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Integrated Approach to Water Pollution Management: Leveraging Environmental Engineering and Legal Expertise: A Review of Taihu Lake

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Abstract

The expansion of human activities, combined with the persistent impacts of the global economy and global warming pressures on water resources, has rendered water pollution in river basins a critical issue, posing significant challenges to the environment and human health. The management framework for aquatic ecosystems within these basins is currently fragile. Despite progress in water quality, substantial risks and deficiencies persist, hindering effective solutions to the adverse impacts of rapid economic growth. Expertise in environmental engineering is crucial for addressing legal cases related to water pollution in river basins, often requiring the integration of ecological engineering technologies with legal frameworks. This review provides a comprehensive overview of water pollution prevention strategies that contribute to the enhancement of water quality of Taihu Lake. Additionally, it proposes a detailed strategy to prevent and manage water contamination by combining innovations in environmental engineering with management approaches grounded in legal frameworks. The goal is to improve water quality in river basins, alleviate biodiversity pressures, and finally address scientific evidence and practical recommendations for integrated river basin management.

Keywords: Pollution Control; Taihu Lake; Water Quality; Ecological Protection; Aquatic Biodiversity

1. Introduction

In recent decades, the ongoing growth of agriculture, industrialization, and urbanization has driven the global decline in lake water quality (Yan et al. 2024; Bhateria and Jain 2016). This pollution has been documented across lakes globally, including Chaohu and Taihu in China (Yu et al. 2023), Winnipeg in Canada (Stewardship 2011), the Great Lakes in the United States (Norton, Driscoll, and Carter 2019), and Kasumigaura in Japan (Mizunoya, Nozaki, and Singh 2021). Water quality deterioration compromises ecosystem stability and human health, compromising water supply, causing toxic algal blooms, and damaging biodiversity (Amorim and do Nascimento Moura 2021). With climate change and increasing populations expected to worsen water quality worldwide (Saxena 2025), assessing lake water quality conservation strategies is imperative to achieve better water quality outcomes.

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Taihu Lake, a significant case study in China, has faced severe eutrophication over the past decade. Since the 1990s, the lake has faced intensified eutrophication, marked by toxic cyanobacterial blooms, primarily driven by excessive fertilizer use. In May 2007, a major algal bloom in Taihu Lake caused contamination of drinking water, disrupting the water supply for 2 million residents in the region of Wuxi. To address this critical situation, the Chinese government has invested heavily in the lake's restoration since 2007. Despite substantial progress, improving water quality in Taihu Lake remains challenging (Zhang et al. 2021). Analyzing Taihu Lake's pollution crisis over the past decade offers valuable strategies and insights, providing a more comprehensive and practical approach to combating water contamination worldwide.

Taihu Lake, located in the extensively urbanized Yangtze Delta (Fig. 1), ranks third in freshwater lakes in China, spanning 2,338 km2 and with an estimated surface area of 2 m. More than 150 rivers flow into Taihu Lake, with a combined route of 12,000 km (Qin et al. 2007). The Taihu Lake basin experiences a humid subtropical climate characterized by distinct rainy seasons, with annual precipitation of 1,115 mm and an annual average temperature of 16 °C (Xia et al. 2016). The basin spans 36,895 km2, encompassing 45 counties across Zhejiang and Jiangsu Provinces. This basin represents a highly developed region in China, contributing 18.3% to national gross domestic product (GDP) while accommodating 10.4% of the country's population and occupying only 0.4% of the total land area (Hu et al. 2023).

