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Views & Comments

Water Diversion is Not to Blame for Phosphorus Enrichment in Taihu Lake

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Despite frequent cyanobacterial blooms increasing in magnitude and duration, Taihu Lake remains one of the most important water sources in the Yangtze River Delta of China. To meet the rising water demand from social–economic development and secure water source during cyanobacterial blooms, the Water Diversion Project from the Yangtze River to Taihu Lake (WDYT) through the Wangyuhe (WYH) River channel was initiated in 2002 and has been in operation since 2007. In the past twenty years, the WDYT has been widely recognized as an urgent and effective engineering measure to increase water resources, ameliorate the hydrodynamics and water quality conditions, and safeguard the water supply of Taihu Basin [1]. However, the impact of river-to-lake water diversion on phosphorus load of Taihu Lake has always been controversial. Debaters put forth some claims that WDYT caused the increase in average phosphorus concentration of Taihu Lake and thus the dramatic expansion of cyanobacterial blooms in recent years. Since the Yangtze River has a higher average phosphorus concentration than Taihu Lake, some previous studies have alleged that water diversion transferred allochthonous nutrients from the Yangtze River to Taihu Lake and is responsible for the dramatic increase in phosphorus loading of Taihu Lake in recent years [2]. Others insist that the high average phosphorus concentration of Taihu Lake should be attributed to the increase in total phosphorus input of Taihu Lake but not water diversion [3]. Phosphorus has been regarded as the prime limiting nutrient element for cyanobacterial bloom development and cyanotoxin synthesis in most lake ecosystems [4]. Hence, research on toxic cyanobacterial blooms caused by excessive phosphorus loading occurring in Taihu Lake have focused on arresting bloom formation and restoring the drinking water sources to acceptable water quality conditions by reducing phosphorus inputs [5]. Therefore, accurate source identification of phosphorus influx into Taihu Lake and quantitative contribution analysis of phosphorus input of water diversion from the Yangtze River to Taihu Lake would ensure a rational public understanding of the effect of WDYT and provide a critical response to this controversial issue. Meanwhile, our study on the eco-environmental impact of WDYT would provide constructive guidance for water resource management of Taihu Basin and phosphorus load control of the second stage of WDYT.

In this study, we collected annual statistical data at the basin level from 2002 to 2019 to explore the contribution of water diversion from the Yangtze River to water inflow and phosphorus input of Taihu Lake (methodology of data collection and analysis shown in Table S1 in Appendix A). The total water inflow of Taihu Lake and that from Huxi Region showed an increasing stepwise trajectory over the past twenty years (Fig. 1(a)). However, WDYT contributed only 0.9%–14.7% of total water inflow of Taihu Lake and the diverted water inflow from WYH River has gradually decreased

