Modeling impacts of water transfers on alleviation of phytoplankton aggregation in Lake Taihu

Jiacong Huang, Junfeng Gao, Yinjun Zhang and Yan Xu

ABSTRACT

A water transfer project has been ongoing since 2002 to alleviate severe phytoplankton aggregation in Lake Taihu. This study aimed to quantify the effectiveness of the water transfer project on alleviation of phytoplankton aggregation in Lake Taihu on a short-term scale. In this study, a spatially distributed hydrodynamic-phytoplankton model was used to predict the short-term (3–4 days) changes in phytoplankton distribution (represented by chlorophyll *a*) in Lake Taihu. Four simulations with different water transfer strategies were carried out based on this model. During the water transfer period, phytoplankton aggregation was alleviated in some areas, suggesting that the water transfer project has the potential to alleviate algal blooms on a short-term scale. However, the effectiveness of the water transfer project on alleviating severe algal blooms was strongly affected by other environmental factors (e.g. wind conditions, chlorophyll *a* distribution, and the amount and quality of the transfer water). This study demonstrates the success of the hydrodynamic-phytoplankton model in evaluating the contribution of the water transfer project to alleviation of phytoplankton aggregation. These evaluation results could assist managers in decision-making before conducting a water transfer plan in Lake Taihu.

Key words | chlorophyll *a*, Lake Taihu, simulation, water transfers, Yangtze River

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INTRODUCTION

Lake Taihu, the third largest freshwater lake in China, has experienced severe algal blooms during the past decade (Guo 2007). To improve the water quality of Lake Taihu, a water transfer project (named WTYT) that transfers water from the Yangtze River to Lake Taihu, was begun in 2002. Water transfer projects have been widely recognized to have significant impacts on surrounding aquatic ecosystems (Verma *et al.* 2009; Zhang 2009; Fornarelli *et al.* 2013a).

To evaluate the impacts of water transfer projects on surrounding aquatic ecosystems, mechanistic and empirical models have generally been used (Moreno-Ostos *et al.* 2007; Fornarelli *et al.* 2013b). Empirical models, such as artificial neural networks (Maier *et al.* 2010), Bayesian networks (Borsuk *et al.* 2004), Markov chains (Dimberg *et al.* 2013), and tree-based models (Fornarelli *et al.* 2013b), allow us to predict highly nonlinear and complex relationships with little knowledge of their behaviors. As an alternative to empirical models, mechanistic models have the ability to describe dynamic processes explicitly (Moreno-Ostos *et al.* 2007). Although complex and computationally demanding, mechanistic models have been used increasingly as additional underlying processes of aquatic ecosystems are understood (Hu *et al.* 2010; Li *et al.* 2013).

Previous studies have investigated the potential impacts of the WTYT project on hydrodynamic conditions (Li *et al.* 2011; Hao *et al.* 2012), water quality (Hu *et al.* 2008, 2010; Li *et al.* 2013) and ecosystem status (Zhai *et al.* 2010) of Lake Taihu. These studies improved our understanding of the potential impacts of the WTYT project on the Lake Taihu ecosystem, and achieved the following findings: (1) the WTYT project has the potential to improve water exchanges in Lake Taihu based on hydrodynamic simulations with Environmental Fluid Dynamics Code (Li *et al.* 2011; Hao

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et al. 2012); (2) the water quality in certain areas of Lake Taihu could be improved because of the WTYT project (Hu *et al.* 2008, 2010; Li *et al.* 2013). However, the success of water transfers in improving water quality in Lake Taihu is strongly associated with wind conditions and inflow/outflow tributaries of the water transfer project (Li *et al.* 2013); and (3) water transfers generally had a positive effect on the ecosystem status of Lake Taihu (Zhai *et al.* 2010).

The above-mentioned studies investigated the influences of the WTYT project from different perspectives. However, the impacts of the WTYT project on short-term changes in phytoplankton distribution have thus far not been quantified due to the challenges involved in implementing short-term simulations. Compared with long-term (from a few months to years) simulations, short-term (a few days) simulations generally require high-frequency sampling data to initialize, calibrate, and validate. For a lake as large as Lake Taihu, these high-frequency data are particularly time-consuming and costly to obtain.

From a management perspective, short-term predictions of chlorophyll *a* (Chl *a*) are important for a lake as large as Lake Taihu. Algal blooms not only result from phytoplankton growth but also from phytoplankton aggregation (i.e. many phytoplankton patches transported together by water flow). Both phytoplankton growth and aggregation may change Chl *a* significantly in the short term (a few days) (Huang *et al.* 2012a). Short-term predictions of Chl *a* distribution could identify the areas where Chl *a* would be particularly high over the span of a few days. Such predictions could support early warnings of algal blooms and assist lake managers in implementing timely emergency measures to minimize the negative impacts of harmful algal blooms (Huang *et al.* 2012a).

Given the important role of the WTYT project in the Lake Taihu ecosystem, this study aimed to investigate the impacts of the WTYT project on short-term changes in Chl *a* distribution in Lake Taihu. A numerical hydrodynamic-phytoplankton model was used for this purpose. Four simulations with different water transfer strategies were carried out. Simulation results were compared to quantify the response of Chl *a* distribution to different water transfer strategies. The factors that influenced the efficiency of algal bloom alleviation during the WTYT project were discussed based on the simulation results.

MATERIAL AND METHODS

Study area

Lake Taihu is a large (surface area 2,338 km^2), shallow (mean depth 1.9 m), and eutrophic lake in eastern China (Figure 1). The mean hydraulic retention time is 284 days (Hu *et al.* 2006). The river and channel network around Lake Taihu is very complicated (Hu *et al.* 2006; Qin *et al.* 2007). The Wangyu and Taipu Rivers are two of the main rivers connecting Lake Taihu and the Yangtze River (Figure 1). During the past few decades, high nutrient loading deteriorated the water quality and resulted in severe algal blooms (Guo 2007; Qin *et al.* 2007). In late May 2007, a severe algal bloom caused a drinking water crisis in the city of Wuxi (Yang *et al.* 2008; Qin *et al.* 2010). During this crisis, the drinking water delivered to roughly two million people from water intakes became colored and foul-smelling (Zhang *et al.* 2010).

The hydrodynamic-phytoplankton model

A hydrodynamic-phytoplankton model and software (Phytoplankton Prediction System for Lake Taihu) to run the model have been developed to aid early warnings of severe algal blooms in Lake Taihu (Huang *et al.* 2012a, 2012b). This model predicts the short-term changes in the chlorophyll *a* concentration (Chl *a*) as a measure of the

Figure 1 | Locations of Lake Taihu and Wangyu and Taipu Rivers.

