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Original Research Article

Significant decline of water pollution associated with inland fishery across China

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ABSTRACT

Water pollution seriously threatens the sustainable development of fisheries in China. To inform effective pollution control policies, a comprehensive understanding of the fishery environment status is needed. However, nationwide data on the temporal changes of major pollutants in the fishery waters of China are scarce. This study collected data on the major water pollutants, including total nitrogen, total phosphorus, heavy metals, and total petroleum hydrocarbons (TPHs), from 2003 to 2017 to evaluate dynamic changes in the inland fishery water environment across China. We discovered that the levels of four heavy metals (Cu, Zn, Pb, and Cd) and TPH decreased during the 15-year period, corresponding to the reduced national discharge of pollution sources from 2003 to 2015. However, nitrogen and phosphorus levels in the inland fishery waters showed no significant changes during this period. A comparative analysis of water quality in different periods indicated that these improvements were highly associated with effective measures for water pollution control in China. In addition, the decline in pollution was consistent among the three regions of China (north, west, and southeast) from 2003 to 2017, while southeast China exhibited the weakest pollution mitigation among the three regions. These findings suggest that the inland fishery water quality improved during 2003–2017, but still faced eutrophication risk.

1. Introduction

Globally, inland waters cover approximately 7.8 million km^2 and constitute some of the most biologically productive and diverse ecosystems on Earth [1]. In China, inland fisheries contribute more than 50% of the total fishery output value [2]. Freshwater environments are the foundations of fishery resources and provide the essential conditions for the survival and reproduction of aquatic organisms. However, water pollution has increased in China due to its rapid economic growth in recent decades [3–8]. The Chinese water ecosystems and aquatic organisms have significantly been affected by multiple water pollutants, including heavy metals, organic pollutants, eutrophication, and plastics, produced by industrial wastewater, domestic sewage, and agricultural non-point source pollution [9–15]. Furthermore, pollution accidents and ecological disasters in fishery areas cause severe losses of fishery resources [16,17]. More than 1,300 major fishery water pollution accidents occurred in China from 2012 to 2018, causing direct economic losses of 707 million yuan and indirect natural fishery resource losses of 77 billion yuan [18]. Therefore, water pollution is a crucial factor that hinders the sustainable development of fisheries in China.

Long-term environmental monitoring of fishery waters provides crucial background information, which is a prerequisite to protecting the fishery environment and aquatic bioresources. In particular, the temporal variations of major pollutants would help assess the effectiveness of the past measures and current regional variations, which is crucial for identifying water quality and pollution control policies and practices that can enhance water security and ecosystem sustainability across the diverse regions in China. Previous studies have examined temporal changes in China's water quality at the regional or watershed levels [19–23]. However, these investigations have typically focused on specific areas with limited spatial implications. Moreover, there is a lack of nationwide information on the temporal and regional patterns of changes

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in major pollutants in fishery waters in China. Therefore, a comprehensive analysis is needed to systematically investigate the levels and evolutionary trends of major pollutants nationwide.

The National Fisheries Eco-Environment Monitoring Network (NFEMN) has monitored the crucial inland fishery waters of China since 1985, covering the spawning grounds, feeding grounds, wintering grounds, migratory passages, nature reserves, and crucial breeding waters of fish, shrimp, shellfish, and algae. In the present study, we collected monitoring data of total nitrogen (TN), total phosphorus (TP), heavy metals, and petroleum hydrocarbons (TPH) from crucial inland fishery waters in China from 2003 to 2017 and analyzed the interannual change trend of these pollution indicators. These results will assist in comprehensively understanding the status of the inland fishery environment in China and provide a scientific basis for formulating strategies for water pollution control and fishery sustainability.

2. Materials and methods

2.1. Study area and monitoring sites

The study area consisted of natural fishery waters in China. The monitoring sites encompassed over 80 natural inland fish spawning grounds, bait grounds, wintering grounds, migratory channels, and 40 inland national aquatic germplasm reserves. The main rivers and lakes were the Nenjiang River, Heilongjiang River, Songhuajiang River, Yalu River, Liaohe River, Yellow River, Huaihe River, Minjiang River, Yangtze River, Qiantang River, Xijiang River, Pearl River, Xingkai Lake, Hulun Lake, Bosteng Lake, Taihu lake, Dongping Lake, Nansi Lake, Dongting Lake, Boyang Lake, Chaohu Lake, Hongze Lake, Luomahu Lake, Wanjiazhai Reservoir, Xiaolangdi Reservoir, Three Gorges Reservoir, Miyun Reservoir, and Zhangze Reservoir. Fig. 1 and Figs. S1–S3 show the details of the sampled water sources. The sampling sites varied between years. Taiwan Province and Tibet Autonomous Region were excluded from this monitor study of fishery waters.

