The spatial variations of water quality and effects of water landscape in Baiyangdian Lake, North China

Liqing Li1 · Xinghong Chen1 · Meiyi Zhang2 · Weijun Zhang1 · Dongsheng Wang1,2 · Hongjie Wang3

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Abstract
Baiyangdian Lake (BYD), a large shallow lake in North China, has complex water landscape patterns that are underlying spatial variations in water quality. In this study, we collected 61 water samples from three water landscapes (reed littoral zones, fish ponds, and open water) and analyzed them for water quality parameters, such as dissolved organic carbon (DOC), total nitrogen (TN), and total phosphorus (TP). Water landscape distribution (determined using remote sensing imagery) was then used to assess correlations between water quality parameters and water landscape proportion in differently scaled buffer zones. There was substantial variation across all subareas, with TN and TP concentrations ranging from 0.90 to 4.10 mg/L and 0.06 to 0.18 mg/L, respectively, in class IV of water quality as a whole. Spatial variations in water quality were mainly caused by water landscape distribution and external nutrient inputs. There were negative correlations between DOC, TN, and TP concentrations and the area proportion of reed littoral zones in the 300 and 500 m buffers. In contrast, DOC, TN, and TP concentrations were significantly positively correlated with the area proportion of fish ponds in the 100 m buffer. Furthermore, compared with reed littoral zones, a lower ratio of nitrogen to phosphorus and a higher proportion of dissolved organic nitrogen and tyrosine-like proteins were found in fish ponds. These effects were mainly attributed to the development of internal sediment loadings due to nutrient exchange across the sediment–water interface. Therefore, dredging-based sediment removal from fish ponds should be considered to suppress internal phosphorus loading and accelerate recovery of the BYD ecosystem.

Keywords Baiyangdian Lake · Water quality · Landscape · Variation

Introduction
Eutrophication of aquatic ecosystems is a global environmental concern, especially in freshwater lakes (Huisman et al. 2018; Tu et al. 2019). In recent years, many efforts have been made to reduce external nutrient loads across whole watersheds and remove internal nutrient recycling from bottom sediments (Chen et al. 2020; Horppila 2019; Lurling and Faassen 2012). Identifying the effects of sediments nutrient release on the overlying water quality is necessary to effectively implement dredging of nutrient-rich sediment. However, previous studies have often focused on the diffusion flux of nitrogen and phosphorus across sediment–water interfaces to determine the internal source impacts (Yang et al. 2020; Yu et al. 2016). Few studies have identified the potential impacts of bottom-sediment nutrient release on the overlying water, by examining the spatial variations of water quality and nutrient processes at water landscape type.

Baiyangdian Lake (BYD), the largest freshwater lake in the North China Plain, is located in Anxin County, Hebei Province, with an average water depth of 2–3 m and an approximate area of 366 km² (Wang et al. 2014). This area is the planned center of a new special economic zone (the Xiongan New Area), for which the lake is expected to play an important role in supplying fresh
water, controlling floods, regulating the local climate, and maintaining biodiversity for the region. However, over the past several decades, it has suffered severe pollution from industrial wastewater, domestic sewage, and agricultural runoff, as well as extensive pond-based aquaculture, due to regional population growth and economic development (Han et al. 2020; Hu et al. 2012). Although its water quality has been somewhat improved recently through reducing external nutrient loading and prohibiting aquaculture, water eutrophication remains a problem, especially in summer.

The implementation of higher water quality requirements in the area makes it necessary to further improve BYD’s water quality and comprehensively restore its aquatic ecology. In many previous shallow lake restorations where external nutrient loading was reduced, sediment internal nutrient loading was likely to recycle nutrients back to the overlying water, preventing further improvements in water quality (Welch and Cooke 2005). Previous studies have shown that large amount of nutrients are accumulated in BYD’s sediments (Ji et al. 2019; Zhu et al. 2019), leading to proposals to remove such nutrient-rich sediments by dredging in order to mitigate internal nutrient impacts and accelerate lake recovery.