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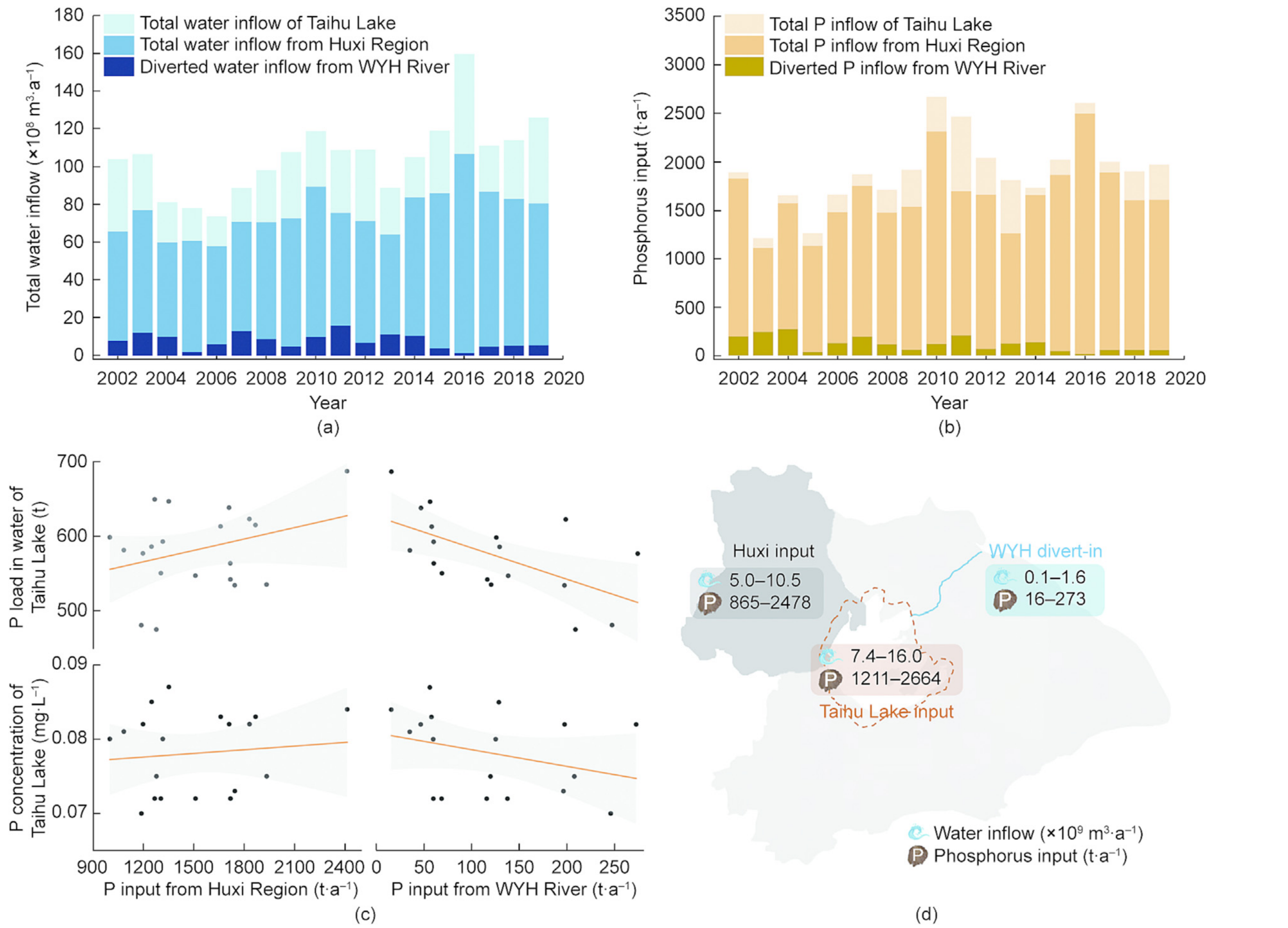

Fig. 1. Contribution of water diversion to phosphorus (P) load and concentration in Taihu Lake. (a) Yearly variation in total water inflow of Taihu Lake, total water inflow from Huxi Region, and diverted water inflow from WYH River between 2002 and 2019. (b) Yearly variation in total phosphorus input of Taihu Lake, total phosphorus input from Huxi Region, and diverted phosphorus input from WYH River between 2002 and 2019. (c) Effect of phosphorus input from Huxi Region and WYH River on phosphorus load and concentration of Taihu Lake since 2002. Each data point represents a different year. (d) Spatial distribution of water inflow and phosphorus input of Taihu Lake, and water inflow and phosphorus input from Huxi Region and WYH River since 2002. The data represent the variation range of water inflow and phosphorus input between 2002 and 2019.