2.2. Data resource

All water pollution monitoring data were collected from our network (NFEMN) from 2003 to 2017. Datasets of five heavy metals (Cu, Zn, Pb, Cd, and Hg), TPH, TN, TP, and pH levels in inland fishery waters were summarized from measurements across China. For each water source area, water samples from 5 to 25 sampling sites were collected every year during the dry season (March) and wet season (August). The standard for water pretreatment has changed since the 2002 issue of “Surface Water Environmental Quality Standards.” Additionally, a change in the monitored water pollution indicators results occurred since the adoption of the new method. Therefore, in this study, only the monitoring data after 2003 were analyzed in the statistics of interannual changes in various pollution indicators. The sample collection and detection of multiple indicators were completed by the member institutes of NFEMN in accordance with the “Water quality standard for fisheries” [24], for heavy metals, TPH, and pH measurement and the “Environmental quality standards for surface water” [25], for TP and TN measurement. In particular, Cd, Zn, and Pb levels were measured by atomic absorption spectrophotometry or diethyldithiocarbamate spectrophotometry; Cu level was measured by atomic absorption spectrophotometry or sodium

Fig. 1. Diagram of sampling sites from inland fishery waters.

diethyldithiocarbamate spectrophotometry; Hg level was measured by cold atomic absorption spectrophotometry or dithizone spectrophotometry; TPH level was measured via ultraviolet spectrophotometry; pH level was measured using the glass electrode method; TN level was measured by alkaline potassium persulfate ultraviolet spectrophotometry, and TP level was measured by ammonium molybdate spectrophotometry.

Wastewater discharge data sets were obtained from the Annual Statistic Report on Environment in China (2003–2015). Due to the unavailability of public statistical data on industrial wastewater discharge in China after 2015, our analysis was mainly based on emissions data from 2003 to 2015.

2.3. *Data analysis*

SPSS 21.0 and Origin 8.0 were used for the data analysis. Data on water pollutants, including TN, TP, heavy metals, and TPH, were fitted (with years) using a linear mixed model [26]. Furthermore, Mann–Kendall model was employed to monitor the interannual change in the average detected levels (ADLs) of these indicators [27,28] to confirm the changes in the levels of water pollutants. The ADLs per year were calculated as the arithmetic average of the monitored results from all the sampling sites. A Z-value greater than 0 indicated an upward trend, whereas a value less than 0 indicated a downward trend (see Fig. S4 and Table S1 for the calculation formula of the Z-value). When the absolute value of Z was greater than 1.28, 1.64, and 2.32, it passed the 90%, 95%, and 99% confidence levels, respectively. Differences in these data among 2003–2007, 2008–2012, and 2013–2017 were statistically compared using the Kruskal–Wallis test [29]. Statistical significance was assumed when the *p*-value was <0.05.

In addition, temporal trends in wastewater discharge were fitted using linear or polynomial regression models. Further details on the datasets and statistical methods are provided in the Supplementary Methods.

3. Results and discussion

3.1. *Reduction in major pollutants during 2003–2017*

3.1.1. *Heavy metal*

Despite site-to-site variability in the data, the detected levels of four heavy metals (Cu, Zn, Pb, and Cd) showed a significant downward trend over 15 years ($p < 0.001$ for Cu, Pb, and Cd; $p = 0.03$ for Zn) (Fig. 2A–D, Fig. S5, Tables S2–S6). The order of decrease in the mean rates in heavy metals, as determined by the linear regression slope, was Pb > Zn > Cu > Cd (which were $-4.99e^{-5}$, $-4.01e^{-4}$, $-4.43e^{-4}$, and $-8.47e^{-4}$ for Cd, Cu, Zn, and Pb, respectively). Accordingly, the ADL of heavy metals decreased from 0.0012 to 0.00055 mg/L (Cd), 0.027 to 0.019 mg/L (Zn), 0.0116 to 0.0069 mg/L (Pb), and 0.0074 to 0.0039 mg/L (Cu), respectively, during 2003–2017. Simultaneously, the detected median level of Cd, Zn, and Cu plummeted from 0.0005 to 0.0003 mg/L (Cd), 0.025 to 0.01 mg/L (Zn), and 0.005 to 0.0025 mg/L (Cu), while the median Pb level remained at 0.005 mg/L during both 2003 and 2017. The trend in the ADL of heavy metals during 2003–2017 was further validated using the Mann–Kendall model, with a Z-value of -2.47 (Cd), -2.67 (Pb), -2.08 (Cu), -1.38 (Zn), and 0.39 (Hg). In addition, Zn had the highest levels among the five heavy metals in the fishery waters of China based on the ADL results, followed by Pb, Cu, Cd, and Hg. Similar recovery from heavy metal

