Environment International 123 (2019) 96–103

Contents lists available at ScienceDirect

Environment International

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

How successful are the restoration efforts of China's lakes and reservoirs?

Jiacong Huang[a,b], Yinjun Zhang[c], George B. Arhonditsis[d], Junfeng Gao[a,*], Qiuwen Chen[b,*], Naicheng Wu[e,f], Feifei Dong[d], Wenqing Shi[b]

[a] Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, 73 East Beijing Road, Nanjing 210008, China
[b] Center for Eco-Environment Research, Nanjing Hydraulic Research Institute, Nanjing 210098, China
[c] China National Environmental Monitoring Centre, 8(B) Dayangfang Beiyuan Road, Chaoyang District, Beijing 100012, China
[d] Ecological Modelling Laboratory, Department of Physical & Environmental Sciences, University of Toronto, Toronto, ON M1C 1A4, Canada
[e] Aarhus Institute of Advanced Studies, Aarhus University, Høegh-Guldbergs Gade 6B, 8000 Aarhus C, Denmark
[f] Department of Bioscience, Aarhus University, Ole Worms Allé 1, 8000 Aarhus C, Denmark

A R T I C L E I N F O

Handling Editor: Yong-Guan Zhu

Keywords:
Lakes
Restoration
Pollution
Eutrophication
Heavy metals

A B S T R A C T

China has made considerable efforts to mitigate the pollution of lakes over the past decade, but the success rate of these restoration actions at a national scale remains unclear. The present study compiled a 13-year (2005–2017) comprehensive dataset consisting of 24,319 records from China's 142 lakes and reservoirs. We developed a novel Water Quality Index (WQI-DET), customized to China's water quality classification scheme, to investigate the spatio-temporal pollution patterns. The likelihood of regime shifts during our study period is examined with a sequential algorithm. Our analysis suggests that China's lake water quality has improved and is also characterized by two WQI-DET abrupt shifts in 2007 and 2010. However, we also found that the eutrophication problems have not been eradicated and heavy metal (HM) pollution displayed an increasing trend. Our study suggests that the control of Cr, Cd and As should receive particular attention in an effort to alleviate the severity of HM pollution. Priority strategies to control HM pollution include the reduction of the contribution from mining activities and implementation of soil remediation in highly polluted areas. The mitigation efforts of lake eutrophication are more complicated due to the increasing importance of internal nutrient loading that can profoundly modulate the magnitude and timing of system response to external nutrient loading reduction strategies. We also contend that the development of a rigorous framework to quantify the socioeconomic benefits from well-functioning lake and reservoir ecosystems is critically important to gain leeway and keep the investments to the environment going, especially if the water quality improvements in many Chinese lakes and reservoirs are not realized in a timely manner.

1. Introduction

Covering a small part (1.8%) of earth's surface (Messager et al., 2016), lake ecosystems provide considerable services to human society including drinking water supply, transportation, recreation, and fisheries. However, the water quality degradation has become a global problem, following the rapid post-World War II economic development (Conley et al., 2009; Hering et al., 2015; Michalak et al., 2013; Stone, 2011; Ulrich et al., 2016). Water quality deterioration may be manifested as toxic algal blooms, prolonged hypoxia, severe contamination, which can collectively undermine the integrity of biotic communities and ultimately lead to loss of biodiversity (Dudgeon et al., 2006; Smith and Schindler, 2009).

China's lake water quality is increasingly disconcerting due to the hazardous impacts of water quality deterioration (Tong et al., 2017; Zhou et al., 2017). Water resources in nearly half of 634 Chinese rivers, lakes and reservoirs are polluted, failing to meet drinking water standards for all or parts of the year. According to a 2009 nationwide survey, one-quarter of 4000 urban water-treatment plants did not comply with quality controls. These worrisome trends of water pollution are responsible for an annual shortage of 40 billion tons of water in China (Tao and Xin, 2014). In May 2007, a severe algal bloom event in Lake Taihu resulted in a drinking water crisis, affecting the drinking water supply for approximately 2 million people in Wuxi, China (Qin et al., 2010). In order to improve China's lake water quality, substantial investments from the Chinese Central government have been made to

* Corresponding authors.
E-mail addresses: gaojunf@niglas.ac.cn (J. Gao), qwchen@nhri.cn (Q. Chen).

https://doi.org/10.1016/j.envint.2018.11.048
Received 8 October 2018; Received in revised form 17 November 2018; Accepted 19 November 2018

environmental remediation (Zhou et al., 2017). Between the 2005–2017 period, the Central government of China has introduced a wide range of strict laws, plans and guidelines, including the Guidelines on Strengthening Water Environmental Protection for Critical Lakes in 2008 and the Water Pollution Control Action Plan (10-Point Water Plan) in 2015 (Table S1 in the Supporting Information).

Given the ominous water quality trends, China's lake water quality has been extensively studied with special emphasis on topics, such as eutrophication (Ni et al., 2016; Tong et al., 2017), harmful algal blooms (Duan et al., 2017; Stone, 2011), and nutrient loading (Cui et al., 2013; Liu et al., 2013; Yi et al., 2017). Three large eutrophic lakes (Lakes Taihu, Chaohu, and Dianchi) have received considerable attention due to their severe pollution and dire ramifications for the urban populations in the surrounding watersheds (Huang et al., 2018; Wu et al., 2017a; Yang et al., 2008). However, little work has been done to evaluate the progress made with respect to the efficiency of water quality mitigation measures at a national scale, likely due to the challenges in obtaining datasets that impartially represent all the geographic regions in China. Based on national records of dissolved oxygen (DO), chemical oxygen demand (COD), and ammonium (NH_4^+), Zhou et al. (2017) reached the conclusion that China's increasing gross domestic product (GDP) during the 2006–2015 period did not occur at the expense of its inland waters, which was highlighted as a promising prospect about our ability to effectively balance between economic growth and environmental sustainability (Zhou et al., 2017). Nonetheless, the sole use of three indicators may not be adequate to capture the multifaceted nature of China's water quality problems. Viewed from this standpoint, the question regarding the degree of success of the restoration efforts in China's lakes and reservoirs has not been unequivocally addressed and invites further investigation.

To this end, we compiled a 13-year (2005–2017) dataset comprising 24,319 records from 142 lakes and reservoirs at a national scale to examine the trends of water quality in China's lakes and reservoirs. Counter to Zhou et al.'s (2017) study, our work offers a more comprehensive assessment of the water quality trends based on twelve (12) environmental quality indicators established in the literature. Our aim is to delineate the presence of distinct spatio-temporal trends and pinpoint promising trajectories and striking problems. Our study also provides recommendations that will consolidate the on-going remediation efforts of eutrophication and heavy metal (HM) pollution, including the rigorous valuation of ecosystem services and the establishment of quality standards that can reliably capture the impact of the multitude of external stressors on China's lakes and reservoirs.

