Science Bulletin 64 (2019) 354–356

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

News & Views

Why Lake Taihu continues to be plagued with cyanobacterial blooms through 10 years (2007–2017) efforts

Boqiang Qin [a,*], Hans W. Paerl [b,c], Justin D. Brookes [d], Jianguo Liu [e], Erik Jeppesen [f,g], Guangwei Zhu [a], Yunlin Zhang [a], Hai Xu [a], Kun Shi [a], Jianming Deng [a]

[a] State Key Laboratory for Lake Science and Environment, Nanjing Institute of Geography & Limnology, Chinese Academy of Sciences, Nanjing 210008, China
[b] The University of North Carolina at Chapel Hill, Institute of Marine Sciences, Morehead City, NC 28557, USA
[c] College of Environment, Hohai University, Nanjing 210098, China
[d] Water Research Centre, School of Biological Science, the University of Adelaide, Adelaide, SA 5005, Australia
[e] Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI 48823, USA
[f] Sino-Danish Centre for Education and Research, Beijing 100190, China
[g] Department of Bioscience and Arctic Research Centre, Aarhus University, Silkeborg DK-8600, Denmark

With the expansion of urban, industry, and agriculture after World War II, eutrophication firstly emerged as a major water quality threat in small water bodies [1]. As the increasing magnitudes and scales of nutrient pollution and habitat alteration, many of the world's large lakes exhibit symptoms of eutrophication, e.g., toxic cyanobacterial blooms, deoxygenation, and habitat loss. These symptoms were noted in shallow large lakes such as Okeechobee and Winnebago (USA), Winnipeg (Canada), Peipsi (Estonia), Balaton (Hungry), Chaohu and Taihu (China), Kasumigaura (Japan); in shallow parts of large lakes including Lakes Champlain, Ontario, and Erie (Canada/USA), Huron (USA), Maracaibo (Venezuela), Victoria (Africa); and in segments of immense water bodies such as Tanganyika (Africa) (Table S1 online). These large aquatic ecosystems pose a tremendous challenge from mitigation and restoration perspectives.

Lake Taihu, China's third largest freshwater lake (2,338.1 km^2), is located in a large, heavily-urbanized (>40 million inhabitants) and agricultural catchment (~36,500 km^2) in the Yangtze River Delta region. Since the 1990s, this shallow (<3 m) nutrient-impacted lake has experienced accelerated eutrophication accompanied by toxic cyanobacterial blooms (*Microcystis* spp.) [2]. Most of the nutrient-rich wastewater comes from the northern and northwestern regions. Combined with southerly or southeasterly winds during summertime, cyanobacterial blooms frequently occur and persist in northern or northwestern lake. In May 2007, a massive bloom overwhelmed the lake's drinking water plants, leading to a highly publicized crisis, leaving millions of local residents without potable water for nearly a week.

Lake Taihu ecological catastrophe has become a rallying cry for establishing an intensive lake restoration program, including massive investment aimed at decreasing wastewater effluent discharge [3]. A series of countermeasures addressing effluent diversion and water quality improvement has been implemented since 2007 (Table 1). For now, these activities have cost ~100 billion RMB (~US$14 billion).

Despite these significant investments in lake restoration, nutrient loading and cyanobacterial blooms have not responded as expected to abatement efforts. Total nitrogen (TN) concentrations have decreased over the last decade but still exceed 2 mg/L (Fig. 1a); mean annual total phosphorus (TP) concentrations declined slightly followed by a recent increase, but overall remain high (~0.1 mg/L, Fig. 1b). Moreover, algal biomass (chlorophyll *a* concentration (Chl *a*)) increased from 2009 to 2017 (Fig. 1c). Satellite imagery further revealed that the average extent and maximum area of the cyanobacterial bloom from 2007 to 2017 showed no decreasing trends (Table S2 online). As recent as May 16, 2017, the cyanobacterial bloom covered 1,582 km^2 (Fig. S1 online) which was the largest area of bloom coverage thus far recorded for the lake. This suggests that the nutrient reduction strategy for mitigating the cyanobacterial blooms has not led to detectable improvements in water quality until now.