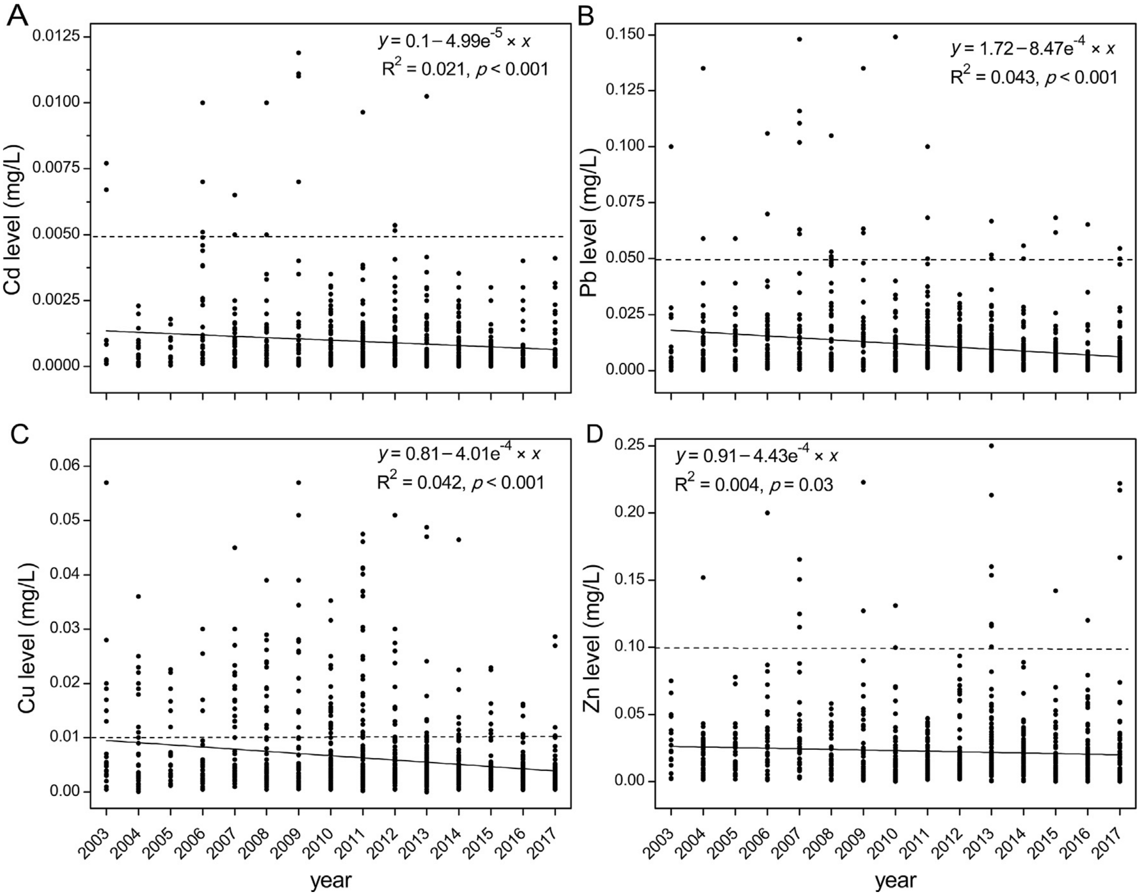

Fig. 2. Trends in the levels of heavy metals in the inland fishery water areas in China between 2003 and 2017. (A) Cd level; (B) Pb level; (C) Cu level; (D) Zn level. All of the four heavy metals have decreased significantly since 2003 according to linear mixed models, despite large site-to-site variability. Dotted lines indicate the limit standards for the corresponding indicators in fishery waters according to “Water quality standard for fisheries”.

pollution in the surface waters of China has been reported in other studies, including the Three Gorges Reservoir (reduced level of As, Cd, Cr, and Cu) [30], Pearl river estuary (reduced level of Hg, Pb, Cd, Cu, and Zn) [21,31], Northern Hangzhou Bay (reduced level of Hg, Pb, Cd, Cu, and Zn) [22], Songhua River Harbin Section (reduced level of Cu and Pb), and Wen-Rui Tang River basin (reduced level of As, Pb, Cr, and Cd) [32,33].

The concentration of heavy metals in a water body is highly influenced by the pH of that water body. Heavy metals tend to precipitate in the sediment under alkaline conditions and get released under acidic conditions. Therefore, we further analyzed the interannual trend of the pH values of inland water bodies to clarify whether the decrease in heavy metal levels was due to the alkalinization of the water bodies. However, no significant interannual changes in pH were identified from 2003 to 2017 (Fig. S6, Table S7). This suggested that the decrease in heavy metal concentrations in inland fishery waters was not associated with the pH of the constituent water body.

3.1.2. Petroleum hydrocarbon

TPH is a crucial pollution indicator of inland fishery environments in China. Similar to heavy metals, we observed that the detected TPH levels showed a significant downward trend over time ($p < 0.001$) during the 15 years (Fig. 3A, Table S8). The ADL decreased from 0.047 to 0.021 mg/L during 2003–2017, and the median level dropped from 0.025 to 0.019 mg/L. The change in the annual ADLs of TPH during 2003–2017 was confirmed using the Mann–Kendall model, with a Z-value of -3.18. Furthermore, the temporal changes in the THP were analyzed.

3.1.3. Nitrogen and phosphorus

In contrast to TPH and heavy metals, the detected levels of TN ($p = 0.752$) and TP ($p = 0.743$) in the inland fishery waters did not show a significant change during 2003–2017 (Fig. 4, Tables S9–S10). Other studies have reported worsening water nitrogen and phosphorus pollution scenarios in China in recent decades, such as in the Yellow River and Dongting Lake [23,34]. A previous study also reported that the TN levels in Chinese surface waters had exceeded the quality standard by the mid-1980, and the current rate of anthropogenic nitrogen discharge into freshwater was substantially higher than the estimated acceptable threshold [35]. This suggested that eutrophication had become a major pollution problem in inland fishery waters and raised great concern.

3.2. Regional trend variations in fishery water pollution

To further analyze regional environmental changes in the inland fishery waters, we divided all monitored areas into three regions: the west, the north, and the southeast (Fig. 5, Fig. S7). Although the four heavy metal levels showed similar downward trends among the three regions from 2003 to 2017, the northern region showed the highest decrease in heavy metal levels, as determined by the linear regression slope, followed by the western region. The weakest heavy metal decline was found in the southeastern region. This pattern was consistent across all four decreased indicators, except for Zn, whose level showed a rapid downward trend in the west and southeastern regions from 2003 to 2017, while no significant change in Zn levels in the northern region was observed ($p = 0.148$). During the regional change analysis, a notable decrease was found in THP in the Northern and Western regions during 2003–2017, which was similar to the nationwide change; however, an apparent disparity was discovered in the southeastern region, where no significant decline in THP occurred (Fig. 3B). Based on the Communique of the Second Pollution Source Census of China, Guangdong, Zhejiang, and Jiangsu (three provinces in the southeast region) ranked the top three in terms of the number of industrial units that accounted for approximately 50% of all industrial units in China [36]. Therefore, one possible explanation for the weak mitigation of heavy metal and petroleum hydrocarbon pollution in southeast China is the higher industrial production in this region.