2. Material and methods

2.1. Study area and data

In China, according to a national survey with satellite images during the 2004–2007 period, there is a total of 2693 lakes (surface area > 1 km^2) covering 81,415 km^2 (Ma et al., 2011). There are also 89,700 reservoirs covering 26,870 km^2 (Yang and Lu, 2014). To address the objectives of our study, we obtained a water quality dataset from the national sampling program in environmentally or socioeconomically important lakes and reservoirs conducted by the China National Environmental Monitoring Centre (http://www.cnemc.cn/). To the best of our knowledge, the present dataset is by far the most intensive to comprehensively represent China's lake and reservoir water quality:

- The large dataset with 24,319 records covered a 13-year (2005–2017) period with a monthly resolution at 80 lakes and 62 reservoirs across 31 Provinces in China (Fig. 1). These monitored lakes and reservoirs were selected due to the prevailing water quality conditions and potential socioeconomic impacts, including the 5 largest freshwater lakes in China. Moreover, 14 lakes and 1 reservoir were of particular concern of the government, and thus have a longer monitoring period (2005–2017) with a total of 16,543 records (68% of the dataset) (Fig. S1). The list of the studied lakes and reservoirs can be found in Table S2 of the Supporting Information.
- This dataset included 12 variables from water quality samples: dissolved oxygen (DO, mg/L), chemical oxygen demand (COD, mg/L), ammonium (NH_4^+, mg/L), total phosphorus (TP, mg/L), copper (Cu, mg/L), zinc (Zn, mg/L), selenium (Se, mg/L), arsenic (As, mg/L), mercury (Hg, mg/L), cadmium (Cd, mg/L), chromium (Cr, mg/L), lead (Pb, mg/L). Eight heavy metals (HMs) were included because the severity of HM pollution is increasingly reported in China's aquatic ecosystems (Bing et al., 2016).

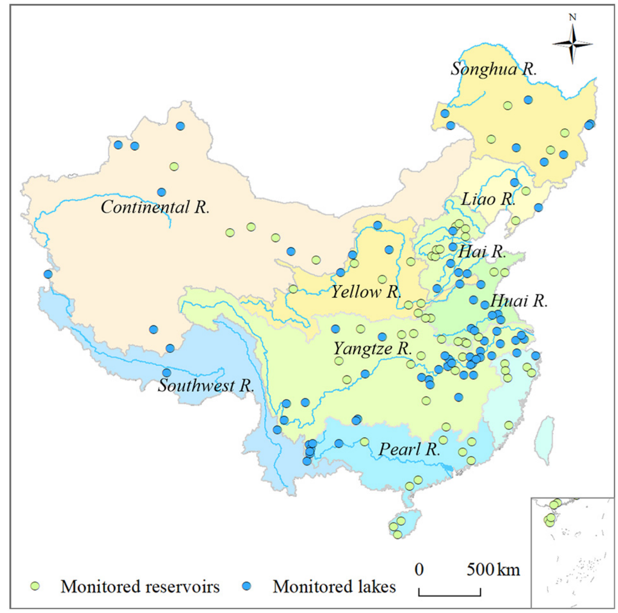

Fig. 1. Locations of China's 80 monitored lakes and 62 reservoirs during the 2005–2017 period.

2.2. Methods

2.2.1. A modified index to evaluate China's lake and reservoir water quality

The Water Quality Index (WQI) has been widely applied to quantify the degree of water quality degradation in a variety of lakes worldwide (Akkoyunlu and Akiner, 2012; Hurley et al., 2012; Wu et al., 2017b). In this study, we used a modification (i.e., linear transformation) of the Water Quality Index (WQI-DET) customized to China's water quality classification scheme. Specifically, WQI-DET is an adaptation of the existing WQI to the five water quality classes of China's “Environmental Quality Standards for Surface Water” (GB3838-2002), i.e., I (excellent), II (good), III (moderate), IV (poor) and V (bad). Compared with the original index, ranging from 0 to 100 (Wu et al., 2017b), WQI-DET has a broader range from -∞ (extremely poor water quality) to 100 (excellent water quality) which allows to clearly differentiate between bad and extremely bad water quality conditions. Calculation details of WQI-DET are as follows:

(1) *Calculating WQI-DET for individuals water samples*

WQI-DET (WQI_{DET}^j) for a water sample j can be calculated as:

$$WQI_{DET}^j = \min\left(WQI_{DET\_1}^j, \ldots, WQI_{DET\_i}^j, \ldots, WQI_{DET\_n}^j\right) \quad (1)$$

$$WQI_{DET\_i}^j = 100 - max\left(0, \frac{C_{ij} - C_i^I}{C_i^V - C_i^I} \times 100\right) \quad (2)$$

where $WQI_{DET\_i}^j$ is the WQI-DET value for the variable i of the water sample j; C_{ij} is the concentration of the environmental variable i of the water sample j; C_i^I and C_i^V are the concentration of the variable i at class I and V, respectively. Twelve (12) water quality variables were used to calculate WQI-DET, i.e., $n = 12$, and their concentrations were evaluated against the corresponding water quality classes (Table S3).

(2) *Calculating monthly and annual WQI-DET values for a lake*

Based on the calculated WQI-DET for individual water samples, monthly WQI-DET was calculated for each lake or reservoir by averaging all the values within a given month. This simple averaging method allowed us to rule out the WQI-DET bias due to the unequal number of samples among the various lakes and reservoirs. Annual WQI-DET value for a given lake or reservoir was calculated by averaging all the monthly WQI-DET values.

2.2.2. A regime shift detection method to characterize the prevailing water quality conditions

We used a sequential method, originally proposed by Rodionov (2004), to tease out any abrupt shifts of the monthly WQI-DET values during the 2005–2017 period. The method uses a pre-whitening procedure to remove the red noise component from the time-series data (Rodionov, 2006), and subsequently examines the likelihood of regime shifts using the Student's t-test (Rodionov, 2004). Compared with other regime shift detection methods, this method has the advantage of detecting an ecological regime shift earlier and then monitoring how its magnitude changes over time. This advantage is mainly due to the use of exploratory analysis that does not require an a priori hypothesis on the timing of regime shifts (Rodionov, 2004; see also the Supporting Information for further technical details).

3. Results

3.1. Spatio-temporal water quality trends in China's lakes and reservoirs

Our results showed that China's lake and reservoir water quality is primarily impacted by HM pollution, especially Cr, and displays significant spatial variation (Fig. 2). Among the 142 monitored lakes and reservoirs, evidence of water quality impairment was recorded in 31 lakes and 7 reservoirs. Polluted water caused by Cr, Cd and As was found in 19, 7 and 7 lakes or reservoirs, respectively, while inferior water quality caused by TP, NH_4^+ and COD was found in 1, 2 and 2 lakes or reservoirs, respectively (Fig. 2b). Several "hot spots" of poor water quality (WQI-DET < 40) were identified, including the Yunnan, the middle reach of Yellow River and Yangtze River (red cycles in Fig. 2a). The main variables responsible for the poor water quality characterization were HMs (Cr, As and Cd) in the middle reach of Yangtze River and Yellow River, and COD, TP, and As in Yunnan (Fig. 2b). Several lakes and reservoirs in Eastern China (see the red cycle in Fig. 2b) were polluted by HMs (Cr, As and Cd), even though their annual WQI-DET values were not low (60 < WQI-DET < 80 in Fig. 2a). Water quality in the lower reach of Pearl River and Yellow River was relatively good, especially in Southeast China with WQI-DET values higher than 80 (Fig. 2a). Our spatial assessment of China's water quality problems differs somewhat from Zhou et al.'s (2017) study, which confined the water quality problems in Eastern China based on DO, COD and NH_4^+ data.