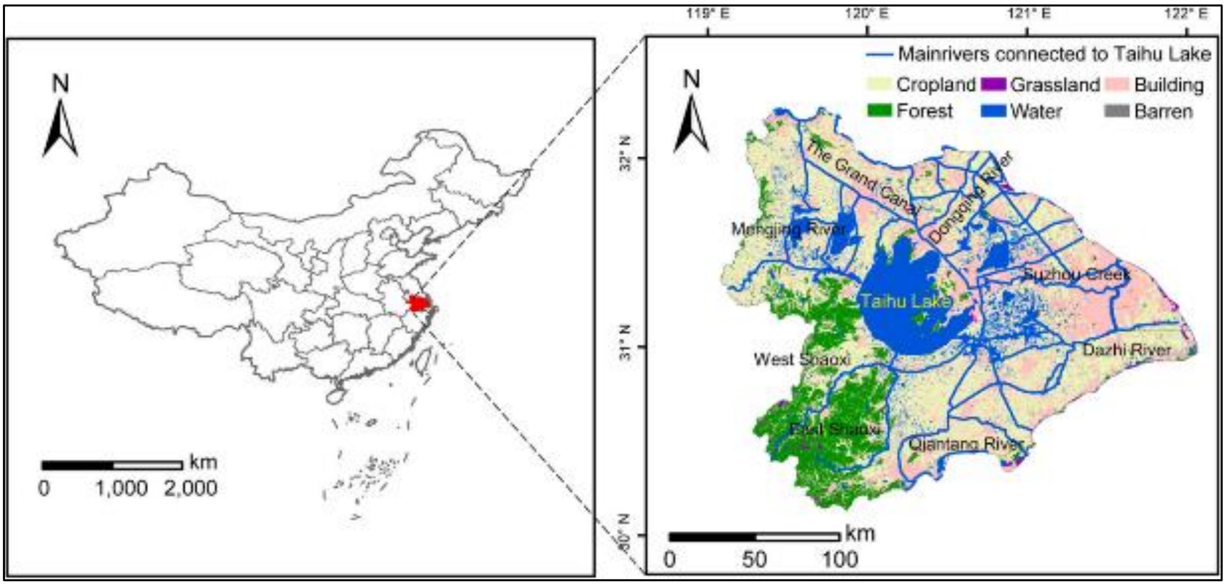

Figure 1 Taihu Lake basin's location (Yan et al. 2024).

Water quality represents a significant ecological challenge that influences governmental policy and impacts local economic growth (Feng, Zheng, et al. 2021). To address the deterioration of water quality, extensive research has been conducted on water pollution regulations, emphasizing areas such as point source and non-point source management, mitigation of harmful algal blooms, and regulations adopted on Taihu Lake. This study seeks to: 1) assess Taihu Lake's water quality over the past decade; 2) critically analyze water pollution management successes and challenges; and 3) identify obstacles and provide practical recommendations for future studies. The findings aim to inform strategies for enhanced preservation and pollution prevention in Taihu Lake and other polluted lakes worldwide.

2. Water quality of Taihu Lake over the last decade

Rapid industrialization and agricultural expansion have exposed Taihu Lake to various anthropogenic pollutants, including pesticides, industrial waste, fertilizers, excessive aquaculture, and eutrophication (Chen et al. 2024). Despite significant efforts by the Chinese government in water quality improvement over the past decades, the lake's water quality remains inadequate (Huang et al. 2021; Tang et al. 2022). Analyses of phosphorus (P) and nitrogen (N) levels between 1985 and 2010 (Fig. 2) reveal that the annual average total phosphorus (TP) rose from 0.04 to 0.10 mg/, while total nitrogen (TN) concentrations increased from 1.79 to 2.85 mg/L, principally because of the rise of urban and rural enterprises near the lake (Dai et al. 2016). Notably, in 1996, the lake recorded its highest historical concentrations of TN and TP, at 3.84 and 0.15 mg/L, respectively (Dai et al. 2016). Previous studies have employed the Long Short-Term Memory (LSTM) model to evaluate the aqueous concentrations of TN and TP in Taihu Lake, which were reported to vary between 0.11 mg/L and 0.017 mg/L, respectively (Fig. 3) (Lu et al. 2022).

In May 2007, a significant algal bloom in Taihu Lake triggered a water-quality emergency, affecting nearly 2 million residents in the Wuxi region (Qin et al. 2010). In response, the government adopted stricter regulations, strategies, and protocols to improve water quality. Consequently, the annual total nitrogen (TN) content steadily declined, reaching 1.10 mg/L by 2021. However, total phosphorus (TP) levels showed no substantial reduction, remaining at 0.07 mg/L in 2021 (Wang et al. 2022). An analysis of pollution mitigation efforts and water quality trends reveals two distinct phases in water pollution management: (I) a period of water quality degradation (1990s–2007) and (II) an era of improved TN levels with fluctuating TP concentrations (2007–present). This study evaluates observations and challenges associated with water pollution management in Taihu Lake during these two phases.

