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Selection of water source for water transfer based on algal growth potential to prevent algal blooms

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ABSTRACT

Water transfer is becoming a popular method for solving the problems of water quality deterioration and water level drawdown in lakes. However, the principle of choosing water sources for water transfer projects has mainly been based on the effects on water quality, which neglects the influence in the variation of phytoplankton community and the risk of algal blooms. In this study, algal growth potential (AGP) test was applied to predict changes in the phytoplankton community caused by water transfer projects. The feasibility of proposed water transfer sources (Baqing River and Jinsha River) was assessed through the changes in both water quality and phytoplankton community in Chenghai Lake, Southwest China. The results showed that the concentration of total nitrogen (TN) and total phosphorus (TP) in Chenghai Lake could be decreased to 0.52 mg/L and 0.02 mg/L respectively with the simulated water transfer source of Jinsha River. The algal cell density could be reduced by 60%, and the phytoplankton community would become relatively stable with the Jinsha River water transfer project, and the dominant species of *Anabaena cylindrica* evolved into *Anabaenopsis arnoldii* due to the species competition. However, the risk of algal blooms would be increased after the Baqing River water transfer project even with the improved water quality. Algae gained faster proliferation with the same dominant species in water transfer source. Therefore, water transfer projects should be assessed from not only the variation of water quality but also the risk of algal blooms.

Introduction

Many lakes are facing the problem of water-level drawdown in recent years due to climate warming and increased water consumption (Evtimova and Donohue, 2016; Xiao et al., 2018). Water-level drawdown could not only lead to the deterioration in water quality but also bring serious eutrophication problems to lakes (Davraz et al., 2019; Gownaris et al., 2018; Peng et al., 2019; Ye et al., 2017; Zhang et al., 2017). The

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frequency of algal blooms could be increased in eutrophic lakes, which would pose a great threat to water trophic status and aquatic ecosystem due to the reduction of dissolved oxygen in water and the release of toxins and taste and odor compounds (Gallardo and Aldridge, 2018; Xu et al., 2019; Zhang et al., 2021).

To alleviate the abovementioned problems induced by water-level drawdown in lakes, water transfer has become the most common and effective measure (Zhuang et al., 2019). However, water transfer projects have also exposed some risks in recent years (Sanchis-Ibor et al., 2019). Although the South-North Water Transfer Project in China could partly relieve water crises in the receiving areas, it caused cross-basin environmental problems, such as water quality deterioration and the spread of schistosomiasis (Liang et al., 2012; Zhang, 2009; Zhu et al., 2008). There are similar problems for the Yangtze River-Huaihe River Water Transfer Project (YHWTP) in China (Cao et al., 2018). Water diversion in Brazil caused impacts on biodiversity linked to bioinvasion and homogenization (Daga et al., 2020; Yuan et al., 2020).

Many researchers have proposed methods to assess the impact of water transfer projects (Guo et al., 2020; Hu et al., 2010; Zhuang et al., 2019). The Driving-pressure-state-impact-response (DPSIR) model in combination with the fuzzy comprehensive evaluation method (FCEM) and the Coordination Development Model (CDDM) was applied to assess the risk level of sudden water pollution accidents for the South-North Water Transfer Project (Li et al., 2019; Yang et al., 2020a). The Environmental Fluid Dynamics Code (EFDC) was applied to determine whether the variation in phytoplankton caused by turbulence is affected by nutrient concentrations (Zhao et al., 2020). The previous research has rarely addressed the risk assessment of algal blooms after water transfer, which just focuses on numerical simulation. These methods have been challenged for using incorrect data inputs, or relying on a single model, which can lead to inaccurate assessment of the effects of water transfer. Water quality standards have often been regarded as an important basis for selecting water sources, while the complexity and dynamics of phytoplankton have been overlooked. Actually, any water transfer project could result in complex physical, chemical, hydrological, and biological implications for the receiving system (Davies et al., 1992; Zeng et al., 2015). Many studies have indicated that phytoplankton is more sensitive to the water environment and has better indicative function than other indicators (Anjusha et al., 2018; Guo et al., 2019; Wu et al., 2019b). Therefore, it is important to pay attention to changes in both water quality and phytoplankton before project execution.

