)
DO (mg/L)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
(d)
COD (mg/L)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
(e)
TP (mg/L)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
(f)
TN (mg/L)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
(g)
NH4+-N (mg/L)
1.00
0.80
0.60
0.40
0.20
0.00
(h)
Chl-a (μg/L)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0
50
100
150
200
250
300
Julian date (day)
Simulated data
Observed data

Fig. 3.

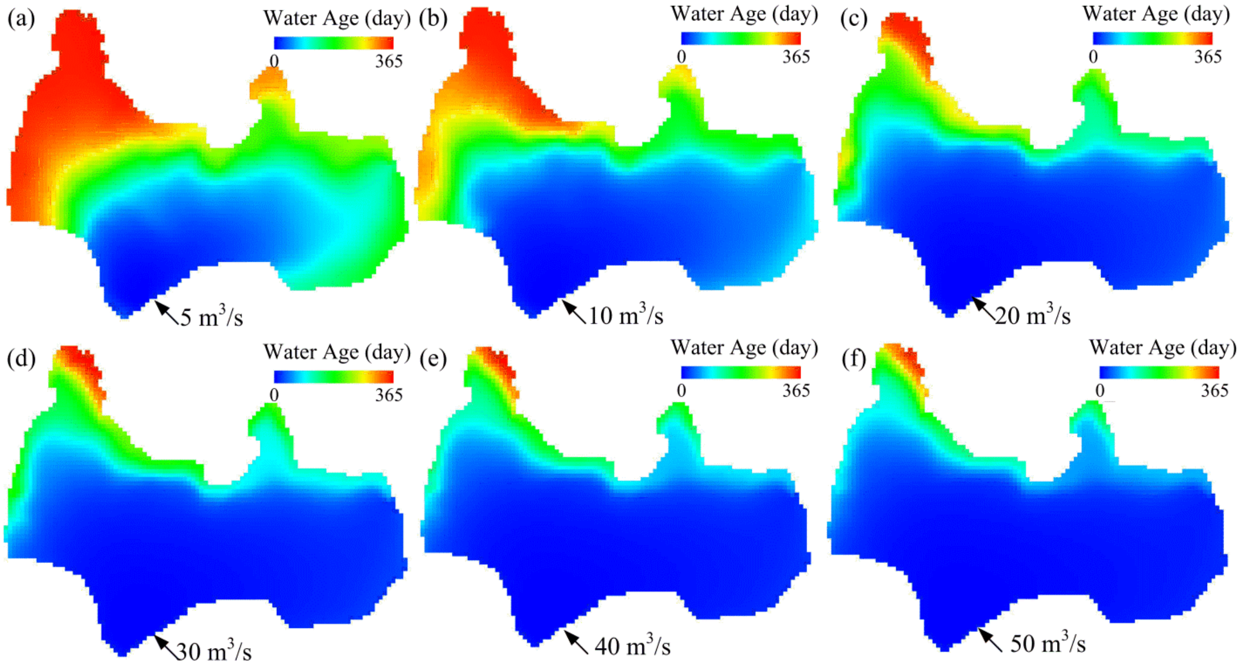

(a)
Water Age (day)
0
365
5 m^3/s
(b)
Water Age (day)
0
365
10 m^3/s
(c)
Water Age (day)
0
365
20 m^3/s
(d)
Water Age (day)
0
365
30 m^3/s
(e)
Water Age (day)
0
365
40 m^3/s
(f)
Water Age (day)
0
365
50 m^3/s

Fig. 4.