Dredging limits can be determined either by investigating the spatial accumulation patterns of sediment nutrients or by identifying internal nutrient release fluxes to the overlying water (Ji et al. 2019; Zhu et al. 2019). Both of the methods are time-intensive, low-precision, and limited in the number of monitoring sites. However, spatial variations in water quality can be also used to determine the effects of sediment internal nutrients on overlying water and define dredging limits, especially for large lakes with highly fragmented landscape patterns (BYD) (Varol 2020). Such variations are not only associated with the watershed landscape patterns, but can also be directly impacted by aquatic conditions and process (Mainali and Chang 2018; Nobre et al. 2020). These patterns have critical influences on hydrological processes, energy flows, and nutrient inputs, leading to spatial variations in water quality (Lee et al. 2009; Xie et al. 2018).

Furthermore, water landscape composition also underlies spatial variations in water quality in large lakes. Many studies have shown that reed littoral zones in large shallow lakes can reduce nitrogen and phosphorus concentration through complex biogeochemical processes such as sedimentation, plant assimilation, and microbial denitrification (Wang et al. 2017). In contrast, large-scale enclosure fishing in lakes increases nutrient concentrations and leads to water quality variations. Fish ponds have high nitrogen and phosphorus content, high algal density, and the accumulation of nutrients in the sediment due to the addition of fish feed (Herbeck et al. 2013). These effects are associated with internal sediment nutrient release that are dominated by biogeochemical processes (Markovic et al. 2019; Parsons et al. 2017). In areas with significant internal releases, organic matter mineralization in the sediment can form anoxic and anaerobic conditions that induced sediment phosphorus release and nitrate denitrification at the same time, resulting in the relative enrichment of phosphorus and lowering the ratio of nitrogen to phosphorus in the overlying water (Zhang et al. 2018).

In this study, we assessed spatial variations in water quality in order to explore differences between water landscape type and the impacts of internal pollution in BYD. Our specific research objectives were to (1) investigate spatial differences in water quality and the influence of water landscape type on water quality and (2) determine effects of water landscape type on N:P, nitrogen and phosphorus composition, and DOM fluorescence components.

**Methodology**

**Study area**

BYD is surrounded by dikes and dams within terrain that gradually slopes from northwest to southeast. It lies within the Daqing River basin, which collects water from eight rivers, including Xiaobai River (XB), Zhulong River (ZL), Xiaoyi River (XY), Tang River (TH), Fu River (FH), Cao River (CH), Ping River (PH), and Baigouying River (BGY) (Fig. 1). FH is the main inflow river of BYD. The area has a semi-arid temperate continental monsoon climate with an average annual temperature range of 7.3–12.7 °C and average annual precipitation of 564 mm, 80% of which occurs in July and August (Xia et al. 2012).

**Subarea delineation and Landscape pattern composition**

According to geographical location and impacts of inflow rivers, the studied BYD area (315.54 km²) was divided into nine subareas, including Fu River (FH), Zaozhaidian (ZZ), Nanliuzhuang (NL), Shaochedian (SC), Quantou (QT), and Zaoling-zhuang (ZL) (Fig. 1). For example, Nanliuzhuang (NL) subarea is located in the northwest of BYD, which is mainly influenced by the Fu River from the city of Baoding.

We used visual interpretation of GF2 imagery (4 m resolution) within ArcGIS to define eight landscape types: 1.6 km² of entertainment land, 15.6 km² of residential land, 24.2 km² of paddy field, 78.1 km² of dry land, 0.4 km²
of woodland, 105.9 km² of reed littoral zones, 42.1 km² of fish ponds, and 47.3 km² of open water (Fig. 1). The waters area of BYD is mainly constituted of three water landscape types, including reed littoral zones (RLZ), fish ponds (FP), and open water (OP), accounting for 54%, 22%, and 24%, respectively. Through visual interpretation of remote sensing images, BYD is characterized by complex terrain, interlacing landscape types and broken landscape pattern. The reed-vegetation ecotone was large, with intermingled reed littoral zones, villages, open water, and fish ponds, constituting a unique landscape. The fish ponds are mostly formed by dividing and cofferdam, and their space environment are closed, unable to exchange with the outside water. BYD has about 345 fish ponds, mainly located in ZL, CP, QT, and DT, with an average area of 0.12 km².