Interestingly, the weakest mitigation was not equivalent to the worst pollution in the southeast region. For example, based on the regional heavy metal concentrations in 2015–2017, despite a slow pollution reduction, the levels of Zn and Pb in the southeast region were lower than those in the north and west regions (Fig. S8). This suggested that differences in the background concentrations of pollution indicators existed among the three regions, which further contributed to a distinct migration degree. In addition, we also identified that the TPH levels in the southeast region were significantly higher than those in the other two regions in 2016 and 2017 (Fig. S9), which indicated the worst TPH pollution status in this region with no downward trend, which raised a great concern.

3.3. Consistent trend in fishery water pollution with wastewater discharge

To understand the effects of wastewater discharge on inland water pollution, we further examined temporal changes in wastewater discharge

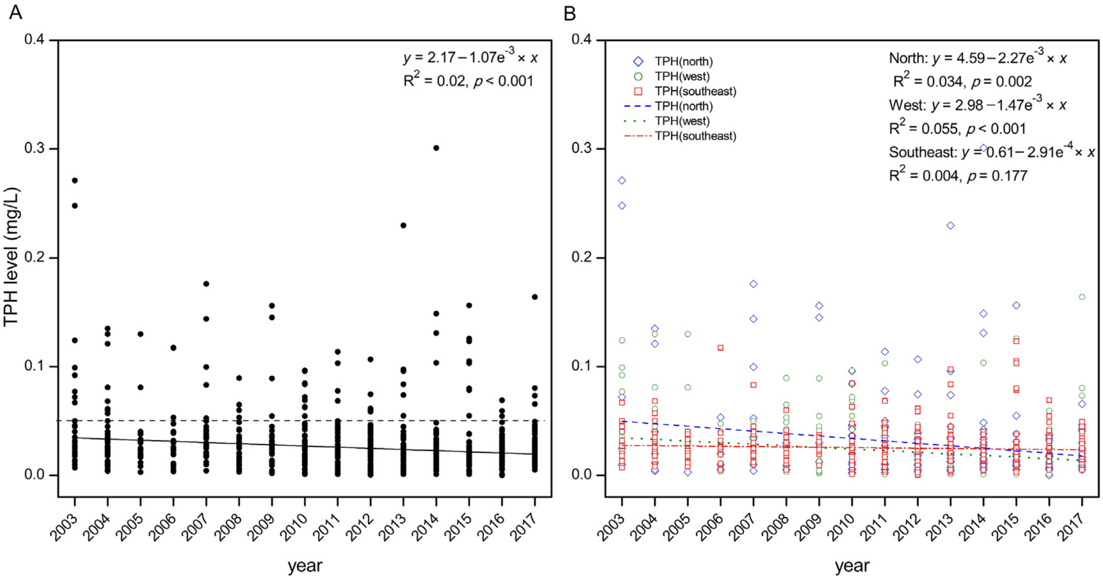

Fig. 3. Trends in TPH between 2003 and 2017. (A) nationwide trends; dotted line indicates the limit standards for TPH in fishery waters according to “Water quality standard for fisheries”. (B) Trends in three regions (north, west, and southeast). A significant decrease in nationwide, northern, and western TPH levels was identified since 2003 according to linear mixed models ($p = 0.002$ for the north; $p < 0.001$ for nationwide and west). Southeast TPH levels did not show a significant trend during 2003–2017. TPH, total petroleum hydrocarbons.