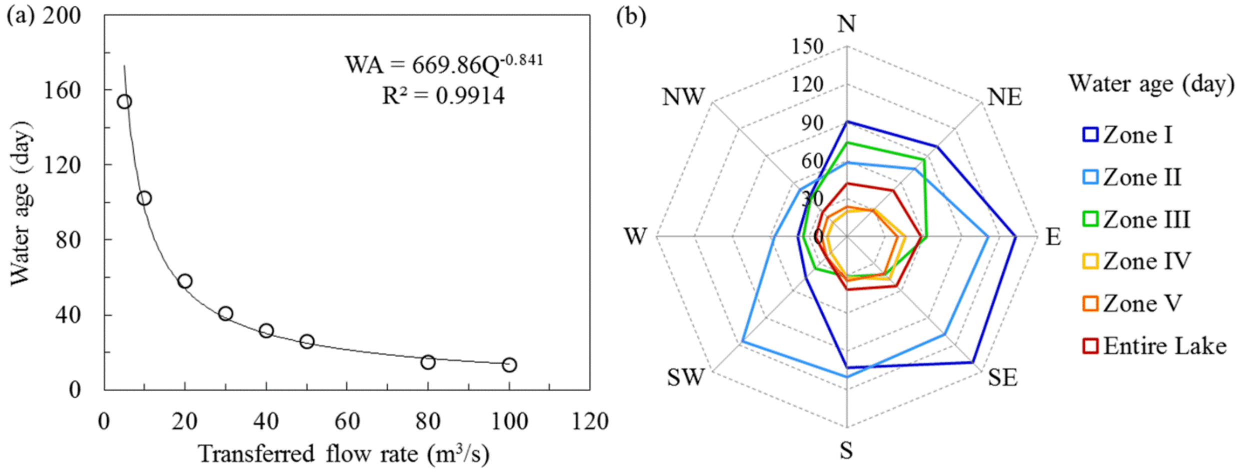

(a)
WA = 669.86Q^-0.841
R² = 0.9914
Water age (day)
Transferred flow rate (m³/s)
0
40
80
120
160
200
0
20
40
60
80
100
120
(b)
N
NE
E
SE
S
SW
W
NW
0
30
60
90
120
150
Water age (day)
Zone I
Zone II
Zone III
Zone IV
Zone V
Entire Lake

Fig. 5.

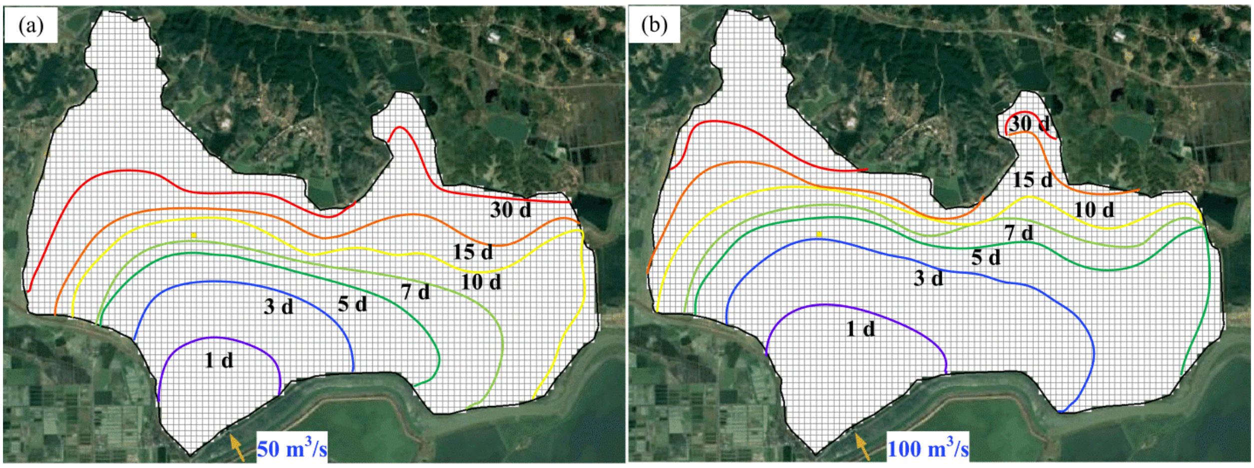


Fig. 6.