Chenghai Lake, located in Yunnan Province, China, is a typical representative of closed plateau lakes with high alkalinity. Water quality deterioration is a persistent problem affecting the ecological health of Chenghai Lake. From 2005 to 2015, the mean value of the trophic level index (TLI) in Chenghai Lake fluctuated around 40. Since 2016, the TLI in Chenghai Lake has risen above 47, and the trend is increasing year by year (Sun et al., 2019; Yan et al., 2019). Based on experiments, monitoring, and modeling, previous studies highlight that nutrient enrichment could be the most important driver of algae growth (Dou et al., 2019; El Asri et al., 2017; Glibert, 2017; 2020). Thus, it has been subject to cyanobacterial bloom outburst in Chenghai Lake during recent years (Zan et al., 2012). Two water transfer sources (Baqing River and Jinsha River) have been proposed by local government in order to deal with the deterioration of water quality and the continuous decline in water level. On the basis of the aforementioned considerations, this study aims to: 1) predict the changes in water quality and evaluate the risk of algal blooms in Chenghai Lake induced by water transfer through algal growth potential (AGP) test; 2) explore the influence mechanism in algal growth resulting from water transfer.

1. Study area

Chenghai Lake (26°27′~26°38′ N, 100°38′~100°41′ E), is a typical plateau lake located in northwestern Yunnan, China (Yan et al., 2019), which belongs to the mid-stream area of Jinsha River, Yangtze River basin (Fig. 1). The lake is 19 km long with an average width of 4.3 km. It has a water area of about 72.9 km^2, a mean water depth of 23.7 m, and an annual average water temperature of 17.8°C. The mean annual precipitation is 738.6 mm and more than 80% of the annual precipitation falls during the summer season (Chen et al., 2019; Sun et al., 2019; Yan et al., 2019). Chenghai Lake plays an important role in flood-mitigation storage and biodiversity protection. Since 1960, the water level of Chenghai Lake has progressively dropped, and it has now evolved into a closed lake (Chen et al., 2019). As a result, since there are no perennial

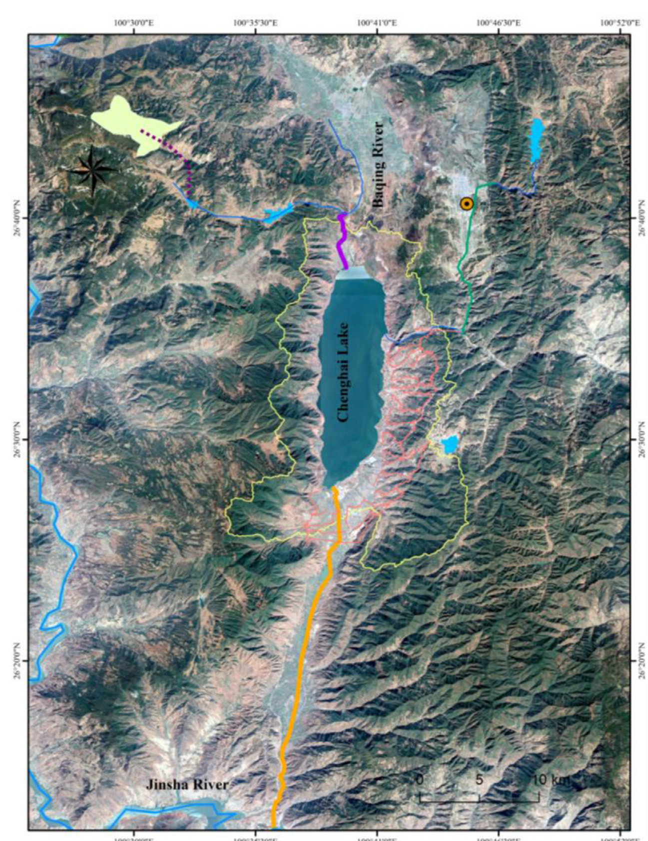

Fig. 1 – Location of Chenghai Lake and routes of water transfer.