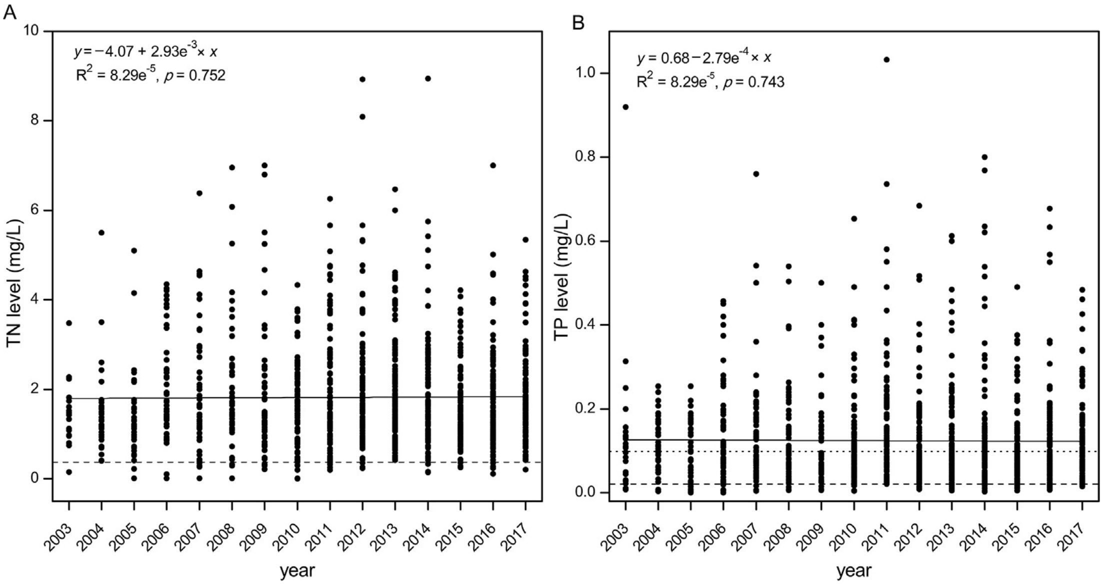

Fig. 4. Trends in total nitrogen (TN, A) and total phosphorus (TP, B) levels in the inland fishery water areas of China between 2003 and 2017. No significant change was identified in TN and TP levels during the period 2003–2017. The dotted line indicates the limit standard for TN (0.5 mg/L) in fishery waters according to the "Environmental quality standards for surface water". The limit standard of TP is 0.1 mg/L and 0.025 mg/L for rivers and lakes/reservoirs, respectively.

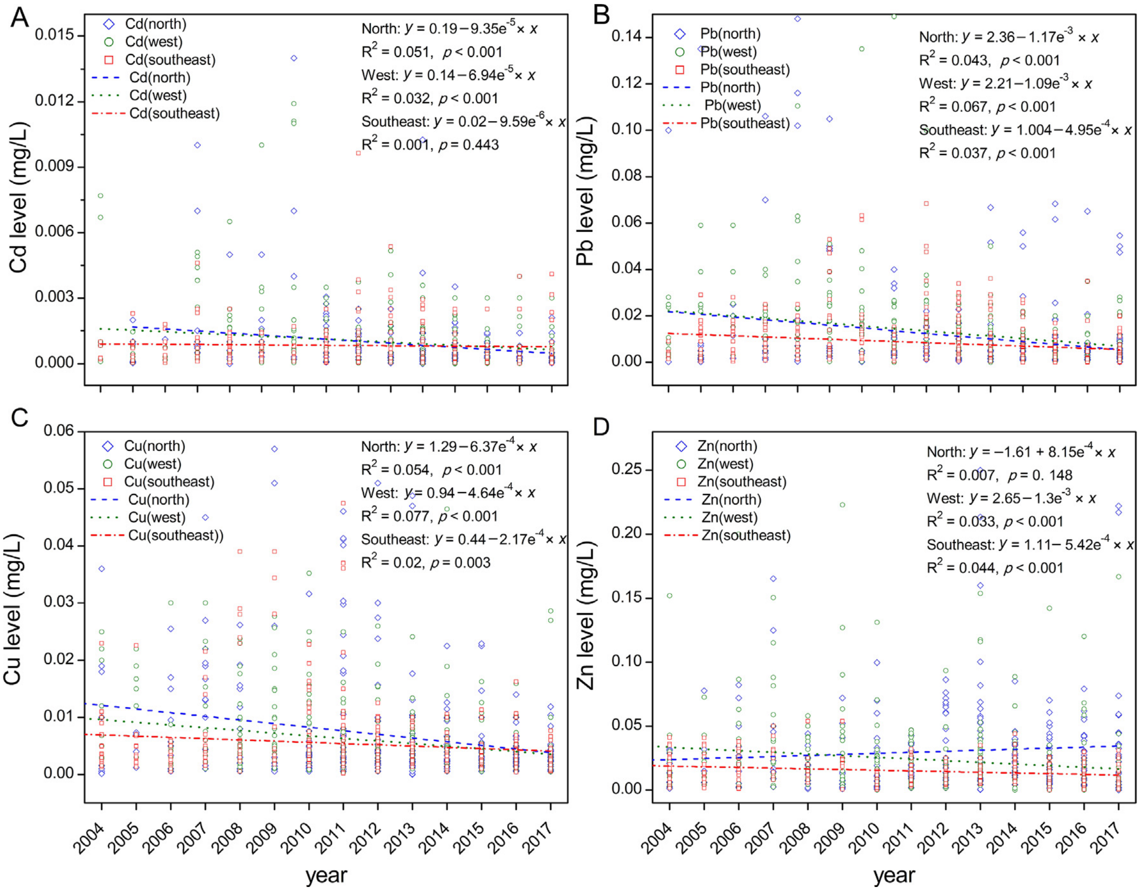

Fig. 5. Regional temporal changes in heavy metal levels between 2003 and 2017 in the inland fishery waters of China. (A) Cd level, a significant decrease in northern and western Cd levels was identified since 2003 according to linear mixed models ($p < 0.001$ for north and west), and southeast Cd levels did not show a significant trend during 2003–2017. (B) Pb level, a substantial decrease in Pb levels in the three regions was identified since 2003 according to linear mixed models ($p < 0.001$ for north, west, and southeast). (C) Cu level, a significant decrease in Cu levels in the three regions was identified since 2003 according to linear mixed models ($p < 0.001$ for north and west, $p = 0.003$ for southeast). (D) Zn level, a significant decrease in Zn levels in the west and southeast was identified since 2003 according to linear mixed models ($p < 0.001$ for west and southeast). The northern Zn levels did not show a significant change trend during 2003–2017.