Both monthly and annual WQI-DET trends provide evidence of an improving water quality in 15 systems with long-term records (Fig. 3). The annual WQI-DET showed an increasing trend during the 2005–2013 period ($p < 0.001$), suggestive of a water quality improvement. Two regime shifts were detected in June 2007 and July 2010 with an increase of the average WQI-DET values from −133.0 to −68.1, and from −68.1 to 8.6, respectively. Polluted water (WQI-DET < 0) in China's lakes accounted for > 10% during the 2005–2009 period, but decreased to < 10% during the 2014–2016 period. WQI-DET was relatively stable from 2011 to 2017 without any significant changes detected. Several lakes, especially Lakes Baiyangdian, Dianchi, Taihu and Chaohu, showed significantly improved water quality from 2005 to 2010 (see annual WQI-DET trends for each lake and reservoir in Fig. S1). Considering that these 15 lakes and reservoirs constitute a primary concern in China, we herein provide their water quality

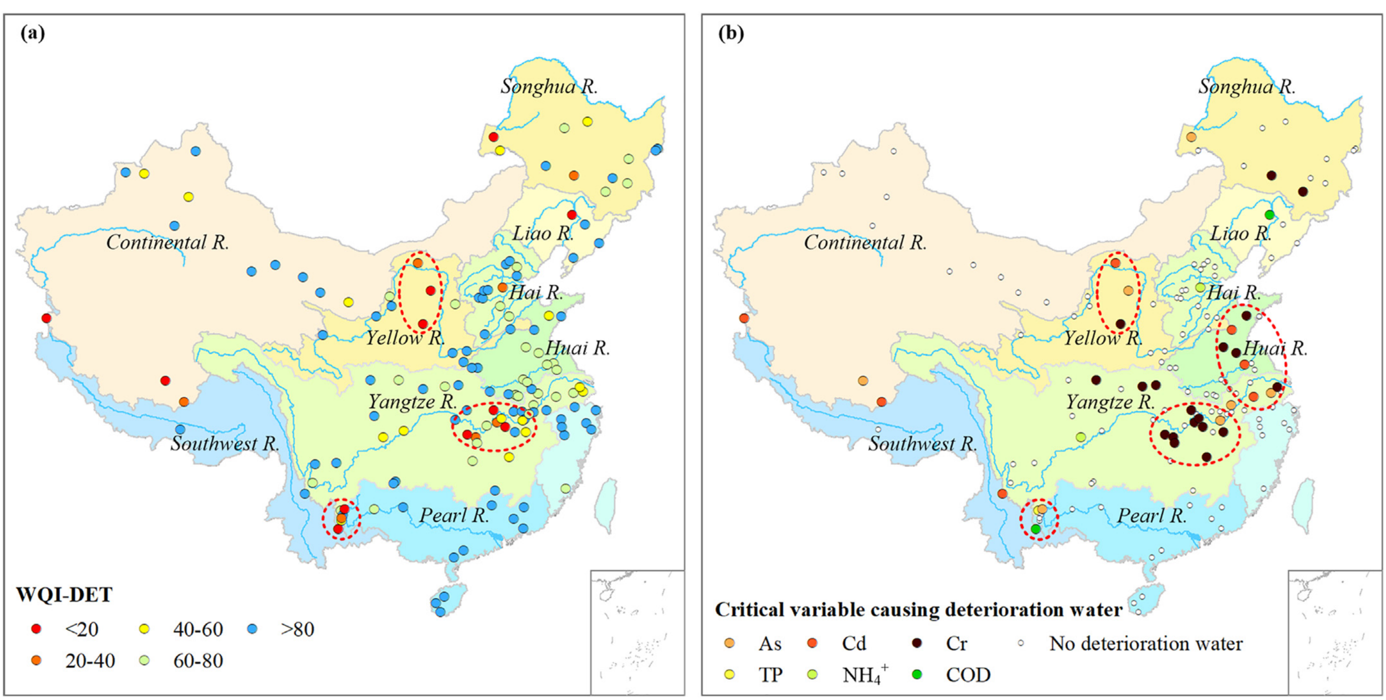

Fig. 2. Spatial patterns of water quality in China's lakes and reservoirs in 2017. (a) Annual WQI-DET values. (b) Critical variables responsible for water quality impairment. Three red cycles (dashed lines) mark the "hot spots" of poor water quality (low WQI-DET). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

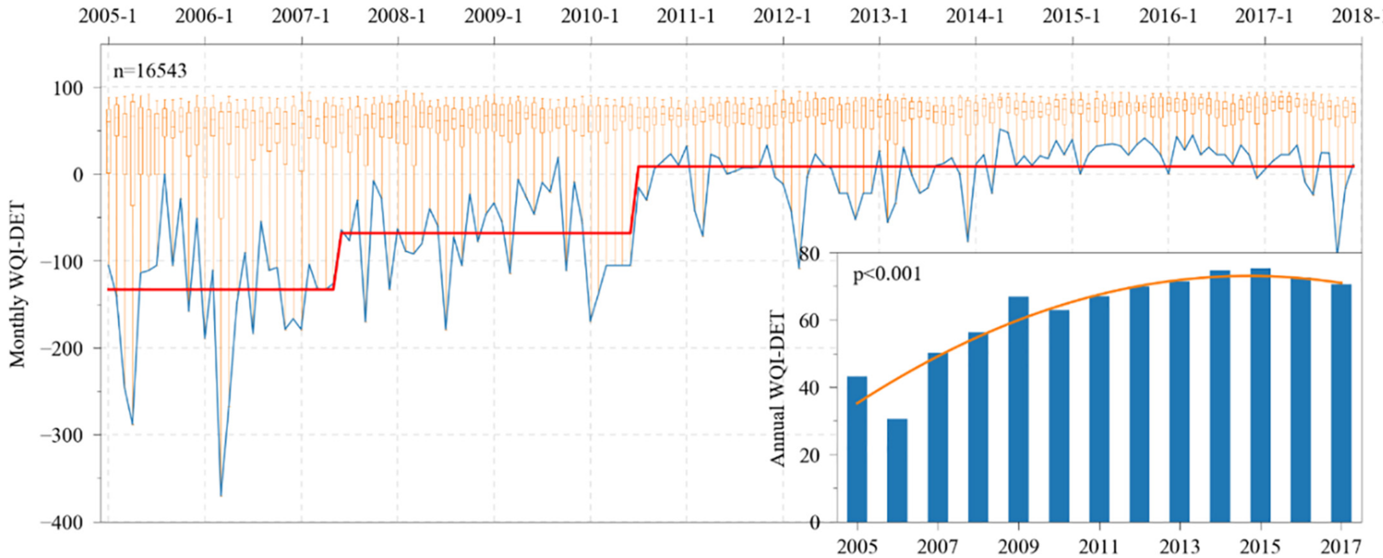

Fig. 3. Trends of the monthly and annual WQI-DET values for China's 15 high-risk lakes and reservoirs during the 2005–2017 period. Blue line represents the 10th percentile of monthly WQI-DET values. Red line represents the average WQI-DET for each period derived from the regime shift detection exercise. Blue bars represent the median of the annual WQI-DET values in 15 lakes and reservoirs. The number of water samples for each month can be found in Fig. S2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

conditions, as well as the exogenous sources of pollutants (Table S4).