inlet or outflow streams in the catchment, it is mainly fed by groundwater and precipitation, and the lake water is slightly brackish and alkaline (Chen et al., 2019; Zheng et al., 2019). By May 2019, Chenghai Lake was 3.8 meters below the permissible minimum control line (1499.2 m). Meanwhile, as there is little water exchange, the eutrophication problem of Chenghai Lake is gradually increasing. The lake remained oligotrophic before the 1910s, and then evolved to a mesotrophic state in 1999. The nutrient levels continued to increase and the lake became eutrophic in the 2000s (Liu et al., 2015). Baqing River and Jinsha River are the water sources in Lijiang City, Yunnan Province (Fig. 1). Baqing River is located in Sanchuan Town (26°40′˜27°08′ N, 100°26′˜100°00′ E), Yongsheng County, Yunnan Province, with an average annual rainfall of 935.4 mm. Jinsha River is located in the southeast of Yongsheng county with a mean annual precipitation of 834 mm. Water quality in two rivers are better than that in Chenghai Lake. Two water transfer schemes were put forward according to the actual local situation. One was proposed based on the annual water loss of Chenghai Lake, and the quantity of water transfer was equal to the loss with an annual water supply of 2.9×10^7 m^3 (Scheme 1). The detailed scheme is described in Appendix A Table S1. The other scheme was established to further evaluate the impact of a larger water transfer capacity on Chenghai Lake with an annual water supply of 1.63×10^8 m^3 (Scheme 2).

2. Materials and methods

2.1. Field sampling and analysis

Water samples from Chenghai Lake, Baqing River, and Jinsha River were all collected under sunny weather conditions to minimize the effects of rainfall in March 2019. The surface water samples were collected in acid-washed10-liter plastic buckets. pH, conductivity (Cond), redox potential (ORP), and total dissolved solids (TDS) were measured on site using a hand-held multi-parameter meter (MYRON L 6P, USA). Total nitrogen (TN), and total phosphorus (TP) were analyzed according to standard methods (Huang et al., 2000). Chloroform, used as a fixing reagent, was added to each sample before the determination of TN and TP. The samples were analyzed within 2 weeks and stored at 4°C before analysis.

2.2. Algal growth potential test

A simulation experiment of AGP was performed to investigate the growth of phytoplankton after water transfer. The simulation time for Scheme 1 and Scheme 2 can reach the year of 2050 and 2030, respectively. All water samples were added into the culture bottles according to the scheme and put into an incubation cabinet under a 14 hr:10 hr light/dark cycle with a light intensity of 5000 lux. The temperatures in light and dark phases were 28°C and 23°C, respectively. TN, TP, pH, and Turbidity were tested for each group. The algal cell density was recorded in regular intervals every other day. The detailed experimental method is presented in Appendix A Text S1.

2.3. Algal cell density detection

The density of algal cells was analyzed by a flow cytometer (Novocyte 1040, USA). The detection wavelengths of BL1 and BL2 channels were 570 nm and 575 nm, respectively. Full details of the cell density analysis are presented in Appendix A Text S2 (Yang et al., 2020b; Zhang et al., 2020). The reduction rate of algal density was calculated by the following formula: Reduction rate of algal density (%) = $[(C_0–C_t)/C_0] \times 100\%$, where C_0 and C_t represent the initial algal cell density and the algal cell density in year *t*, respectively.

Table 1 – Initial water quality status of the three water sources.