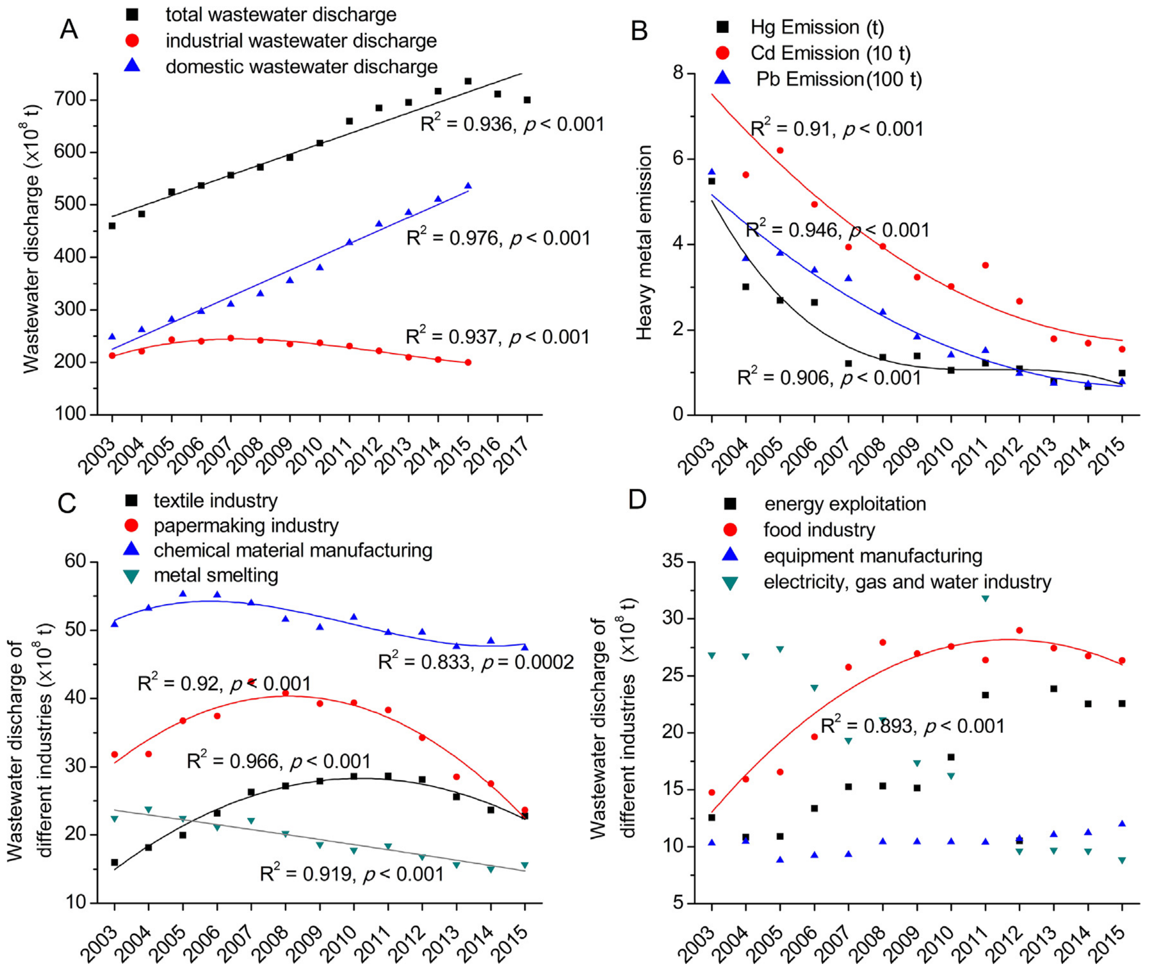

Fig. 6. Temporal trends of wastewater discharge during 2003–2017. (A) Temporal trends of total wastewater discharge, industrial wastewater discharge, and domestic wastewater discharge; (B) industrial emissions of Hg, Cd, and Pb; (C–D) wastewater discharge from different industries. All the data were fitted by a linear or polynomial regression model. "t" stands for ton.

during 2003–2017, including total wastewater discharge, industrial wastewater discharge, domestic wastewater discharge, and industrial wastewater emissions of heavy metals. Although total wastewater discharge continuously increased from 2003 to 2017, domestic and industrial wastewater discharge showed the opposite trend during this period, and industrial wastewater discharge showed a distinct decline since 2007, while domestic sewage discharge continued to increase (Fig. 6A). Refined industrial emissions further revealed that the wastewater emissions of several sub-industries that were closely related to the heavy metal emissions (including metal smelting, chemical material manufacturing, and papermaking) showed a downward trend from 2003 to 2015 (Fig. 6C and D). In addition, a temporal decline in the industrial heavy metal emissions, including those of Hg, Cd, and Pb, was identified during 2003–2015 (Fig. 6B), which further supported the source reduction of heavy metal water pollution. Although there were no direct data on annual agricultural wastewater emissions in China, limited statistics showed that the annual nitrogen and phosphorus emissions of the livestock industry dropped by 1,280,000 tons (47.4%) and 72,700 tons (25.5%) in 2017, respectively, compared to 2007 data [36,37]. These temporal changes in wastewater discharge corresponded with improvements in inland fishery water quality.

Contrastingly, the increased domestic sewage discharge levels partly explained the reason for the unchanged nitrogen and phosphorus pollution despite emission reductions in the agriculture and industry sectors of China. A previous study also reported that municipal wastewater treatment is crucial in affecting the nitrogen and phosphorus pollution levels in lakes in populated regions [38]. Transportation is another vital source of nitrogen deposition in water bodies. It has been reported that vehicular NOx emissions doubled during 1998–2013, and the annual increase rate of total vehicular emissions from 2008 to 2013 was close to 10% [39]. Regional studies have also demonstrated that vehicular emissions were prominent NOx contributors [40,41].