by 2.3% since 2002. The yearly averages of total water inflow of Taihu Lake increased by 2.8 $\times$ 10^9 m^3 from 1986–2001 to 2002–2019, while the yearly averages of diverted inflow of WDYT was only 7.9 $\times$ 10^8 m^3 during 2002–2019. Our study revealed that water diversion from the Yangtze River to Taihu Lake should not take responsibility for the increase in water inflow of Taihu Lake. The WYH River served as an emergency controlling measure of water compensation, primarily in autumn and winter, to adjust the water level of Taihu Lake, prevent the formation of large-scale harmful algal blooms (HABs), and ensure the water quality of drinking water sources of Gonghu Lake. The increase in total water inflow of Taihu Lake primarily resulted from the increase in water inflow from the Huxi Region, which was interactively influenced by rainfall, land surface, river channel dredging, and increased water withdrawal from the Yangtze River. Water inflow from the Huxi Region increased by 65% after 2009, with its proportion to total water inflow of Taihu Lake ranging from 55.2% to 64.7%. The rapid urbanization process has induced changes in land use of the Huxi Region, with developed area quadrupled and runoff coefficient increasing by 60% since 1985 (Fig. S1 in Appendix A). With average rainfall frequency lower than 40%, mean annual precipitation of the Huxi Region increased by 160 mm and rainfall runoffs in the Huxi Region increased by 1.5 $\times$ 10^9 m^3 after 2009. Meanwhile, river channel dredging and improvement has accelerated regional water flow and exchange. For instance, reconstruction and improvement of the Danjinlicao River and Wushen Canal in the Huxi Region (locations shown in Fig. S2 in Appendix A) has largely enhanced water inflow of the Chengdonggang River, which account for 55% of total water inflow from the Huxi Region in 2005 and 70% in 2018. The increase of water inflow from Huxi Region could also be related to the large improvement of water intake capacity of all pumping stations along the Yangtze River after a series of upgrading and reconstruction projects around 2000. Answering the local need of inland water transportation, farmland irrigation, and water environment amelioration of regional river network, the main pumping stations along the Yangtze River promoted water withdrawal in lack of basin-level overall planning and caused unexpected increase in water inflow from Huxi Region in recent years. For instance, water withdrawal from the Jianbi and Jiuquhe Pumping Station (locations shown in Fig. S2), accounting for 30% of total water withdrawal from the Yangtze River in the Huxi Region, is responsible for water quality protection of three national inspection sections, controlling the ecological water level of Danyang City, and 1667 km^2 farmland irrigation of the Huxi Region. However, the yearly average water withdrawal of these two pumping stations increased from 1.7 $\times$ 10^8 m^3 during 1986–2006 to 4.6 $\times$ 10^8 m^3 during 2007–2016 and 14.6 $\times$ 10^8 m^3 during 2017–2018. Similarly, the excessive water withdrawal from the Yangtze River and the regular out-pumping of Meiliang Bay have caused the water level to rise in the Grand

Canal, flow direction alteration, and water resource reallocation of the river network of the Huxi Region; consequently, 2.5×10^8–7.0×10^8 $m^3 \cdot a^{-1}$ water flow is transferred from the Grand Canal to Taihu Lake via the Huxi Region.

Water Diversion Project from the Yangtze River to Taihu Lake through the WYH River channel is not responsible for the increase in phosphorus loading in Taihu Lake. In parallel to water inflow, total phosphorus input of inflowing rivers of Taihu Lake and that from Huxi Region showed an obvious increasing trend in the last twenty years, while diverted phosphorus input from the WYH River gradually decreased by 9.5% (Fig. 1(b)). WDYT only diverted an annual average of 9.8% and 4.3% of total phosphorus input of Taihu Lake during 2002–2009 and 2010–2019, respectively. The negative correlation between diverted phosphorus input from WDYT and phosphorus concentration of Taihu Lake indicated that the dilution effect of divert-in water flow from the Yangtze River contributed positively to the amelioration of water quality of Taihu Lake (Fig. 1(c)). The high phosphorus load and concentration of Taihu Lake showed a significantly positive correlation with local phosphorus input from the Huxi Region instead of the divert-in phosphorus burden from the Yangtze River. The Huxi Region, whose phosphorus input has increased by 34% over the last twenty years, contributed 57.8–95.3% (78% on average) of total phosphorus input of Taihu Lake (Fig. 1(d)). The decreasing proportion of diverted phosphorus input from WYH River in recent years should be attributed to the decreasing total phosphorus concentration of diverted water inflow of WYH River and the increasing local phosphorus loading of the Huxi Region. The Taihu Basin Authority, which is in charge of the regulation of WYH Project, executes the diversion of allochthonous water from the Yangtze River into Taihu Lake through the WYH River only after the inflow water quality of WYH River reaches or precedes the third level of national surface water quality standards in China (total phosphorus concentration <0.2 $mg \cdot L^{-1}$) [6]. Despite the phosphorus influx from tributaries along the river channel, average total phosphorus concentration of the WYH River has decreased from 0.18 to 0.09 $mg \cdot L^{-1}$ since 2002 (Fig. S3 in Appendix A), which is substantially lower than those of the inflowing rivers in the Huxi Region (decreasing from 0.35 to 0.18 $mg \cdot L^{-1}$) and the threshold value of dispatching rule of the WYH Water Diversion Project [7].