Parameter	Chenghai Lake	Baqing River	Jinsha River
pH	9.42±0.18	8.32±0.10	8.03±0.16
ORP (mV)	164±4	187±2	227±6
Cond (μS/cm)	1269±15	105±8	487±11
TDS (mg/L)	895.2±9.5	66.9±2.5	331.4±10.2
TN (mg/L)	1.26±0.03	0.84±0.02	0.42±0.02
TP (mg/L)	0.06±0.01	0.03±0.01	0.01±0.00
Algal density (10^4 cells/L)	557.5±10.8	79.5±3.6	3.0±0.4

2.4. Qualitative and quantitative analysis of phytoplankton

The phytoplankton were fixed immediately with Lugol iodine solution (2%) after sampling. The fixed samples were concentrated to 10-20 mL after being settled for 48 hr (Hilaluddin et al., 2020; Pan et al., 2020). The qualitative and quantitative analysis of phytoplankton samples were performed under an inverted microscope (Hu and Wei, 2006). The entire chamber was examined, and each cell was counted as a unit.

3. Results and discussion

3.1. Water quality analysis of water sources

Water quality, which reflects the degree of eutrophication, is one of the important parameters for assessing water transfer projects (Purvis and Dinar, 2020; Zhang et al., 2019). Eutrophication has been affecting the ecological health of many lakes and reservoirs worldwide. Table 1 shows the water quality of the three water sources. Obviously, the general water quality of Chenghai Lake is poor, and is worse than the previous report (Zan et al., 2012). The density of algae cells was 5.57×10^6 cells/L, corresponding to risk for algal blooms (Fang et al., 2019; Xin et al., 2020). We found that the water quality of Baqing River and Jinsha River was significantly better than Chenghai Lake. Water transfer has been regarded as one of the most effective solutions to alleviate the aforementioned problems induced by water-level drawdown in lakes. This provides the possibility to solve the problems of water quality deterioration and water level drawdown simultaneously by water transfer.

3.2. Changes in water quality after proposed water transfer

To assess the feasibility of proposed water transfer projects, many researchers have focused on the potential changes in

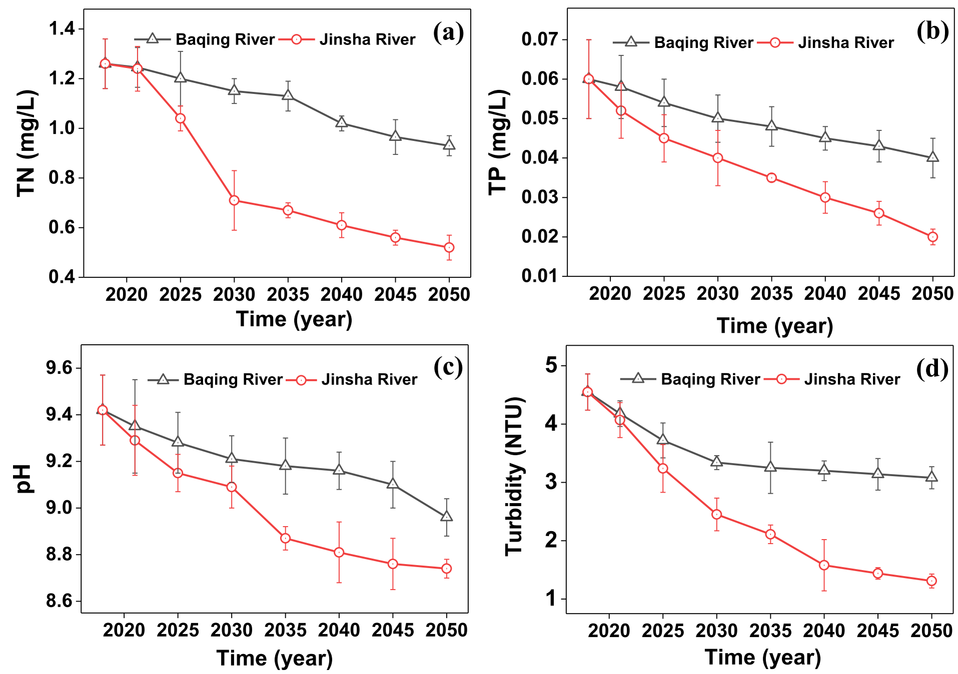

Fig. 2 – Changes in the water quality in Chenghai Lake after simulated water transfer from Baqing River and Jinsha River. The simulated range of years is from 2020 to 2050. The results shown are mean data from triplicate experiments, and error bars indicate standard deviations based on triplicate analyses. (a) TN; (b) TP; (c) pH; (d) Turbidity.