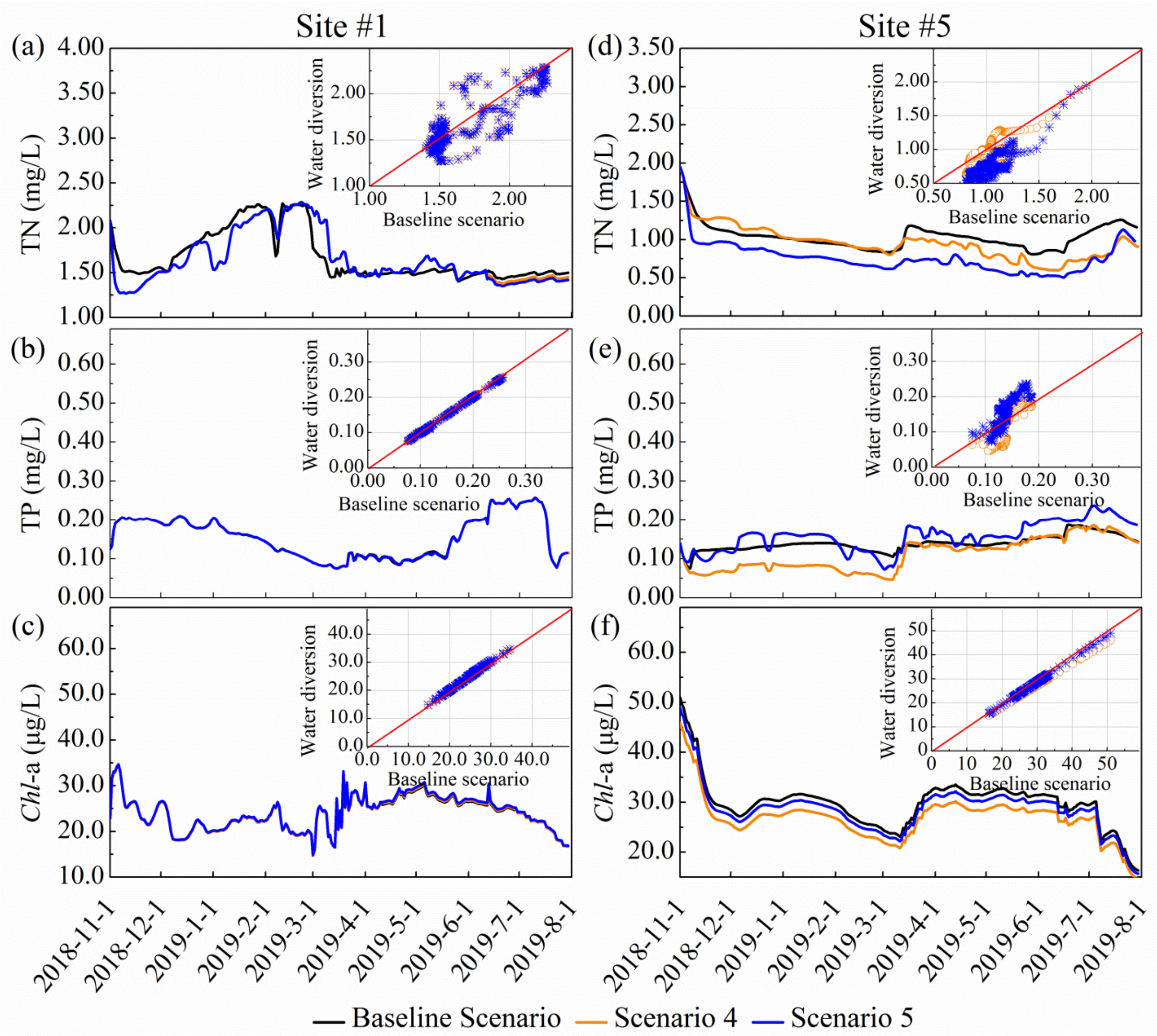

Site #1
Site #5
(a)
(b)
(c)
(d)
(e)
(f)
TN (mg/L)
TP (mg/L)
Chl-a (μg/L)
Water diversion
Baseline scenario
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.60
0.50
0.40
0.30
0.20
0.10
0.00
60.0
50.0
40.0
30.0
20.0
10.0
0.0
50
40
30
20
10
0
2018-11-1
2018-12-1
2019-1-1
2019-2-1
2019-3-1
2019-4-1
2019-5-1
2019-6-1
2019-7-1
2019-8-1
Baseline Scenario
Scenario 4
Scenario 5

