Science of the Total Environment 689 (2019) 1336–1347

Contents lists available at ScienceDirect

Science of the Total Environment

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

Review

Phosphorus mitigation remains critical in water protection: A review and meta-analysis from one of China's most eutrophicated lakes

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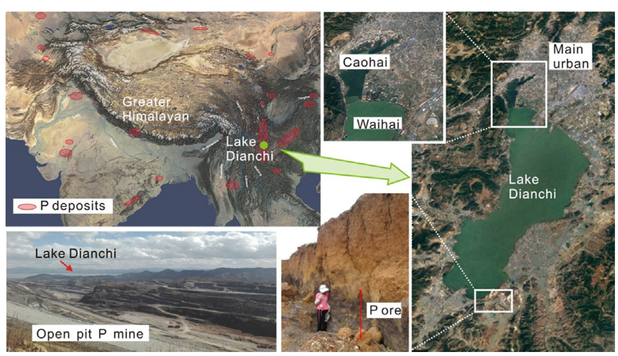
HIGHLIGHTS

- Systematic review is used to develop consensuses regarding the role of phosphorus (P) and its budget in Lake Dianchi.
- P pollution in Lake Dianchi has been stabilized, however it still suffers from high pressures on P enrichment.
- Continuous urbanization and degradation in geological P-rich mountains could introduce additional P into Lake Dianchi.
- Ecological approaches to geological factors, human activities and economic income, should be incorporated into protection.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 February 2019
Received in revised form 17 May 2019
Accepted 19 June 2019
Available online 21 June 2019

Editor: José Virgílio Cruz

Keywords:
Lake Dianchi
Phosphorus budget
Markov chain Monte Carlo simulation
Bayesian hierarchical model
Watershed management
Geological phosphorus-rich mountains

ABSTRACT

The processes of urbanization and industrialization within geological phosphorus-rich mountains (GPMn) have resulted in water degradation within southwest China. Lake Dianchi, one of the most eutrophicated lakes in China, has epitomized this issue. Clear understandings of phosphorus (P) mitigation efforts, the evolution of P budgets, and possible risks in the Dianchi system will benefit future eutrophication control, providing valuable lessons for other plateau freshwater lakes. In this study, we applied systematic review methodology to investigate the above questions, and then compared the results with other lakes worldwide. Generally, meta-analytical approaches have indicated P levels remain a key factor in causing algal blooms. Post-2015, the P budget of the Dianchi system, especially in Caohai section, was modified. However, it's still experiencing high pressures from P enrichment (Caohai: 0.4 $mg \cdot l^{-1}$; Waihai: 0.2 $mg \cdot l^{-1}$). The flux of P in Dianchi remains high, both through the external P load (556 $ton \cdot a^{-1}$), and an internal cycle (304 $ton \cdot a^{-1}$ associated with the absorption, deposition and removal of algae biomass; and 380 $ton \cdot a^{-1}$ associated with sediment exchange). Meanwhile, significant P retention has been observed in the lake, in particular within the Waihai section (211 $ton \cdot a^{-1}$). Currently, water diversion (from external watersheds), sewage diversion, and sediment-dredging projects have benefited

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https://doi.org/10.1016/j.scitotenv.2019.06.302

Dianchi. However, continuous urbanization and GPMn ecological degradation could introduce hundreds of tons of additional P, leading to subsequent algal blooms. Furthermore, beyond Lake Dianchi, other lakes and reservoirs in southwest China are facing similar issues regarding P mitigation, especially in GPMn regions, though corresponding knowledge is still limited. Therefore, effective and flexible sub-regional protection strategies and research related to external and internal P mitigations have become key requirements for Lake Dianchi management. Meanwhile, ecologically sensitive approaches to GPMn regions, as well as city development within basin and market driven treatments, should be incorporated into regional water source protection for southwest China.

Contents

1. Introduction

Nutrient enrichment impairs surface water quality and leads to harmful algal blooms (HABs) in freshwater systems (Carpenter et al., 1998; Rockström et al., 2009). Reductions in human-induced nutrient loads are the foci of mitigating global HABs, particularly phosphorus (P) (Carpenter et al., 1998; Conley et al., 2009; Paerl et al., 2016; Wang et al., 2019). Continuous efforts to better understand and manage P pollution have generally resulted in significant declines in total phosphorus (TP) concentration in lakes across China (Stone, 2011; Zhou et al., 2016; Liu, 2017; Tong et al., 2017). A recent review found that the average P levels from 324 lakes in China declined from 0.081 mg·l^{-1} in 2006 to 0.039 mg·l^{-1} in 2014 (Tong et al., 2017). However, P pollution within Southwest China, in particular in the upper and middle reaches of the Yangtze River basin, remains critical for regional water quality protection (Powers et al., 2016; MEE-China, 2019).

Southwest China lies within a fragile ecological region where the environment has been increasingly degenerated by human activities, but little research has been completed to date (Peng et al., 2011). To the best of our knowledge, this region contains the largest area of Geological P-rich Mountains (GPMn) in the world (Section 1 in the Supporting Information (SI)) (ChinaIRR, 2016; Yan et al., 2017), which formed millions of years ago by the effect of Tethys Ocean currents and subsequent Himalayan orogeny (Mckelvey, 1986; Zapata and Roy, 2004). Therefore, lakes in this region are often formed by rift-subsidence due to the above geological processes, and they share the common problem of fragile ecosystems (e.g., small basins and significant lake aging) (Yin and Harrison, 2003; Mats et al., 2009). Moreover, these basins have been preferentially selected for human settlement. The natural geology of the area, coupled with intensive human activities, has brought several environmental problems to the region (Das, 1999; Pomeranz, 2009; Wang et al., 2016). In 2014, >200 lakes within this region were suffering from severe P pollution (i.e., TP > 0.10 mg·l^{-1}, 7% of all regional lakes) (Tong et al., 2017), and the situation is even worse at present. Of these, Lake Dianchi is the most notable case, and P levels exceeding 1.5 mg·l^{-1} have been recorded (Liu et al., 2015; Wang, 2015; Zhang et al., 2016).

Lake Dianchi, the largest plateau freshwater lake in China, is representative of other lakes in this mountainous region. In the southern lake basin and surrounding areas, there are large P ore reserves of around five billion tons (roughly 16% of total reserves in China) (Section 2 in SI) (ChinaIRR, 2016; Yan et al., 2017). Also present are the largest open-pit P mines in Asia (Shang et al., 2015; Yan et al., 2015; Kim et al., 2018). The surrounding area is also the political and economic center of Yunnan province. In 2017, Kunming city's Gross Regional Product was 72.5 billion US dollars, and the number of people living near the shores of Lake Dianchi had grown to >3.5 million (Yu, 1981; Wang, 2015; Xu et al., 2016). Importantly, beginning in the 1980s, Lake Dianchi earned the reputation of being one of the most polluted lakes in China (MEE-China, 2003; Wang, 2015; Wu et al., 2015). Into the 21st century, costly treatments have finally begun to result in significant improvements in Dianchi water quality. In 2016, Lake Dianchi achieved the best water quality recorded over the prior 30 years (Liu et al., 2015; Zheng et al., 2018). Therefore, it is our opinion that a clear understanding of P mitigation efforts and the evolution of P budgets in Lake Dianchi will benefit future eutrophication control directly, and provide valuable lessons for P management of other freshwater shallow lakes within this region as well (Liu et al., 2016; Schindler et al., 2016; Tong et al., 2017).

However, previous studies have not fully addressed the above issues. To date, there have been only a handful of studies focusing on the external watershed discharge (loads) and water TP in Lake Dianchi (Ma and Wang, 2015; Wang, 2015). Meanwhile, a wide variety of methods and databases used in these studies prevents us from developing a broader consensus regarding the role of P and its budget. Furthermore, prior to Wu et al.'s research in 2017, no studies have focused on internal cycling budgets (e.g. sediment release and P uptake by algae). This study used a temporal Bayesian Hierarchical Framework (BHF) model to explore sediment release and growth limitation on algae, which is the first attempt to link Dianchi nutrient budgets with its HABs. However, this model ignored P loads through water diversion, P removal through artificial treatment, and P sequestrated in algae, etc. In addition, the model does not work for the entire lake, only uses a short time series (2002–2009), and does not include the impact from degraded GPMn regions across the Dianchi basin. So far there is still no clear understanding of the P cycle within the Dianchi system; further comprehensive knowledge of these issues is needed, which could aid both P mitigation and eutrophication control (Schindler et al., 2016; Zhang et al., 2016).