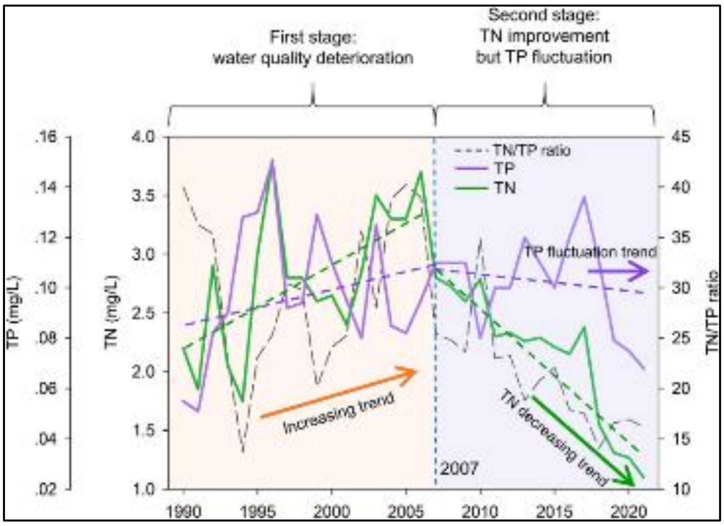

Figure 2 Annual concentrations of TN and TP over the last decades (Dai et al. 2016; Xu et al. 2021; Qin et al. 2019).

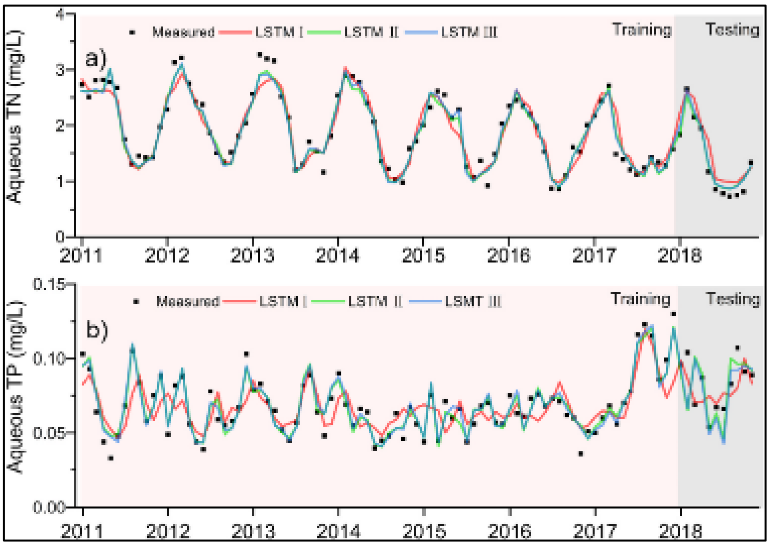

Figure 3 a) TN and b) TP values in Taihu Lake (Lu et al. 2022).

3. Experience in water pollution control

3.1. Main pollution prevention approaches

The initial phase of water quality degradation in the Taihu Lake region began in the 1990s and persisted until 2007. This period of deterioration coincided with rapid agricultural and industrial growth, alongside a rising population. Consequently, water quality management efforts targeted specific sources and adhered to policy directives (Fig. 4) (Organization 2022). Two phases of water purification efforts were undertaken to address point-source pollution. The first phase, initiated in 1991, resulted in the enactment of pollution prevention laws for the Taihu Lake Basin in 1996 (Huang and Zhu 1996) and the development of ecological restoration plans for Taihu Lake in 1998 (Qin et al. 2007). These regulations established management targets for the lake and mandated compliance with discharge requirements for all point-source pollutant loads by 1998 (TP = 0.5 or 1 mg/L). However, despite these efforts, TP levels increased over the following two years, resulting in decreased water quality (0.2 mg/L), even as N content declined.

