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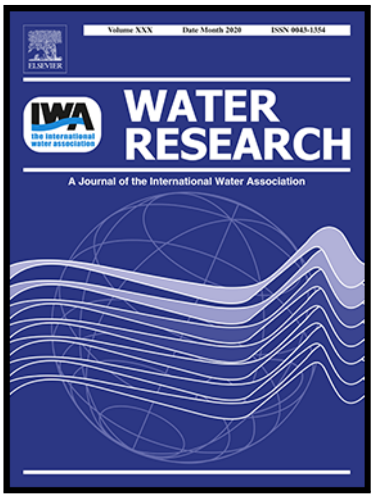

Eutrophication exacerbated organic pollution in lakes across China during the 1980s-2010s

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Highlights

- Lake organic pollution across China during the 1980s-2010s was investigated.
- Organic pollution levels of lakes were high in the north and low in the south.
- Eutrophication and salinization were the key factors varying organic pollution.
- Eutrophication exacerbated lake organic pollution during the 1980s-2010s.
- Lake expansion had dilution effects on organic pollution in saline lakes.

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Eutrophication exacerbated organic pollution in lakes across China during the 1980s-2010s

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Abstract: Lakes are vital sources of drinking water and essential habitats for humans and various other living organisms. However, many lakes face organic pollution due to anthropogenic disturbance and climatic influence, and the spatiotemporal changes of organic pollution in lakes over a large area are still unclear. Based on three monitoring datasets of chemical oxygen demand (COD) in 390 lakes, this study demonstrated the apparent spatiotemporal differences of organic pollution in lakes during the 1980s-2010s and the effects of water eutrophication and salinization. Throughout China, lake organic pollution showed a general spatial trend of being more severe in the north compared to the south. This pattern is reflected in the positive linear correlations between *in-situ* COD concentrations and lake latitude, observed in both the 1980s ($p < 0.05$) and the 2010s ($p < 0.01$). In terms of spatial differences, the influence of total nitrogen concentrations increased from 0.27% in the 1980s to 35.24% in the 2010s. Moreover, with increasing human activity, 78.31% of the studied lakes ($N = 83$) showed increasing COD concentrations during the 1980s-2010s. In addition, the logarithmic dissolved organic carbon concentrations were linearly correlated with log water conductivities (/ ÌÈÙÚÖÕζÚ𝕨 $r = 0.49$, $p < 0.01$), suggesting that lake expansion would attenuate organic pollution in saline lakes through dilution effects. These results are valuable for understanding the spatiotemporal dynamics of organic pollution and are crucial for effective management of organic pollution in different lakes.

Keywords: Organic pollution; Chemical oxygen demand; Spatiotemporal changes; Water eutrophication; Lake expansion

1 Introduction

Lakes play an essential role in supporting drinking water for human society, providing habitats for plants and animals, and reducing water pollutants through biogeochemical processes (NIGLAS, 2019; Zhang et al., 2023). However, due to anthropogenic disturbance and climate change, many lakes are facing organic pollution that degrades water quality, affects the health of species in the food chain, and threatens the safety of lake ecosystems (Gullian-Klanian et al., 2021; Nosrati et al., 2012). Thus, grasping the spatiotemporal dynamics of lake organic pollution is essential for maintaining the health of lake ecosystems, securing water resources, and guiding effective pollution control and management strategies for lakes.

The commonly used metrics of organic pollution in lakes are chemical oxygen demand (COD) and total organic carbon (TOC). Of these, COD determines organic pollution levels using the amount of oxidant required to break down organic matter, and potassium permanganate is often used as the oxidant (Laszakovits et al., 2020). The International Organization for Standardization recommends the use of COD to measure organic matter concentrations, and the Chinese government stipulates that good lake waters should have COD concentrations of < 6.0 mg/L (MEEC, 2002). Being different from COD, TOC concentrations determine organic pollution levels using the weight of organic carbon atoms per unit volume, which is measured by converting organic matter into carbon dioxide (Artifon et al., 2019). In comparison, TOC can better reflect the total organic matter content, but has a higher measurement cost (Knap et al., 1996); in addition, COD concentration is

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often linearly correlated with TOC concentration (Jiao et al., 2021). As a result, COD has become one of the standard indicators widely used to indicate organic pollution in lakes and as a surrogate for TOC concentration (Han and Ma, 2015; Jiao et al., 2021; MEEC, 2002).

Organic pollution in lakes is regulated by several anthropogenic and natural factors. Human activity not only introduces anthropogenic organic byproducts into lakes, but also elevates water eutrophication levels and increase autochthonous organic matter from algal production (Artifon et al., 2019; Baines and Pace, 1991). For lakes in the Changjiang Delta, China, the amount of dissolved organic matter is strongly determined by eutrophication levels in the lakes and the percentages of artificial surface areas in the lake basins (Liu et al., 2020a). Similarly, natural factors influence organic pollution in lakes by transporting terrigenous organic matter into lakes and influencing the production and transformations of organic matter in lakes (Nosrati et al., 2012). In addition, natural factors also influence organic pollution in lakes by altering water evapoconcentration and dilution effects (Butturini et al., 2022; Nosrati et al., 2012). Due to water evapoconcentration, saline lakes in China (30.0 mg/L) usually have higher dissolved organic carbon (DOC) concentrations than freshwater lakes (8.1 mg/L) (Song et al., 2018a). In contrast, precipitation has low DOC concentrations and has been reported to dilute organic pollution in Chinese lakes (Liu et al., 2021a; Safieddine and Heald, 2017). Furthermore, due to the spatial variability of various factors, we need to know the organic pollution in different lakes over a large area.