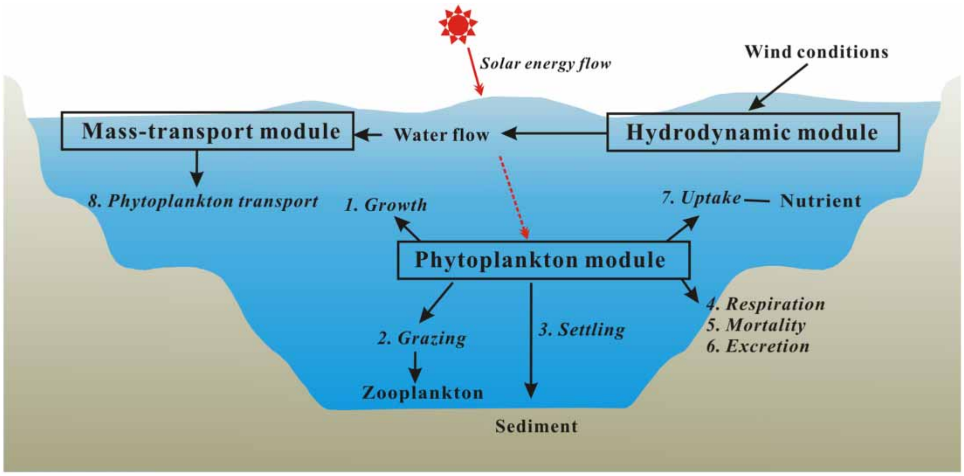

Figure 2 | Model structure of the hydrodynamic-phytoplankton model (redrawn from Huang *et al*. (2014b)).

phytoplankton biomass. Severe algal blooms are closely related to high Chl *a* concentration and can be preliminarily identified based on Chl *a* prediction.

Three modules (i.e. a two-dimensional hydrodynamic module, a mass-transport module, and a phytoplankton module) are included in this hydrodynamic-phytoplankton model (Figure 2). The hydrodynamic module generated horizontal water velocities and used an empirical parabola to describe the vertical profiles of the horizontal water velocity in Lake Taihu (Cheng *et al*. 2006; Huang *et al*. 2012a). This empirical parabola assumes that horizontal water velocity attenuates at a depth near the surface and reverses direction near the bottom (Figure 3). This assumption is reasonable

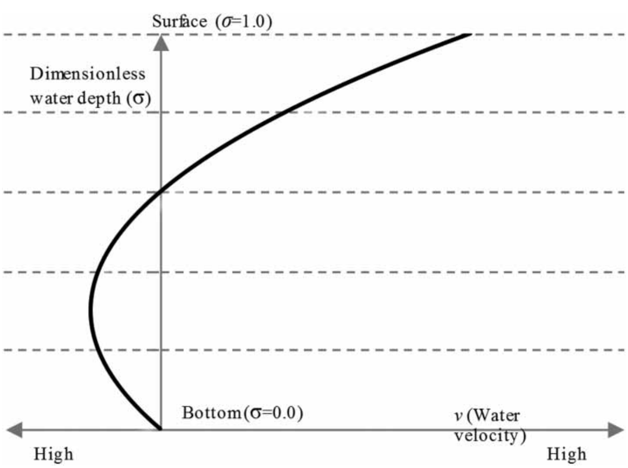

Figure 3 | Empirical parabola representing vertical profiles of the horizontal water velocity (redrawn from Huang *et al*. (2012a)).

for the wind-induced circulation of Lake Taihu (Qin *et al*. 2007; Huang *et al*. 2012a). Water velocity in the vertical direction was not included. This was acceptable for a large shallow lake because wind can lead to high Chl *a* heterogeneity in a short amount of time (Carrick *et al*. 1993). Thus, horizontal transport of Chl *a* could be more important than vertical mixing. The mass-transport module describes Chl *a* transport based on the water velocities generated by the hydrodynamic module. The phytoplankton module describes phytoplankton growth and loss with a time step of 1 day. A time step of 200 seconds was used for the hydrodynamic and mass-transport modules (Huang *et al*. 2012a). A spatial resolution of 250×250 m was used for all modules.

For short-term prediction purpose, two simplifications were used for the hydrodynamic-phytoplankton model: (1) exclusion of some processes related to Chl *a* dynamics like nutrient dynamics, sediment resuspension, mineralization, and nitrification; and (2) use of monthly measured data of the nutrient state. These two simplifications imply that the model requires fewer parameters and inputs than other more complex models, and can thus be of practical use in water management (Huang *et al*. 2012a). The model inputs include the initial conditions of Chl *a* distribution, and the time series data of wind conditions, solar radiation, water temperature, total dissolved nitrogen, and phosphorus.

The hydrodynamic-phytoplankton model was originally developed by Huang *et al*. (2012a), and has been calibrated and validated based on measured data from Lake Taihu (Huang *et al*. 2012a). The calibration and validation results

Table 1 | Parameters used in the hydrodynamic-phytoplankton model (Huang *et al.* 2012a)

Parameters	Values
Maximum growth rate of the phytoplankton	1.145 d^{-1}
Optimum water temperature	27.5 °C
Average spectral extinction coefficient for the absorption of short-wave radiation by water and its non-phytoplankton component	0.45 m^{-1}
Average spectral extinction coefficient for the absorption of short-wave radiation by the phytoplankton	0.016 m^2 (mg Chl)$^{-1}$
Saturation light intensity	12 MJ m^{-2} d^{-1}
Michaelis constant for phosphorus uptake	0.01 mg L^{-1}
Michaelis constant for nitrogen uptake	0.022 mg L^{-1}
Sinking velocity of the phytoplankton	0.0864 m d^{-1}
Maximum grazing rate of the zooplankton	0.09 d^{-1}
Minimum concentration of phytoplankton available for grazing	100 μg L^{-1}
Michaelis-Menten constant of phytoplankton available for grazing	500 μg L^{-1}
Rate coefficient for the chlorophyll *α* loss caused by mortality	0.027 d^{-1}
Rate coefficient for the chlorophyll *α* loss caused by respiration	0.17 d^{-1}
Rate coefficient for the chlorophyll *α* loss caused by excretion	0.01 d^{-1}
Temperature multipliers	1.08

(Appendix A, available online at http://www.iwaponline.com/jh/017/023.pdf) demonstrate its reliability for short-term prediction of Chl *a* in Lake Taihu. The parameters used in this study are listed in Table 1 (Huang *et al.* 2012a).

Water transfer project

A water transfer project (WTYT) has been used as an emergency measure to improve water quality and alleviate severe algal blooms since 2002. The main strategy in this project involves transferring water from the Yangtze River into Lake Taihu through the Wangyu River, and taking water out of the lake through the Taipu River (Hu *et al.* 2008; Taihu Basin Authority 2014). However, depending on the time period, the Wangyu River can be an inflow or outflow (Figure 4). The inflow and outflow of water are controlled by floodgates (Figure 1). The inflow and outflow discharges of the Wangyu and Taipu Rivers depend on various factors, such as the water level and quality of Lake Taihu. Generally, water is transferred from the Wangyu River to improve water quality of Lake Taihu. In summer and autumn, a larger amount of water flows out through Wangyu River to alleviate flood pressure in Lake Taihu. The amount of water exchanged annually between the Yangtze River and Lake Taihu varies considerably. The Taipu River is the largest outflow river for Lake Taihu. Although the WTYT project has been ongoing for years, the 2006 measurement data from Taihu Basin Authority show that phosphorus and nitrogen concentrations in the inflow (Wangyu River) water are higher than those in the outflow (Taipu River) water. This suggests that the WTYT project may result in importation of phosphorus and nitrogen to Lake Taihu.