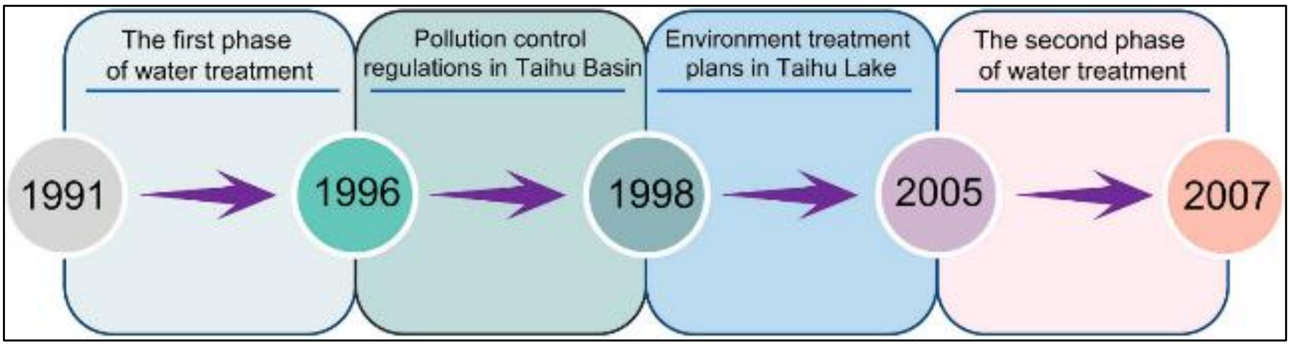

Figure 4 Summary of Taihu Lake's governance methods from 1991–2007 (Yan et al. 2024)

Taihu Lake, in the second phase, was intended to reduce pollution and improve water quality (Yang and Liu 2010). Water management, industrial point source regulation, environmental restoration, drinking water protection, and ecological restoration were all included in this strategy (Feng, Liu, et al. 2021). The investments and the percentage of completed projects were significantly higher for point sources compared to nonpoint sources before 2007 (Ding, Qi, and Zhang 2023). The sewage treatment capacity in Jiangsu, Zhejiang, and Shanghai provinces increased from 2.43 million tons to 5.59 million tons between 2000 and 2005 (Xu and Liu 2023; Zheng and Kamal 2020). This improvement is reflected in a reduction of effluent water TN and TP concentrations by 22 mg/L and 3.35 mg/L, respectively, relative to influent water, with an average sewage treatment plant workload of 67.5%. The Taihu Basin Authority (2007) estimated that sewage treatment capacities for total nitrogen (TN) and total phosphorus (TP) increased by 7,100 tons and 46,900 tons, respectively, from 2000 to 2005 (Yan et al. 2024). However, the reduction of non-point source pollution for TN and TP was limited, with decreases of only 391 tons and 16,300 tons during the same period, based on the projected nutrient reduction capacity of non-point source pollution (2,500 tons and 600 tons for TN and TP, respectively) and a project completion rate of 65.2% (Yan et al. 2024). Additional point source management efforts, including trash disposal, water supply safety, and factory closures, further contributed to reducing point-source pollution in the Taihu Lake Basin. Despite these advancements, a significant blue-green algal bloom in 2007 caused a drinking water pollution crisis for 4.43 million residents of Wuxi City, attributed to elevated NH_4^+ concentrations reaching 4.0 mg/L (Plec 2020).

3.2. Issues in water pollution control at this point

Identifying pollution origins is crucial for effective pollution control. Pollutants in surface water and deep groundwater are primarily attributed to urban wastewater, rural animal and human waste, and domestic wastewater. For example, industrial and domestic sources together contributed over 72% of total phosphorus in the Taihu Lake basin in 1998 (Qin et al. 2007). However, recent studies reveal that contaminants in aquatic systems are predominantly transported from agricultural land through leaching and runoff of N fertilizers and soil N (Weldeslassie et al. 2018; Follett and Delgado 2002; Rashmi et al. 2020). In 1994, agricultural sources accounted for 15% of TP and 38% of TN in the Taihu Lake region, as determined by Qin et al. through farmland sample analyses (Qin et al. 2007). By 2000, agricultural nonpoint source pollution constituted over 38% of TP and 57% of TN (Ongley, Xiaolan, and Tao 2010). These values surged to 51% for TP and 68% for TN by 2003 (Yang, Wang, and Xu 2003). The Tenth Five-Year Plan for Water Pollution Management in Taihu Lake, hereafter referred to as 'the Scheme' (Chen 2005; Feng, Shi, and Reidsma 2012), highlighted for the first time that mitigation efforts for agricultural nonpoint source contamination in Taihu Lake were considerably behind those for point source contamination up to 2007. It further emphasized the need for a transition in water pollution management from focusing solely on point sources to addressing both point and nonpoint sources (Xue, Wang, and Zhang 2022). This strategic shift guided decision-makers toward more efficient measures to limit agricultural nonpoint source contamination.