In this study, we systematically analyzed publications and publicly available datasets obtained from Lake Dianchi using a BHF Model and meta-analysis. Meanwhile, comparative analyses were used to distinguish the difference between Lake Dianchi and other lakes worldwide. We have three primary goals associated with this work: (1) Confirm if Lake Dianchi is still suffering from higher levels of P enrichment; (2) Understand the efforts toward P mitigation and the evolution of P budgets in Lake Dianchi in the 21st century; and (3) Speculate about possible risks regarding future P management in Lake Dianchi, and conduct an analysis of corresponding scenarios.

2. Materials and methods

2.1. Study area and background

Lake Dianchi (102°29′ E to 103°01′E; 24°29′N to 25°28′N) is a 2920 km^2 water basin located in central Yunnan province; outflow from the lake serves as a tributary to the upper reaches of the Yangtze River (Gao et al., 2014a, 2014b; Ma and Wang, 2015; Li et al., 2019). The lake is composed of two primary sections, a smaller section called Caohai near the main urban center of Kunming city, and a main section called Waihai (Fig. 1) (Wang, 2015). The Caohai section has a mean depth of 2.5 m and a surface area of 10.67 km^2, while Waihai has a mean depth of 4.4 m and a surface area of 298.4 km^2.

The Lake Dianchi area is densely populated and has been undergoing rapid urbanization since the early 1980s (Gao et al., 2015; Wang, 2015). By 2017 the total population in Kunming city had reached 6.78 million. Kunming's population is concentrated around the main urban area on the north shore of Lake Dianchi, where 86.7% of the basin's inhabitants live (Ma and Wang, 2015; Wu et al., 2015). At present, sewage is recorded as the primary source contributing to the external P load in the northern part of Dianchi Basin (Li et al., 2019). Within the southern basin, large, shallow P deposits (some <2 m deep) are distributed widely throughout the region (12,000 km^2), especially the southern part of the Dianchi basin (Yuan and He, 2008; Yan et al., 2015; Yan et al., 2017).

Since the 1990s, many measures have been undertaken to address water pollution (Liu et al., 2015; Wang, 2015; Xu et al., 2016). In 1996, the Xiyuan Water Tunnel and Caohai–Waihai Lock were built to reduce the impacts of pollution from the main urban area on the main body of Lake Dianchi, splitting Caohai and Waihai into two separate systems. Since 1998, sediment dredging projects have been undertaken to reduce internal pollution from sedimentation. Diversion projects to address water shortages were also launched in the last decade. The Niulan River Diversion Project is the largest effort, which has introduced >400 million m^3 of water in 2015 alone (Fig. 1). Likewise, the sanitation enhancement and treatment capacity of sewage plants reached >500 million tons per annum in 2017. In addition, there are plans to redirect all municipal wastewater past Waihai into downstream rivers through urban piping and the Xiyuan Water Tunnel by 2020 (RMW project). Although the above constitute only a small portion of the treatment effort, they have certainly changed the P cycle in the Dianchi system, and thus have had a far-reaching effect on Dianchi P management (Liu et al., 2005; Liu et al., 2014; Wang, 2015).

2.2. Data sources and search strategy

Selection of publications and data used in this paper was based on the following approaches: (1) Hydrological monitoring data were obtained from Kunming Environmental Monitoring Center (Gao et al., 2014a).

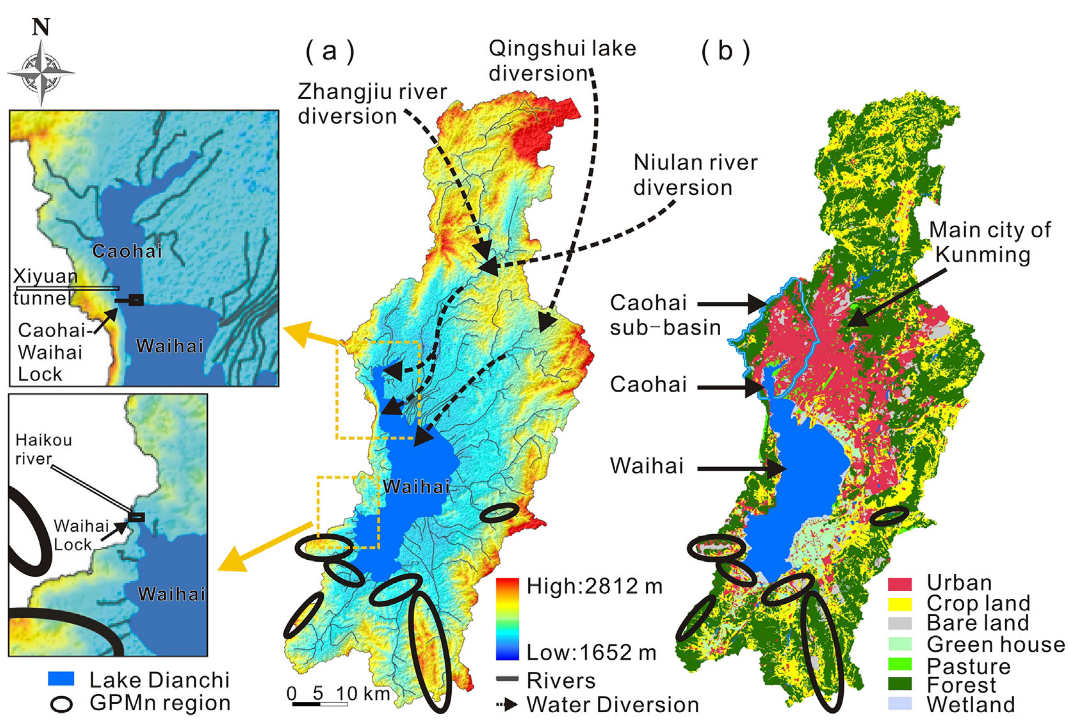

Fig. 1. Characteristics of Lake Dianchi basin: (a) River system and terrain (elevation) within the basin; Caohai and Waihai locations; insets show water injection points for diversion projects; elevation range is marked by color gradation (low: blue, high: red), (b) Landscapes within Dianchi basin (data from 2010). Geologically P-rich Mountain (GPMn) regions have been marked in (a) and (b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(2) Published data were collected from online searches for P budget and pollution both in English and Chinese (ISI Web of Knowledge, China National Knowledge Infrastructure or CNKI). Publication searches were carried out in March 2018. Meanwhile, government reports, statistical yearbooks, and monographs from the past 35 years were also collected. For specific strategies please see (Section 3 in SI). The raw data were either obtained from tables or extracted by digitizing graphs using the GetData Graph Digitizer (version 2.24, Russian Federation).

2.3. Data analysis and model development

Using the data sources described above (Section 4 in SI), we performed six independent analyses, which are described below. Analyses (1) and (2) were used to address the first goal of the paper; (3) and (4) were used to address the second goal of the paper; and (5) and (6) were used to address the third goal of the paper. In the discussion section, analysis (7) was used to compare Lake Dianchi with other lakes in both southwest China and around the world.

(1) Lake TP and TP discharge data were collected worldwide (Section 4.1 in SI), and compared across different regions after log transformations. TP retention (Eq. (1)) and TP retention ratio (Eq. (2)) were used to determine the lake's self-purification capability (Brett and Benjamin, 2010). A positive value indicates that a P sink in the lake system would increase, while a negative value indicates a P sink would be reduced.

$$\text{TP retention}\ (\text{ton}\cdot\text{a}^{-1}) = \text{TP discharge} - \text{TP export}. \quad (1)$$

$$\text{TP retention ratio} = \frac{\text{TP discharge} - \text{TP export}}{\text{TP discharge}} \quad (2)$$

TP discharge is defined as P pollution loading into the lake annually ($\text{ton}\cdot\text{a}^{-1}$), and TP export indicates P removal from the lake. TP discharge (load) and retention per unit area were also calculated (Eqs. (3), (4)):

$$\text{TP load intensity}\ (\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}) = \frac{\text{TP discharge}}{\text{lake area}} \quad (3)$$

$$\text{TP retention intensity}\ (\text{g}\cdot\text{m}^{-2}\cdot\text{a}^{-1}) = \frac{\text{TP retention}}{\text{lake area}} \quad (4)$$

TP retention data was also log-transformed before comparison, although we added 2 for each data set before this process, because some values were less than −1. Our transformations took the form $\log(x+2)$ (Fig. 2).