Data

This study took advantage of an intensive sampling program by Nanjing Institute of Geography and Limnology to obtain relatively high-frequency data to support short-term simulations of Chl *a* changes. The hydrodynamic-phytoplankton model requires lake bathymetry and initial distribution of chlorophyll *a* concentration (Chl *a*, μg/L) as input data. A time series dataset to drive the model includes flow discharge (FD, m^3/s) of the Wangyu and Taipu Rivers, wind speed (WS, m/s), wind direction (WD, °), photosynthetically active radiation (PAR, W/m), water temperature (WT, °C), total dissolved phosphorus (DP, mg/L), and nitrogen (DN, mg/L). The simulation period was between 3 May and 30 September 2010, and between 2 May and 29 September 2011, when algal blooms are most likely to occur in Lake Taihu. Brief information regarding the data collected in this study is listed in Table 2.

The depth-averaged Chl *a* and WT were obtained at 17 sampling sites (Figure 5). At each sampling site, a water column was collected with a 2-m-long, 0.1-m-wide hand-made plastic tube with a one-way valve at the upper part of the tube. The water was mixed completely in a plastic bucket. Chl *a* and WT were measured twice a week in the plastic bucket using a Yellow Springs Instrument (6600,

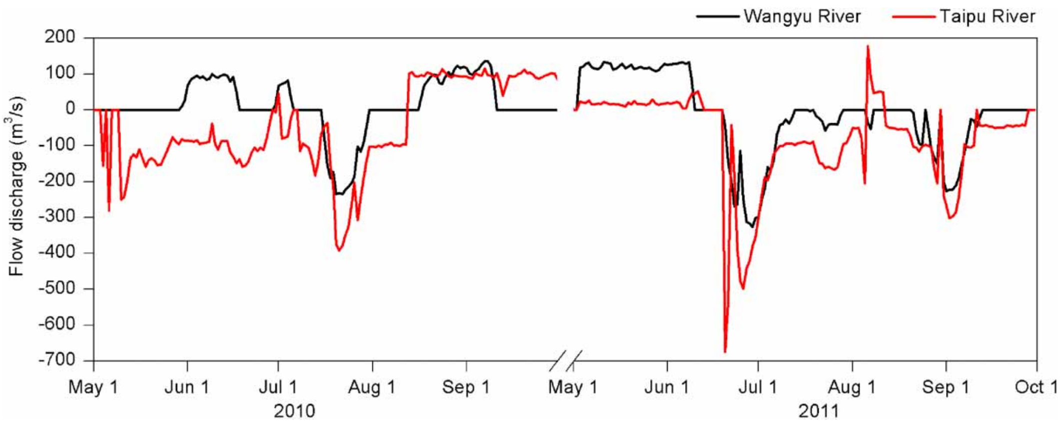

Figure 4 | The inflow and outflow discharges of the Wangyu and Taipu Rivers between May and September of 2010 and 2011. The positive and negative values represent inflow and outflow river, respectively.

Table 2 | Data collected for the hydrodynamic-phytoplankton model

Time period	Items	Temporal resolution	Sampling sites	Sampling time
3 May–30 September 2010 and 2 May–29 September 2011	Chl *a* and WT	Twice a week	17 (see Figure 4)	07:00–11:00 h
	DP and DN	Once a month	29 (see Figure 4)	07:00–17:00 h
	WS, WD and PAR	Once a day	1 (see Figure 4)	–
	FD	Once a day	2 (see Figure 4)	–

Chl *a*, chlorophyll *a* concentration; WT, water temperature; DP, total dissolved phosphorus; DN, total dissolved nitrogen; WS, wind speed; WD, wind direction; PAR, photosynthetically active radiation; FD, flow discharge.

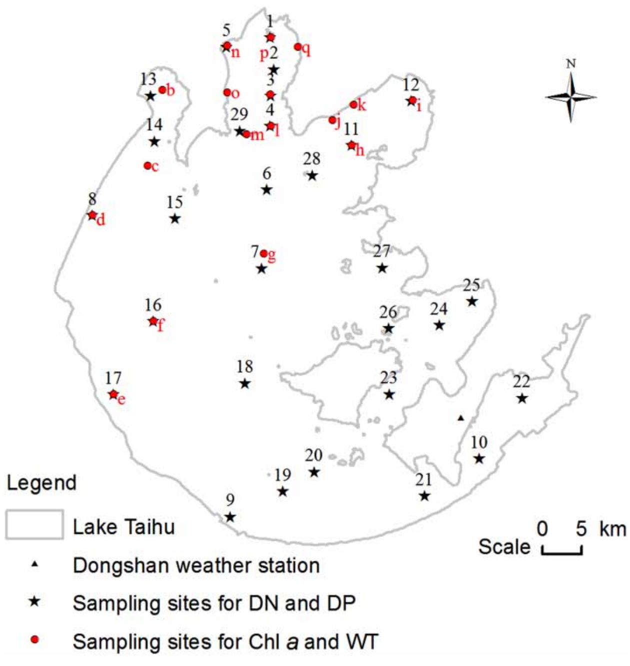

Figure 5 | Locations of the weather station and the sampling sites in Lake Taihu.

Yellow Springs, USA). A total of 1,343 samples were collected. DP and DN data were obtained from another sampling program. In this program, DP and DN were measured monthly at 29 sampling sites (Figure 5), with a total of 348 samples. DP and DN were assumed constant within a month.

The spatial distributions of Chl *a*, WT, DP, and DN in Lake Taihu were interpolated using the inverse distance weighted method. Most of the sampling sites for Chl *a* and WT are located in the north-western part of Lake Taihu (Figure 5). This may result in relatively large errors in estimation of Chl *a* distribution in the south-eastern part. However, this is acceptable for Lake Taihu because Chl *a* in the north-western part is generally higher than that in the south-eastern part. Thus, severe algal blooms are more likely to occur in the north-western part. A lake manager concerned with Chl *a* prediction would be more likely to focus on Chl *a* dynamics in the north-western part of Lake Taihu.

Daily meteorological data (i.e. WS, WD, and sunshine hours) were obtained from the China Meteorological Administration. The weather station was located in Dongshan near East Taihu bay (Figure 5). Spatial heterogeneity of these meteorological variables was not accounted for. The PAR was derived from the sunshine hours. The daily flow discharges of the Wangyu and Taipu River were recorded at the floodgates (Figure 5) by the water management agency of Taihu Basin Authority.

Model simulations

The hydrodynamic-phytoplankton model aims to predict short-term changes in Chl *a* distribution in Lake Taihu. The simulation results would assist managers in identifying areas where severe algal blooms may occur in the next few days. A data assimilation scheme based on the ensemble Kalman filter was tested to update model variables and parameters. However, the assimilation results were not used in this study due to the limited improvement of model performance (Huang *et al*. 2013). The initial conditions of Chl *a* were updated based on the measurement results twice a week during the simulation period between 3 May and 30 September 2010, and between 2 May and 29 September 2011 (Figure 6).

To investigate the impacts of the water transfer project (WTYT) on Chl *a* distribution, a total of four simulations were carried out (Figure 6). A baseline simulation (named SimBase) that did not consider inflows and outflows was conducted to compare with other simulations. Another simulation (named SimFlow), that considered the flow discharge of the Wangyu and Taipu Rivers was conducted. The Chl *a* concentration of the inflow water from the Wangyu River (Chl_{FW} in Figure 6) was not measured and was assumed to be equal to the average Chl *a* concentration in Gonghu Bay (Chl_{Gonghu} in Figure 6). Thus, the differences between SimBase and SimFlow would reveal the response of short-term Chl *a* dynamics to hydrodynamic changes due to the WTYT project. The impacts of the WTYT project on DP and DN were not addressed. This omission is acceptable for this short-term model for Lake Taihu because DP and DN in Lake Taihu were relatively high in 2010 and 2011 (i.e. phytoplankton growth is limited only slightly, or even negligibly, by phosphorus and nitrogen). Thus, some fluctuations of DP and DN due to the WTYT project would not affect Chl *a* dynamics significantly on a short-term (3–4 days) scale.