Although the contribution of WDYT to the phosphorus inventory of Taihu Lake is negligible, the chronic effect of WDYT on the internal phosphorus cycling should be tracked in future works. From the mass balance point of view, 800–1000 t of phosphorus are annually retained in the lake and the sediment of Lake Taihu is still a phosphorus sink at present [8]. Previous study revealed that WDYT caused an increase in the proportion of particulate phosphorus in Taihu Lake (particularly in Gonghu Lake) and reversion of the current phosphorus sedimentation–release balance might be the long-term result [3]. The new overall pattern of "two diversions and three drainages" of Taihu Lake has taken shape (Fig. S4 in Appendix A). As a key component of the second stage of WDYT, Xinmenghe River directly transfers water from the Yangtze River to Zhushan Bay for the purpose of alleviating cyanobacterial blooms and improving water quality of Zhushan Bay as well as Meiliang Bay. With the expected expansion of water diversion by over 2×10^9 $m^3 \cdot a^{-1}$ from Xinmenghe River after the implement of the second stage of WDYT, the increased phosphorus contribution of WDYT may exert potential effect on the phosphorus cycling and inventory of Taihu Lake. Hence, phosphorus input control of the incoming water should be conducted in order to ensure the benefits of the ongoing WDYT. The optimal outlet path design and multi-objective joint dispatching of the new water diversion pattern should be indispensable for risk prevention of increased phosphorus load of Taihu Lake.

The increasing total phosphorus input from the Huxi Region should be attributed to expansion of local phosphorus emission over the last twenty years (Fig. 2(a)). Variation of total phosphorus input from the Huxi Region correlated with the precipitation regime. Peaks of total phosphorus input occurred in wet years, revealing that rainfall–runoff–overflow has played a major role in the generation of local phosphorus burden. It should also be cautioned that freewheeling local water withdrawal from the Yangtze River motivated by regional polluted water flushing has led to the increase in water inflow and phosphorus input from the Huxi Region. Although domestic and industrial water consumption of Taihu Basin decreased since 2007, total industrial output values and wastewater discharge of Huxi Region have been continuously increasing over the last twenty years (Table S2 in Appendix A). The effort to reduce extensive phosphorus emission has decreased the total phosphorus concentration of inflowing rivers from the Huxi Region from 0.35 to 0.18 $mg \cdot L^{-1}$ since 2002, but the enormous amount of phosphorus from wastewater discharge from phosphorus-related enterprises, domestic wastewater, and agricultural non-point source pollution keeps increasing due to the rapid economic and population development. These local phosphorus burdens would eventually enter Taihu Lake, regardless of water withdrawal from the Yangtze River promoting interior water exchange in the river network of the Huxi Region and accelerating the riverine input process of phosphorus loads. For the purpose of phosphorus reduction in Taihu Lake, local phosphorus discharge originating from the Huxi Region should be strictly controlled. Besides the increase in phosphorus input of the inflowing rivers, the rise in phosphorus concentration of Taihu Lake should also be attributed to the decline of aquatic vegetation as well as sediment resuspension and cyanobacterial blooms. Enormous historical phosphorus loading retained in Taihu Lake (about 63%–75% of external phosphorus loading) has delayed the recovery from eutrophication [9]. The substantial loss in aquatic vegetation of Taihu Lake, particularly in macrophyte-dominated eastern Taihu Lake [10], prevented the phosphorus adsorption from sediments and indirectly enhanced the wind-induced sediment resuspension so as to hamper phosphorus burial and promote the release of endogenous phosphorus, leading to a degraded underwater light climate that further inhibited the growth of aquatic vegetation. Cyanobacteria proliferation has been reported to be the driving force for bio-available phosphorus mobility between sediments and water column [11]. Despite the great effort in nutrient reduction and lake restoration for mitigating the cyanobacterial blooms, Taihu Lake has been plagued with cyanobacterial blooms in recent years [9], which accelerated the internal phosphorus cycling of the lake and promoted the release of cyanobacteria-derived phosphorus in the water column.