(2) Meta-analysis was launched to explore the relationships between HABs and P levels in Dianchi. First, we used published correlation coefficients (Section 4.2 in SI) as effect sizes in a formal meta-analysis across datasets regarding HABs, using the random-effect DerSimonian and Laird approach (Schulze, 2004) to understand the general relationship between HABs and P by the results of accumulative effect size. A positive value of accumulative effect size indicates a general increase in HABs as P enrichment occurs in the lake. The 'metacor' package was used to perform meta-analysis (details see Section 5 in SI) (Fig. 2).

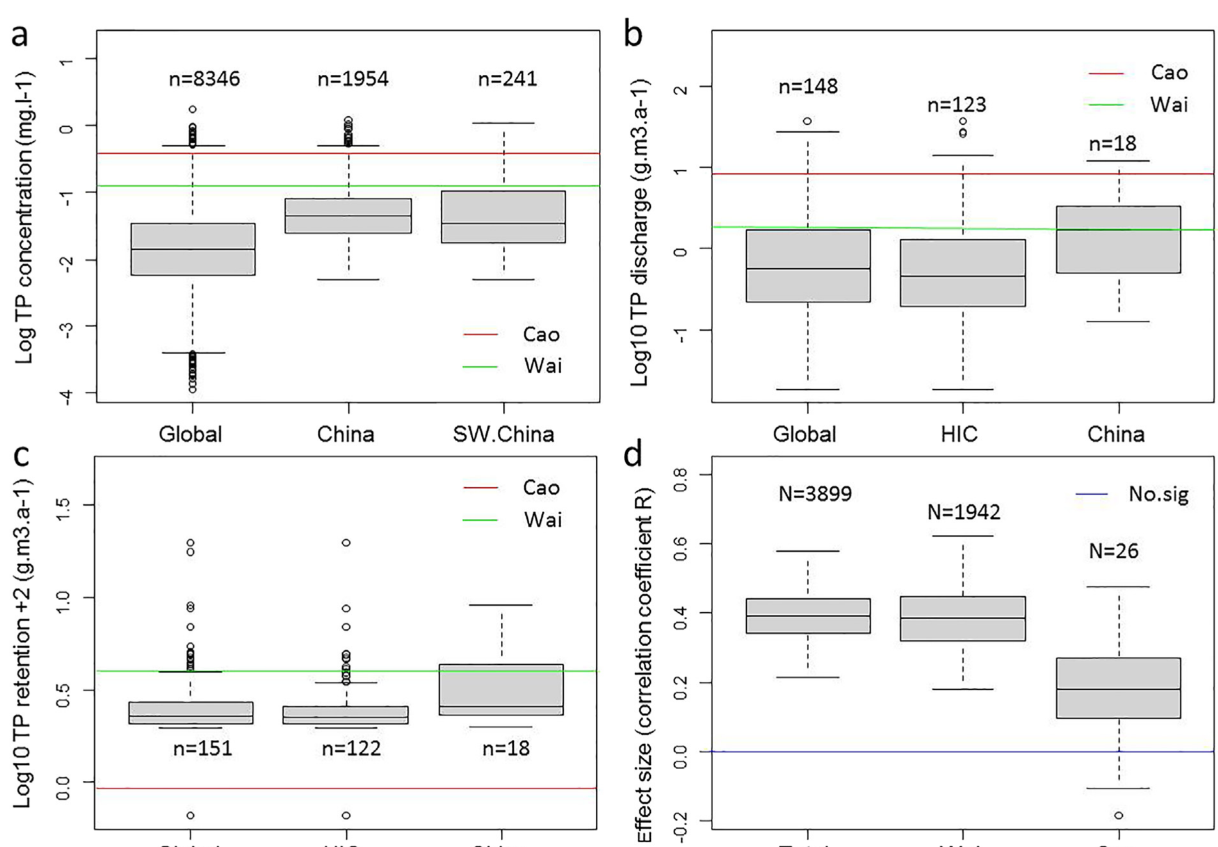

Fig. 2. Comparing TP concentration (a), TP load (discharge) (b), and TP retention (c) for Lake Dianchi and other lakes worldwide. Sample numbers (n) are marked in each box. HIC: lakes in high-income countries, including the United States, Europe, Oceania, and Japan. SW.China: lakes in southwest China. (d) Meta-analyses of the effect of P increase on HABs in Dianchi system. 95% CI is given, with values across zero indicating no significant effect to algae (No.sig). 'Fail Safe Number' is marked with N, a larger number indicates more confidence. Cao: Caohai section, Wai: Waihai section.