4. Overview of pollution prevention since 2007

The Chinese government has directed significant efforts toward managing non-point source pollution since the extensive blue-green algae outbreak in Taihu Lake in 2007. This document assesses the control measures implemented post-2007 to provide insights for improving water quality in the Taihu Lake Basin. Non-point source pollution management can be categorized into four strategies (Figure 5): source control, transport interception, in-lake interventions, and integrated approaches combining these technologies (Wu et al. 2017). Furthermore, challenges related to water quality enhancement at this scale have been outlined.

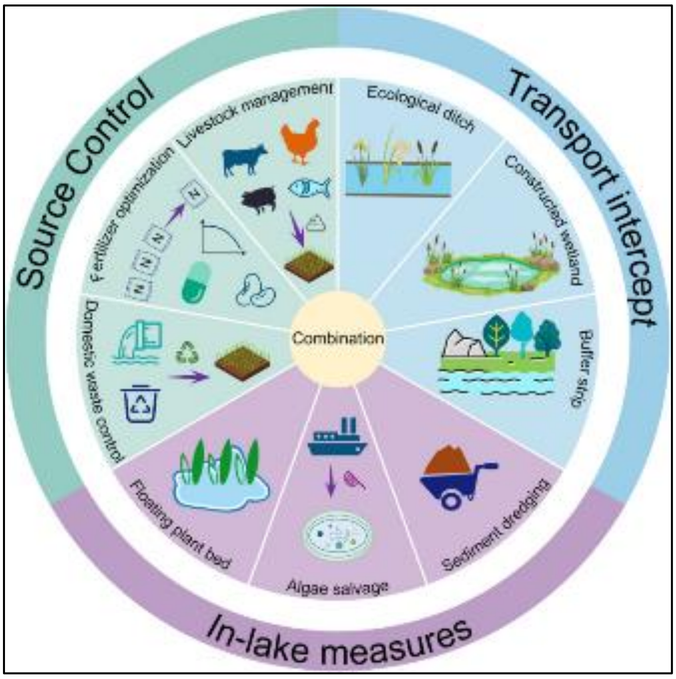

Figure 5 Comprehensive approaches to control non-point source pollution (Yan et al. 2024)

4.1. Progress in non-point source pollution control after 2007

Source control serves as the principal mechanism for mitigating sediment and nutrient runoff originating from agricultural areas. Source control practices are classified into three main categories: fertilizer use efficiency, animal breeding management, and rural domestic waste management. These approaches collectively reduce both the concentration of nutrient runoff.

Numerous optimized fertilizer control techniques, including legume crop rotation, reduced application rates, and the use of nitrification inhibitors and controlled-release fertilizers, have been widely adopted in the Taihu Lake region (Zheng et al. 2023; Hofmeier et al. 2015; Myrbeck and Stenberg 2014; Jin BaoMing, Yang ShiHong, and Xu JunZeng 2018; Hou et al. 2021). A reduction in N fertilizer concentrations is recognized as the most effective approach for field nutrient control, showing a significant exponential relationship between N fertilizer concentrations and TN loading in leachate and runoff (Xia and Yan, 2012; Xia and Yan, 2011; Zhao et al., 2023) (Xia and Yan 2012; 夏永秋 and 颜晓元 2011; Zhao et al. 2023). Extended field trials at Taihu Lake have demonstrated that a 20–30% decrease in N fertilizer application maintains vegetable yields while simultaneously reducing TN loss by 20% (Min et al. 2015). Alongside the reduction of fertilizers, nitrification inhibitors, crop rotation, organic fertilizer alternatives, controlled-release fertilizers, and catch crop interception have proven effective in minimizing N reduction. For instance, specific rotations such as rice/Chinese milk vetch and rice/fava bean exhibit significant decreases in TN degradation compared to a rice/wheat rotation, with an average nutritional loss decrease of 45% (Zhao, Wang, and Xing 2015). Studies suggest that nitrification inhibitors and controlled-release fertilizers can reduce TN loss by 22–73% (Min et al. 2011; Li et al. 2009; Wang, Zhao, et al. 2015). Beyond field-level practices, initiatives to standardize technical strategies across the 6100 km^2 of Taihu Lake include soil test-based fertilization over 670 km^2, controlled-release fertilizer use over 670 km^2, organic fertilizer application across 670 km^2, and green manure application on 200 km^2 (Xia and Yan 2020). In addition, these comprehensive measures play a crucial role in controlling N losses from agricultural activities on Taihu Lake, offering a sustainable solution to nutrient control in the region.