water quality (Yao et al., 2019; Zeng et al., 2015). As we can see from Fig. 2, the water quality in Chenghai Lake can be improved after simulated water transfer. TN and TP values could be decreased by 28.3% and 33.3% respectively with the simulated water transfer from Baqing River, while the mean value of pH would be reduced from 9.42 to 8.82. In addition, TN and TP values in Chenghai Lake could be decreased to 0.52 mg/L and 0.02 mg/L respectively with the simulated water transfer source of Jinsha River, and the turbidity could be decreased to 1.3 NTU. The critical values of TN and TP for eutrophication were reported to be 0.2 mg/L and 0.02 mg/L, respectively (Li et al., 2020; Zhang et al., 2018). Although the concentrations of TN and TP for Lake Chenghai could be decreased after simulated water transfer from Baqing River, they were both beyond the reported limiting concentration of eutrophication (Rolle Longley et al., 2019; Zhou et al., 2020). Water transfer from Baqing River hardly worked in reducing the eutrophication of Chenghai Lake, which meant that there was still a risk of algal blooms (Yan et al., 2021). Therefore, it is necessary to consider the water transfer from the perspective of the phytoplankton community to further explore which water source is more suitable for Chenghai Lake.

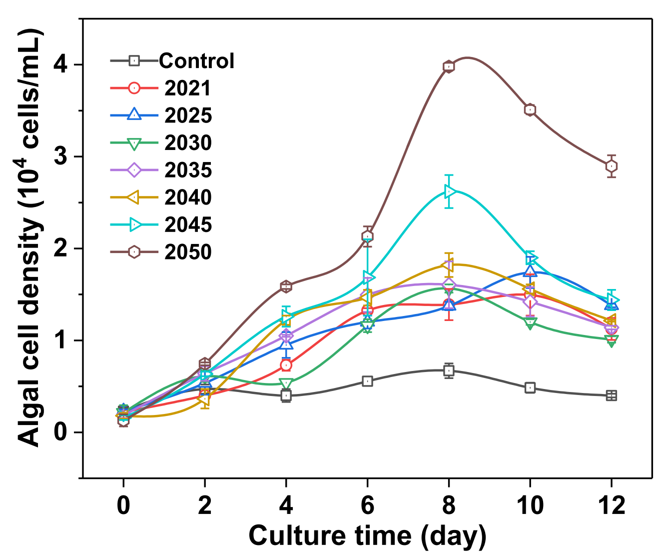

Fig. 3 – Changes in the algal density in Chenghai Lake after simulated water transfer from Baqing River (Scheme 1). The results shown are mean data from triplicate experiments, and error bars indicate standard deviations based on triplicate analyses.

3.3. Algal bloom risk assessment after proposed water transfer

The growth of planktonic algae is highly dependent on the physicochemical parameters (Hu et al., 2020; Jiang et al., 2019). Changes in water quality caused by water transfer will affect the growth of algae (Wu et al., 2019a; Zhong et al., 2019). Algal cell density was monitored to investigate the possibility of algal blooms after simulated water transfer from Baqing River (Fig. 3). These results suggested that algae proliferation would be promoted rather than controlled after the simulated water transfer. In all treatments, algal cell density appeared to peak after being cultured for 8 days. The peak value of algal cell