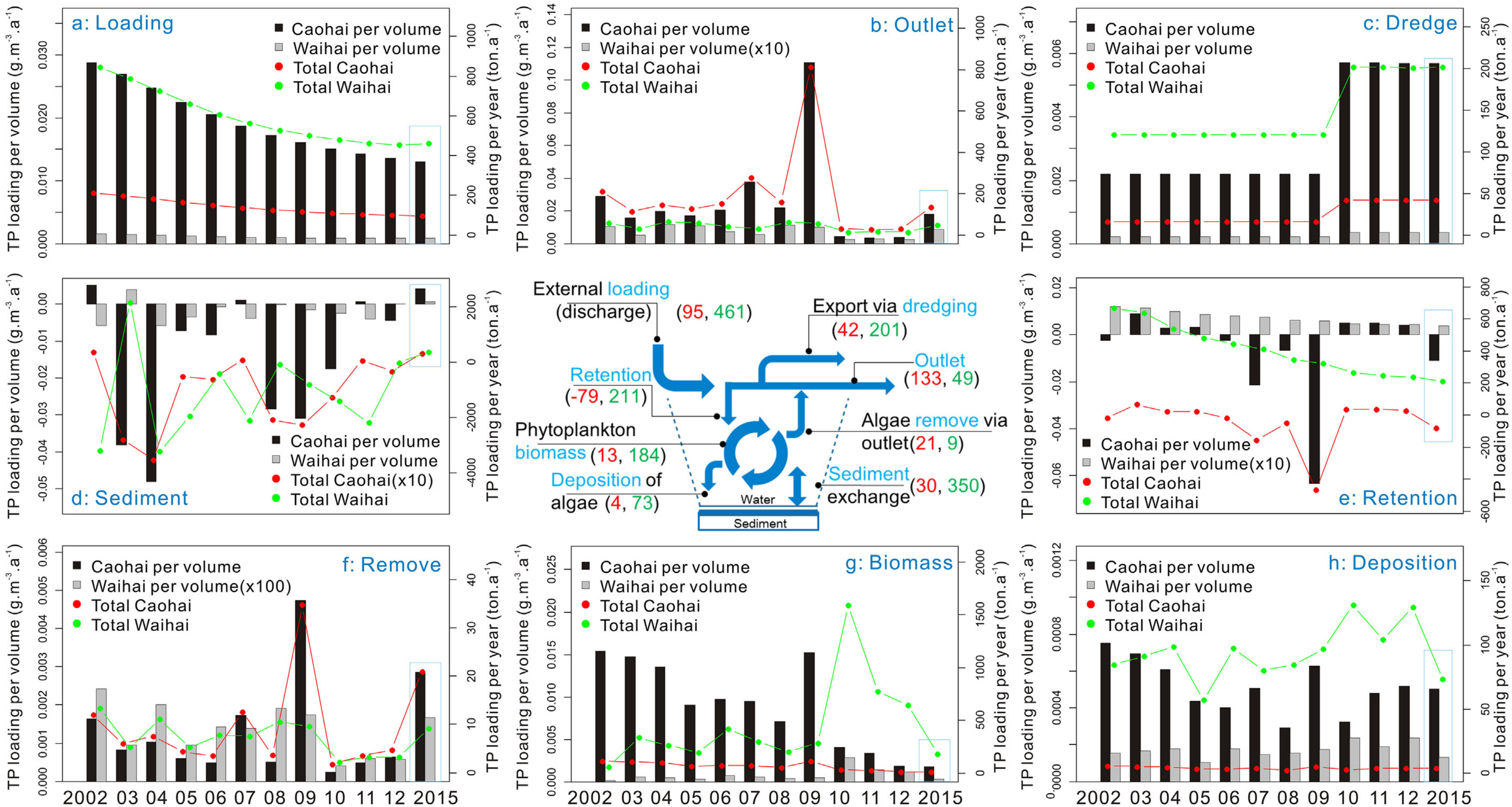

Fig. 3. Dynamic of annual P budget in Lake Dianchi: (a) External P loading through basin. (b) P removals through outlets. (c) P removals through sediment dredging projects. (d) P flux through sediment exchange. (e) TP retention, the difference between external loads and P removals (Eq. (6)). (f) P removals through outlets in the form of algae. (g) P stays in lake system in the form of phytoplankton. (h) Algae sink. The middle graph shows annual P budget in Lake Dianchi (ton·a^{-1}), Caohai budget is marked in red, and Waihai budget in green. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Secondly, to confirm if the relationship between HABs and P (effect size) changed over time, generalized linear mixed effects models were used. If research time (completion dates) had no effect on the effect size trend, it indicated that the general relationship between HABs and P did not change, even under continuous treatments. The 'lme4' package was used to perform these analyses.

(3) A lake eutrophication model was developed using a BHF model to calculate nitrogen (N) and P budgets in both Caohai and Waihai (Fig. 3). This model was improved with the previous model developed by Wu et al. (2017), with the equations shown below (Eqs. (5)–(10)). Our improvements to this model include the incorporation of monthly average phytoplankton biomass to N, P, and lake hydrodynamic characteristics; the use of a longer time series (2002–2015); the explicit incorporation of algae biomass and P uptake by algae; and P removal via artificial treatment like sediment dredging. The budget in Waihai was calculated in this study as Wu et al. did in 2017, and the P budget in Caohai section was calculated as well.

$$\frac{dB}{dt} = \left(M * f_N * f_P - mo - \frac{vs}{h}\right) * B - L * B^2 - \frac{Q}{V} * B \quad (5)$$

$$B = Chla * ca \quad (6)$$

$$f_P = \frac{TP \cdot R_P}{TP \cdot R_P + K_P} \quad (7)$$

$$f_N = \frac{TN \cdot R_N}{TN \cdot R_N + K_N} \quad (8)$$

$$\frac{dTP}{dt} = \frac{L_P}{V} - \frac{O_P}{V} + S_P * TP - \frac{Q}{V} * TP - \left(M * f_N * f_P - mo - \frac{vs}{h}\right) * B * pa \quad (9)$$

$$\frac{dTN}{dt} = \frac{L_N}{V} - \frac{O_N}{V} + S_N * TN - \frac{Q}{V} * TN - \left(M * f_N * f_P - mo - \frac{vs}{h}\right) * B * na \quad (10)$$

where B is the biomass phytoplankton; $M * f_N * f_p$ is the actual growth rate of phytoplankton; M is the maximum growth rate of phytoplankton; S_P is the sediment exchange rate of total P; S_N is the sediment exchange rate of organic N; K_N is the Michaelis-Menten constant for N; K_P is the Michaelis-Menten constant for P; Q is the out flow of the lake; L_P and L_N represent the external load entering the lake of N and P; O_P and O_N represent other pathways (e.g. sediment dredging) that TP and TN remove from the Dianchi system, rather than outlets. The datasets for L_P, L_N, O_P, O_N, T_P, T_N and Chla were collected based on published results and reports. Synthetic analysis was used to identify loadings by external nutrients (L_N, L_P) through a generalized additive model; we used the 'mgcv' package to perform this analysis. Description of other symbols in the equations and further details are provided in Section 6 in SI.

(4) Model parameters for the BHF Model, e.g. M, S_P, S_N, K_N, and K_P, were estimated via Markov chain Monte Carlo (MCMC), and seasonal pattern of heterogeneity was also considered (Wu et al., 2014; Li et al., 2015; Wu et al., 2017; Wang et al., 2019). Parameters of each sub-model representing the same process shared the same prior distributions. Three processes were chosen to build the hierarchical framework: algae growth (M), sediment exchange of P (S_P), and sediment exchange of N (S_N).

$$M_i \sim N(m_M, \sigma_M)\ i = 1, 2, \ldots, 31, 32 \quad (11)$$

$$S_{pi} \sim N(m_{SP}, \sigma_{SP})\ i = 1, 2, \ldots, 31, 32 \quad (12)$$

$$S_{Ni} \sim N(m_{SN}, \sigma_{SN})\ i = 1, 2, \ldots, 31, 32 \quad (13)$$

In this structure, m_M, m_{SP}, and m_{SN} were global parameters for M, S_P, and S_N respectively, and M_i, S_{pi}, and S_{Ni} were the equivalent for each sub-model. M_i followed a normal distribution with m_M as the average and σ_M as the standard deviation (SD). S_{pi} followed a normal distribution with m_{SP} as the average and σ_{SP} as the SD. S_{Ni} followed a normal distribution with m_{SN} as the average and σ_{SN} as the SD. We used the 'R2WinBUGS' packages to perform this section, and further details are provided in Section 6 in SI. Moreover, given the purpose of this research, only P-related results are presented here.

(5) Through a systematic review of the literature regarding P pollution in the Dianchi system, as well as government reports on Lake Dianchi from 2016, an analysis of the challenges regarding future P management has been carried out (the analysis has unfortunately not been able to address all possible issues) (GRLD, unpublished document) (Section 7 in SI). Consequent analysis of scenarios are concerned with the following aspects: Given that sewage is the primary contributor for the external P load (Wang, 2015; Li et al., 2019), what would happen once the RMW project is completed in 2020? Given that sediment release is the primary contributor for the internal P load (Wu et al., 2017), what would happen when costly dredging treatments are stopped? Given that large GPMn lie around Dianchi basin (Yan et al., 2017), what would happen when serious degradation appears? So far, Niulan River diversion projects have been regarded as one of the key contributions to modifying Dianchi's pollution. But the degradation risk in the Niulan River is not low—in part of its reach TP concentration is even higher than 0.35 $mg \cdot l^{-1}$, and there are still some GPMn regions in its basin (Gao et al., 2005; Luo and Ma, 2010; Zheng et al., 2018). Moreover, considering the variation in results across the literature, and that corresponding data is limited in these P pathways, MCMC simulations were used for posterior probability based on the published results through the 'wiqid' package. Following the requirements of the Kunming Development Program (2016–2020), Kunming city will continue to expand; see website for details: http://www.km.gov.cn/c/2016-08-22/1433198.shtml. Analysis of corresponding scenarios was launched based on the results from GRLD.

(6) Using the results from our BHF Model, scenario analysis was conducted by solving differential equations (Li et al., 2015; Wu et al., 2017), that TP and algae biomass could be predicted under seven different scenarios regarding future challenges facing Lake Dianchi (details see Section 8 in SI). Total P retention was calculated following Eq. (1). Inputs for this model included Q, L_P, L_N, and flux shifts via sediment dredging, water diversion, GPMn degradation, and urban extension (Fig. 4). The inputs of the baseline were the observed data and parameters in 2015 (12 months in all) (Scenario_0). To compare Wu's results (2017) with ours, input of Scenario_1 was the observed data in 2009. Scenario_2: projected results for RMW project. Scenario_3: projected results for no sediment dredging project. Scenario_4: projected results for Kunming Development Program 2020. Scenario_5: GPMn re-degradation. Based on the results from Yuan and He (2008) and Li et al. (2019), extra P load is semi-quantitative if re-degradation happened in the Southern Dianchi basin. Scenario_6: GPMn degradation happened in Niulan River basin. Currently, the Niulan River has an average TP concentration of 0.055 $mg \cdot l^{-1}$ (Scenario_0), but some segments reach higher than 0.35 $mg \cdot l^{-1}$ (Gao, 2008). So if serious degradation were to occur in the Niulan River basin and lead its average TP to the worst level, large extra exogenous tons P would discharge into the Dianchi system via diversion projects when it under the same water-flow as in Scenario_0. Scenario_7: GPMn degradation happened both in the Niulan River basin and Dianchi basin. For specific selecting reasons and parameter information, please see Section 8 in SI.