Why the intensive restoration efforts have not achieved desired outcome? In fact, water discharged from wastewater treatment plants has very high nutrient concentrations that be the source of pollution for lake, but within legal limits based on the State Wastewater Emission Standard (GB18918-2002, Standard A of the first class: COD = 50 mg/L, TN = 15 mg/L, TP = 0.5 or 1 mg/L) in China. These standards historically were a compromise between what was achievable at wastewater treatment plants and what was economically acceptable. In addition, non-point pollution sources from agricultural operations, small municipalities, and rural areas, as well as atmospheric deposition have not been collected and/or treated/reduced [4]. Without tackling non-point pollutants head-on at a scale where significant reductions are achieved, expectations of lake recovery are unrealistic. In the past ten years, the external riverine input of TN and TP averaged 46,900 and 2,200 tons/a (1 ton = 1,000 kg), respectively (Fig. S2 online), which was equivalent to annual TN and TP loading prior to the drinking water crisis in 2007 [2]. On the other hand, the GDP has

---

[*] Corresponding author.
E-mail address: qinbq@niglas.ac.cn (B. Qin).

https://doi.org/10.1016/j.scib.2019.02.008

Table 1
Summary of measures taken to restore Lake Taihu since 2007.

Pollution type and management	General measures	Specific measures	Remarks
Point source pollution management	Industrial restructuring	Closed down more than 4339 chemical enterprises which did not meet the emission standards	About 1/3 of the small polluting enterprises were closed. Larger enterprises were mandated to install treatment facilities, which are hampered by inadequate funds
	Municipal domestic wastewater treatment	The number of wastewater treatment plants and treatment capacity increased from 139 and 3.23 million tons per day in 2007 to 244 and 8.48 million tons in 2016. About 95% of municipal wastewater is being collected and treated in 2016	The TN and TP concentration in treated water were 10–15 mg/L and ~0.5 mg/L, respectively, which are still much higher than the TN and TP concentrations in Lake Taihu. Increase in the efficiency of nitrogen and phosphorus removal is necessary
	Sewage pipeline network	Totally 24,500 km sewage pipelines were installed	The sewage pipeline system now covers about ~90% of large cities/urban areas but much less in small towns
Non-point source pollution management	Rural domestic wastewater treatments	More than 3,000 household-based rural domestic sewage treatment facilities have been established in the past ten years	It is far from enough as millions of household-based rural domestic wastewater treatment facilities are needed
	Ecological restoration and sustainable landuse	Totally 384 km^2 land have been reforested and ~100 km^2 wetland around the lake have been restored	This is an effective way to control diverse non-point pollution. The area of wetland for non-point pollution retention is far from what is needed
	Livestock and poultry breeding manure	2,762 small size (<500 livestock or <10,000 poultry) farming have been shut down and more than 3,000 large size livestock farming manure have been treated	There are still 9,909 livestock operations in which 4,511 are large in size. They need to be either closed or installed with treatment facilities
In-lake management	Pen-fish culture removal	Over 29,000 ha of pen-fish culture have been removed	All pen-fish culture sites distributed in upstream rivers and ponds need to be removed
	Sediment dredging	In total, about 37 million m^3 from ca. 100 km^2 polluted sediments have been dredged	Because of the large size of sediment inside lake, this dredged extent was far from what the internal loading is restrained significantly
	Blue-green algae salvage	Since 2007, over 10 million tons (wet weigh) of algae has been harvested	Because of low efficiency, new technology is urgent need to reduce the algae biomass economically
Hydrologic management	Water diversion	Since 2007, about 8.7 billion m^3 water have been diverted from the Yangtze River to the lake with high concentrations of TN and TP	Because of little effectiveness, this measure should be discontinued

doubled in the major Taihu Basin cities Wuxi, Changzhou and Huzhou since 2007 (Table S3 online). Thus it is likely that the nutrient loads and cyanobacterial blooms would have increased even further under such intense development pressure without the initial investment in restoration measures. Moreover, water diversion to flush the cyanobacteria is almost impossible because of the shortage of large quantities of unpolluted water from nearby basin. The water diverted from the nearby nutrient-enriched Yangtze River actually increased the nutrient load to Taihu (~5%–10% of total external input TN and TP) [5].

