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A historical overview of water quality in the coastal seas of China

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Using historical data, long-term variations in pollutant sources and water quality in China's coastal waters over the last three decades are reviewed. The results show that the total area of non-clean water, which reflects state of total water quality, increased rapidly before 2000, but then underwent two stages of decline, with a modest decline by one-quarter between 2001 and 2015, followed by a sharp decline of more than half of that in 2015 since then. Consequently, water quality at present is better than it was at the beginning of the 1990s. The total area of polluted water fluctuated without any trend from the end of the 1990s until 2015, but has declined sharply by nearly two-thirds since 2015, indicating that the water quality in China's coastal seas has improved substantially. Geographically, the Bohai Sea was the first to see a turning point in water quality, followed by the Yellow Sea and East China Sea, while the South China Sea was the last. The main pollutants that govern the water quality grade and area are dissolved inorganic nitrogen and phosphate as well as petroleum hydrocarbons. As a response to variations in water quality, changes in both the frequency and total area affected by harmful algal blooms were similar to those of water quality over the last three decades, albeit with a slight lag. Analysis showed that variations in water quality were closely related to the land- and sea-sourced pollutant inputs. The combination of shift in the mode of economic growth from high-speed growth to high-quality development and the enforcement of the new, strictest ever *Environmental Protection Law* resulted in a significant decline of pollutant emissions, inducing a turning point in the water quality in the coastal seas of China in the mid-2010s.

KEYWORDS
water quality, coastal water, red tide, environmental pollution, China Seas

1 Introduction

Coastal waters are characterized by high productivity, and are relatively complex, sensitive and fragile ecological environments, which moreover are intensely affected by land-sea interactions (Olli et al., 2008; Wells et al., 2015; Chen et al., 2019). Globally, more than 60% of the world population and two-thirds of large- and medium-sized cities are concentrated in coastal areas (Ma et al., 2010; Lv et al., 2016). Coastal areas are therefore influenced directly and significantly by anthropogenic activities whilst also experiencing natural changes (Chen et al., 2006; Howard et al., 2016; Malone and Newton, 2020). This can result in the degradation of coastal eco-environments and the frequent occurrence of environmental disasters (Anderson et al., 2002; Cai et al., 2011; Liu et al., 2013; Strokal et al., 2014; Xiao et al., 2019).

All industrial nations have experienced environmental degradation that represents the ecological consequences of growth, and China is no exception. With the rapid socio-economic development in China, the coastal seas of China, which from north to south are the Bohai Sea (BS), Yellow Sea (YS), East China Sea (ECS) and South China Sea (SCS), became subject to intense pressure from human activities, which inevitably brought about serious environmental degradation. For instance, coastal eutrophication was only low to moderate level before the 1980s, but worsened rapidly from the end of the 1980s to the 2000s due to an acceleration in nutrient inputs (Wang et al., 2018; Wang et al., 2021). This eutrophication was also accompanied by widespread hypoxia (Zhu et al., 2011; Wei et al., 2019) and an increased frequency of harmful algal blooms (Zhou and Yu, 2007; Song et al., 2016; Xin et al., 2019; Wang et al., 2023).

Wang et al. (2011) provided an overview of the historical variations in water quality and pollutant origins in the coastal seas of China during the 1990s and 2000s, finding that the total area of polluted water fluctuated without any trend. They thus considered water quality to have not been improved significantly during those two decades. More than 10 years have now since passed, during which some different changes may have occurred. We therefore repeat the analysis using the new data, combined with the application of nonparametric test for trend detection, with emphases on the identification of turning points in coastal water quality and the examination of the effects of environmental policy stringency.

2 Materials and methods

2.1 Data sources

Data on water quality status in coastal seas of China were collected from the *Marine Environment Quality Communique of China* (1989–2018), the *Bulletin on the State of Marine Ecology and Environment of China* (2018–2021), and the *Bulletin on Environmental Quality of China Seas* (2000–2017), published by the State Oceanic Administration (SOA), the Ministry of Ecological Environment (MEE), and the State Environmental Protection Administration (SEPA) of China, respectively. These reports were based on routine monitoring data from more than 1,000 fixed stations in the coastal seas of China. Monitoring variables included dissolved inorganic phosphate (DIP), dissolved inorganic nitrogen (DIN = nitrite + nitrate + ammonia), total petroleum hydrocarbons, and other conventional hydrochemical variables. The data on incidents of red tide were obtained from the *Bulletin on China Marine Disaster* published by SOA (1989–2017) and the Ministry of Natural Resources (2018–2021). Data on terrestrial inputs of pollutants (including Total phosphorus (TP), ammonia, etc.) into sea were based on reports published by SOA, SEPA and other published documents (Kroeze and Qu, 2012; Gu et al., 2013; Wu et al., 2023). In addition, the riverine fluxes of TP and ammonia were calculated by multiplying the runoff and concentration of major rivers entering the coastal seas of China. The maricultural area data were collected from the *China Fisheries Yearbook* (1981–2021), which was published by Ministry of Agriculture and Rural Fisheries (2022). Data on the Gross Domestic Product (GDP) were obtained from the *Annual Statistical Report of China* (2021), which was published by the National Bureau of Statistics of China (2022).