3.2. Critical variables causing water quality deterioration in China's lakes and reservoirs

Our investigation results showed that China's lake and reservoir water quality impairment was due to both HM pollution (i.e., high Cr, Cd and As) and eutrophication (i.e., high TP, NH_4^+ and COD). Nonetheless, there is a clear shift from eutrophication to HM pollution in 2012. More than 60% of polluted water was caused by eutrophication during the 2005–2011 period (green colors in Fig. 4), but both TP and NH_4^+ over-enrichment appear to have been reduced during the 2011–2017 period (Fig. 4). HM pollution evidently becomes more pronounced, especially Cr pollution (brown color in Fig. 4). Water quality impairment caused by Cr pollution increased from 2.0% in 2011 to 52.1% in 2017.

The critical variables responsible for the water quality impairment in China's 15 lakes and reservoirs with long-term record suggest that eutrophication (NH_4^+, TP or COD) has been alleviated but not fully eliminated, while HM pollution displayed a distinctly increasing trend due to excessive discharges of Cr, Cd and As from industrial wastewater. Eutrophication was the main cause of water quality degradation in Lakes Baiyangdian, Chaohu and Dianchi, while HM pollution was the predominant stressor in Lakes Poyang and Dongting (Fig. 5). Both Lakes Taihu and Dalai showed a decreasing eutrophication trend, but increasing HM pollution, whereas no impaired water quality was found in Lakes Jingbo and Qiandao during the 2005–2017 period.

4. Discussion

4.1. How successful have been the restoration efforts of China's lakes and reservoirs over the past decade?

Our analysis suggests that China has made considerable progress in improving water quality, especially in alleviating eutrophication. Clear evidence about the latter conclusion is provided by the significant decline of both TP and NH_4^+ concentrations. This success was mainly due to China's ambitious plans and considerable efforts in mitigating lake eutrophication, especially after the Lake Taihu's drinking water crisis in late May of 2007 (Qin et al., 2010).

In 2008, a legislative framework came into effect to protect China's critical lakes and control water pollution (Fig. 4). Since 2008, many guidelines, plans, and regulations were released to ensure that the appropriate remedial measures were taken to improve water quality, especially to control phosphorus and nitrogen loading (Table S1). Investments to total environmental restoration for improving China's lake and river water quality significantly increased from nearly 0 in 1994 to 1000 billion RMB yuan in 2014 (Zhou et al., 2017). The most important strategy to control water pollution was based on the construction of wastewater treatment plants (WWTPs) that can effectively remove pollutants (TP, NH_4^+ and COD) from sewage (Yang et al., 2015; Zhang et al., 2016). Both the number and daily wastewater treatment capacity of WWTPs in China increased significantly from 2000 (176 and 1.64×10^7 t/d) to 2010 (2739 and 1.25×10^8 t/d) (Fig. S3). In particular, during the 2008–2011 period, 2006 WWTPs with a total wastewater treatment capacity of 6.39×10^7 t/d were built that can partly explain the significant decrease of TP, NH_4^+ and COD pollution in 2012.

Although TP, NH_4^+ and COD levels have been considerably reduced in effluents from WWTPs, there is still a distinct proportion (16.3%) of polluted water caused by eutrophication in 2017 (Fig. 4). Eutrophication is still a predominant factor of water quality impairment in many large lakes (e.g., Lakes Baiyangdian and Dianchi) that provide important ecosystem services, thereby posing considerable socioeconomic threats. With the increasing number of WWTPs in place to control point-source pollution, the major drivers of China's lake eutrophication are gradually shifting from point to diffuse/non-point sources and internal nutrient loading (Huang et al., 2016; Wu et al., 2017a).

- Non-point source pollution from agriculture has been widely recognized to be a critically important source of nutrients for lakes due to intensive fertilization. Although there are several guidelines and rules (e.g., Action plan for water pollution controls in China in Supporting Information) to mitigate non-point source pollution from agriculture, it is still very challenging for local farmers to effectively apply them in the field. China's crop production maintained an average P fertilization rate of 80 kg/ha in 2012, more than double the input intensity that crops can assimilate (Liu et al., 2016). Even though the estimation of the magnitude of non-point source pollution can be particularly uncertain (Ongley et al., 2010; Shen et al.,