The geomorphological characteristic of the lake largely determined the nutrient cycling, which result in the most in-lake measures (e.g., the sediment dredging and bloom salvage) have no significant effect. Historical nutrient loading to Lake Taihu has increased the nutrient "legacy" stored in sediments (about 63%–75% of external P loading retained in the lake), which will delay the lake's recovery from eutrophication. As a shallow system, nutrient loss from the water column and burial through sedimentation is hampered by frequent wind-induced sediment resuspension. Cyanobacteria proliferation increases the abundance of organic aggregates in the water column. The degradation and mineralization of organic aggregates deplete the dissolved oxygen at water-sediment interface. All these factors accelerate the bio-available phosphorus releasing from sediment [6], which can sustain the cyanobacteria bloom persistence even if the external loading were diverted completely. Dredging has been aimed at reducing the internal phosphorus load in Lake Taihu. However, the small area which was dredged and the high cost for relocation make it very inappropriate, at least for now, in such large shallow system from the economic perspective (Table 1). Salvage of surface blooms is an inefficient and quantitatively insignificant method when considering the rapid algal growth rates and huge standing stock of toxic algae (Table 1).

As globe climate change, the abatement of bloom shad been hindered by warmer winters and springs to boost cyanobacterial growth [7] in recent years. During 2007–2017, the winter and spring water temperature has elevated since 2011 and peaked during the winter of 2016–2017 (Fig. S3 online). As a result of warming winter, a large cyanobacterial bloom with an area of 718 km^2 was detected by remote sensing at the end of 2016. Its influence extended to the next spring and caused a record-setting cyanobacterial bloom extent in May 2017 (Fig. S1 online). This warming and nutrient enrichment synergy has "raised the bar" for required nutrient reduction levels aimed at mitigating the blooms [8].

Although there are several lake restoration successes in Europe [9] and USA [1], these sites were either relatively small in area or deep and stratified. In fact, there is little evidence that symptoms of eutrophication in large aquatic ecosystems have been alleviated significantly [9]. In Lake Taihu, restoration has yet to be achieved despite 10-year intensive restoration. The lessons of Lake Taihu restoration demonstrate that large lakes may be quite resistant to currently-prescribed restoration efforts.

In light of the above, it is essential to push technology and policy further in order to achieve lower nutrient loading in these large systems. To enact stricter wastewater treatment standards, set mandatory nutrient reduction levels, and take more ambitious actions to reduce the non-point sources are necessary for these large lake restorations. It must be aggressively addressed because the non-point sources from over-fertilized soils in Taihu watershed [4] act as a "slow release fertilizer" and delay nutrient input reductions [10]. In the meantime, a variety of innovative technologies for internal loading reduction is urgent need for those large systems because most current in-lake measures are inappropriate from economic prospective. These new technologies should be able to treat the symptom not only efficiently, but also economically. In addition, nutrient management policy must be integrated with

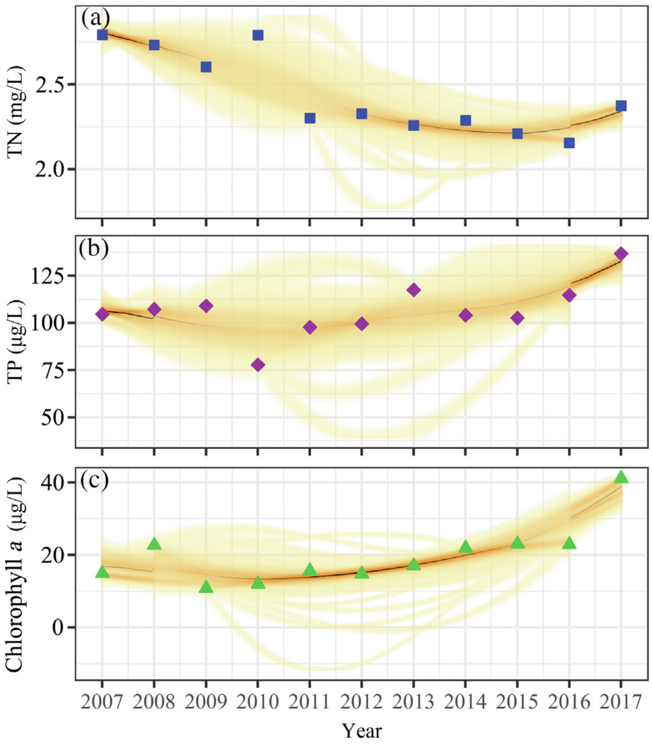

Fig. 1. Changes in concentrations of total nitrogen (TN) (a), total phosphorus (TP) (b), and chlorophyll *a* (Chl *a*) (c) since 2007 estimated from 32 monitoring sites distributed all over Lake Taihu, expressed as area weighted average.