**Water sampling and analytical methods**

In order to study the spatial variations of water quality and effects of water landscape in BYD, we chose 6–10 sampling sites in each subarea, with 2 or 3 sites for each type of water landscape
landscape. A total of 61 samples were collected from the nine subareas in October 2019 (Table 1, Fig. 1), including 26 samples from open water, 16 samples from reed littoral zones, and 19 samples from fish ponds. Since four samples from open water were collected in the FH impacted area, we considered these four open water sites as an individual water landscape type (FH). All samples were collected at ~0.5 m below the water surface, within a period of 3 days, then saved in a high-density polyethylene container, and filtered using 0.45-μm Millipore nitrocellulose membrane filters within 24 h.

Eighteen water quality parameters were monitored and analyzed, including pH, electrical conductance (EC, μs/cm), dissolved oxygen (DO, mg/L), redox potential (ORP, mv), dissolved organic matter (DOM) fluorescence properties, dissolved organic carbon (DOC, mg/L), total nitrogen (TN, mg/L), particulate organic nitrogen (PON, mg/L), dissolved nitrogen (DN, mg/L), ammonia nitrogen (NH4⁺-N, mg/L), nitrate nitrogen (NO3⁻-N, mg/L), dissolved organic nitrogen (DON, mg/L), total phosphorus (TP, mg/L), particulate phosphorus (PP, mg/L), dissolved phosphorus (DP, mg/L), dissolved organic phosphorus (DOP, mg/L), soluble reactive phosphorus (SRP, mg/L), pH, EC, DO, and ORP were measured in situ using a portable multiparameter water quality instrument. DOC was determined using high temperature catalytic oxidation with a total organic carbon analyzer (TOC-VCPh, Shimadzu, Japan). TN, DN, NH4⁺-N, NO3⁻-N, TP, DP, and SRP were determined by ultraviolet spectrophotometer (UV1900, Shimadzu, Japan) and according to the standard method recommended by the State Environmental Protection Administration of China (SEPA 2002).

The DOM fluorescence properties were measured using a fluorescence spectrophotometer (Hitachi F97, Japan) with a 150 W xenon excitation source. The excitation (ex) wavelength scanned between 250 and 550 nm, with a scanning speed of 12,000 nm/min. The excitation and emission wavelength increments were 5 and 1 nm, respectively. All 3D-EEM analyses were conducted using quartz cells with a 1 cm path length and corrected using a Milli-Q blank to eliminate the effects of Raman scatter. All samples were diluted with Milli-Q water to control UV254 to < 0.05/cm to eliminate the inner filter effect in the fluorescence measurements. PARAFAC analysis of the EEM datasets for the 61 samples was conducted using the DOM Flour toolbox of the MATLAB software package, which can decompose the EEM spectrum into relatively independent fluorescent components and perform residual errors and split-half diagnostics. Finally, up to five components (two classes of aromatic protein-like materials, fluvic acid-like materials, microbial by-product-like materials, and humic acid-like materials) were separated (Lv et al. 2019).

### Statistical methods

We examined correlations between water quality parameters and the area proportion of water landscape types (reed littoral zones, fish ponds, and open water) in differently sized buffers. Using the sampling points as samples, circular buffers were extracted using a buffering tool in ArcGIS version 10.2 (Fig. 2). We selected three buffer sizes (100, 300, and 500 m) to identify the correlations by considering the distance between sampling sites and lake area, providing multiple spatial scales for exploring these relationships.

The area percentages of the three water landscape types by different buffer scales were calculated using ArcGIS and Excel. Spearman rank correlation analysis was used for bivariate analysis of water quality parameter concentrations and area proportions of landscape types in the multivariate statistical analysis software SPSS Statistics 21. The two-sided test method was chosen for significance tests. ANOVA was used to determine if spatial difference of water quality and the influence of water landscape type on water quality were statistically significant. Tukey test was used to determine differences among means, and significance was accepted at $p < 0.05$.