2.2 Classification of water quality

Water quality was classified into five categories according to the *Sea Water Quality Standard of China* (GB3097–1997) of the Ministry of Environmental Protection of China (MEP), namely clean water (Category I) for marine fishery waters and marine natural reserves, relatively clean water (Category II) for aquaculture zones and bathing beaches, slightly polluted water (Category III) for general industrial areas and scenic coastal locations, medium polluted water (Category IV) for marine port waters and exploitation areas, and heavily polluted water (inferior to Category IV) (please refer to Table 1 in Wang et al. (2011) for further details). In this paper, the sum of all sea area classes with water quality inferior to Category I is referred to as total non-clean water, and the sum of all sea area classes with water quality inferior to Category II is referred to as total polluted area.

2.3 Data processing

Given the different data sources involved, it was necessary to conduct statistical tests for difference prior to the analysis. First, homogeneity of variance was assessed by applying Levene's test in the SPSS software (SPSS Inc., USA). Where homogeneity was satisfied, Tukey's Honestly Significant Difference (HSD) test was used to determine significant differences among the data from different sources. Second, a paired–sample t-test was used to compare the different groups of data. For all statistical analyses, $p < 0.05$ was considered significant.

The Sequential T–test Analysis of Regime Shift (STARS) algorithm developed by Rodionov (2004) was used to examine trends in the integrity and connectivity of each time series, and to identify the turning points and thresholds, which represent the transition of different level of eutrophication or the pollution. STARS algorithm mainly determined the mutation point by the Regime Shift Index (RSI) calculated through the selected cut–off length L and the preset confidence p–value (as detailed in Rodionov and Overland, 2005). The larger the RSI value, the higher the confidence. The specific method applied was that of Xie et al. (2021). Considering the development plan made by the Chinese government per five years, the L value in this study was set as 5, and the p value was selected as 0.1.

3 Results

3.1 Variations of water quality in coastal seas of China

The long-term variations in water quality in the coastal seas of China differed across different categories (Figure 1). The total area of non-clean water increased rapidly from 1.0×10^5 km^2 at the beginning of the 1990s to a peak of 2.06×10^5 km^2 in 2000, after that it decreased by nearly one–quarter to 1.5×10^5 km^2 and fluctuated until 2015. Following 2015, it declined sharply 0.7×10^5 km^2 at the beginning of 2020s, an even lower value than at the beginning of the 1990s. The total area of polluted water fluctuated from the end of the 1990s until 2015 but then decreased rapidly by about 60% from 2015 to 2021, while the area of relatively clean water declined by nearly two-thirds from the beginning of the 2000s to the beginning of 2020s (Figure 1B). This implies that the modest decline in the total non-clean water during the mid-2000s was mainly due to the decrease in the area of relatively clean water.

The variations in water quality were also different in different coastal seas of China. In the BS, the area of non-clean water fluctuated in the 2000s, but it increased rapidly doubled from the end of the 2000s to the beginning of the 2010s. A high level was maintained until 2015, after which it decreased sharply by nearly two-thirds until the beginning of 2020s. Although the trend of the total polluted water area was the same as that of non-clean water, the extent of both the increase from the beginning of the 2000s to the beginning of the 2010s and the decline after that were much more pronounced than those of the non-clean water. This implies that water quality in the BS worsened from the beginning of the