Over the past decades, global lakes have been changing under the pressure of increasing human activity and climate warming. Algal blooms have become more common in lakes, with 8.8% of global lakes experiencing an increase in bloom risk between the 1980s and 2010s (Ho et al., 2019). In addition, the water volume of many lakes (79.38%) has also increased, and one of the five hotspots for volume increase is located on the Tibetan Plateau (Luo et al., 2022). Along with changes in algal blooms and water volumes, satellite-based monitoring of eutrophic lakes along the Changjiang River in China has shown that both DOC and particulate organic carbon (POC) concentrations fluctuate obviously over different seasons (Liu et al., 2023, 2021b). In these cases, organic pollution in lakes should vary temporally in the context of global change, and understanding their long-term changes can provide valuable insights for improving lake water quality.

Across the vast territory of China, there are thousands of lakes influenced by various anthropogenic and/or natural factors (NIGLAS, 2019); moreover, many lakes show obvious changes in various influencing factors during the 1980s-2010s (Zhang et al., 2019). Therefore, here we attempt to investigate the spatiotemporal changes and underlying forces influencing the organic pollution of lakes across China during the 1980s-2010s. We have three objectives: (1) to reveal the spatial pattern of organic pollution in Chinese lakes; (2) to identify the changes in organic pollution during the 1980s-2010s; (3) to assess the effects of different driving forces. Due to the lack of TOC concentration in the 1980s, we used COD to indicate the

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level of organic pollution. This study is very valuable for understanding and controlling organic pollution in different lakes in the context of a changing world.

2 Materials and Methods

2.1 Research area

China contains 2,693 lakes that are larger than 1 km^2 in size (NIGLAS, 2019), and we focus on 390 Chinese lakes where measurements were taken (Fig. 1). The lakes studied cover a total area of 65,850 km^2, representing 88.5% of the total area ÖÍ " ÏÐÕÈ¿ÚÓÈÒÌÚ (NIGLAS, 2019). Biogeochemical processes in lakes are strongly influenced by environmental characteristics, which present great spatial differences across China. Comparatively, population density is high in the east; altitude indicated by digital elevation model (DEM) is higher in the west; precipitation and vegetation coverage are high in the southwest; and cropland is mainly distributed in the northeast (Liu et al., 2020). According to the topographic and ecological conditions, China is divided into five limnetic zones: the Inner Mongolia-Xinjiang Lake zone (IMXL); the Tibetan Plateau Lake zone (TPL); the Yunnan-Guizhou Plateau Lake zone (YGPL); the Northeast Plain and Mountain Lake zone (NPML); and the Eastern Plain Lake zone (EPL) (NIGLAS, 2019). During the 1980s-2010s period, precipitation and glacier melting led to lake expansion in the TPL (Zhang et al., 2019), while anthropogenic pollution led to lake eutrophication in the EPL (NIGLAS, 2019). Therefore, Chinese lakes are ideal areas to study changes in organic pollution in a changing world.

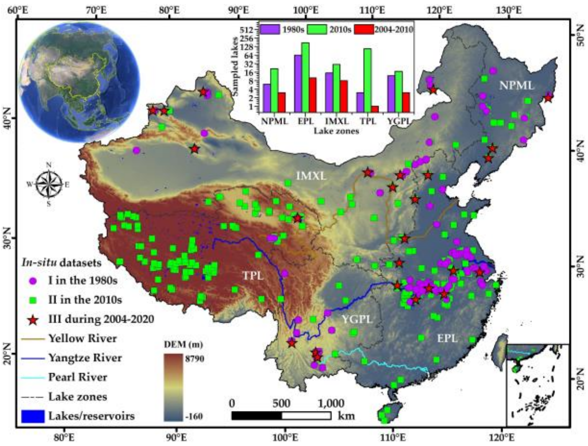

Fig. 1. The sampled lakes in the 1980s (*N* = 102), in the 2010s (*N* = 346), and during 2004-2020 (*N* = 25). The inset histogram shows the number of sampled lakes in the five lake zones.

2.2 *In-situ* data collection

2.2.1 Field investigation

This study used three datasets of *in-situ* measurements acquired via field sampling or automatic monitoring. Three *in-situ* datasets are included (Fig. 1, (Supplementary Table S1). ŵ Dataset I contains lake-based mean COD, total nitrogen (TN), total phosphorus (TP), chlorophyll-a (Chl-a) concentrations, conductivities, and water transparency as indicated by Secchi-disk depth (SDD) for 102 lakes, calculated by averaging three measurements obtained from the National Lake Survey in the 1980s. Ŷ Dataset II contains COD, TN, TP, Chl-a, DOC concentrations, excitation-emission matrix fluorescence spectra of colored dissolved organic matter (CDOM-EEMs), conductivity, and SDD values at 1795 stations for 346 lakes in the 2010s (Dataset II), which were collected in this study. ŷ Dataset III contains time series of COD concentrations for 25 lakes during 2004-2020. Among them, weekly COD values at representative stations for 18 lakes during 2004-2020 were automatically monitored by the Ministry of Ecology and

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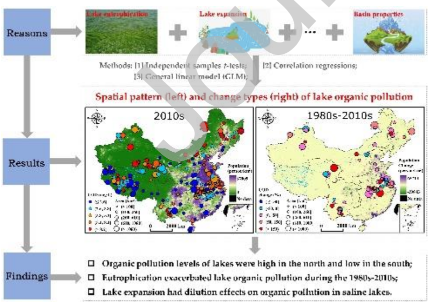
Graphical Abstract



Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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