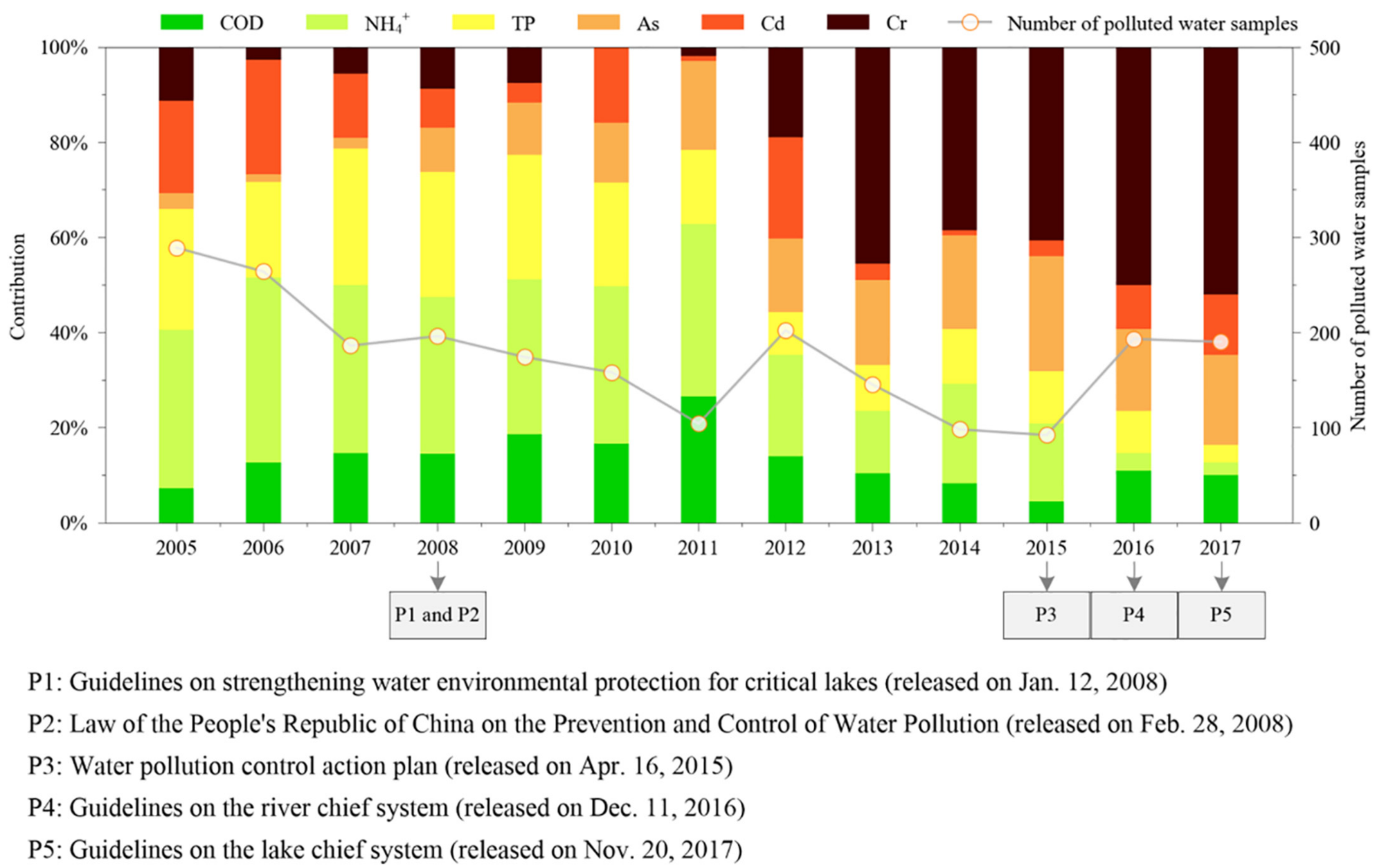

Fig. 4. Contribution of critical variables to water quality impairment in China's lakes and reservoirs during the 2005–2017 period, combined with important laws, plans, and guidelines established to improve China's water quality. The contribution value for each variable was calculated by $n_{DET}^{i}/\sum_{i=1}^{m} n_{DET}^{i}$, where $n_{DET}{}^{i}$ is the number of water samples with a WQI-DET value lower than 0 for the *i* variable, and *m* (=12) is the total number of variables used for our analysis. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

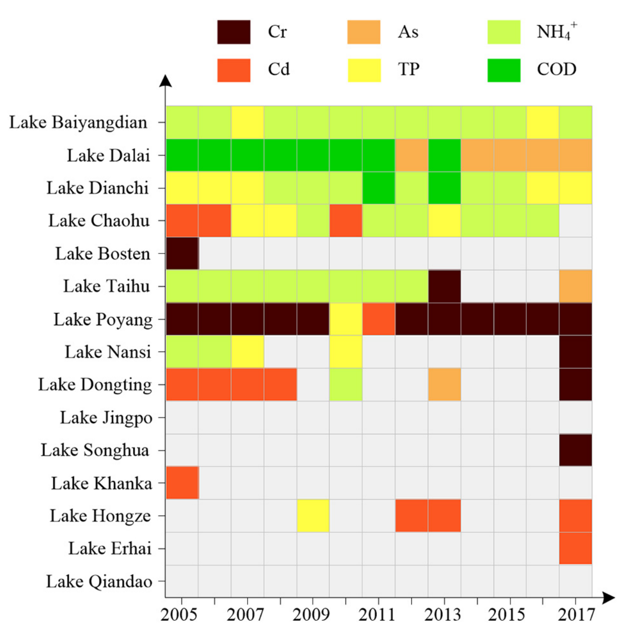

Fig. 5. Critical variables responsible for the water quality impairment in China's 15 lakes with long-term record during the 2005–2017 period. It should be noted that Lake Qiandao is a reservoir.

2012), China's N runoff is similarly projected to have increased by 46% and 31% for rice paddy fields and upland areas since 1990, respectively (Hou et al., 2018).

- Despite the substantial external nutrient loading reduction for China's lakes, it is not surprising that eutrophication is not well controlled so far, because internal nutrient loading from lake sediments would delay their recovery (Schindler et al., 2016). A case study in Lake Dianchi revealed an overwhelmingly high (72–77%) contribution of internal phosphorus and nitrogen loading (Wu et al., 2017a). Another case study in Lake Taihu was suggestive of significant internal nutrient fluxes primarily mediated by wind resuspension (Huang et al., 2016). Therefore, eutrophication of these lakes cannot be well-controlled until the internal nutrient sources are permanently buried and/or washed out.
- Although our study is based on a comprehensive dataset, it is important to note that there are still data limitations and knowledge gaps. Water samples were collected from 80 lakes and 62 reservoirs that cannot fully represent China's lake and reservoir water quality. For example, there are > 3000 reservoirs in Fujian Province, Southeast China (Zhu and Yang, 2018), but only one reservoir was available in our dataset (Table S2 in the Supporting Information). Moreover, the dataset used includes 12 water quality variables from water samples, but does provide any information for other contaminants, such as pesticides and Persistent Organic Pollutants (POPs). Consequently, a similar assessment exercise with more environmental variables could paint a somewhat different picture with respect to the spatiotemporal water quality trends in China.

4.2. Why heavy metal pollution has been increasing in China over the past decade?

Although China's lake and reservoir water quality showed an overall improvement from 2005 to 2017, HM pollution showed an increasing trend. This problem becomes gradually worrisome for the Chinese government due to the high toxicity, prevalent existence and persistence of HMs (He et al., 2013). Our detected trends of elevated Cr, Cd and As concentrations can mainly be attributed to the following intensive anthropogenic activities.

4.2.1. Industrial production

China is responsible for a considerable amount of Cr, Cd and As wastes due to industrial production. Coal and oil combustion are two main sources of Cr pollution, contributing > 60% of the Cr emissions to the atmosphere in China (Cheng et al., 2014). Cd has been widely used in electroplating due to its corrosion resistance. Both Cr and Cd emissions to atmosphere can profoundly shape soil and water pollution (Wei and Yang, 2010). As is widely used in glass making, wood preservatives, batteries, semi-conductors and alloys, which can explain the significant increase in As mining activity from about 67,000 t in 1990 to over 300,000 t in 2010 (Shi et al., 2017). As losses from the anthroposphere to natural environment increased from about 60,000 t in 1990 to > 320,000 t in 2010. An exceptionally high fraction (about 98.7% in 2010) of these losses have been discharged into soils (Shi et al., 2017), and can subsequently cause As pollution in lake waters.

4.2.2. Atmospheric deposition

Cr, Cd and As emissions into the air are considerable due to coal and oil combustion (Cheng et al., 2014; He et al., 2013; Tang et al., 2016). Cr emissions to atmosphere amounted to approximately 20,000 t/yr in 2009, and demonstrated an increasing trend during the 1990–2009 period (Cheng et al., 2014). These high emissions can lead to an excessively high atmospheric deposition of Cr, Cd and As into China's lakes and reservoirs.

4.2.3. Sludge production

The amount of sludge waste from China's WWTPs displayed an annual increase rate of 13% during the 2007–2013 period (Yang et al., 2015; Zhang et al., 2016). In 2013, China's WWTPs produced 6.25 million tons of sludge (dry solids) containing considerable amounts of Cr, Cd and As. Although the maximum allowable levels for Cr and Cd concentrations in the sludge from China's WWTPs are much lower than those in the European Union and the United States, most of the residues after sludge anaerobic digestion still cannot meet the standard of sludge land application (Yang et al., 2015). The sludge can also potentially cause HM pollution of groundwater and rivers, which are ultimately connected with lakes and reservoirs.