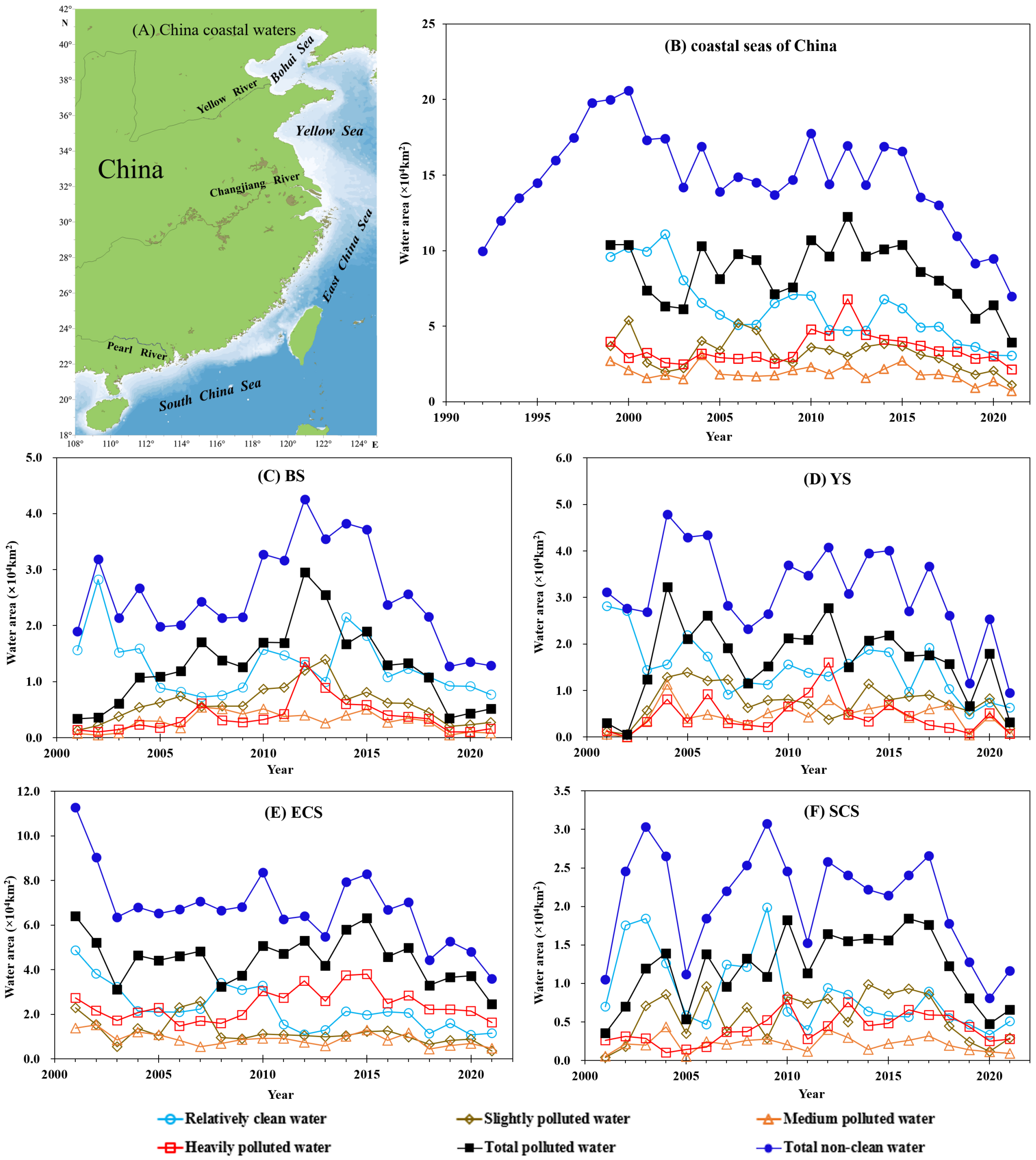

FIGURE 1
Geographical location of the China coastal waters **(A)** and variations in water quality in the coastal seas of China **(B–F)** over the last three decades.

2000s to the beginning of the 2010s, but afterwards improved rapidly. Current water quality has returned to the same level as it was at the beginning of the 2000s (Figure 1C).

In the YS, both the areas of total non-clean water and total polluted water fluctuated in the shape of a saddle, with one peak in the mid-2000s and a second in the first half of the 2010s (Figure 1D). The area of relatively clean water accounted for a large proportion at the beginning of the 2000s, but declined to a level of less than the total polluted water since the mid-2000s. The variation of water quality in the SCS was essentially the same as that in the YS. However, the total area of polluted water in the SCS was much greater than that of relatively clean water in the 2010s, which differed from the situation in the BS and YS (Figure 1F).