3.4. *Association between the improvement in water quality and the national control policy*

To better understand the temporal changes in heavy metals in the inland fishery waters of China, we divided the monitoring results into three periods of five years for each stage (2003–2007, 2008–2012, and 2013–2017) and analyzed the disparity among these three stages. Based on the Kruskal–Wallis test, we found that the Cd, Pb, and Cu concentrations during 2013–2017 were significantly different from that of both 2003–2007 (except Cu) and 2008–2012 ($p < 0.001$) (Figs. 7A–C). This suggested that the Cu, Pb, and Cd levels showed a rapid downward trend during 2013–2017 compared to the other stages. A previous regional study also reported a rapid decrease in heavy metal levels (Cu, Zn, Cd, and As) in the sediments of the Yangtze River Estuary during 2013–2016 [42]. The concentration distributions of Zn during both 2008–2012 and 2013–2017 differed from that of 2003–2007 ($p < 0.05$) (Fig. 7D).

Wastewater discharge is the primary source of heavy metals in water bodies. Before 2011, the production technology and pollution control of the heavy metal industry in China were of low quality. In 2011, the

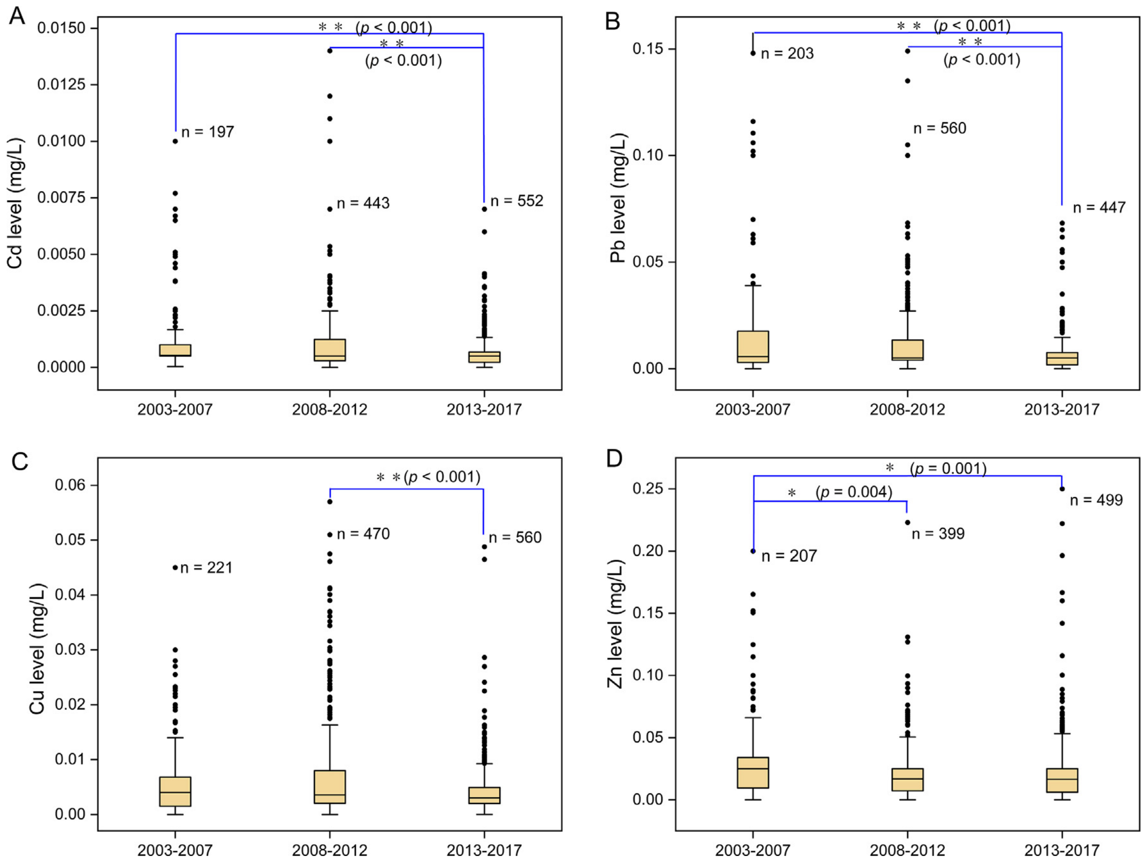

Fig. 7. The temporal disparity in heavy metal concentrations in the inland fishery water areas of China during 2003–2007, 2008–2012, and 2013–2017. (A) Cd level; (B) Pb level; (C) Cu level; (D) Zn level. Asterisk marks indicate the significant difference in heavy metal levels between different periods according to the Kruskal–Wallis test.

Chinese government approved a "Five-Year Plan" for the comprehensive prevention and control of heavy metal pollution. Statistics from the Ministry of Ecology and Environment of China indicated that more than 4,000 heavy metal companies had been eliminated nationwide, and the smelting elimination of Cu, Pb, and Zn reached 2.88, 2.81, and 0.86 million tons, respectively, during 2011–2015 [43]. The statistical data coincided with the inflection year point (2013) of rapid heavy metal mitigation observed in this study. Therefore, these effective actions were the key reasons for the rapid mitigation of heavy metal pollution during 2013–2017 in inland fishery waters.