Another two simulations (named SimFlowChl_0.8 and SimFlowChl_1.2) were carried out by changing the Chl *a* concentration of the inflow water from the Wangyu River by ±20% ($Chl_{FW} = (1 \pm 0.2) \times Chl_{Gonghu}$) (Figure 6). These two simulations were compared with SimBase to evaluate the impact of the Chl *a* concentration of the inflow water from the Wangyu River on the short-term Chl *a* dynamics in Lake Taihu.

RESULTS

Chlorophyll *a* changes

Chl *a* dynamics were different in various areas of Lake Taihu due to the water transfer project. Because SimBase represented the case without any inflows or outflows, the differences between the three simulations (SimFlow, SimFlowChl_0.8, and SimFlowChl_1.2) and SimBase represented the changes in Chl *a* due to the water transfers from the Wangyu River. Figure 7 shows the change in average Chl *a* in Gonghu Bay due to the water transfers from the Wangyu River during the modeling period. The average Chl *a* changes in all grid cells in Gonghu Bay were positively related to the flow discharge from the Wangyu River with an r^2 (coefficient of determination) value of 0.548. During the period when water was transferred from the Yangtze River into Lake Taihu, the average Chl *a* change in all grid cells in Gonghu Bay was highly dependent on the Chl *a* concentration of the inflow water from the Wangyu River. High Chl *a* in the inflow water (SimFlowChl_1.2) resulted in a significant increase in Chl *a* in Gonghu Bay. Relatively low Chl *a* in the inflow water (SimFlowChl_0.8) resulted in a decrease in Chl *a* in Gonghu Bay. The average Chl *a* in Gonghu Bay generally decreased during the period when water was transferred from Lake Taihu to the Wangyu River.

The changes in Chl *a* distribution during two typical water transfer events are presented to investigate the impact of the WTYT project on Chl *a* distribution (Figures 7 and 8). During the water transfer event of 10–12 May 2011, 33.26 million m^3 of water was transferred from the Yangtze

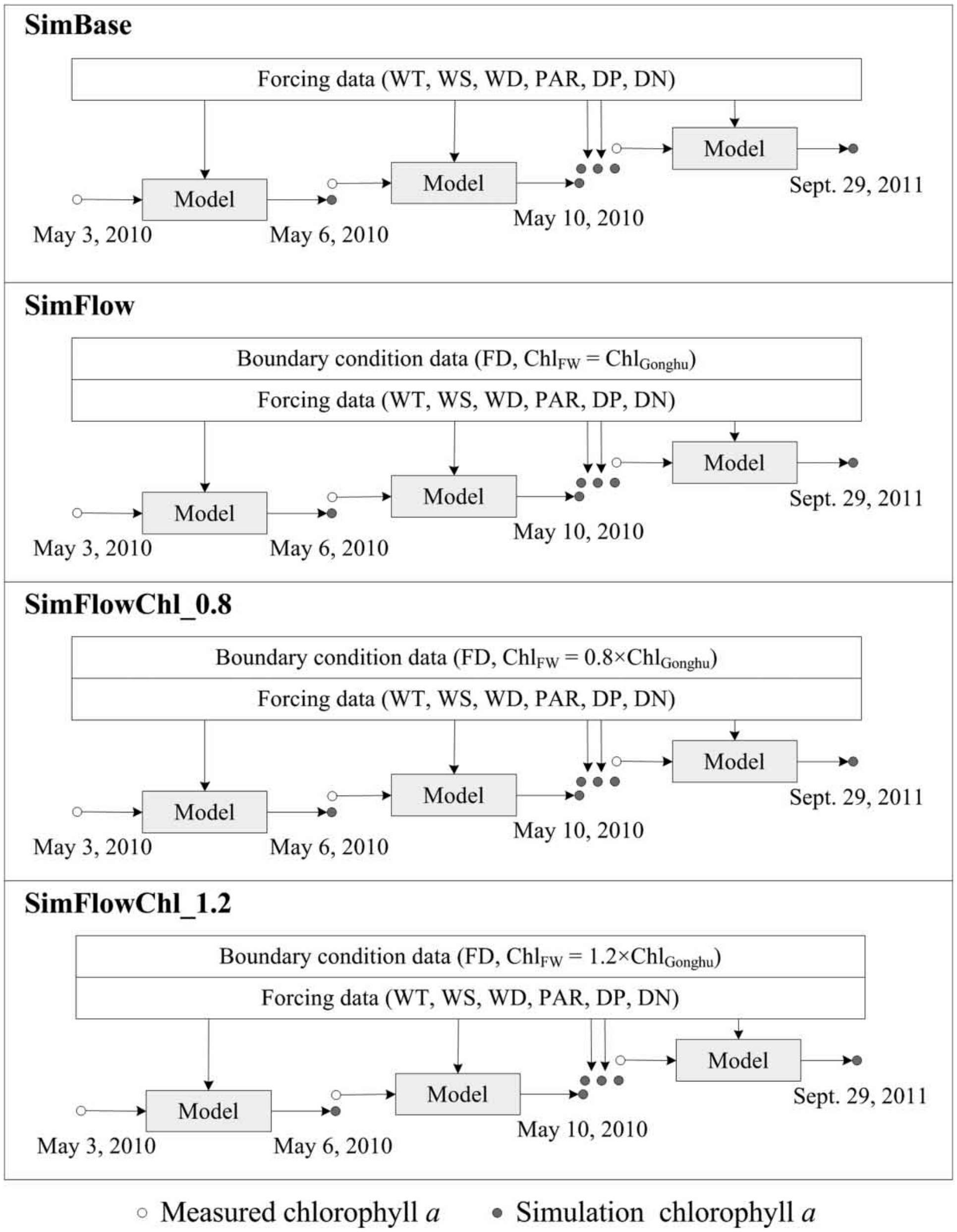

Figure 6 | Four simulations (SimBase, SimFlow, SimFlowChl_0.8, and SimFlowChl_1.2) with different water transfer strategies. FD, flow discharge; Chl_{FW}, Chl *a* concentration of the inflow water from the Wangyu River; Chl_{Gonghu}, average Chl *a* concentration in Gonghu Bay; WT, water temperature; WS, wind speed; WD, wind direction; PAR, photosynthetically active radiation; DP, total dissolved phosphorus; DN, total dissolved nitrogen.

River to Gonghu Bay through the Wangyu River, and 5.05 million m^3 of water was transferred out of Lake Taihu through the Taipu River (Figure 8). The simulated Chl *a* in Gonghu Bay is different between SimBase and SimFlow, especially in the area near the floodgate of the Wangyu River. Chl *a* changes in the area near the floodgate of the Taipu River were low (between −0.1 and 0.1 μg/L).