other governance policies, such as adjustment of economic structure via services development instead of polluting industry, shifts from the historical agricultural methods to modern sustainable farming, and air-pollution policy directing what atmospheric nutrient-containing contaminants and deposition are permissible. Finally, additional steps are needed to ensure safe water and food supplies from the lakes, such as forecasts and warnings for toxic cyanobacterial blooms and advanced drinking water treatment for the removal of toxins, and taste and odor compounds.

With an increasing living standard, citizens will pursue a high quality lifestyle reliant on an aesthetically desirable environment. Managing community expectations in the policy arena is necessary. The public has witnessed a large investment to tackle nutrient inputs while the lake continues to be plagued with cyanobacterial blooms. Convincing stakeholders to continue to invest in nutrient reductions may prove challenging without evidence of rapid improvement, but it is necessary for long-term water quality improvement [9]. It is hoped that the ecological and socio-economic realities and lessons learned from Lake Taihu will benefit management steps needed to advance the protection and restoration of large lakes/waters globally.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work was supported by the National Natural Science Foundations of China (41621002, 41661134036), the Key Research Program of Frontier Sciences of the Chinese Academy of Sciences (QYZDJ-SSW-DQC008), the USA National Science Foundation (1240851), MARS Project Funded Under the 7th EU Framework Program (603378), the AU Water Technology Centre (WATEC) and the University of Adelaide Environment Institute. We thank R. Stone for helpful comments, and Jian Zhou and Feng Li for text editing. We are grateful to Taihu Laboratory for Lake Ecosystem Research, Chinese Academy of Sciences, Jiangsu General Office of Lake Taihu Water Pollution Prevention and Control, and Taihu Basin Authority, Ministry of Water Resources of China, for providing the observation data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2019.02.008.

References

[1] Cooke GD, Welch EB, Peterson S, et al. Restoration and management of lakes and reservoirs. 3rd ed. Boca Raton: CRC Press; 2005.
[2] Qin B, Xu P, Wu Q, et al. Environmental issues of lake Taihu, China. Hydrobiologia 2007;581:3–14.
[3] Stone R. China aims to turn tide against toxic lake pollution. Science 2011;333:1210–1.
[4] Huang J, Gao J, Jiang Y, et al. Sources, distribution and export coefficient of phosphorus in lowland polders of Lake Taihu Basin, China. Environ Pollut 2017;231:1274–83.
[5] Tong Y, Bu X, Chen J, et al. Estimation of nutrient discharge from the Yangtze River to the East China Sea and the identification of nutrient sources. J Hazard Mater 2016;321:728–36.
[6] Ding S, Chen M, Gong M, et al. Internal phosphorus loading from sediments causes seasonal nitrogen limitation for harmful algal blooms. Sci Total Environ 2018;625:872–84.
[7] Paerl HW, Huisman J. Blooms like it hot. Science 2008;320:57–8.
[8] Brookes JD, Carey CC. Resilience to blooms. Science 2011;334:46–7.
[9] Jeppesen E, Søndergaard M, Jensen JP, et al. Lake responses to reduced nutrient loading-an analysis of contemporary long-term data from 35 case studies. Freshwater Biol 2005;50:1747–71.
[10] Carpenter SR. Eutrophication of aquatic ecosystems: bistability and soil phosphorus. Proc Natl Acad Sci USA 2005;102:10002–5.

Boqiang Qin is a professor in Nanjing Institute of Geography & Limnology, Chinese Academy of Sciences, and Director of Taihu Laboratory for Lake Ecosystem Research. His research field includes hydrology, physical limnology, and aquatic ecology. Currently he focuses on dynamics of lake eutrophication, nutrient reduction and ecological restoration.