With the standardization of feed ingredients for livestock, poultry, and aquaculture, the implementation of solid waste treatment, livestock wastewater discharge standards, and heavy metal emissions from agricultural sources has decreased notably. As a result, the comprehensive utilization rate of livestock and poultry manure increased from 50% in 2012 to nearly 60% in 2015. Moreover, from 2015 to 2018, more than 262,000 livestock and poultry farms (communities) in confined areas were closed or relocated, and 5,628 healthy aquaculture demonstration farms were established [44]. Based on statistical data, the total inland fishery yield increased from 20.2 to 33.2 million tons during 2003–2017, while the pollution emissions per unit output significantly decreased, revealing the effectiveness of green development in aquaculture [45–47]. Overall, the decrease in heavy metals in inland fishery waters was due to reduced heavy metal emissions from both industry and agriculture, indicating that the comprehensive control of water pollution (at least for heavy metals) in China has made progress. A previous nationwide study also reported an improvement in inland surface water quality based on changes in the chemical oxygen demand, ammonium nitrogen (NH_4^+-N), and dissolved oxygen during 2003–2017 [48].

3.5. *Future implications*

Several previous studies have reported improved surface water quality in China based on data from both specific water bodies and diverse regions [49,50]; however, there is a lack of information on nationwide changes in heavy metals and TPH pollution in inland fishery waters. This study provides the first systematic evaluation of temporal changes in major pollutants in fishery waters nationwide in China. Our findings indicated that the pollution of heavy metals and TPH in the inland fishery waters of China showed a significant recovery during the last 15 years (2003–2017) and confirmed the effectiveness of heavy metal pollution control efforts through rapid pollution mitigation during 2013–2017. A regional division analysis showed that the pollutants in the three regions (north, west, and southeast) displayed similar declining trends during 2003–2017, while the southeast showed the weakest pollution mitigation among the three regions. These results could offer new insights into management strategies for the future pollution control of fishery waters and related research directions.

First, as TN and TP levels remained high, with no sign of relief during 2003–2017, stringent policies were enacted to reduce TN and TP emissions, particularly from domestic and vehicular sources. Moreover, since nitrogen and phosphorus in water bodies impart both favorable and unfavorable conditions for fishery organisms, these indicators should be maintained within an optimal range. Thus, further research is needed to elucidate the specific adverse effects and the dose–effect relationship of excessive nitrogen and phosphorus on aquatic organisms.

Second, our findings revealed regional variations in pollution reduction and distribution. Considering the regional disparities in the driving factors and pollution status across the country, more tailored measures and strategies for pollution prevention and control could potentially enhance the inland fishery water quality in China. For instance, the southeastern region should prioritize the security of underwater oil pipelines and fuel oil pollution from mobile sources, such as shipping and land transportation.

Third, in terms of environmental monitoring, apart from traditional indicators, emerging contaminants, such as environmental endocrine disruptors, plastics, pharmaceuticals, and personal care products, particularly drugs and disinfectants used to prevent and treat COVID-19 [51,52], should receive the utmost attention. It is advisable to persist in strengthening and expanding monitoring of the conventional pollution indicators (nitrogen, phosphorus, metals, etc.) and conduct the monitoring and safety risk assessment of the emerging pollutants, including exogenous contaminants and chemical inputs for important aquaculture regions, advancing the development of pollution prevention and control measures with the aim of “source optimization and precise control”.

Finally, regarding the fishery industry, optimization of the aquaculture layout and mode effectively reduced the discharge intensity of major pollutants in the aquaculture industry; however, challenges persist for the remediation of aquaculture environments. The next step should focus on demonstrating and promoting ecological fishery models, such as rice-fish farming, non-feeding multiplication in surface waters, multi-nutrient level culturing, fish-vegetable symbiosis culturing, and the natural carbon sink of fisheries. Furthermore, emphasis should be placed on promoting research on technologies for aquaculture water eco-regulation and optimization, sediment quality improvement, tailwater treatment and comprehensive utilization, lake and reservoir ecosystem function recovery and reconstruction, and so on. Simultaneously, more investment should be allocated to improve the infrastructure level of aquaculture ponds and promote the discharge of tailwater to comply with standards.

3.6. Limitations

Our study had certain limitations. (1) Although the monitoring data used for annual and regional analysis were the average concentrations measured in both the wet and dry seasons, the water storage in the water bodies could vary yearly due to rainfall and evaporation, which could introduce uncertainty in the pollution concentrations. (2) In the regional analysis, considering the geographical environment and fishery development, the western region could have been further divided into the northwest and southwest regions. However, the number of fishery waters in the northwest area is much lower than that in the other regions; thus, we combined the northwest and southwest regions into the western region to ensure an adequate sample size in each region. (3) Because the characteristics, pollution factors, and driving sources in the marine environment differ from those of the inland, the conclusions of this study are restricted to the marine fishery environment.

In conclusion, it can be anticipated that the inland fishery waters of China will achieve acceptable ecological status in the near future if current trends are sustained. Further implementation of measures for mitigating fishery water pollution should focus on controlling the emission of critical elements and their regional variations.

Author contributions

X.Y.M., J.Z.C and Y.R.L. conceived the framework; L.L.Y., H.W., S.L.M., and X.Y.M. processed environment monitoring data; L.L.Y., Y.H., and J.L. undertook the data analysis; X.Y.M and L.L.Y. wrote the paper with contributions by all authors.

Data availability statement

The source data in this study are available from the authors upon reasonable request.

Declaration of competing interests

The authors declare no conflicts of interest.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eehl.2023.05.002.

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