4.3. What are the appropriate next steps to mitigate water pollution in China's lakes and reservoirs?

Our study provides evidence that remedial efforts to control eutrophication and HM pollution should continue to be a priority in China's research and environmental management agenda in order to eliminate issues of water quality impairment. Although eutrophication has been alleviated in recent years, the trends are still disconcerting due to its harmful effects (Sinha et al., 2017; Stone, 2011). Nutrient load reduction and ecological restoration are the most widely used mitigation strategies (Le et al., 2010).

In lakes and reservoirs, where the external nutrient loading is the predominant factor modulating the eutrophication severity, the control of non-point source pollution is widely recognized as the most effective framework (Schindler et al., 2016; Smith and Schindler, 2009). A variety of costly best management practices (BMPs) is available to control pollution from diffuse agricultural and urban sources (Leitão et al., 2018; Sharpley et al., 2011). Although their implementation has been based on the stipulation that both short- and long-term effectiveness are guaranteed, emerging evidence is suggestive of moderate water quality improvements in many watersheds and significant variability in BMP performance (Jarvie et al., 2013; Kleinman et al., 2011). In order to rectify the discrepancy between expected and actual BMP effectiveness into watershed management plans, Liu et al. (2018) proposed a framework that explicit accounts for the variability in starting BMP efficiency to reduce the severity of runoff and pollutant concentrations due to local condition differences and installation practices; an intrinsic variability of operational performance due to watershed geophysical conditions, differential response to storm events, and seasonality; and an expected decline in BMP performance over time, which in turn underscores the need for regular maintenance.

For the lakes with substantial internal nutrient loading (e.g, Lakes Dianchi and Taihu), ecological restoration can be helpful and has been generally implemented by restoring aquatic vegetation (Qin, 2009). The measure can be effective in remedying relatively small areas with substantial internal nutrient loading, but so far is scarcely applied to a larger scale due to its costly implementation and variant degree of success. Thus, before outlining the most suitable remedial measures, it is important to improve our mechanistic understanding of sediment diagenesis in most of China's freshwater lakes, i.e., the characterization of organic matter mineralization and redox-controlled nutrient transformation processes, or the determination of phosphorus fractionation within different sediment layers. A rich research agenda should be in place in order to effectively predicting the degree and timing of the sediment response or the likelihood of unexpected feedback loops that could delay the realization of the anticipated outcomes of the on-going restoration efforts.

Eliminating HMs from lake and reservoir water is very challenging, because they cannot be removed by the natural in-lake decomposition processes, which in turn can partly explain the increasing HM pollution in China's lakes and reservoirs. Therefore, we believe that one of China's next priorities should be the control of HM sources and soil remediation.

Reducing Cd, Cr and As pollution from anthropogenic activities. In China, the most important sources of Cd, Cr and As stem from mining activities with substantial waste discharge (Li et al., 2014). Therefore, the most effective approach is the strict regulation and meticulous control of mining discharges, especially small-scale mining, due to the application of obsolete technology and inefficient mining operations (Li et al., 2014). From a long-term perspective, we strongly advocate the optimization of China's energy-resource sector by opting for the development and gradual establishment of renewable energy sources as an alternative to coal and oil combustion.

Soil remediation. HM pollution in China's soil is severe (He et al., 2013). These HM pollutants in agricultural soils are conceivably transported to rivers, lakes and reservoirs, and thus accentuate the extent and severity of HM pollution. Soil remediation, such as electrokinetic remediation, chemical elution, stabilisation and solidification, represent a promising suite of techniques to alleviate HM pollution in both soils and lake water (Tang et al., 2016). This strategy is particularly important to control Cd pollution, because 25.2% of China's agricultural soils are characterized by excessively high Cd levels (Teng et al., 2014). Soil remediation is both technically difficult and costly, and therefore a priority list necessitates to first carry out soil remediation in heavily polluted and/or high-risk areas (Li et al., 2014).

Viewing lakes and reservoirs as providers of economically valuable benefits to society, the concept of ecosystem services effectively links their structural and functional integrity with human welfare (Pascual et al., 2010). Given that environmental policy affects both the ecosystem state and the provision of services that human societies benefit from, we argue that the efficacy of China's lake and reservoir restoration efforts will be significantly enhanced by the development of a rigorous framework that quantifies the economic benefits from investing in environmental sustainability. To best communicate the trade-offs among policy choices, ecosystem service valuation must examine the marginal improvement in ecosystem services attributable to a policy change. Economic values of ecosystem services can help policymakers determine the optimal degree of investment and action needed at each time step by defining the monetary trade-offs from different courses of management action (Egoh et al., 2007). Viewed it from this perspective, at the beginning of each restoration effort, the total returns and benefits are typically commensurate with the costs and investments, but this pattern may not hold true after a certain point, where we get diminishing (and ultimately negative) returns and marginal benefits. Given the presence of a wide array of feedback loops, ecological unknowns, and other external stressors, the rigorous valuation of the ecosystem services gained by China's lakes and reservoirs will likely provide the much-needed leeway to keep the investments to the environment going.

5. Conclusions

Spatio-temporal water quality trends in China's 142 lakes and reservoirs were investigated using a 13-year dataset with 24,319 records. Our results suggest that China has been successful in improving water quality during the 2005–2017 period. The mitigation of eutrophication has been particularly successful, but there is still significant space for improvement in many lakes and reservoirs of societal and ecological importance. HM (Cr, Cd, and As) pollution showed an increasing trend as a result of the significant contributions from industrial activities, atmospheric deposition, and sludge production. Reduction of non-point source pollution, internal nutrient loading, and cost-effective soil remediation represent major challenges in our efforts to restore China's water resources.

Acknowledgments

This work was supported by Major Science and Technology Program for Water Pollution Control and Treatment of China (2017ZX07301-001-02) and "135" Key Program in Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences (NIGLAS2018GH06). The authors would like to thank the Lake and Watershed Data Center (http://lwdc.niglas.cas.cn) in Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences for providing China's geographical data. Special thanks to Hongbin Lian (Wuyi University) for his considerable work on data collection and processing.

Appendix A. Supporting Information

Supporting Information to this article can be found online at https://doi.org/10.1016/j.envint.2018.11.048.

References

Akkoyunlu, A., Akiner, M.E., 2012. Pollution evaluation in streams using water quality indices: a case study from Turkey's Sapanca Lake Basin. Ecol. Indic. 18, 501–511. https://doi.org/10.1016/j.ecolind.2011.12.018.

Bing, H., Zhou, J., Wu, Y., Wang, X., Sun, H., Li, R., 2016. Current state, sources, and potential risk of heavy metals in sediments of Three Gorges Reservoir, China. Environ. Pollut. 214, 485–496. https://doi.org/10.1016/j.envpol.2016.04.062.

Cheng, H., Zhou, T., Li, Q., Lu, L., Lin, C., 2014. Anthropogenic chromium emissions in China from 1990 to 2009. PLoS One 9 (2), e87753. https://doi.org/10.1371/journal.pone.0087753.

Conley, D.J., Paerl, H.W., Howarth, R.W., Boesch, D.F., Seitzinger, S.P., Havens, K.E., Lancelot, C., Likens, G.E., 2009. Controlling eutrophication: nitrogen and phosphorus. Science 323 (5917), 1014–1015. https://doi.org/10.1126/science.1167755.