The variation of water quality in the ECS was quite different from that in the other three coastal seas of China. The area of total non-clean water declined linearly by about 50% over the three years of the beginning of 2000s. It then fluctuated at an average value of 7×10^4 km^2 until the mid-2010s, after which it decreased by nearly 50% to the lowest level at the beginning of 2020s (Figure 1E). The variation of the total polluted water in the ECS was similar to that of the total non-clean water. In contrast to BS and YS, the area of total polluted water was much greater than that of relatively clean water. Across all the four coastal seas of China combined, the total area of polluted water made up the largest share of the total area of non-clean water, and the area of heavily polluted water made up the largest share of the total area of polluted water in the ECS, implying that the level of pollution in the ECS was the worst among the four coastal seas of China.

The non-clean waters, especially the polluted waters, were mainly concentrated in estuaries (Wang et al., 2021; Wang et al., 2023) and bays (Wang et al., 2018; Dou and Zhang, 2019), which receive most of the land- and sea-sourced pollutant inputs. The main pollutants governing water quality grade and area in coastal seas of China are dissolved inorganic nitrogen and phosphate as well as petroleum hydrocarbons (Zhang, 2016; Wang et al., 2021).

3.2 Identifying trends in water quality

The STARS–based regime shift analysis revealed clear changes in water quality, although these trends varied in the different coastal seas. In the BS, two shifts (breakpoints) were detected during the two-decade period in both the total non-clean water and total polluted water time series, namely one abrupt increase at the beginning of the 2010s, and one abrupt decline in the mid-2010s. However, there was only one abrupt decline in the mid and late 2010s in the other three regions. Across all coastal seas of China, an abrupt decline in the total polluted water (for which two-decade time series were available) was also observed in the mid-2010s. However, for the much longer time series of total non-clean water, three shifts were detected with one abrupt increase in the 1990s, and two abrupt declines at the beginning of the 2000s and in the mid and late 2010s, respectively (Figure 2).

3.3 Occurrence of red tides as a response to changes in water quality

Since water quality is mainly governed by dissolved inorganic nitrogen and phosphate, which in sufficient quantities leads coastal eutrophication, the occurrence of red tide might reflect the changes in coastal water quality. The annual frequency of red tide was less than ten before the 1980s (Wang et al., 2018), and it fluctuated during 1990-2000, with an annual average of 23. However, it increased significantly to an average of 80 times per year during 2001-2012, with a peak in 2003. The frequency subsequently declined and remained fairly constant at approximately 50 times per year during 2013-2022 (Figure 3). In general, the trend in the area affected by red tides was very similar to that of frequency, although its rate of decline was much faster from the mid-2000s peak to the end of the 2010s than that of the frequency. The unexpected increase of the affected area in 2021 was mainly due to the occurrence of a large area of red tide in Beibu Gulf, in the western SCS, that had rarely been seen before.

Among the four coastal seas of China, the proportions in both the red tide incidents and affected area varied in different sea areas. Before 2000, red tides occurred mainly in the ECS and SCS, accounting for more than 40% and 30%, respectively; in the 2000s, red tide incidents accounted for more than 50% in the ECS; in the last decade, the proportions of red tide occurrences increased in the BS and SCS. The ECS had the largest share of both

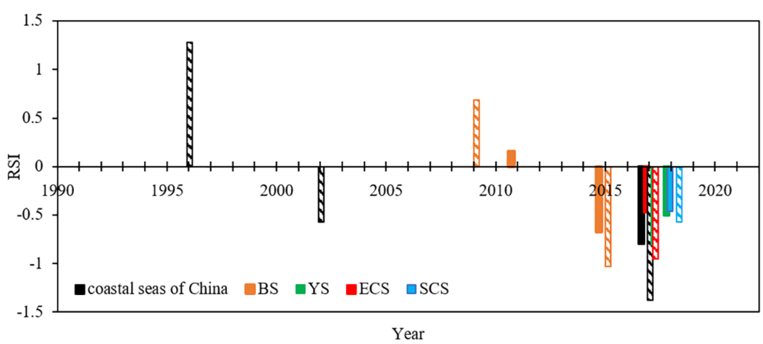

FIGURE 2
Regime shifts of water quality by STARS in the coastal seas of China in the last three decades (The shaded columns represent the total non-clean water, and the solid columns represent the total polluted water).