Overall, WDYT has substantially alleviated the formation of cyanobacterial blooms and ameliorated the hydrodynamic condition and water quality of the drinking water sources of Taihu Lake. We compared the water quality parameters of the drinking water sources (locations shown in Fig. S5 in Appendix A) before and after WYH emergent water diversion of each year for 2007, 2017, and 2020 (Fig. 2(b)), when large-scale blooming events occurred in Taihu Lake. Total nitrogen, ammonium, total phosphorus, and chemical oxygen demand decreased, and dissolved oxygen increased after emergent water diversion (Table S3 in Appendix A). The decline of chlorophyll a (Chl-a) concentration suggested that the diluting effect of emergent water diversion has been effective in alleviating cyanobacterial blooms in drinking water sources and satisfies the urgent need of water supply. According to the previous modelling results, the average velocity, water exchange rate and semi-exchange period of Gonghu Lake were significantly improved after water diversion (Table S4 in Appendix A). As the

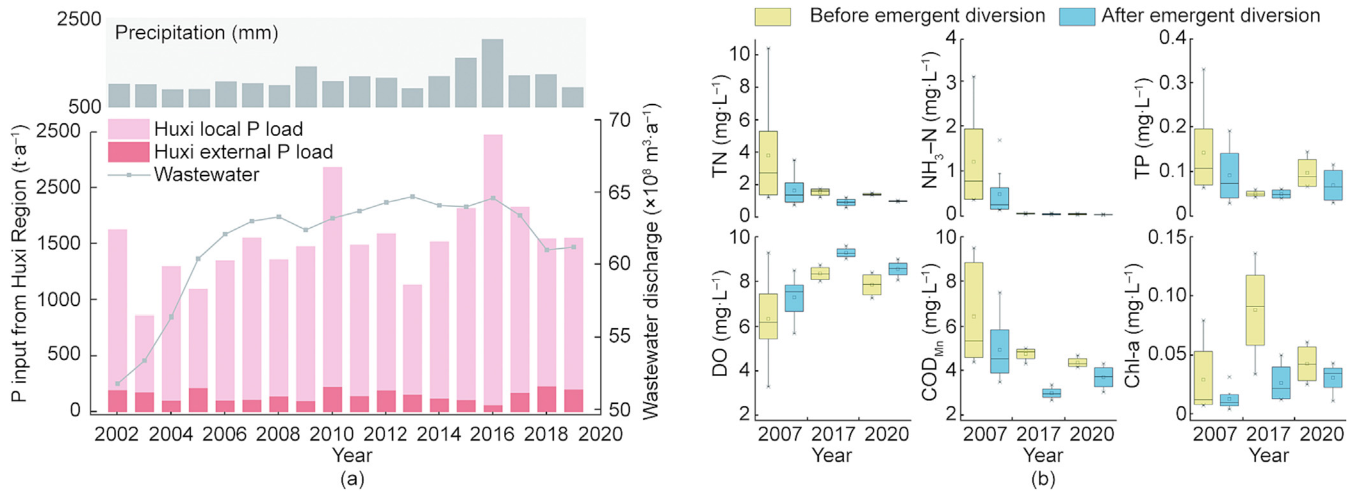

Fig. 2. Key parameters affecting phosphorus input from Huxi Region and contribution of emergent water diversion to water quality amelioration of Taihu Lake. (a) Yearly variation in precipitation, wastewater discharge, and external and local phosphorus load of Huxi Region. (b) Variation in water quality of the drinking water sources of Taihu Lake before and after emergent water diversion of the WYH River Project for each year of 2007, 2017, and 2020. The water quality averages of 10 days before and 10 days after the operation of emergent water diversion were compared for each year. TN: total nitrogen; TP: total phosphorus; DO: dissolved oxygen; COD_{Mn}: chemical oxygen demand (using $KMnO_4$ as the oxidant); Chl-a: chlorophyll a.