(7) Generalized linear models used to understand the relationships among lake TP, population density, soil TP geological makeup,

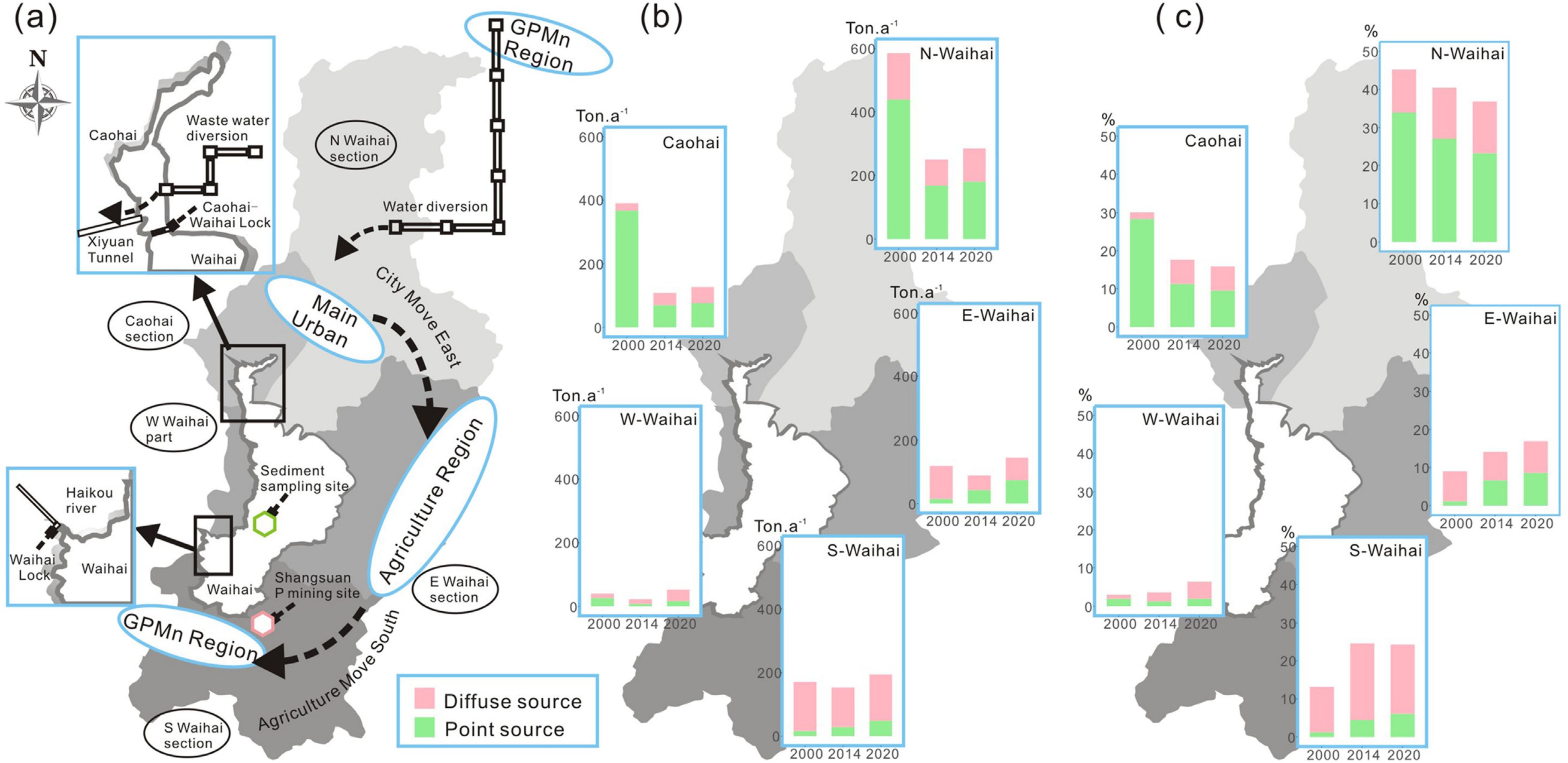

Fig. 4. (a) Schematic diagram of shift in land uses and possible challenges. The sediment sampling site (Liu, 2014), Shangsuan P mining site (Yuan and He, 2008), and geological phosphorus-rich mountains (GPMn) are marked. (b) Dynamics of external P load (discharge ton·a^{-1}) and (c) load proportions (%) into lake within different sub-basin in Dianchi system basing the results from government reports on Lake Dianchi in 2016 (GRLD).

and P mining actions, southwest China, using R version 3.3 and the 'Bestglm' package. The soil TP map was obtained from China Geological Survey datasets (CGS); the population map was obtained from National Earth System Science Data Sharing Infrastructure. P mining data was also obtained from CGS, and then calibrated with Google Earth. Furthermore, TP, TP retention (Eq. (1)) and TP retention ratio (Eq. (2)) among GPMn lakes were collected (Section 4.1 and Section 9 in SI) and compared across different regions after log transformations. Because data available for GPMn lakes is limited, one sample *t*-test was used to test the differences between GPMn lakes and the upper quartile of the other lake datasets.

3. Results

3.1. Lake Dianchi continues to suffer from high levels of P enrichment

Continuous efforts have generally resulted in the improvement of water qualities in Lake Dianchi; however, P enrichment and consequent HABs still challenge Dianchi management. Even after 2015, water P concentration remains at high levels (Waihai = 0.11 $mg \cdot l^{-1}$, Caohai = 0.22 $mg \cdot l^{-1}$), which are 3 to 14 times the global mean or the means of other key regions (Fig. 2a). By now, its load intensities are still high in both the Waihai and Caohai sections. Of these the load intensity in the Caohai section (9.2 $g \cdot m^{-2} \cdot a^{-1}$) is 20 to 40 times the global mean or the means in other key regions (Fig. 2b). On the contrary, TP retention intensity in the Waihai section is 3 to 5 times the global mean or the means in other key regions (Fig. 2c). Moreover, HABs still occur every year. The results of the meta-analysis have indicated that P level is closely linked to HABs in Lake Dianchi, especially in Waihai section ($p < 0.05$), whether throughout history or recently ($p > 0.05$) (Fig. 2d). Generally, the Dianchi system remains under high pressure of P pollution, and P concentration still forms a key factor impacting HABs in Lake Dianchi. Therefore, a full understanding of P budgets in Dianchi is one of the foundations for future eutrophication control.

3.2. Evolution of P budgets in Lake Dianchi basing BHF model

The lake P cycling model was developed based on collected data sets, and by adapting Wu et al.'s (2017) BHF model (Fig. 3). Our findings indicate that contiguous P mitigation efforts have resulted in a decrease in external P loading (basin discharge) since 2002. These mitigations, combined with treatment projects like sediment dredging, have led to yearly observations of reduced P retention within Dianchi. However, external P loading remains to date higher than 550 $ton \cdot a^{-1}$. Besides, natural P removal is lacking: only a small amount of P can be removed through river outflow (outlets: 182 $ton \cdot a^{-1}$ in 2015), and sediment dredging has become the primary P removal pathway (Export via dredging: 243 $ton \cdot a^{-1}$ in 2015). Meanwhile, large P flux in Lake Dianchi (304 $ton \cdot a^{-1}$ in 2015) is still associated with algae (biomass, deposition and removal); P release from sediments seems to have increased since 2002 (380 $ton \cdot a^{-1}$ in 2015). Generally, P flux remains high, both through external P loading and the internal P cycle (within lake) in Lake Dianchi as a whole.