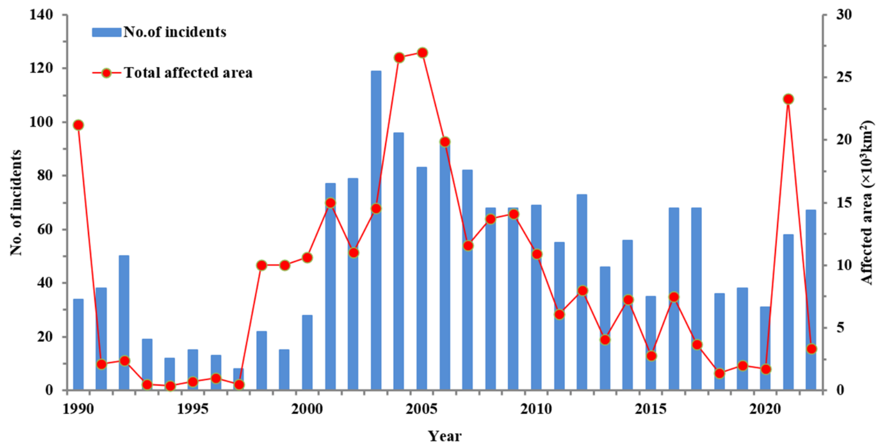

FIGURE 3
Annual variations of red tide incidents and total affected area in the coastal seas of China over the last three decades.

red tide incidents (more than 40%) and affected area (more than 30%), which was consistent with the ECS having the poorest water quality conditions. Compared to the variation in water quality, red tide occurrence exhibited a slight time-lag in response to changes in water quality. For instance, the area of total non-clean water peaked in 2000, but red tide frequency and affected area peaked in 2003 and 2005, respectively.

4 Discussion

4.1 Influence of land- and sea-sourced pollutant inputs

Polluted water was usually concentrated in the estuaries, bays and their adjacent waters because of the direct influence of terrestrial inputs (Ma et al., 2013; Wang et al., 2018; MEE, 2022). In general, riverine inputs of pollutant account for more than 70% of the terrestrial inputs (Qu and Kroeze, 2010; Sun et al., 2012). As shown in Figure 4, the riverine input of TP increased by one-third from the mid-2000s to 2015, but after that it decreased significantly by more than 50% at the beginning of 2020s. Due to the lack of long-term monitoring data on the flux of total nitrogen (TN), ammonia was used to represent the changes of terrestrial nitrogen input to the coastal seas of China. Similar to the variations in TP, the flux of ammonia also fluctuated at high level until 2015, but then declined rapidly by nearly 80% to the lowest value at the beginning of 2020s. Previous studies showed that the variations of DIN in the Changjiang River (Wu et al., 2023), the Yellow River and the Pearl River (Wang et al., 2018; Wang et al., 2021) presented the similar trends to that of ammonia, which also provided evidences for the trends in water quality. Moreover, due to the largest riverine discharges (including China's largest river, the Changjiang River) (Cheng and Zhao, 1985; Wu et al., 2019), the ECS received the most amount of terrestrial pollutants (e.g., nutrients) (Wang et al., 2020; Yang et al., 2023), leading to the largest areas of total non-clean and polluted waters in the ECS.

Mariculture represented the main sea-sourced input of nutrients in the coastal seas of China (Xiao et al., 2017; Zhang et al., 2022). The mariculture area steadily increased approximately three-fold from the beginning of 1990s to the mid-2010s, but has declined slightly in the last five years, likely contributing to the improvement of water quality after the mid–2010s (Luo et al., 2018). It is worth noting that seaweed farming could relieve eutrophication and improve the water quality by absorbing nutrients in the growth process (Wang and Ji, 2017). The area of seaweed farming has increased about 2–fold over the last

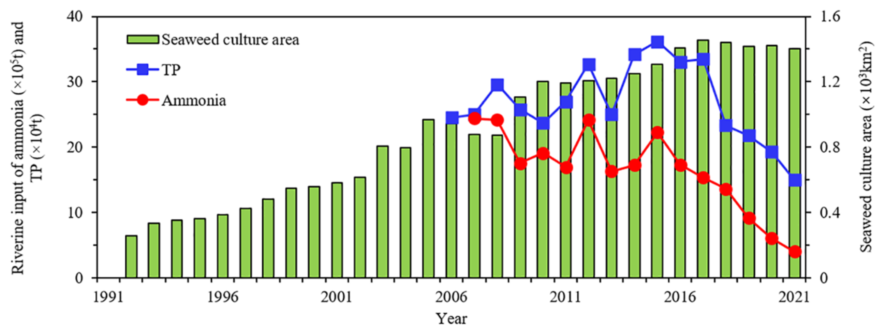

FIGURE 4
Variations in riverine inputs of TP and ammonia, and area of seaweed farming in the coastal seas of China over the last three decades.

three decades (Figure 4), and this may have had a positive impact on the improvement of water quality.