### Results

#### Spatial variations in water quality

In addition to NH4⁺-N, the other eight water quality parameters, including TN, NO3⁻-N, DOC, TP, SRP, PP, pH, and EC, showed significant differences across the nine subareas (Fig. 3). TN concentrations ranged from...
0.90 to 4.10 mg/L (mean 1.86 ± 0.95 mg/L), with highest values in FH, followed by ZZ, NL, DT, CP, QT, DC, ZL, and SC. According to the water quality standards for lakes and reservoirs in China’s Surface Water Environmental Quality Standards, BYD as a whole was in class IV, and FH, ZZ, NL, DT, CP, QT, DC, ZL, and SC were classes V, V, V, IV, IV, IV, IV, IV, and III, respectively. NO₃⁻-N concentrations ranged from 0.15 to 3.49 mg/L (mean 1.00 ± 1.07 mg/L), also with highest values in FH. These decreased eastward and southward toward the minimum concentration in ZL. NH₄⁺-N concentrations ranged from 0.32 to 0.55 mg/L (mean 0.41 ± 0.08 mg/L), with no significant difference among the 9 subareas.

As with the spatial variations of TN and NO₃⁻-N, TP concentrations ranged from 0.06 to 0.18 mg/L (mean 0.11 ± 0.04 mg/L), with highest values in FH, decreasing eastward and southward toward their minimum concentrations in SC. According to the water quality standards, BYD as a whole was in class IV, and FH, ZZ, NL, DT, CP, DC, QT, ZL, and SC were classes V, V, V, IV, IV, IV, IV, and IV, respectively. And SRP concentrations were also highest in FH.

In contrast to TN and TP, concentrations of DOC, pH, and EC were lowest in FH and increased eastward and southward, reaching highest concentrations in the QT subarea.

**Influences of water landscape type on water quality**

Correlation analysis between 11 water quality parameters (T, pH, EC, DO, DOC, TN, PON, NH₄⁺-N, NO₃⁻-N, DON, and TP) and area proportion of landscape type (reed littoral zones, open water, and fish ponds) by 100, 300, and 500 m buffers (Fig. 4) showed negative correlations between all but NH₄⁺-N and the area proportion of reed littoral zones for the 300 m and 500 m buffers. Open water generally contributed to the concentrations of DO, DOC, TN, PON, and NH₄⁺-N for the 300 m and 500 m buffers. In contrast, the concentrations of DO, DOC, TN, PON, DON, NO₃⁻-N, and TP were significantly positively correlated with the area proportion of fish ponds for the 100 m buffer.

There were significant differences in some (TN, NO₃⁻-N, TP, PP, SRP, DOC, pH, and EC) but not all (NH₄⁺-N) parameters among the four water landscape types of FH, open water, reed littoral zones, and fish ponds (Fig. 5). TN concentrations were significantly
lower in open water (1.67 ± 0.66 mg/L), reed littoral zones (1.07 ± 0.34 mg/L), and fish ponds (1.66 ± 0.70 mg/L) than in FH (3.90 ± 0.31 mg/L). Similarly, NO$_3^-$-N concentrations were significantly lower in open water (0.75 ± 0.72 mg/L), reed littoral zones (0.35 ± 0.20 mg/L), and fish ponds (0.40 ± 0.28 mg/L) than in FH (3.28 ± 0.32 mg/L). In contrast, NH$_4^+$-N concentrations were no significant difference between the four water landscape types.

TP concentrations were lower in open water (0.09 ± 0.03 mg/L) and reed littoral zones (0.09 ± 0.05 mg/L) than in fish ponds (0.13 ± 0.09 mg/L) and FH (0.14 ± 0.05 mg/L). Similarly, PP concentrations were lower in open water (0.04 ± 0.03 mg/L) and reed littoral zones (0.04 ± 0.04 mg/L) than in fish ponds (0.07 ± 0.05 mg/L) and FH (0.05 ± 0.05 mg/L). However, the highest SRP concentrations were found in FH (0.06 ± 0.01 mg/L), with lower concentrations in open water (0.02 ± 0.01 mg/L), reed littoral zones (0.02 ± 0.02 mg/L), and fish ponds (0.02 ± 0.03 mg/L).