Significant efforts have been directed toward reducing pollution from rural residential waste and livestock in the Taihu Lake region. Since 2007, approximately 4,000 cattle and poultry farms, along with 50 km^2 of aquaculture zones, have been closed or relocated in the region (Jiangsu Provincial People's Government, 2019). In the remaining animal farms, waste generation has been minimized through modifications to breeding techniques, such as changing traditional water-washed pigsties into bio-fermentation beds (Chandrasekhar and Ahn 2017). Moreover, improving the recycling rate of livestock manure, rather than directly throwing it into rivers, supports water quality preservation and may decrease fertilizer utilization by 20–27% while maintaining crop yields (Xue et al. 2020). In addition to addressing pollutants from livestock and poultry, improving the management of solid waste and domestic sewage emitted by rural populations also enhances the water quality of Taihu Lake. A three-year water filtration project in a village covering approximately 20 km^2 in the Taihu Lake region, which included biogas tanks, public toilets, and sewage pipeline networks, achieved the removal of over 70% of TN and 80% of TP from rural household sewage (Wu, Hu, and Yang 2011). Furthermore, more than 90% of agricultural solid waste could be collected indoors at designated locations to mitigate significant nutrient loss caused by surface runoff during periods of heavy rainfall (Wu, Hu, and Yang 2011). Between 2007 and 2019, 25,000 km of upgraded sewage lines were established in urban areas within the Taihu Lake Basin, according to Jiangsu Provincial People's Government, 2019.

4.2. Problems in water pollution control

Since 2007, TN concentrations in Taihu Lake have shown a declining rate, whereas TP concentrations have shown a slight decrease followed by a recent increase (Figure 2). Several critical factors complicate TP regulation. From an economic feasibility perspective, the effluent from wastewater treatment facilities contains elevated levels of TP, consistent with the limits outlined in GB18918-2002 (TP = 0.5 or 1 mg/L). This increased TP concentration in discharged sewage remains a major factor contributing to lake contamination. Additionally, the extended water residence time of Taihu Lake, exceeding 180 days, poses a substantial challenge not only for P removal but also for overall TP management. Unlike N, which can be mitigated through denitrification, no analogous gaseous loss process exists for P within the lake ecosystem. Furthermore, the considerable accumulation of P in lake particles maintains high TP levels in the water column due to ongoing diffusion between surface water and sediments (Qin et al. 2019; Xu et al. 2017). Notwithstanding, the implementation of various high-cost interventions, such as dredging and extensive hydrological engineering, their effect in reducing TP concentrations is insufficient due to the substantial costs and challenges related to sediment displacement (Qin et al. 2019). Large-scale hydrological engineering, including the Yangtze River diversion, proves inadequate due to the insufficient availability of unpolluted water. Water diversion from the Yangtze River accounted for only approximately 5%–10% of the total external P input to Taihu Lake (Tong et al. 2017; Tang et al. 2021). Since lakes can mitigate for reduced atmospheric N via biological N retention, future strategies should emphasize on mitigating internal P loads in lakes to prevent cyanobacterial blooms.

Moreover, a substantial challenge in water pollution management at present is the complexity of determining the potential impact of interventions on a broad geographical scale in terms of transport interception and nutrient loss. The efficiency of control strategies aimed at mitigating nutrient losses from sources is primarily determined by crop varieties, fertilizer application rates, meteorological conditions, soil composition, and management approaches (Tang et al. 2021). However, the available data is largely derived from studies focusing on particular environmental conditions and specific crop species, which do not fully represent the comprehensive impact of these measures across the entire Taihu Lake basin. Additionally, collecting diverse data types over the extensive 36,985 km^2 area of Taihu Lake is highly challenging. The effectiveness of management techniques intended to improve N removal in nutrient transportation systems is significantly influenced by the location and size of ditches, reservoirs, and ponds (Xia and Yan 2020). For example, downstream wetlands often exhibit better capacity for pollutant removal than upstream wetlands because they are exposed to a higher influx of pollutants (Hansen et al. 2018). Acquiring geographic data for large water bodies, notably smaller ones, presents major obstacles to the wide lake basin. Moreover, modeling and computational demands for such data require substantial resource demands. We propose developing models that integrate factors contributing to the effectiveness of various control strategies to address this issue. This technique would facilitate precise assessment of non-point source pollution management strategies across extensive geographical areas in the future.