During the water transfer event of 28–30 June 2011, 81.65 and 100.05 million m^3 of water was transferred out of Lake Taihu through the Wangyu and Taipu Rivers, respectively (Figure 9). The difference in simulated Chl *a* in Gonghu Bay between SimBase and SimFlow was generally larger than −0.5 μg/L. The water with a relatively high Chl *a* concentration was

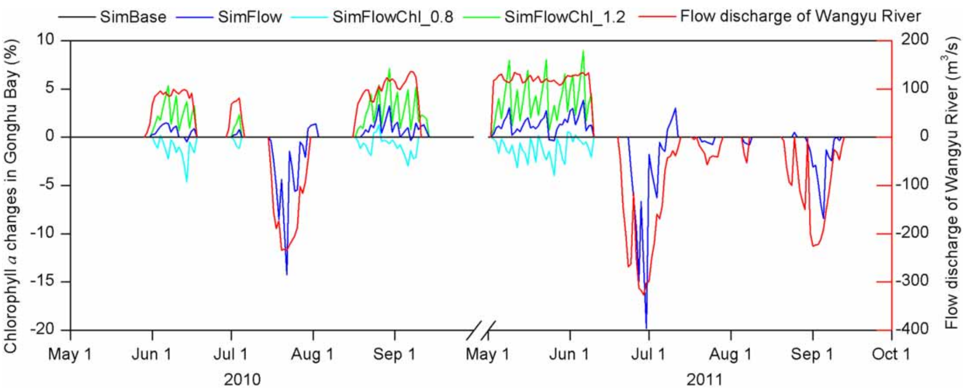

Figure 7 | The change in average chlorophyll *a* in Gonghu Bay due to water transfers to the Wangyu River during the modeling period.

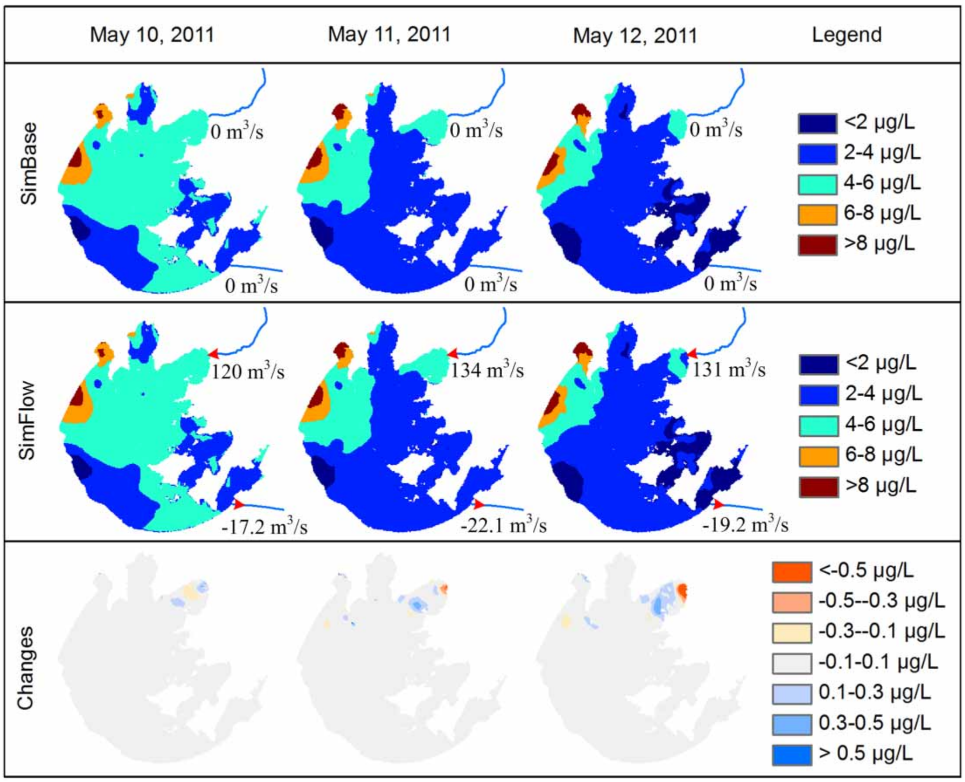

Figure 8 | Comparison of chlorophyll *a* distribution in Lake Taihu during 28–30 May 2011 from two simulations (SimBase and SimFlow). SimBase represents the baseline simulation neglecting inflows and outflows from Lake Taihu. SimFlow represents the simulation considering the water transfers from the Wangyu and Taipu Rivers. 'Changes' represents the Chl *a* difference between SimBase and SimFlow. Negative 'Changes' values indicate that simulated Chl *a* from SimFlow is lower than that from SimBase.

transferred out of Lake Taihu through the Wangyu River (Figure 9). The water with a relatively low Chl *a* concentration flowed into Gonghu Bay to compensate for the water loss through the Wangyu River. Although the water transfer amount from the Taipu River (between -422 and $-356\ m^3/s$) was larger than that from the Wangyu River (between -327 and $-301\ m^3/s$), SimBase and SimFlow did not show significant differences in simulated Chl *a* in the area near the floodgate of the Taipu River.

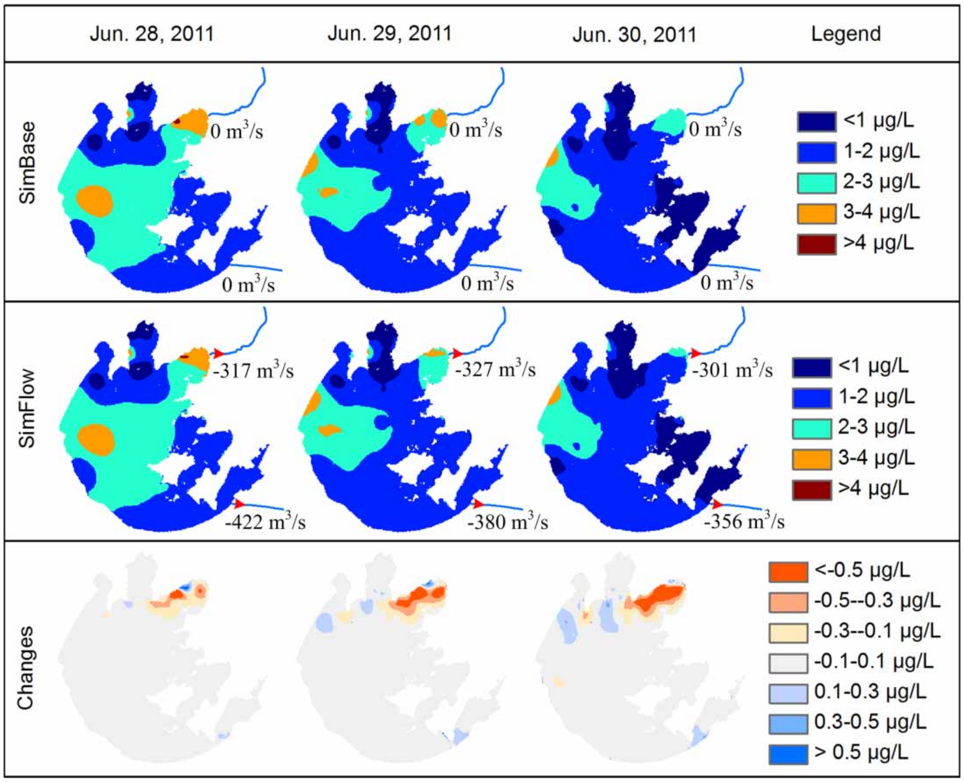

Figure 9 | Comparison of chlorophyll *a* distribution in Lake Taihu during 10–12 June 2011 from two simulations (SimBase and SimFlow). SimBase represents the baseline simulation neglecting inflows and outflows from Lake Taihu. SimFlow represents the simulation considering the water transfers from the Wangyu and Taipu Rivers. 'Changes' represents differences between SimBase and SimFlow in the Chl *a*. Negative 'Changes' values indicate that simulated Chl *a* from SimFlow is lower than that from SimBase.