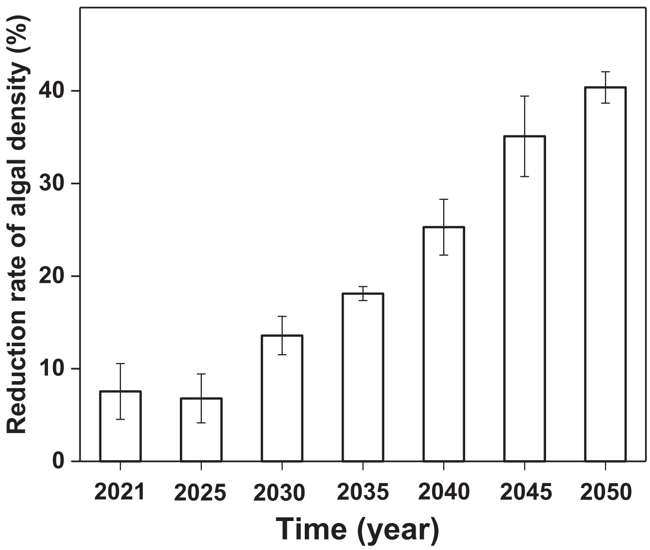

Fig. 4 – Reduction rate of algal density in Chenghai Lake after simulated water transfer from Jinsha River (Scheme 1). The results shown are mean data from triplicate experiments, and error bars indicate standard deviations based on triplicate analyses.

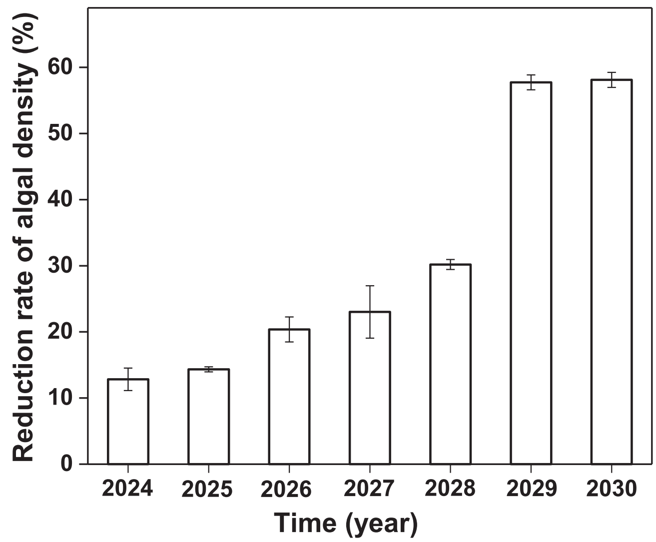

Fig. 5 – Reduction rate of algal density in Chenghai Lake after simulated water transfer from Jinsha River (Scheme 2). The results shown are mean data from triplicate experiments, and error bars indicate standard deviations based on triplicate analyses.

density also increased with the prolonging of water transfer. After 2045, the peak value of algal cell density could on the brink of 40 million cells/L, reaching mild bloom level (Jiang et al., 2019). In the case of a lower algal cell density in 2025 than in 2021, we hypothesize that the contrast may be partly due to species competition. In addition, changes in the algal density in Chenghai Lake after simulated water transfer from Baqing River for Scheme 2 are shown in Appendix A Fig. S1. The results of Scheme 2 were found to be similar to those of Scheme 1 and also showed that there were risks in the water transfer of Baqing River. Therefore, the Baqing River water transfer project would not eliminate the risk of algal blooms, even with the improved water quality. For the Jinsha River water transfer project, the risk of algal blooms was assessed firstly with the same water transfer project as proposed for Baqing River. As we can see from Fig. 4, the reduction rate of algal cell density increased with the extension of simulated water transfer from Jinsha River. Although the reduction rate of algal density did not change markedly compared with the control group before 2025, it could reach more than 20% after 2035. The maximum reduction rate of algal density could cumulatively amount to 45%. In short, simulation results indicated that the water transfer project of Jinsha River could reduce the risk of algal blooms in Lake Chenghai.

To further assess the effect of mass water transfer from Jinsha River, an additional simulation experiment (Scheme 2) was conducted with an annual water supply of 1.63×10^8 m^3. As shown in Fig. 5, the increase of algal cell density was remarkably controlled, and the reduction rate of algal density was nearly 60% after 2029. Overall, this water transfer scheme could greatly alleviate the original risk of algal bloom outburst in Chenghai Lake, which further verified the feasibility of the Jinsha River water transfer project.