Cui, S., Shi, Y., Groffman, P.M., Schlesinger, W.H., Zhu, Y., 2013. Centennial-scale analysis of the creation and fate of reactive nitrogen in China (1910–2010). Proc. Natl. Acad. Sci. https://doi.org/10.1073/pnas.1221638110.

Duan, H., Tao, M., Loiselle, S.A., Zhao, W., Cao, Z., Ma, R., Tang, X., 2017. MODIS observations of cyanobacterial risks in a eutrophic lake: implications for long-term safety evaluation in drinking-water source. Water Res. 122, 455–470. https://doi.org/10.1016/j.watres.2017.06.022.

Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.-I., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A.-H., Soto, D., Stiassny, M.L., 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol. Rev. 81 (2), 163–182. https://doi.org/10.1017/S1464793105006950.

Egoh, B., Rouget, M., Reyers, B., Knight, A.T., Cowling, R.M., van Jaarsveld, A.S., Welz, A., 2007. Integrating ecosystem services into conservation assessments: a review. Ecol. Econ. 63 (4), 714–721. https://doi.org/10.1016/j.ecolecon.2007.04.007.

He, B., Yun, Z., Shi, J., Jiang, G., 2013. Research progress of heavy metal pollution in China: sources, analytical methods, status, and toxicity. Chin. Sci. Bull. 58 (2), 134–140. https://doi.org/10.1007/s11434-012-5541-0.

Hering, D., Carvalho, L., Argillier, C., Beklioglu, M., Borja, A., Cardoso, A.C., Duel, H., Ferreira, T., Globevnik, L., Hanganu, J., Hellsten, S., Jeppesen, E., Kodeš, V., Solheim, A.L., Nõges, T., Ormerod, S., Panagopoulos, Y., Schmutz, S., Venohr, M., Birk, S., 2015. Managing aquatic ecosystems and water resources under multiple stress — an introduction to the MARS project. Sci. Total Environ. 503-504, 10–21. https://doi.org/10.1016/j.scitotenv.2014.06.106.

Hou, X., Zhan, X., Zhou, F., Yan, X., Gu, B., Reis, S., Wu, Y., Liu, H., Piao, S., Tang, Y., 2018. Detection and attribution of nitrogen runoff trend in China's croplands. Environ. Pollut. 234, 270–278. https://doi.org/10.1016/j.envpol.2017.11.052.

Huang, L., Fang, H., He, G., Jiang, H., Wang, C., 2016. Effects of internal loading on phosphorus distribution in the Taihu Lake driven by wind waves and lake currents. Environ. Pollut. 219, 760–773. https://doi.org/10.1016/j.envpol.2016.07.049.

Huang, J., Zhang, Y., Huang, Q., Gao, J., 2018. When and where to reduce nutrient for controlling harmful algal blooms in large eutrophic lake Chaohu, China? Ecol. Indic. 89, 808–817. https://doi.org/10.1016/j.ecolind.2018.01.056.

Hurley, T., Sadiq, R., Mazumder, A., 2012. Adaptation and evaluation of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) for use as an effective tool to characterize drinking source water quality. Water Res. 46 (11), 3544–3552. https://doi.org/10.1016/j.watres.2012.03.061.

Jarvie, H.P., Sharpley, A.N., Spears, B., Buda, A.R., May, L., Kleinman, P.J.A., 2013. Water quality remediation faces unprecedented challenges from "legacy phosphorus". Environ. Sci. Technol. 47 (16), 8997–8998. https://doi.org/10.1021/es403160a.

Kleinman, P.J.A., Sharpley, A.N., McDowell, R.W., Flaten, D.N., Buda, A.R., Tao, L., Bergstrom, L., Zhu, Q., 2011. Managing agricultural phosphorus for water quality protection: principles for progress. Plant Soil 349 (1), 169–182. https://doi.org/10.1007/s11104-011-0832-9.

Le, C., Zha, Y., Li, Y., Sun, D., Lu, H., Yin, B., 2010. Eutrophication of lake waters in China: cost, causes, and control. Environ. Manag. 45 (4), 662–668. https://doi.org/10.1007/s00267-010-9440-3.

Leitão, J.P., Carbajal, J.P., Rieckermann, J., Simões, N.E., Sá Marques, A., de Sousa, L.M., 2018. Identifying the best locations to install flow control devices in sewer networks to enable in-sewer storage. J. Hydrol. 556, 371–383. https://doi.org/10.1016/j.jhydrol.2017.11.020.

Li, Z., Ma, Z., van der Kuijp, T.J., Yuan, Z., Huang, L., 2014. A review of soil heavy metal pollution from mines in China: pollution and health risk assessment. Sci. Total Environ. 468-469, 843–853. https://doi.org/10.1016/j.scitotenv.2013.08.090.

Liu, X., Zhang, Y., Han, W., Tang, A., Shen, J., Cui, Z., Vitousek, P., Erisman, J.W., Goulding, K., Christie, P., Fangmeier, A., Zhang, F., 2013. Enhanced nitrogen deposition over China. Nature 494 (7438), 459–462. https://doi.org/10.1038/nature11917.

Liu, X., Sheng, H., Jiang, S., Yuan, Z., Zhang, C., Elser, J.J., 2016. Intensification of phosphorus cycling in China since the 1600s. Proc. Natl. Acad. Sci. 113 (10), 2609–2614. https://doi.org/10.1073/pnas.1519554113.

Liu, Y., Engel, B.A., Flanagan, D.C., Gitau, M.W., McMillan, S.K., Chaubey, I., Singh, S., 2018. Modeling framework for representing long-term effectiveness of best management practices in addressing hydrology and water quality problems: framework development and demonstration using a Bayesian method. J. Hydrol. 560, 530–545. https://doi.org/10.1016/j.jhydrol.2018.03.053.

Ma, R., Yang, G., Duan, H., Jiang, J., Wang, S., Feng, X., Li, A., Kong, F., Xue, B., Wu, J., Li, S., 2011. China's lakes at present: number, area and spatial distribution. Sci. China Earth Sci. 54 (2), 283–289. https://doi.org/10.1007/s11430-010-4052-6.

Messager, M.L., Lehner, B., Grill, G., Nedeva, I., Schmitt, O., 2016. Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nat. Commun. 7 (13603). https://doi.org/10.1038/ncomms13603.

Michalak, A.M., Anderson, E.J., Beletsky, D., Boland, S., Bosch, N.S., Bridgeman, T.B., Chaffin, J.D., Cho, K., Confesor, R., Daloğlu, I., Depinto, J.V., Evans, M.A., Fahnenstiel, G.L., He, L., Ho, J.C., Jenkins, L., Johengen, T.H., Kuo, K.C., LaPorte, E., Liu, X., McWilliams, M.R., Moore, M.R., Posselt, D.J., Richards, R.P., Scavia, D., Steiner, A.L., Verhamme, E., Wright, D.M., Zagorski, M.A., 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. Proc. Natl. Acad. Sci. 110 (16), 6448–6452. https://doi.org/10.1073/pnas.1216006110.