5. Future perspectives and recommendations

Considering the insufficient improvement in the water quality of Taihu Lake, it is imperative to consistently ensure the implementation of strategies focused on source management, transport interception, and in-lake interventions. Additionally, we highlight several significant challenges and recommendations, particularly the need to enhance nutrient contamination modeling and offer valuable perspectives for pollution prevention efforts in Taihu Lake.

5.1. Governance policies for lake protection

Lake conservation depends on the adoption of numerous pollution prevention strategies alongside the establishment of governance and management frameworks (Shkaruba et al. 2024). In China, authorities at national, provincial, and municipal levels have introduced regulations to mitigate pollution and protect lake ecosystems. These policies are grounded in the principle that "green water and mountains are equivalent to gold and silver mountains," underscoring the importance of sustainable development and environmental preservation. The local government has proposed several measures for lake governance, specifically designed to address the unique characteristics of the Taihu lake region and its urgent conservation requirements. Additionally, numerous local management rules aligned with provincial principles have been implemented. These policies specify detailed approaches for controlling and managing lake pollution over the next 5 to 15 years and establish legal frameworks for lake conservation measures. For instance, in Yunnan province, yellow and red protection zones have been designated around the nine plateau lakes to restrict human engineering development and harmful activities in critical areas dedicated to lake conservation (Wang, Wang, et al. 2015). These regulations are essential for mitigating adverse human impacts on lake environments and promoting public participation in lake conservation efforts (Wang, Wang, et al. 2015).

5.2. Public contribution

Public participation, through dialogue and collaborative evaluation of relevant concerns, enables independent participants to contribute to planning outcomes and operational processes independently of government officials (Hophmayer-Tokich and Krozer 2008). Europe and the United States have strong histories of public engagement in managing water resource decisions. The Swedish experience highlights the challenge of sustaining long-term public and stakeholder involvement (Jöborn et al. 2005). The North Sea nations in Europe illustrate the importance of individual involvement and equity in effectively assessing non-point source contamination locally (Hophmayer-Tokich and Krozer 2008).

However, our initiatives to regulate water quality and nutrient discharge have largely relied on legislation, yet the expected outcomes have not been completely achieved. Insufficient and irregular public engagement has inadequately represented the Taihu Lake population's interests. Consequently, public collaboration is expected to generate two main outputs: (i) improved decision-making through clear prioritization of actions and the integration of local perspectives, solutions, and knowledge; and (ii) effective implementation supported by increased participation, stakeholder engagement, and an equitable democratic framework (Hophmayer-Tokich and Krozer 2008). Public engagement is also anticipated to result in a more informed populace, authentic remediation strategies, enhanced measures execution, and reduced stakeholder conflict.

6. Conclusion

Research efforts and intensive field activities have been undertaken to improve Taihu Lake's water quality through pollution control measures. The effectiveness of these measures in mitigating runoff and pollutants warrants further investigation to inform the development of adequate water control policies. Over the past thirty years, water quality has evolved into two distinct phases: a period of degradation (1990s–2007) followed by an improvement in total nitrogen (TN) and fluctuating levels of total phosphorus (TP) (2007–present). We synthesized the water quality progress achieved across two phases and underscored the crucial role of model analysis in predicting the future of non-point source pollution control measures for Taihu Lake. This requires a comprehensive analysis of nutrient depletion mechanisms (such as lateral seepage runoff in paddy fields, increased saturation, irregular tailwater discharge in aquaculture, the rainfall flush phenomenon in courtyards, and free-range livestock and poultry), as well as nutrient transport mechanisms, including the influence of dense polder-river structures, multiple pumping installations, recurrent counterflow, and a constant nutrient interchange involving groundwater and surface water. Additionally, public participation, alongside policies and regulations, is crucial to assist local communities, management, and researchers in designing, implementing, and maintaining both standalone and integrated strategies and methods.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there is no conflict of interest.

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