3.4. *Proposed influence mechanism in algal growth*

Phytoplankton diversity is considered to be an important ecological parameter in lakes. Because of their short life spans, phytoplankton can respond quickly to environmental changes (Bondarenko et al., 2020; Kang et al., 2019; Nankabirwa et al., 2019; Wu et al., 2019a). Therefore, it provides us the possibility to find the influence mechanism for algal growth resulting from water transfer from the perspective of the phytoplankton community structure.

Scheme1 was taken as a typical example to analyze the phytoplankton community. The change in the phytoplankton community in Chenghai Lake before and after simulated water transfer is summarized in Fig. 6. The dominant species was determined to be *Anabaena cylindrica* for both Baqing River and Chenghai Lake. Thus, the water transfer from Baqing River could not cause a large amount of competition between algae. In addition, the pH value slowly decreased from 9.5 to 8.88 with the increased water transfer quantity. Many studies have shown that the optimum pH for algal growth is 8.5 (Imhoff et al., 2009; Liu et al., 2020), and the decreased pH value after water transfer was closer to the reported optimum pH. Therefore, it can be speculated that both the decreased pH and the same dominant species in the two water bodies created a more suitable environment for promoting the rapid growth of algae. However, the dominant species in Jinsha River and Chenghai Lake are different. There would be competition between the different dominant algae species in Jinsha River and Chenghai Lake. In the simulation, the dominant species of *Anabaena cylindrica* evolved into *Anabaenopsis arnoldii* after water transfer. The importance of competition for limiting the establishment and proliferation of other nuisance species has been well supported in the literature. Once pH, salinity, temperature or light levels are favorable, some algae

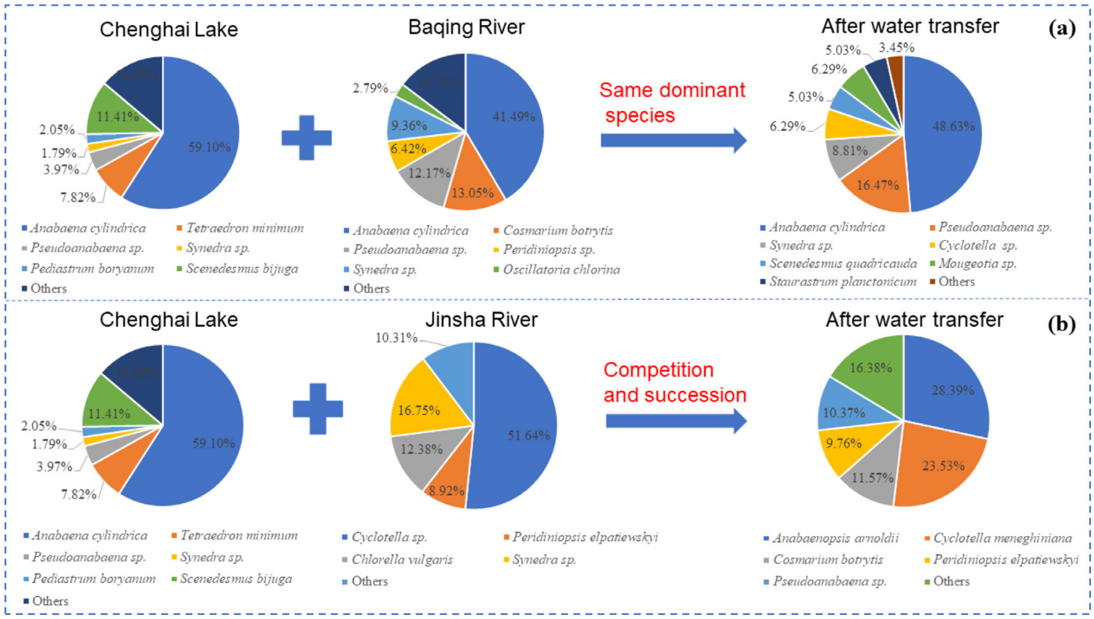

Fig. 6 – Schematic diagram of algae succession in Chenghai Lake before and after simulated water transfer for Scheme 1. (a) Baqing River; (b) Jinsha River.

species growth occurs. There are interesting similarities and significant differences in the influences of important environmental factors on competition between these harmful algal species. However, even when abiotic conditions could be favorable for biotic interactions, such as competition among different algae species, it may promote the succession of species (Buenau et al., 2012; Neury-Ormanni et al., 2020; Nolan and Cardinale, 2019; Wang, 2015).