Hydrodynamic changes

Hydrodynamic condition is a dominant factor leading to significant transport of Chl *a* in large shallow lakes (Carrick *et al.* 1993). The depth-averaged water velocities (the average value of horizontal velocities over depth) from SimBase and SimFlow were significantly different during these two water transfer events (Figure 10). Generally, the WTYT project enhanced the water exchange of Lake Taihu during 10–12 May and 28–30 June 2011, especially in the areas near the floodgates of Wangyu and Taipu Rivers. The area with significant differences in hydrodynamic conditions between SimBase and SimFlow (named hydrodynamic change region in this study) is shown in Figure 10. This region had significant changes in hydrodynamic conditions due to the WTYT project (i.e. a flow direction change larger than 15° or a water velocity change larger than 1 cm/s).

The changes in hydrodynamic conditions due to the WTYT project were highly dependent on the discharges of the connecting rivers. During 10–12 May 2011, the hydrodynamic change region was mainly located in Gonghu Bay and covered an area ranging between 95.0 and 177.6 km^2. The flow discharge of the Taipu River was low (17.2–22.1 m^3/s), and there was almost no change in hydrodynamic conditions in the region near the floodgate of the Taipu River. In contrast, the hydrodynamic conditions changed considerably during 28–30 June when the outflow discharge of the Taipu River ranged between 356 and 422 m^3/s (Figure 10). The area of the hydrodynamic change region was large during 28–30 June (ranging between 649.3 and 695.2 km^2). However, there was almost no change in hydrodynamic conditions in Zhushan and Meiliang Bays, dispite the fact that the outflow discharge was as large as 422 m^3/s on 28 June 2011.

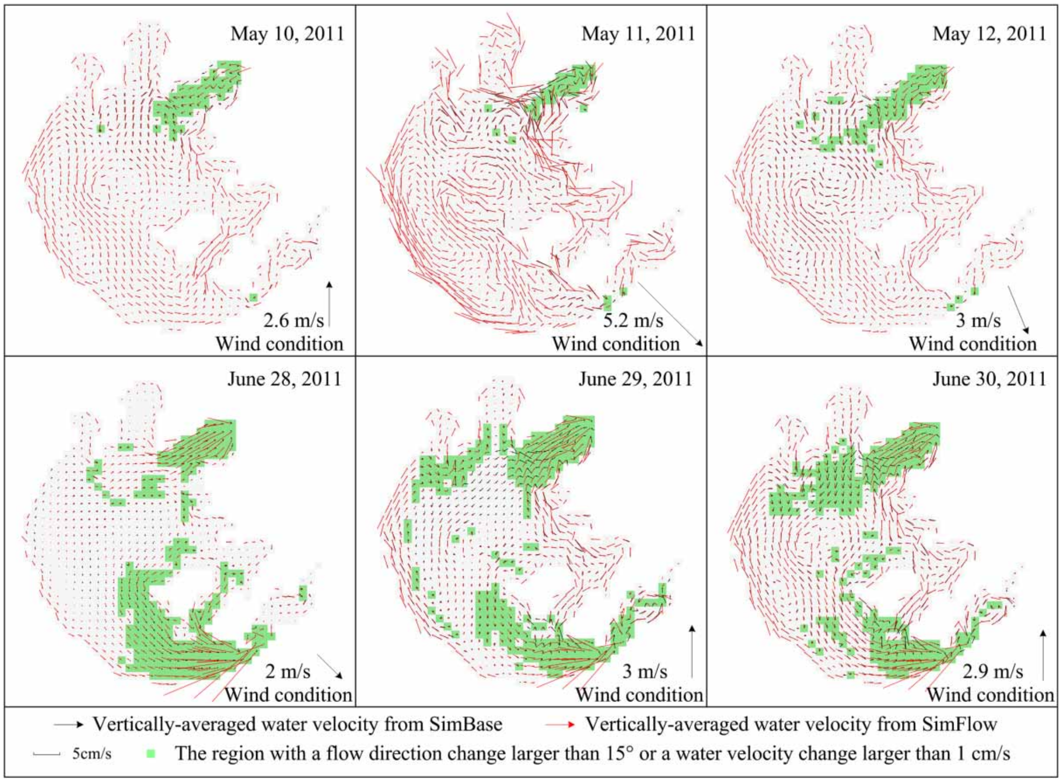

Figure 10 | The depth-averaged water velocities from two simulations (SimBase and SimFlow) during 28–30 May and 10–12 June 2011. SimBase represents the baseline simulation neglecting inflows and outflows from Lake Taihu. SimFlow represents the simulation considering the water transfers from the Wangyu and Taipu Rivers. The spatial resolution of this figure is adapted to 1,750 × 1,750 m by resampling.

DISCUSSION

Contribution of water transfers to alleviation of phytoplankton aggregation

In Lake Taihu, it is widely recognized that natural factors, such as water temperature, wind conditions, and light intensity significantly affect Chl *a* dynamics (Qin *et al.* 2007; Huang *et al.* 2014a). The Chl *a* distribution may be significantly affected by hydrodynamic conditions even on a short-term time scale (Huang *et al.* 2012a). This study investigated the potential impacts of the WTYT project on Chl *a* dynamics, and found that hydrodynamic conditions in the near-floodgate areas were strongly influenced by the WTYT project on a short-term scale, a conclusion that is consistent with previous studies (Li *et al.* 2013). The fluctuation of hydrodynamic conditions caused by the WTYT would likely change Chl *a* distribution (Figures 8 and 9). In summer, the prevailing wind conditions are likely to result in phytoplankton aggregation in Gonghu Bay and other northern bays of Lake Taihu (Qin *et al.* 2010). In this case, the water transfer project may transfer high-Chl *a* water out of Gonghu Bay through the Wangyu River, and thus alleviate algal blooms in Gonghu Bay (Figure 8). The alleviation of algal blooms in Gonghu Bay would be meaningful for lake management, because several drinking water intakes are located here.

Although the WTYT project has the potential to alleviate algal blooms in Lake Taihu, it is important to note that it does not necessarily alleviate phytoplankton aggregation in Gonghu Bay. For example, the WTYT project resulted in a decrease in Chl *a* in most areas of Gonghu Bay during 28–30 June 2011 (Figure 9). However, Chl *a* increased in a small area at the northwest corner of Gonghu Bay (Figure 9). Several environmental factors, such as wind conditions, Chl *a* distribution, and the amount and water quality of the transfer water, may affect the efficiency of the WTYT project in alleviating phytoplankton aggregation in Gonghu Bay.