Fish ponds had the highest DOC concentrations (12.23 ± 4.38 mg/L), open water (8.54 ± 2.24 mg/L), and reed littoral zones (8.58 ± 2.07 mg/L) were mid-level, and FH (5.70 ± 0.52 mg/L) was lowest. EC and pH followed the same trend as DOC.

**Effects of water landscape type on N:P, nitrogen and phosphorus composition, and DOM fluorescence components**

TN:TP, DN:DP, and NO$_3^-$-N:SRP were all significantly affected by water landscape type (Fig. 6). TN:TP was highest for FH (29.5 ± 9.2), followed by open water (19.8 ± 7.8), fish ponds (15.7 ± 6.6), and reed littoral zones (13.2 ± 5.8), and the same trend occurred for DN:DP and NO$_3^-$-N:SRP. These results suggested that BYD has the ability to remove incoming nitrogen. In contrast, phosphorus appears to be relatively enriched compared to nitrogen, while SRP concentrations were reduced in open water, fish ponds, and reed littoral zones.
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Variations in nitrogen and phosphorus composition were significantly affected by water landscape type (Fig. 7). The proportion of NO$_3^-$-N was significantly higher in FH, open water, and reed littoral zones than in the fish ponds. NH$_4^+$-N accounted for the highest and lowest proportion of TN in the reed littoral zones and FH, respectively, and the proportion of NH$_4^+$-N was not markedly different between open water and fish ponds. DON accounted for the highest proportion of TN in the fish ponds. Meanwhile, PON accounted for the highest proportion of TN in the fish ponds, declining in open water and reed littoral zones. SRP accounted for the highest and lowest proportion of TP in the FH and fish ponds, and the proportion of SRP had no significant difference between the open water and reed littoral zones. The proportion of PP was significantly lower in FH, open water and reed littoral zones than in fish ponds.

PARAFAC analysis separating the different 3D-EEM spectral components detected three main fluorescence components in BYD (Fig. 8). Component 1 and component 2 were indicative of the presence of tyrosine-like proteins (ProI) and tryptophan-like proteins (ProII), respectively, both of which could be produced by plankton death, and decomposition along with microbial metabolism. Component 3 was attributable to humic acid substances (HA), which could be decomposed as plant residues and not easily degraded or utilized by microorganisms (Zhao et al. 2016). The proportions of Pro I in fish ponds accounted for 39 $\pm$ 11%, significantly higher than in FH, open water, and reed littoral zones (Fig. 9). In contrast, the proportions of HA in fish ponds were 23 $\pm$ 15%, significantly lower than those in FH, reed littoral zones, and similar to open water.

Discussion

The spatial variations in nutrients suggested that their input into BYD could be diluted and reduced across the whole lake. TN and TP concentrations in FH and NL were significantly higher than those in SC, DT, DC, CP, QT, and ZL subareas. FH was the main source of nitrogen and phosphorus for BYD, and these inputs contributed significantly to the higher TN and TP concentrations in NL. In addition to the influences of the external source inputs and residential land on the water quality, diverse water landscape types have significant influences and lead to the spatial variations. The lower TN and TP concentrations in the other subareas, which were further from FH’s inputs, could be explained by ecological buffering capacity or resilience to nutrient inputs. Spatial variations within and between subareas can be further explained by unique landscape compositions and distributions. The water quality of fish ponds was significantly worse than open water and reed littoral zones. Variations in nitrogen and phosphorus composition and their ratio were likely dominated by biogeochemical processes (e.g., sedimentation, plant uptake, and microbial immobilization) (Markovic et al. 2019; Parsons et al. 2017), which differed in the three water landscape types.