As mentioned previously, we found that the concentration of TN and TP in Chenghai Lake decreased after simulated water transfer from Jinsha River. Meanwhile the growth of algal density could be controlled with the increase of species diversity and evenness. Owing to the decrease in the nutrient concentration (Fig. 2), direct competition among different dominant species could drive niche partitioning between members of these species groups. Finally, the transfer would cause significant changes in phytoplankton community structure. The N/P ratio in water can affect the biochemical composition of algal biomass (Liu and Vyverman, 2015). The N/P ratio in Jinsha River was twice that in Baqing River and Chenghai Lake. This means that phosphate may soon be consumed after simulated water transfer from Jinsha River and may limit the growth of algae. Taking Scheme 1 as an example, the main categories of algae in Chenghai Lake before and after simulated water transfer from Jinsha River are shown in Fig. 7. Overall, the phytoplankton community of Chenghai Lake was dominated by Cyanobacteria and Chlorophyta, which was reported to be the hallmark of a eutrophic lake (Garmendia et al., 2013; Matthews and Odermatt, 2015; Nankabirwa et al., 2019; O'Neil et al., 2012). The Cyanobacteria and Chlorophyta in Chenghai Lake accounted for 62.3% and 32.5%, respectively. Although Cyanobacteria was still the dominant species after simulated water transfer, the proportion of Cyanobacteria and Chlorophyta was significantly lower than before. The proportion of Cyanobacteria, Chlorophyta, Diatoms, and Dinoflagellate was 40.7%, 22.5%, 28.4%, and 8.4%, respectively. Furthermore, the presence of dinoflagellates indicated that the water could gradually become clearer (Deng et al., 2016; Skinner et al., 2013). It could be speculated that Cyanobacteria may lose their dominant position with prolonged water transfer.

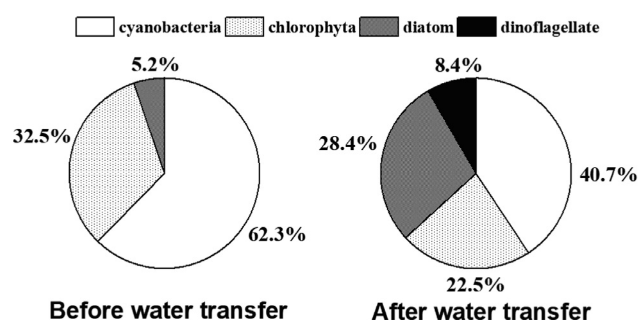

Fig. 7 – Changes in the phytoplankton community structure in Chenghai Lake before and after simulated water transfer from Jinsha River (Scheme 1).

4. Conclusions

In the present study, we investigated and predicted the changes in water quality and evaluated the risk of algal blooms in Chenghai Lake induced by water transfer through algal growth potential (AGP) test. Our study showed that the concentration of TN and TP in Chenghai Lake could be decreased by 28.3% and 33.3% respectively after simulated water transfer from Baqing River. However, the Baqing River water transfer project would increase the risk of algal blooms, which may be caused by suitable pH and same dominant algae species. Conversely, due to the competition of different dominant algae species and reduction in nutrients, the proliferation of algal density could be controlled after simulated water transfer from Jinsha River, and the species of phytoplankton greatly increased in diversity. Our findings highlighted the importance of considering phytoplankton community in designing water transfer projects for solving the problems of water quality deterioration and water level drawdown in lakes. In addition to focusing on changes in water quality, it is necessary to investigate the changes in the phytoplankton community to improve the evaluation system for water transfer projects.

Acknowledgments

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Appendix A Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2020.10.020.

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