Wind condition is the most important factor affecting Chl *a* transport in a lake as large as Lake Taihu (Huang *et al.* 2012a). Relative to the wind condition factor, the WTYT project influences Chl *a* transport only in a limited area near the floodgates of inflows and outflows (Figure 9). During 10–11 May 2011, the changes in wind conditions (i.e. wind velocity changed from 2.6 to 5.2 m/s, and wind direction changed from 180° to 315°) resulted in significant changes in hydrodynamic conditions in the whole lake. However, the changes in hydrodynamic conditions due to the WTYT project were relatively small with a small hydrodynamic change region (an area of 95.0 km^2) (Figure 9).

The average Chl *a* concentration in Gonghu Bay decreased during the period when water flowed out of Lake Taihu through the Wangyu River (Figure 7). This decreasing trend in Chl *a* occurred largely because Chl *a* in Gonghu Bay is generally higher than that in the surrounding area. During 28–30 June 2011, the Chl *a* dynamics from SimFlow (Figure 8) showed that the Chl *a* in the outflow water was relatively high. This result implies that Chl *a* distribution contributes to the alleviation of phytoplankton aggregation in the WTYT project. In the case that Chl *a* near Gonhu Bay is higher than that in Gonghu Bay, water transferred out of Lake Taihu through the Wangyu River may result in phytoplankton importation to Gonghu Bay.

The simulation results of SimFlow, SimFlowChl_0.8, and SimFlowChl_1.2 (Figure 7) imply that Chl *a* dynamics in Gonghu Bay are sensitive to the Chl *a* concentration in the inflow water from the Wangyu River on a short-term scale (Figure 7). Inflow water with a relatively low Chl *a* concentration could alleviate algal blooms on a short-term scale. For example, during the period between 3 May and 9 June 2011, the water in Gonghu Bay flowed out through the Wangyu River at an average discharge rate of 120.9 m^3/s. The simulation results from SimFlow and SimBase showed that Chl *a* in Gonghu Bay increased by 1.39% due to the WTYT project. However, when modeled in SimFlowChl_0.8, Chl *a* in Gonghu Bay decreased by 1.18%, indicating that the Chl *a* concentration in the inflow water significantly affected the efficiency of the WTYT project in alleviating phytoplankton aggregation in Gonghu Bay.

Potential impacts of water transfers on Lake Taihu

Water transfers have been employed all over the world as one of the most important strategies for alleviating algal blooms in lakes (Welch *et al.* 1972; Schwierzke-Wade *et al.* 2010). However, the influences of the WTYT project on the lake ecosystem and its surrounding aquatic ecosystems are still far from adequately studied. There is still no firm conclusion on whether the WTYT project is justified. Some unexpected effects, such as deterioration of water quality, species invasion, and shifts in phytoplankton and fish species, may cause harm to the Lake Taihu ecosystem over the long term (Welch 2009; Amano *et al.* 2010; Fornarelli & Antenucci 2011). Especially in recent years, the Yangtze River has been severely polluted due to increased nutrient loading (Müller *et al.* 2008). The concentrations of phosphorus and nitrogen in the inflow water from the Wangyu River were generally higher than in the outflow water through the Taipu River in the last few years (Hu *et al.* 2008). This implies that there was a net input of nutrients during the water transfer period. Severe algal blooms would thus be more likely to occur due to the high nutrient levels in Lake Taihu over the long term. From this perspective, the WTYT project is not as promising as some other water transfer projects that transfer low-nutrient water to eutrophic lakes (e.g. Welch *et al.* 1992). Further studies are essential to evaluate the comprehensive social, economic, and ecological impacts of the WTYT project to maximize its benefits and avoid its negative impacts on surrounding aquatic ecosystems.

Potential use of process-based models for evaluating water transfers

The hydrodynamic-phytoplankton model used in this study is process-based, and is well suited to predict the short-term changes in Chl *a* in the context of a water transfer project. This process-based model described hydrodynamic conditions and biological processes of phytoplankton explicitly and was demonstrated to be an option for predicting the disturbances of the water transfer project on an aquatic ecosystem. The outstanding advantage of the process-based model is its ability to predict water quality changes in the context of any hypothetical water transfer strategy.

However, the intensive data requirement of the process-based model restricts its application, especially for short-term simulations. The simulation results in Figure 7 demonstrate that the Chl *a* changes in Gonghu Bay are sensitive to the Chl *a* concentration in the inflow water on a short-term scale. This implies that high-frequency data would be helpful to achieve a reliable evaluation of water transfer projects. In this study, water quality data were obtained by intensive fieldwork, which is time-consuming and costly. For example, the sampling work at the 29 sampling sites shown in Figure 5 would require an entire day's work. This weakness could be partially overcome through installation of automatic monitoring systems in Lake Taihu, aiming to collect real-time water quality data (Huang *et al*. 2013). Real-time measurements of the inflow water would be particularly useful to evaluate the potential impacts of water transfer projects.

Possible applications of evaluation results to lake management

The hydrodynamic-phytoplankton model has provided useful information for early warning of severe algal blooms and has already been used in lake management practices. In this study, the hydrodynamic-phytoplankton model was successfully used to evaluate the contribution of the WTYT project to alleviation of phytoplankton aggregation on a short-term scale. Such evaluation could assist lake managers in conducting efficient water transfer projects to combat algal blooms occurring within a time scale of a few days. Moreover, the evaluation is useful to ensure that algal blooms are not transported to water intake areas of the lake by the water transfer project.

The WTYT project may result in several changes in the Lake Taihu ecosystem; for example, changes in Chl *a* dynamics over a few days, water quality over a few years, and ecological stability over tens of years. The hydrodynamic-phytoplankton model in this study only focuses on the change in Chl *a* dynamics due to water transfers. Additional models (e.g. Hu *et al*. 2008; Li *et al*. 2011) are needed to investigate other impacts of the WTYT project on Lake Taihu. These additional studies would contribute to achieving a comprehensive evaluation of all potential impacts of a water transfer plan on the Lake Taihu ecosystem. This comprehensive evaluation would support reasonable decision-making for water transfers.

CONCLUSIONS

Four short-term simulations with different water transfer strategies were carried out to investigate the potential impacts of a water transfer project on Lake Taihu. The simulation results showed that Chl *a* in Gonghu Bay generally decreased when water flowed out of Lake Taihu through the Wangyu River. Water transfers from the Yangtze River could be a measure for reducing the Chl *a* concentration in Gonghu Bay if Chl *a* concentration in the inflow water was relatively low. These simulation results imply that the water transfer project has potential, but does not necessarily alleviate algal blooms in Gonghu Bay. Success of the water transfer project in alleviating severe algal blooms was strongly associated with other environmental factors (e.g. wind conditions, Chl *a* distribution, the amount and quality of the inflow water). A preliminary evaluation is needed before conducting a water transfer project to combat severe algal blooms.

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REFERENCES

Amano, Y., Sakai, Y., Sekiya, T., Takeya, K., Taki, K. & Machida, M. 2010 Effect of phosphorus fluctuation caused by river water dilution in eutrophic lake on competition between blue-green alga *Microcystis aeruginosa* and diatom *Cyclotella sp*. *J. Environ. Sci.* **22**, 1666–1673.

Borsuk, M. E., Stow, C. A. & Reckhow, K. H. 2004 A Bayesian network of eutrophication models for synthesis, prediction, and uncertainty analysis. *Ecol. Model.* **173**, 219–239.