Fig. 7.

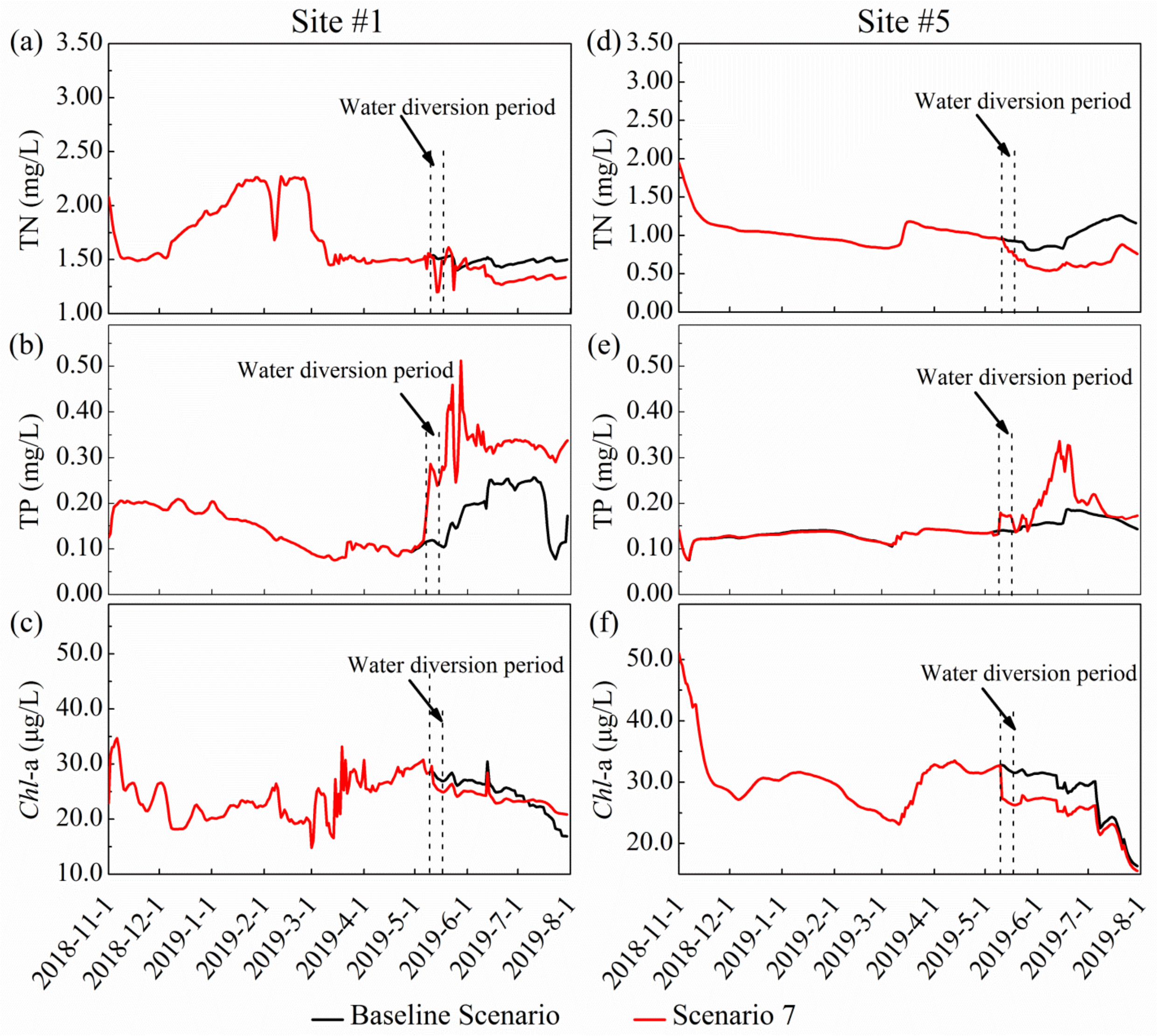

Site #1
Site #5
(a)
(b)
(c)
(d)
(e)
(f)
TN (mg/L)
TP (mg/L)
Chl-a (μg/L)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.40
0.30
0.20
0.10
50.0
40.0
30.0
20.0
10.0
Water diversion period
2018-11-1
2018-12-1
2019-1-1
2019-2-1
2019-3-1