Specifically, different situations are observed within diverse sections of Lake Dianchi. In terms of the Caohai section, annual external P loads per volume are significantly higher (0.013 $g \cdot m^{-3} \cdot day^{-1}$ in 2015) than in the Waihai section (Fig. 3). Current management practices have led to successful mitigation in Caohai (P retention = −79 ton in 2015) (Fig. 3e). This negative P flux within the Caohai sub-system is a positive indication of the current recovery effect vis-à-vis P budget improvement. In contrast, the Waihai section shows significant external loads (461 $ton \cdot a^{-1}$) and P retention (211 $ton \cdot a^{-1}$), which lead to large P deposits as sediment (sediment exchange = 350 $ton \cdot a^{-1}$) (Fig. 3d). By the results of the BHF Model, the Michaelis-Menten constant for P (K_P) in the Waihai section (0.02 $mg \cdot l^{-1}$) is significantly lower than that in the Caohai section (0.04 $mg \cdot l^{-1}$), again suggesting that HABs in Waihai would be more sensitive to P levels. Moreover, the current P budget in Lake Dianchi remains unclear, especially the TP export to Waihai section deriving from GPMn degradation (Section 8 in SI).

3.3. Challenges of phosphorus mitigation in the Dianchi system and analysis of corresponding scenarios

Into the 21st century, improvements in sewage sanitation and deindustrialization have led to modified P pollution in both the Caohai and Waihai sections. Of these, the Caohai section benefits more from reinforced pollution control than Waihai. Significant decrements in external P loading (discharge) and load proportion were recorded in the Caohai sub-basin between 2000 and 2014 (Fig. 4). However, large P quantities deriving from sewage (point source) is still a key hindrance for its management. In terms of the Waihai section, aside from the weak self-purification capacity mentioned above (Fig. 3), the increments in external P load proportions are observed across the eastern, southern, and western Dianchi basin (Fig. 4). Notably, continued urban expansion would bring more P loads from both point source and diffuse sources over the whole Dianchi basin, and make agricultural activities have shifted southwards in response. Those agricultural activities would also cause ecological degradation to occur in the large GPMn region of southern Dianchi (Fig. 4). In general, different sections of Lake Dianchi are at risk of facing diverse challenges in the future.

Therefore, based on the diverse P situations of the Caohai and Waihai sections in 2015, scenario analysis was launched to predict Dianchi TP and algae changes under possible scenarios in the future (Fig. 5). Comparing the situation in 2009 (Scenario_1) with that of 2015 (Scenario_0), it was found that a significant reduction in annual external P loads could effectively decrease lake TP concentration and algae biomass. If the proposed RMW sewage project could be completed in 2020 (Scenario_2), it would also reduce Dianchi TP and algae biomass by 10% and 25%, respectively. In contrast, if sediment dredging projects had not been implemented (Scenario_3), >240 ton P could be retained in Lake Dianchi. This would certainly aggravate P sinks in Waihai (TP retention 412 $ton \cdot a^{-1}$) and lead to a consequent increment in lake TP by 16% and algae biomass by 34%. Generally, nature (outflow river) alone cannot cope with Dianchi P issues; instead, costly artificial measures are essential to modifying the large P imbalances in the Dianchi system.

Moreover, at present Kunming's new round of developments (Scenario_4) could introduce more risk to water quality, and the main Waihai section in particular. TP discharge per unit area in Waihai may increase to 2.1 $g\ m^{-2} \cdot a^{-1}$, adding 140 tons of P annually to Waihai, and could increase the TP retention by 214 tons. Moreover, GPMn region or recovered P mining sites could degrade again (Scenario_5). In fact, there are large GPMn regions not only south of Dianchi basin but also upstream of Niulan River (Section 8 in SI). The continued degradation of this region could lead to hundreds of tons of additional P entering Lake Dianchi (115 $ton \cdot a^{-1}$) (Scenario_6). If GPMn degradation occurs in both the Dianchi and Niulan River basins, an extra 200 tons of P would enter Dianchi, and consequent Waihai TP and algae biomass would increase by 16% and 49%, respectively (Scenario_7). In sum, rapid urbanization, combined with special natural features within the basin, would lead to a high pressure of P pollution for Dianchi.

4. Discussion

4.1. Phosphorus mitigation remains a challenge in water quality protection for Lake Dianchi

At the beginning of the 21st century, the Chinese government struggled to deal with pollution (Day, 2016; Tong et al., 2017). Improvements in sewage sanitation and deindustrialization have resulted in a decrease

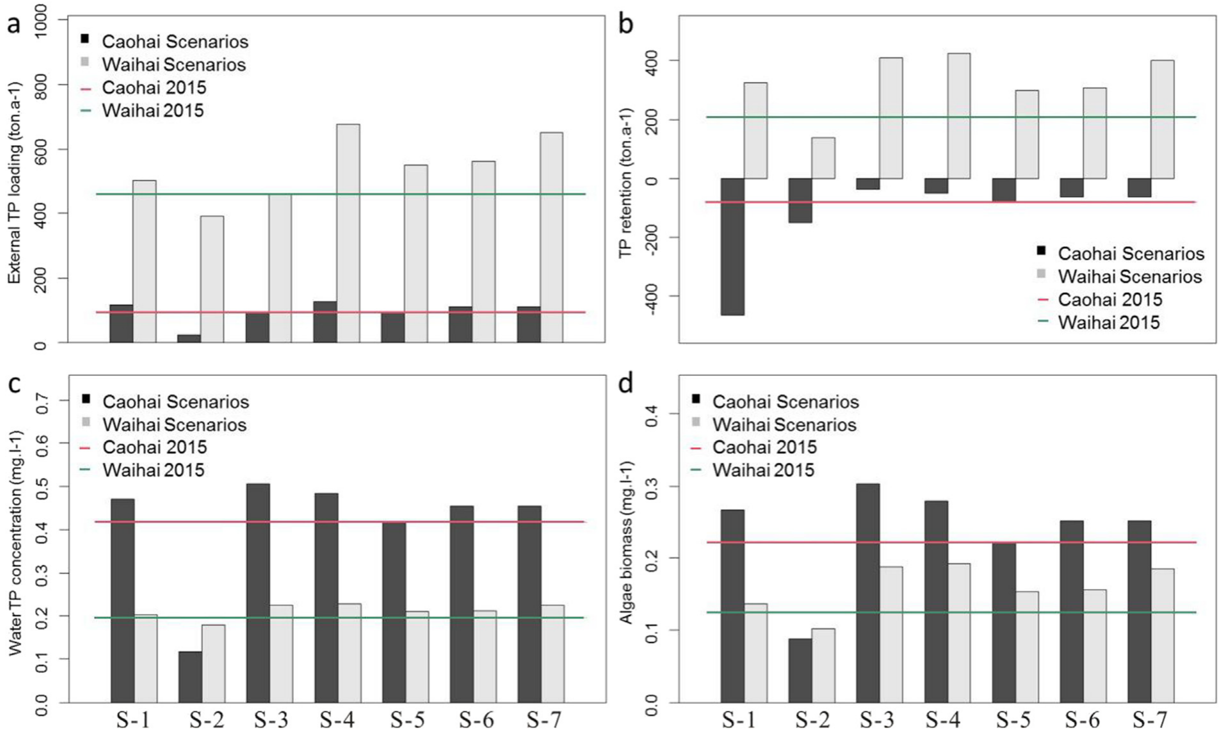

Fig. 5. Results of scenario analysis: (a) External TP discharge (loads) into lake across different scenarios. (b) TP retention in Caohai and Waihai across different scenarios (Eq. (6)). (c) TP concentration of Lake Dianchi across different scenarios. (d) Algae biomass of Lake Dianchi across different scenarios. Caohai 2015 or Waihai 2015 means Scenario-0, S-1: situation in 2009, S-2: RMW project, S-3: No sediment dredging, S-4: situation under Kunming development program '2020', S-5: GPMn degradation happened in Southern Dianchi basin, S-6: GPMn degradation happened in Niulan River basin, S-7: GPMn degradation happened both in Niulan River basin and Dianchi basin.

of P concentrations within Lake Dianchi (Liu et al., 2015). However, current TP values remain above government targets (Waihai < 0.1 $mg\cdot l^{-1}$, Caohai < 0.2 $mg\cdot l^{-1}$), and far exceed international standards (0.024 $mg\cdot l^{-1}$, or 0.05 $mg\cdot l^{-1}$) (Carpenter and Bennett, 2011; Schindler et al., 2016) recommended for avoiding or mitigating harmful algal blooms. Based on the results of the meta-analysis, HABs in Lake Dianchi are still closely linked to the latter's P level. Meanwhile, from the results of the BHF model, large P fluxes associated with external loads (550 $ton\cdot a^{-1}$), algae (304 $ton\cdot a^{-1}$), and sediment release (380 $ton\cdot a^{-1}$) were observed, which are similar with the results from Wu et al. (2017). However, Wu et al.'s model does not include phytoplankton cycling and artificial removal (treatments), so that it would have overestimated P fluxes through sediment release while simultaneously underestimating P fluxes within algae and the food web. The above results have at least indicated P mitigation to remain a challenge in Dianchi management. Noticeably, the Caohai and Waihai sections are encountering different challenges, and thus corresponding management strategies are of critical importance (Wang et al., 2019).