Carrick, H. J., Aldridge, F. J. & Schelske, C. L. 1993 Wind influences phytoplankton biomass and composition in a shallow, productive lake. *Limnol. Oceanogr.* **38**, 1179–1192.

Cheng, W., Wang, C. & Zhu, Y. 2006 *Taihu Basin Model*. 1st edn, HoHai University Press, Nangjing, China (in Chinese).

Dimberg, P. H., Bryhn, A. C. & Hytteborn, J. K. 2013 Probabilities of monthly median chlorophyll-a concentrations in subarctic, temperate and subtropical lakes. *Environ. Modell. Softw.* **41**, 199–209.

Fornarelli, R. & Antenucci, J. P. 2011 The impact of transfers on water quality and the disturbance regime in a reservoir. *Water Res.* **45**, 5873–5885.

Fornarelli, R., Antenucci, J. P. & Marti, C. L. 2013a Disturbance, diversity and phytoplankton production in a reservoir affected by inter-basin water transfers. *Hydrobiologia* **705**, 9–26.

Fornarelli, R., Galelli, S., Castelletti, A., Antenucci, J. P. & Marti, C. L. 2013b An empirical modeling approach to predict and understand phytoplankton dynamics in a reservoir affected by interbasin water transfers. *Water Resour. Res.* **49**, 3626–3641.

Guo, L. 2007 Doing battle with the green monster of Lake Taihu. *Science* **317**, 1166.

Hao, W., Tang, C., Hua, L. & Acharya, K. 2012 Effects of water diversion from Yangtze River to Taihu Lake on hydrodynamic regulation of Taihu Lake. *J. Hohai Univ. (Nat. Sci.)* **40**, 129–133 (in Chinese).

Hu, L., Hu, W., Zhai, S. & Wu, H. 2010 Effects on water quality following water transfer in Lake Taihu, China. *Ecol. Eng.* **36**, 471–481.

Hu, W., Jørgensen, S. E. & Zhang, F. 2006 A vertical-compressed three-dimensional ecological model in Lake Taihu, China. *Ecol. Model.* **190**, 367–398.

Hu, W., Zhai, S., Zhu, Z. & Han, H. 2008 Impacts of the Yangtze River water transfer on the restoration of Lake Taihu. *Ecol. Eng.* **34**, 30–49.

Huang, J., Gao, J. & Hörmann, G. 2012a Hydrodynamic-phytoplankton model for short-term forecasts of phytoplankton in Lake Taihu, China. *Limnologica* **42**, 7–18.

Huang, J., Gao, J., Hörmann, G. & Mooij, W. M. 2012b Integrating three lake models into a Phytoplankton Prediction System for Lake Taihu (Taihu PPS) with Python. *J. Hydroinform.* **14**, 523–534.

Huang, J., Gao, J., Liu, J. & Zhang, Y. 2013 State and parameter update of a hydrodynamic-phytoplankton model using ensemble Kalman filter. *Ecol. Model.* **263**, 81–91.

Huang, J., Gao, J., Hörmann, G. & Fohrer, N. 2014a Modeling the effects of environmental variables on short-term spatial changes in phytoplankton biomass in a large shallow lake, Lake Taihu. *Environ. Earth Sci.* **72**, 3609–3621.

Huang, J., Gao, J., Mooij, W. M., Hörmann, G. & Fohrer, N. 2014b A comparison of three approaches to predict phytoplankton biomass in Gonghu Bay of Lake Taihu. *J. Environ. Inform.* **24**, 39–51.

Li, Y., Acharya, K. & Yu, Z. 2011 Modeling impacts of Yangtze River water transfer on water ages in Lake Taihu, China. *Ecol. Eng.* **37**, 325–334.

Li, Y., Tang, C., Wang, C., Anim, D. O., Yu, Z. & Acharya, K. 2013 Improved Yangtze River diversions: are they helping to solve algal bloom problems in Lake Taihu, China? *Ecol. Eng.* **51**, 104–116.

Maier, H. R., Jain, A., Dandy, G. C. & Sudheer, K. P. 2010 Methods used for the development of neural networks for the prediction of water resource variables in river systems: current status and future directions. *Environ. Modell. Softw.* **25**, 891–909.

Moreno-Ostos, E., Elliott, J. A., Cruz-Pizarro, L., Escot, C., Basanta, A. & George, D. G. 2007 Using a numerical model (PROTECH) to examine the impact of water transfers on phytoplankton dynamics in a Mediterranean reservoir. *Limnetica* **26**, 1–11.

Müller, B., Berg, M., Yao, Z. P., Zhang, X. F., Wang, D. & Pfluger, A. 2008 How polluted is the Yangtze river? Water quality downstream from the Three Gorges Dam. *Sci. Total Environ.* **402**, 232–247.

Qin, B., Xu, P., Wu, Q., Luo, L. & Zhang, Y. 2007 Environmental issues of Lake Taihu, China. *Hydrobiologia* **581**, 3–14.

Qin, B., Zhu, G., Gao, G., Zhang, Y., Li, W., Paerl, H. W. & Carmichael, W. W. 2010 A drinking water crisis in Lake Taihu, China: linkage to climatic variability and lake management. *Environ. Manage.* **45**, 105–112.

Schwierzke-Wade, L., Roelke, D. L., Brooks, B. W., Grover, J. P. & Valenti, T. W. 2010 *Prymnesium parvum* bloom termination: role of hydraulic dilution. *J. Plankton Res.* **33**, 309–317.

Taihu Basin Authority 2014 http://www.tba.gov.cn/ztbd/yjjt/index.asp (accessed January 19, 2014).

Verma, S., Kampman, D. A., van der Zaag, P. & Hoekstra, A. Y. 2009 Going against the flow: a critical analysis of inter-state virtual water trade in the context of India's National River Linking Program. *Phys. Chem. Earth* **34**, 261–269.

Welch, E. B. 2009 Phosphorus reduction by dilution and shift in fish species in Moses Lake, WA. *Lake Reservoir Manage.* **25**, 276–283.

Welch, E. B., Buckley, J. A. & Bush, R. M. 1972 Dilution as an algal bloom control. *J. Water Pollut. Control Fed.* **44**, 2245–2265.

Welch, E. B., Barbiero, R. P., Bouchard, D. & Jones, C. A. 1992 Lake trophic state change and constant algal composition following dilution and diversion. *Ecol. Eng.* **1**, 173–197.

Yang, M., Yu, J., Li, Z., Guo, Z., Burch, M. & Lin, T. 2008 Taihu Lake not to blame for Wuxi's woes. *Science* **319**, 158.

Zhai, S., Hu, W. & Zhu, Z. 2010 Ecological impacts of water transfers on Lake Taihu from the Yangtze River, China. *Ecol. Eng.* **36**, 406–420.

Zhang, Q. 2009 The South-to-North water transfer project of China: environmental implications and monitoring strategy. *J. Am. Water Resour. Assoc.* **45**, 1238–1247.

Zhang, X., Chen, C., Ding, J., Hou, A., Li, Y., Niu, Z., Su, X., Xu, Y. & Laws, E. A. 2010 The 2007 water crisis in Wuxi, China: analysis of the origin. *J. Hazard. Mater.* **182**, 130–135.

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