direct water-receiving area of WDYT, Gonghu Lake has been reported to have a lower phosphorus concentration than Central Lake, Zhushan Bay, and Meiliang Bay in Taihu Lake [12–14]. Although the average phosphorus concentration of WDYT was greater than that of Gonghu Lake for most of the time during the water diversion period, the transferred water commonly contained over 60% particulate phosphorus [15] and its total phosphorus concentration rapidly decreased to the level comparable to or relatively lower than that of Gonghu Lake through sedimentation after entering the lake [16]. Notably, the average total phosphorus concentration of WDYT influent water has decreased below that of Gonghu Lake since 2020 because of the comprehensive water environment management and tributary pollution control of the WYH River [17]. WDYT can preferentially enhance water exchange and nutrient dilution, and substantially improved self-purification capacity for the drinking water sources of Gonghu Lake. Due to its extra phosphorus burden to Taihu Lake, WDYT should only be used as an emergency measure to raise the water level, abate the blooming risk, or ameliorate the water quality of the drinking water sources. Otherwise, the water transfer may pose a threat to eutrophication management of Taihu Lake if the phosphorus concentration of the influent water was not cut down to a reasonable level.

Although water diversion from the Yangtze River has been bringing extra phosphorus load into Taihu Lake, the aggravation of cyanobacterial blooms in Taihu Lake should be attributed to eutrophication exacerbated by extreme regional climate anomalies [18]. Intensive blooming events in Taihu Lake were synergistically driven by high nutrient input from basin-level flooding and a notably warm winter that was favorable for cyanobacteria recruitment. Under the synergistic effect of persistently elevated winter temperatures since 2011 and a dramatic surge of total phosphorus load of inflowing rivers due to the great flood of Taihu Basin in 2016, a record-setting cyanobacterial bloom with an area of 936 km^2 was observed in the summer of 2016 and extended to over 1400 km^2 lasting until May 2017 [19]. Surprisingly, the WYH River only contributed 0.6% of the total phosphorus input of Taihu Lake in the same year and phosphorus load of Gonghu Lake (receiving lake zone) exhibited a surprising decrease of 2.6 t compared to 2015 (Fig. S6 in Appendix A). Moreover, WDYT has benefited the water resource management by increasing the effective supply of water resources and guaranteeing the ecological and economic water demand of Taihu Lake Basin. WDYT has hampered the water level decline of Taihu Lake and the regional river network in dry seasons and under climate anomalies, avoiding that the water level of Taihu Lake dropped below 2.80 m (drought limit level). WDYT has also improved the carrying capacity of water environment and the beneficial area reached over 20 000 km^2 of Taihu Lake Basin [17].

In summary, the WDYH Project has been transferring allochthonous phosphorus loadings to Taihu Lake in recent years, but the amount and proportion is limited, and thus it is not responsible for the increase in phosphorus concentration of Taihu Lake. Increasing local phosphorus input from the Huxi Region should be primarily responsible for the high phosphorus concentration of Taihu Lake. In support of the sustainable socio–economic development of the Taihu Basin, the WDYH Project plays an important role in ameliorating the hydro-environment, alleviating cyanobacterial blooms in the drinking water sources, and improving water supply and flood control capacity of Taihu Basin. Future endeavors for phosphorus input reduction of Taihu Lake should focus on the reduction of local phosphorus input from the Huxi Region: ① cutback on phosphorus stocking of proposed lakes (Gehu Lake and Changdanghu Lake), river network, and sewage drainage pipes; ② source identification of phosphorus load at the basin-level, upgrading the effluent discharge standard of wastewater treatment plants, and stricter reduction of phosphorus emission from phosphorus-related industrial wastewater, domestic wastewater, and agricultural drainage in the Huxi Region; and ③ comprehensive monitoring and management of water withdrawal from the Yangtze River, especially to prevent polluted water flushing.

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Author contributions

Qiuwen Chen and Jianyun Zhang designed the study and methodology. Zhiyuan Wang and Hanlu Yan performed the data curation, analysis and validation. Zhiyuan Wang drafted figures and wrote original draft. Qiuwen Chen and Jianyun Zhang supervised, revised the manuscript, and provided funds and resources.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2023.07.007.

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