In terms of the Caohai section, it benefits from the best pollution control across the whole Dianchi system. Current sanitation efforts, combined with diversion projects and rapid water exchange (Gao et al., 2015; Wang, 2015), have led to negative P retention (−79 $ton\cdot a^{-1}$). Concomitant reductions in P concentration in the Caohai section have also been observed (>1.5 $mg\cdot l^{-1}$ in 2009 and <0.3 $mg\cdot l^{-1}$ in 2016). However, its annual external P loads still show significantly higher intensities than those of other lakes (Fig. 2b and Section 9 in SI), because Caohai is near in proximity to the main city of Kunming, a producer of large amounts of sewage and industrial wastewater. Furthermore, it is unclear why negative P retention is observed in the Caohai section in spite of the fact that P release through sedimentation seems to have increased continuously (Fig. 3d). Both P loading and P release, as potential key contributors to future control of HABs in the Caohai section, need to be given more attention.

Although the Waihai section has a lower p value (0.11 $mg\cdot l^{-1}$ in 2016) than that of Caohai, the incidences of algae blooms in Waihai's southern section have been increasing. Based on evidence from sediment analysis, several studies show a continuous increase in algal chlorophyll content within the sediment of Waihai's southern section (Gao et al., 2005; Liu, 2014), thus the factors driving future environmental challenges will remain complex. Specifically, the Waihai section has shown significant external loads (461 $ton\cdot a^{-1}$) and P retention (211 $ton\cdot a^{-1}$), which could be explained by its large catchment (i.e., received pollutant) area, long hydraulic retention times, and/or high evaporation rates. P flux through sediment release seems to have increased, and the self-purification capacity is likely to be weak in Waihai. These are highly consistent with observations from Wu et al. (2017). Several studies have indicated that urban expansion would bring more sewage and diffuse pollution, and concomitant GPMn degradation (Yan, 2015; Li et al., 2019), leading to consequent HABs (Fig. 4 and Fig. 5). Therefore, there is consensus that effective measures should be taken to control the size of cities and improve sanitation facilities (Gao et al., 2014b; Wu et al., 2015). In terms of GPMn degradation, one case study estimated that runoff from the Shangsuan mining area alone would introduce approximately 11.8 t TP into Waihai annually (Yuan and He, 2008). Li et al. (2019) also indicated that P mining added >60 $ton\cdot a^{-1}$ dissoluble P (20% diffuse source, 80% point source) into the Waihai section in 2012. But we are still unclear as to the full picture of TP load derived from GPMn degradation. Generally, urbanization, combined with a special geological environment, has led to complex issues in the Waihai section. More accurate P budget calculations, flexible sub-regional P mitigation, and careful GPMn protection strategies are therefore needed.

Overall, self-purification is limited in the Dianchi system (Figs. 2 and 3). Current modifications in the Dianchi P budget are driven by costly artificial treatments, but these projects could also cause unintended consequences. For example, sediment dredging improves the P budget (Scenario_3, Fig. 5), yet could also harm local food webs and affect P release via algae die-off (Hu et al., 2010; Binzer et al., 2015), which is a vital part of lake P internal cycling. Although the RMW project could improve Dianchi water quality, around 140 tons of P would be directed into the upper reaches of the Yangtze River, based on current techniques (Scenario_2, Fig. 5). For diversion projects, they have somewhat addressed Dianchi water shortages and P enrichment (Liu et al., 2014). However, if degradation occurs in the GPMn region upstream of the Niulan River, hundreds of tons of P would enter the Dianchi system, resulting in subsequent HABs (Scenario_4–7, Fig. 5). Therefore, ecological insights are needed in both Dianchi and regional P mitigation strategies.

Last but not least, all of these high-cost treatments are currently only supported by governmental investment, which is not a sustainable situation in low-income southwest China. To take dredging projects as an example, >15 million m^3 of dredged sediment has only been used by the government to build cofferdams, or thrown into landfills around Lake Dianchi (Wu et al., 2016). The treatment methods of dredged sediment are chosen due to limitations of investment and technology, despite the stink and risk of a second round of pollution. While there are already some technicians dedicated to the resourceful utilization of dredged sediment, by means of use in agriculture and forestry, the production of building materials, and the production of gas for energy, there is still not enough large-scale promotion due to the limited economic benefits (Wu et al., 2016). Therefore the development of market incentives and introduction of private capital for the recovery of the lake ecosystem will be important for initiating and maintaining future treatment projects in Lake Dianchi (Kato et al., 2016; Roy, 2017).

In general, P mitigation remains a challenge in water quality protection for the Caohai and Waihai sections. Urban expansion and GPMn degradation pose problems for future Dianchi management. These are not simply technical problems; ecologically sensitive approaches to geological factors, environmental policy, and economic income should be incorporated (Matson et al., 2016; Roy, 2017). Moreover, these issues do not occur only in Dianchi and other water bodies in GPMn regions, but rather the whole of southwest China faces similar problems.

4.2. Dilemmas for water source management in Southwest China

In Southwest China, the Himalayan Orogeny (Yin and Harrison, 2003), which began millions of years ago, formed the largest inland GPMn region in the world (Section 9 in SI). Notably, there are >90 million tons of P ore, constituting half the global annual production (Zapata and Roy, 2004; Cooper et al., 2011; ChinaIRR, 2016). Also due to this orogeny, large numbers of lakes and reservoirs are located here, which have been preferentially selected as destinations for human settlement. However, lakes in this region often form by rift-subsidence, thus forming fragile ecosystems with small basins, long water exchange times, high evaporation rates, and significant lake aging (Yin and Harrison, 2003). All of these issues increase the difficulty and complexity of local water protection efforts.

Some studies have indicated that significant P loss could occur within degraded GPMn by intensive human activity (Kuo and Muñozcarpena, 2009; Abdalla and Khalifa, 2013). In fact, surrounding water bodies are often accompanied by aquatic system degradation, such as plateau freshwater lakes like Xingyun (Sakamoto et al., 2002) or Hongfeng (Jiang et al., 2011), or reservoirs like the Three Gorges (Wang et al., 2016). But notably, high P content within these basins may not necessarily mean that serious P pollution has occurred in a water body. We have found that lake TP in Southwest China is affected by a multitude of interactions among soil P content, population density ($p < 0.05$), and mining activity ($p < 0.05$) (Fig. 6, Section 10 in SI). As such, large amounts of P could enter the water through diffuse pathways, such as from runoff or aerial deposition from degraded GPMn (Kuo and Muñozcarpena, 2009; Kop et al., 2011; Bachmann et al., 2012). Therefore, it is necessary to adopt reasonable treatment methods in regional management practices based on local geological factors.

Moreover, it has been reported recently that P is currently the main pollutant in the Yangtze River (MEE-China, 2017a). Notably, 80% of P deposits in China are located in its mid-to-upper reaches (ChinaIRR, 2016; Powers et al., 2016; MEE-China, 2017a). However, some local governments and enterprises in the area do not want to acknowledge the negative impacts derived from the degradation of GPMn regions, as they believe that this would affect local income and employment. Instead, some agricultural environmentalists prefer to attribute this portion of P pollution to agriculture, in the hope that the government would further increase its investment in agricultural management (Personal communication). Therefore, these issues are not only technological in scope, but also involve complex social and political regimes (Cordell et al., 2011; Yu et al., 2013; Kato et al., 2016).