Reed littoral zones covered 105.9 km$^2$, 54% of the total BYD waters area and were distributed throughout it. As aquatic terrestrial ecotones, these are hotspots for biogeochemical cycling of nitrogen and phosphorus in BYD. The reed littoral zones markedly reduced incoming nitrogen and lowered the N:P ratio in water, likely due to biological uptake and denitrification of nitrate (Wang et al. 2017). Consequently, the unique spatial distribution of reed littoral zones underlies the spatial differences and resilience of water quality in BYD.

Fish ponds covered 42.2 km$^2$, 22% of the total BYD waters area. Many hundreds of these ponds, with an average area of 0.12 km$^2$, have been constructed by dividing and enclosing reed littoral zones or open water since the 1990s. They had higher TN and TP concentrations than the open water and reed littoral zones. Although they have not been used for fishing since 2017, they still affect water quality in the entire...
lake. The 30-year history of aquaculture, including inputs of fish feed, has increased nutrient availability (especially phosphorus and nitrogen) that supports high phytoplankton densities and has led to the development of sediments rich in organic matter and nutrients. Consequently, the high nutrient concentrations in fish ponds were likely due to the development of internal loadings, which recycles phosphorous back to the overlying water and exacerbate algal blooms. In addition, the low N:P ratio in these ponds can be further explained by complex biogeochemical processes in the sediments (Zhang et al. 2018). Phosphorus mineralized during organic matter decomposition is readily released from sediments, while denitrification in sediment is a major process removing available nitrogen. As a result, nutrient fluxes from sediment are relatively depleted in nitrogen compared to phosphorus, leading to declining N:P in fish ponds. Furthermore, compared with reed littoral zones and open water, a higher proportion of DON and Pro I was found in fish ponds, likely due to sediment organic matter mineralization and microbial and algal release (Lusk and Toor 2016; Meng et al. 2013). The elevated DON, in turn, could be a potential source of bioavailable N to phytoplankton and bacteria that cause water quality degradation (Lu et al. 2020).

Consequently, many fish ponds in BYD not only reduce its spatial resilience to nutrient inputs but also serve as a source of biodegradable organic nitrogen and increase the ecological risk when water is discharged or exchanged. Therefore, fish ponds are a major challenge for the recovery of water quality in BYD. The key to effectively improving water quality and ecological resilience here is to restore the physical environment from fish ponds to open water. Sediment removal by dredging in fish ponds should be considered to suppress internal phosphorus loading and accelerate lake recovery.
Conclusions

Our analysis of water quality parameters from 61 sample sites across three water landscapes of BYD showed highly spatial variations. TN and TP concentrations ranged from 0.90 to 4.10 mg/L and 0.06 to 0.18 mg/L, respectively, which was in class IV of water quality as a whole. These spatial variations were mainly caused by the distribution of different water landscape types and external nutrient inputs. Reed littoral zones were capable of reducing nitrogen and phosphorus concentrations, while fish ponds had higher nitrogen and phosphorus concentrations, resulting in lower water quality. Furthermore, compared with reed littoral zones and open water, fish ponds had lower N:P ratios.

Fig. 6 Variations in a TN:TP, b DN:DP, and c NO$_3^-$:SRP for the four water landscape types.

Fig. 7 Variations in a nitrogen and b phosphorus composition in the four water landscape types. Numbers in each box indicate mean ± standard deviation.

Conclusions
ratios and higher proportions of DON and Pro I. These effects were mainly attributed to internal sediment nutrient release, dominated by biogeochemical processes. Therefore, sediment removal by dredging in fish ponds should be considered to suppress internal phosphorus loading and to accelerate water quality recovery in BYD.

**Author contribution** All authors contributed to the study conception and design. Liqing Li gave the idea of this research work. Material preparation, data collection, and analysis were performed by Liqing Li and Xinghong Chen. The first draft of the manuscript was written by Liqing Li and Xinghong Chen. Meiyi Zhang, Weijun Zhang, Dongsheng Wang, and Hongjie Wang helped the work with their ideas and made a critical editing and reviewing of the whole manuscript. All authors read and approved the final manuscript.

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Declarations

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