2019-4-1
2019-5-1
2019-6-1
2019-7-1
2019-8-1
Baseline Scenario
Scenario 7

Fig. 8.

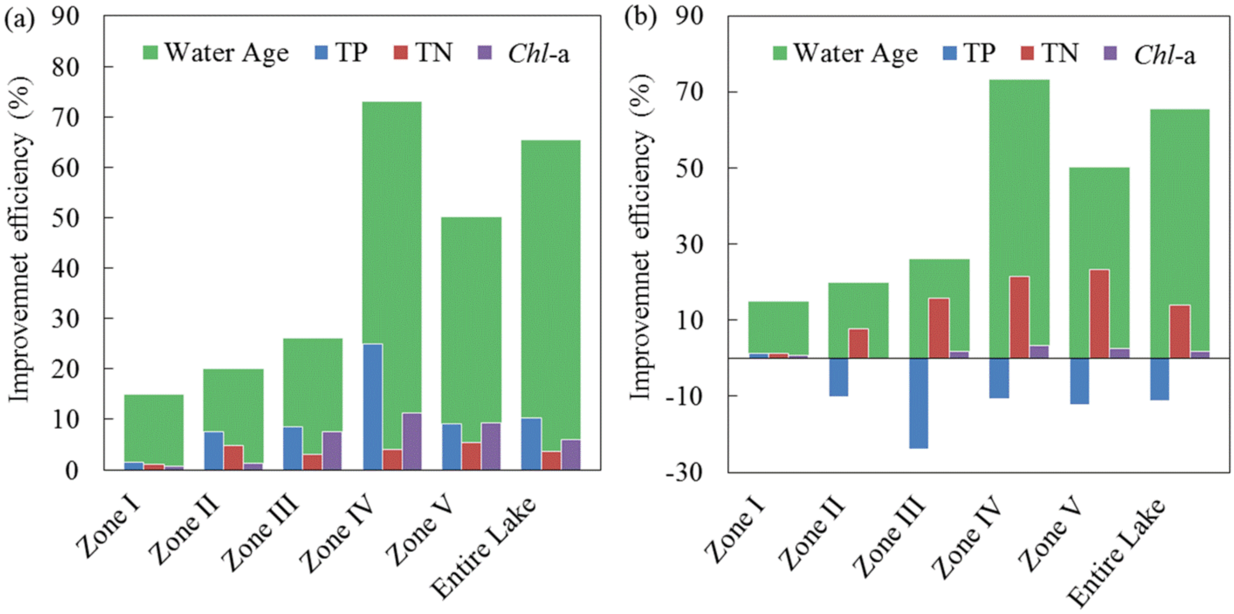

(a)
(b)
Water Age
TP
TN
Chl-a
Improvemnet efficiency (%)
90
80
70
60
50
40
30
20
10
0
90
70
50
30
10
-10
-30
Zone I
Zone II
Zone III
Zone IV
Zone V
Entire Lake

Fig. 9.