In fact, there are numerous GPMn areas distributed worldwide. Aside from the Dianchi basin and other basins in Southwest China, both Southeastern North America and Northwestern Africa are also primary distribution areas. Studies have shown that P discharge in the southeastern United States is primarily derived (31%) from GPMn regions (García et al., 2011), and abandoned P mines in Florida are an important pollution source (Bachmann et al., 2012). We have also found that these lakes often have higher TP (mean $= 0.21\ mg \cdot l^{-1}$), which are 3 to 14 times the global mean or the means in other key regions (Section 9 in SI). Furthermore, GPMn lakes often have a higher TP retention ratio (0.72), regardless of whether they have high TP discharge/retention (Section 9 in SI). These are somewhat similar with Dianchi's situation, indicating that lakes in GPMn regions could face more P stress in the future.

Generally, the southwest region is an important ecological buffer in China, where the upper reaches of key rivers such as the Yangtze and Pearl are situated. Meanwhile, this region is undergoing rapid urbanization, as a result of the China Western Development policy (Démurger et al., 2001). This has promoted local economic development, but would also harm regional ecology if reasonable management were limited. Furthermore, P rocks and global GPMn regions are indeed natural gifts for humans to address food security problems, but unreasonable management and consequent GPMn degradation could pose serious problems for local water management and de-eutrophication (Cordell et al., 2011; Elser and Bennett, 2011). In sum, these issues are not only technological in scope: targeted technologies and flexible policies regarding regional P management are needed to relieve the contradiction among geological factors and human activities.

5. Conclusions

By systematically reviewing the literature and performing a quantitative meta-analysis, we have shown that in spite of the fact that P budgets in the Dianchi system have been modified; HABs are still significantly associated with the lake's P level (Fig. 2). Specifically, P flux remains at a high level, both through external P loading and the internal P cycle. Significant P retention in the lake was also observed, in particular in the Waihai section (Fig. 3). Moreover, phosphorus loading from GPMn and phytoplankton death has been largely overlooked, hindering further water management strategies. As such, we suggest that P needs to be closely monitored, and technological innovations involving P recycling through sewage and sediment, clean mining, and GPMn restoration should be developed.

Notably, beyond Lake Dianchi, other lakes in China will also face problems stemming from ecological degradation and urban expansion. To our knowledge, two of the three priority lakes (Lake Dianchi (Kim et al., 2018) and Lake Chaohu (Sun, 2017)) selected by the Chinese government in 1995, as well as one of the three "new" priority lakes (Danjiangkou Reservoir (WTPO, 2015)) selected in 2017 (MEE-China, 2017b) for water pollution control are suffering from the degradation of geological P-rich regions. One of the three "new" priority lakes, Lake Erhai (Zhang et al., 2016), is also located in central Yunnan, and would face similar risks to Lake Dianchi, derived from urbanization and the fragile ecology of its basin.

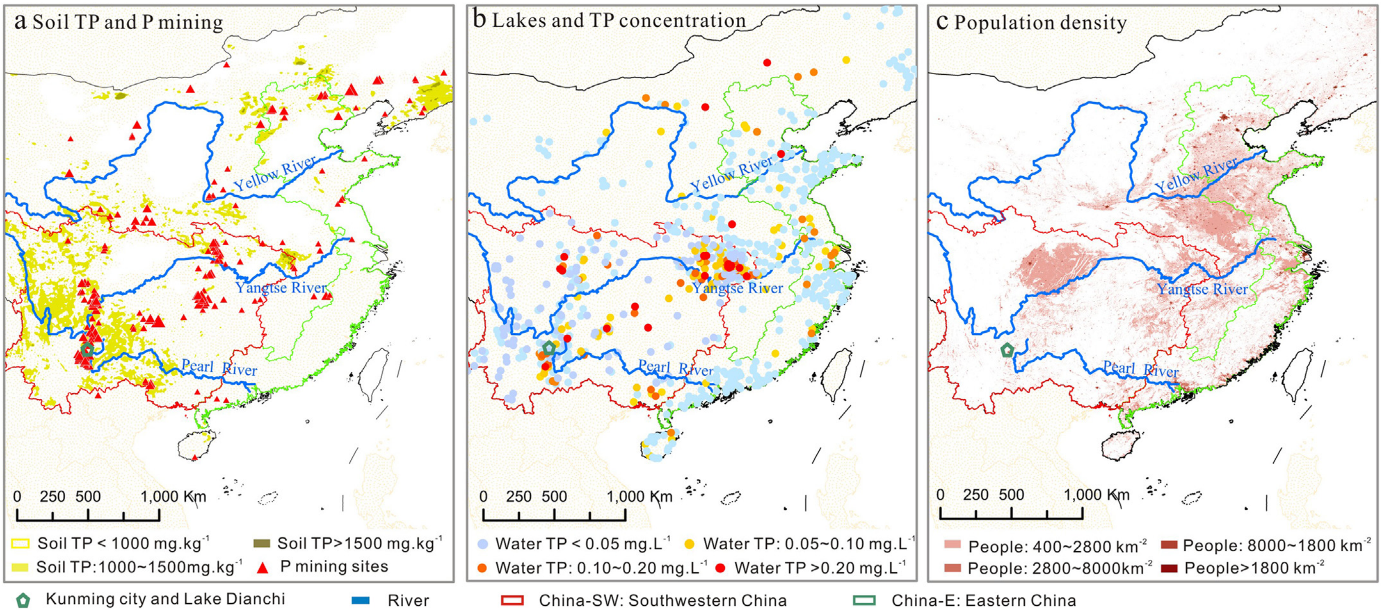

Fig. 6. Distributions of (a) soil TP and P mining sites, (b) TP concentrations in Chinese freshwater lakes, and (c) population density. In Fig. 4(b) and (c), China-E: lakes in provinces of eastern China, including Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, and Guangdong; China-SW: lakes in provinces of southwestern China, including Sichuan, Yunnan, Guangxi, Guizhou, Chongqing, Hubei, and Hunan.

Last but not least, P dynamics and other nutrients such as C, N, Si, and Fe have been observed to have synergic effects (Conley et al., 2009; Smith et al., 2010; Paerl et al., 2016). Our work focuses on P and provides "P-mitigation" suggestions; however, we do not advocate that the effort should ignore the other nutrients. In general, ecologically sensitive approaches to geological factors, multi-nutrients reduction, human activities, and economic income should be incorporated into regional lake protection in China.

Author contributions

J.C. Xu and F.S. Zhang conceived the project; K. Yan, J.C. Xu and Z.W. Yuan designed the research; the manuscript was written through contributions of all authors. K. Yan and Z.W. Yuan contributed equally to this work. All authors have given approval to the final version of the manuscript.

Funding sources

This research was supported by the Chinese National Natural Science Foundation (41807524), Response of Asian Mountain Ecosystems to Global Change, CAS, Grant No: QYZDY-SSW-SMC014, and Provincial Innovation Group for Farmland Non-pollution Production, Yunnan Agricultural University (2017HC015). The last but not the least important, many thanks to my wife S.Gou. Thank you for your continuous support! I love you!

Declaration of Competing Interest

The authors declare no competing financial interest.

Appendix A. Supplementary data

Additional information has been provided online, including: Section 1, population density and P deposits around the Greater Himalayan area and Southwest China; Section 2, P deposits located in Southwestern China, Central Yunnan and around Dianchi basin; Section 3, search strategy for data collection; Section 4, data sources (publication list) for Fig. 2 in main text; Section 5, equation for meta-analysis; Section 6, Bayesian model development and detail equations; Section 7, data source (publication list) for possible challenges for future P management in Lake Dianchi; Section 8, scenario analyses, parameters and the distribution of P-rich region in central Yunnan province; Section 9, in term of Lake TP, TP discharge, TP retention and TP retention ratio data, we compared the difference between Lake Dianchi and other lakes across different regions worldwide; Section 10, the results of generalized regression regarding population, soil TP and mining sites across southwest China. Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.06.302.

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