4.2 Impacts of environmental policy stringency and economic growth

Since the reform and opening-up, China's economy has entered a period of rapid development. The average annual economic growth rate reached a high speed of 10.0% during the period from 1978 to 2011. In the 1990s (and especially after 1992), China launched a new round of large-scale economic development and construction. However, during this period, the implementation of environmental protection policies was not strict, and the investment in environmental protection was insufficient (Xie, 2019). This resulted in a rapid deterioration of water quality, accompanying GDP growth during this period (Figure 5). In the 2000s (and especially after 2002), China entered a new era of scientific development that emphasized the coordinated more balanced and environmentally conscientious economic development. During this period, environmental protection policies and measures were implemented more strictly (Xie, 2019), and thus slowed down the deterioration of, or even improved, coastal water quality (Figures 1, 5). Since 2012, China's economy has entered a period of medium-high economic growth and high-quality development with an average annual GDP growth rate of 6.7% from 2012 to 2021. Especially since the enforcement of the new, strictest ever *Environmental Protection Law of China* in 2015, the concept of ecological civilization which means harmonious coexistence and comprehensive development between human and nature has been deeply rooted in the mindset of the population. The recent progress towards ecological civilization is unprecedented (Xiao and Zhao, 2017; Xie, 2019), and had led to continuous improvement in the coastal water quality after 2015 (Figures 1, 5).

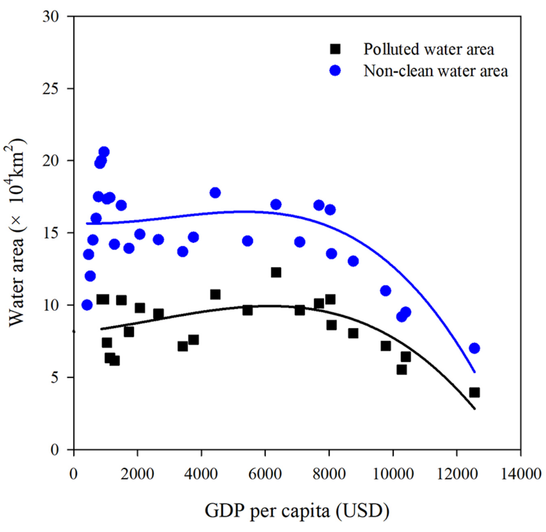

FIGURE 5
The relationship between GDP and water quality in the coastal seas of China (the solid lines are quadratic fitting curves).

Our analysis shows that the Environmental Kuznets Curve for water quality is not a regular inverted U-shape (Figure 5); rather, the water quality plateaued after reaching its peak when average GDP per capita reached 4,500 USD in 2010. Water quality clearly left the plateau period and entered a pathway of continuous improvement only after the year 2015, when average GDP per capita reached 8,000 USD. Therefore, as a relatively conservative judgment, the year 2015 may be regarded as the turning point of water quality in the coastal seas of China.

5 Summary

Variations of water quality in the coastal seas of China over the last three decades can be divided into three stages: rapid deterioration before 2000, slight mitigation between 2001 and 2015, and significant improvement post 2015. Changes in both the incidents and total area affected by red tide were similar to those of water quality over the last three decades, albeit with a slight time-lag. The variations in water quality were closely related to the economic development patterns and the stringency of environmental policy. Rapid economic growth combined with the insufficient implementation of environmental protection policies before 2000 had given rise to the rapid increase in pollutant emissions and thus the rapid deterioration of coastal water quality. After 2000 (and especially after 2002), stricter environmental protection policies and measures were implemented, leading to a slight mitigation and the maintenance of relatively stable water quality until 2015. Finally, since the implementation of the concept of ecological civilization, and especially since the enaction of the new Environmental Protection Law in 2015, pollutant emissions has been decreasing significantly, leading to a continuous and significant improvement of coastal water quality since that time.

Chinese authorities have issued a circular on further promoting the nationwide effort to prevent and control pollution during the 14th five-year plan period (2021–2025). The circular details major targets for improving the country's ecological environment, whereby the total discharge of major pollutants should continuously decline until 2025. It is therefore expected that the water quality and ecological status of the coastal seas of China will continue to improve in the future.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MX: data process, methodology and writing-original. XS: data process. L-PX: data process and methodology. B-DW: funding acquisition, conceptualization, and writing-review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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