Ni, Z., Wang, S., Wang, Y., 2016. Characteristics of bioavailable organic phosphorus in sediment and its contribution to lake eutrophication in China. Environ. Pollut. 219, 537–544. https://doi.org/10.1016/j.envpol.2016.05.087.

Ongley, E.D., Zhang, X., Yu, T., 2010. Current status of agricultural and rural non-point source pollution assessment in China. Environ. Pollut. 158 (5), 1159–1168. https://doi.org/10.1016/j.envpol.2009.10.047.

Pascual, U., Muradian, R., Rodríguez, L.C., Duraiappah, A., 2010. Exploring the links between equity and efficiency in payments for environmental services: a conceptual approach. Ecol. Econ. 69 (6), 1237–1244. https://doi.org/10.1016/j.ecolecon.2009.11.004.

Qin, B., 2009. Lake eutrophication: control countermeasures and recycling exploitation. Ecol. Eng. 35 (11), 1569–1573. https://doi.org/10.1016/j.ecoleng.2009.04.003.

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. Manag. 45 (1), 105–112. https://doi.org/10.1007/s00267-009-9393-6.
Rodionov, S.N., 2004. A sequential algorithm for testing climate regime shifts. Geophys. Res. Lett. 31 (9). https://doi.org/10.1029/2004GL019448.
Rodionov, S.N., 2006. Use of prewhitening in climate regime shift detection. Geophys. Res. Lett. 33 (12). https://doi.org/10.1029/2006GL025904.
Schindler, D.W., Carpenter, S.R., Chapra, S.C., Hecky, R.E., Orihel, D.M., 2016. Reducing phosphorus to curb lake eutrophication is a success. Environ. Sci. Technol. 50 (17), 8923–8929. https://doi.org/10.1021/acs.est.6b02204.
Sharpley, A.N., Kleinman, P.J., Flaten, D.N., Buda, A.R., 2011. Critical source area management of agricultural phosphorus: experiences, challenges and opportunities. Water Sci. Technol. 64 (4), 945–952. https://doi.org/10.2166/wst.2011.712.
Shen, Z., Liao, Q., Hong, Q., Gong, Y., 2012. An overview of research on agricultural non-point source pollution modelling in China. Sep. Purif. Technol. 84, 104–111. https://doi.org/10.1016/j.seppur.2011.01.018.
Shi, Y., Chen, W., Wu, S., Zhu, Y., 2017. Anthropogenic cycles of arsenic in mainland China: 1990–2010. Environ. Sci. Technol. 51 (3), 1670–1678. https://doi.org/10.1021/acs.est.6b01669.
Sinha, E., Michalak, A.M., Balaji, V., 2017. Eutrophication will increase during the 21st century as a result of precipitation changes. Science 357 (6349), 405–408. https://doi.org/10.1126/science.aan2409.
Smith, V.H., Schindler, D.W., 2009. Eutrophication science: where do we go from here? Trends Ecol. Evol. 24 (4), 201–207. https://doi.org/10.1016/j.tree.2008.11.009.
Stone, R., 2011. China aims to turn tide against toxic lake pollution. Science 333 (6047), 1210–1211. https://doi.org/10.1126/science.333.6047.1210.
Tang, X., Li, Q., Wu, M., Lin, L., Scholz, M., 2016. Review of remediation practices regarding cadmium-enriched farmland soil with particular reference to China. J. Environ. Manag. 181, 646–662. https://doi.org/10.1016/j.jenvman.2016.08.043.
Tao, T., Xin, K., 2014. A sustainable plan for China's drinking water: tackling pollution and using different grades of water for different tasks is more efficient than making all water potable. Nature 511 (7511), 527–529. https://doi.org/10.1038/511527a.
Teng, Y., Wu, J., Lu, S., Wang, Y., Jiao, X., Song, L., 2014. Soil and soil environmental quality monitoring in China: a review. Environ. Int. 69, 177–199. https://doi.org/10.1016/j.envint.2014.04.014.
Tong, Y., Zhang, W., Wang, X., Couture, R.-M., Larssen, T., Zhao, Y., Li, J., Liang, H., Liu, X., Bu, X., He, W., Zhang, Q., Lin, Y., 2017. Decline in Chinese lake phosphorus concentration accompanied by shift in sources since 2006. Nat. Geosci. 10, 507–511. https://doi.org/10.1038/ngeo2967.
Ulrich, A.E., Malley, D.F., Watts, P.D., 2016. Lake Winnipeg Basin: Advocacy, challenges and progress for sustainable phosphorus and eutrophication control. Sci. Total Environ. 542 (Part B), 1030–1039. https://doi.org/10.1016/j.scitotenv.2015.09.106.
Wei, B., Yang, L., 2010. A review of heavy metal contaminations in urban soils, urban road dusts and agricultural soils from China. Microchem. J. 94 (2), 99–107. https://doi.org/10.1016/j.microc.2009.09.014.
Wu, Z., Liu, Y., Liang, Z., Wu, S., Guo, H., 2017a. Internal cycling, not external loading, decides the nutrient limitation in eutrophic lake: a dynamic model with temporal Bayesian hierarchical inference. Water Res. 116, 231–240. https://doi.org/10.1016/j.watres.2017.03.039.
Wu, Z., Zhang, D., Cai, Y., Wang, X., Zhang, L., Chen, Y., 2017b. Water quality assessment based on the water quality index method in Lake Poyang: the largest freshwater lake in China. Sci. Rep. 7 (1), 17999. https://doi.org/10.1038/s41598-017-18285-y.
Yang, X., Lu, X., 2014. Drastic change in China's lakes and reservoirs over the past decades. Sci. Rep. 4 (6041). https://www.nature.com/articles/srep06041.
Yang, M., Yu, J., Li, Z., Guo, Z., Burch, M., Lin, T., 2008. Taihu Lake not to blame for Wuxi's woes. Science 319 (5860), 158. https://doi.org/10.1126/science.319.5860.158a.
Yang, G., Zhang, G., Wang, H., 2015. Current state of sludge production, management, treatment and disposal in China. Water Res. 78, 60–73. https://doi.org/10.1016/j.watres.2015.04.002.
Yi, Q., Chen, Q., Hu, L., Shi, W., 2017. Tracking nitrogen sources, transformation, and transport at a basin scale with complex Plain River networks. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.6b06278.
Zhang, Q.H., Yang, W.N., Ngo, H.H., Guo, W.S., Jin, P.K., Dzakpasu, M., Yang, S.J., Wang, Q., Wang, X.C., Ao, D., 2016. Current status of urban wastewater treatment plants in China. Environ. Int. 92-93, 11–22. https://doi.org/10.1016/j.envint.2016.03.024.
Zhou, Y., Ma, J., Zhang, Y., Qin, B., Jeppesen, E., Shi, K., Brookes, J.D., Spencer, R.G.M., Zhu, G., Gao, G., 2017. Improving water quality in China: environmental investment pays dividends. Water Res. 118, 152–159. https://doi.org/10.1016/j.watres.2017.04.035.
Zhu, Z., Yang, J., 2018. The spatial distribution of reservoirs in Fujian Province: higher density but lower storage in coastal than inland regions. J. Lake Sci. 30 (2), 567–580. https://doi.org/10.18307/2018.0227.