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Spatial and Temporal Distribution of the Impact of Socio-economic Factors on Water Pollution in China

Przestrzenny i czasowy rozkład wpływu czynników społeczno-ekonomicznych na zanieczyszczenie wody w Chinach

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Abstract
Access to safe water and ensuring residents' health are the main components of the United Nations Sustainable Development Goals (SDGs). Water pollution has a significant impact on residents' health, and there are many factors that exacerbate water pollution. In this study, we applied the geographically and temporally weighted regression (GTWR) model to analyze the spatiotemporal distribution characteristics of factors affecting water pollution in China from 2005 to 2021. Hence, this article takes the chemical oxygen demand emissions (CODE) as the dependent variable, and the independent variables are ending permanent population (EPP), urbanization rate (UR), comprehensive production capacity of water supply (CPCOWS), per capita GDP (PCGDP), industrial water consumption proportion (IWCP), and per capita water consumption (PCWC). The conclusions are as follows: (1) The temporal evolution of CODE in different regions is highly consistent, with the order of water pollution severity being central, northeast, eastern, and western. (2) The effects of different factors on water pollution have obvious spatial and temporal heterogeneity. Overall, EPP, UR, CPCOWS, and PCWC have positive effects on water pollution, and PCGDP and IWCP have negative effects. (3) The direction of EPP and PCGDP impacts on CODE remains consistent across regions. UR impacts are primarily in the northeast, CPCOWS impacts are primarily in the eastern, central, and northeast, IWCP impacts are primarily in the central and western, and PCWC impacts are primarily in the eastern and central. Ultimately, some practical and feasible policy recommendations were proposed for different regions.

Key words: socio-economic factors; water pollution; water environment; chemical oxygen demand; geographically and temporally weighted regression

Streszczenie
Dostęp do bezpiecznej wody i zapewnienie zdrowia mieszkańców należą do najważniejszych Celów Zrównoważonego Rozwoju Organizacji Narodów Zjednoczonych (SDGs). Zanieczyszczenie wody ma znaczący wpływ na zdrowie mieszkańców, a istnieje wiele czynników, które zwiększają zanieczyszczenie wody. W tym badaniu zastosowaliśmy model regresji ważonej geograficznie i czasowo (GTWR) do analizy charakterystyki czasoprzestrzennego rozkładu czynników wpływających na zanieczyszczenie wody w Chinach w latach 2005-2021. Dlatego w tym artykule przyjęto emisję chemicznego zapotrzebowania tlenu (CODE) jako zależną zmienną, a zmiennymi niezależnymi są końcowa liczba ludności (EPP), wskaźnik urbanizacji (UR), całkowita zdolność produkcyjna zaopatrzenia w wodę (CPCOWS), PKB na mieszkańca (PCGDP), udział zużycia wody przemysłowej (IWCP) i zużycie wody na mieszkańca (PCWC). Wnioski są następujące: (1) Czasowa ewolucja CODE w różnych regionach jest wysoce spójna, przy czym kolejność zagrożeń wynikających z zanieczyszczenia wody jest następująca: regiony centralny, północno-wschodni, wschodni i zachodni. (2) Wpływ różnych czynników na zanieczyszczenie wody jest wyraźnie zróżnicowany przestrzennie i czasowo. Ogólnie rzecz biorąc, EPP, UR, CPCOWS i PCWC

mają pozytywny wpływ na zanieczyszczenie wody, a PCGDP i IWCP mają skutki negatywne. (3) Kierunek wpływu EPP i PCGDP na CODE pozostaje spójny we wszystkich regionach. Oddziaływania UR występują głównie na północnym wschodzie, oddziaływania CPCOWS występują głównie na wschodzie, środku i północnym wschodzie, oddziaływania IWCP występują głównie w środkowej i zachodniej części, a oddziaływania PCWC występują głównie na wschodzie i w środku. W końcowej części pracy zaproponowano praktyczne i wykonalne zalecenia polityczne dla różnych regionów.

Słowa kluczowe: czynniki społeczno-ekonomiczne; zanieczyszczenie wody; środowisko wodne; chemiczne zapotrzebowanie na tlen; regresja ważona geograficznie i czasowo

1. Introduction

In the past few decades, China's economy has developed rapidly. However, with the rapid growth of China's economy, the phenomenon of increasingly serious environmental pollution has also begun to emerge. In many countries, water pollution poses significant challenges to human health and the environment. Although access to clean drinking water and sanitation has greatly increased, billions of people still lack these basic services, and one-third of the world's population lacks access to safe drinking water. The United Nations Sustainable Development Goals (SDGs) state that water is essential not only to health, but also to poverty reduction, food security, peace and human rights, ecosystems and education. Nevertheless, countries face growing challenges linked to water scarcity, water pollution, degraded water-related ecosystems and cooperation over transboundary water basins. Water is a central part in sustainable development, all SDGs are interlinked with sustainable water use (Weerasooriya et al., 2021). In addition, the United Nations Sustainable Development Goal 6 states that by 2030, everyone will have universal and equitable access to safe and affordable drinking water. Water pollution is one of the main manifestations of environmental pollution. As a necessity of human life, water resources, once polluted, will bring huge harm to social development and residents' health. For a long time, water pollution has been one of the main threats to environmental security and a prominent issue worldwide. On a global scale, most industrial and urban wastewater is discharged into the environment without any prior treatment, which has adverse effects on human health and ecosystems. The effects of water pollution on human health are significant, although there may be regional, age, gender and other differences in magnitude. The most common disease caused by water pollution is diarrhea, which is transmitted primarily through enteroviruses in the aquatic environment (Lin et al., 2022).

Water pollution and socio-economic development are closely linked, with industrialization, agricultural production and urban life leading to environmental degradation and pollution, adversely affecting the water resources needed for life. The inefficient utilization and irrational allocation of water resources may generate a series of adverse effects on the regional water security and sustainable socio-economic development. In recent years, with the rapid socio-economic development, a series of evolutions have taken place in various elements of the socio-economy, such as population size, economic growth, industrial structure and water-use structure, which have had a significant impact on the urban water environment. Therefore, water pollution prevention has become very complex and challenging (Chen et al., 2022). The socio-economic development among different provinces in China is uneven. Systematic analysis and quantitative study of the water pollution control becomes particularly important for regional sustainable water management (Liu et al., 2019). Therefore, this paper considering regional differences, starting from achieving sustainable development goals. Studying the impact mechanism of water pollution, effectively preventing and controlling water pollution, and improving the water environment are not only important issues that China needs to face at present, but also important means to achieve the SDGs of the United Nations.

Compared with existing studies, the innovation of this study is mainly in two aspects. On the one hand, the innovation of research perspective. For a long time, researchers have mainly focused on the water pollution situation in a single region, while less considering regional differences and analyzing from a national perspective. This paper introduces the geographically and temporally weighted regression model, which can simultaneously consider the spatio-temporal heterogeneity and analyze the impact mechanism of water pollution for regions. On the other hand, the research content is innovative. According to the general STIRPAT model, environmental pressure is mainly related to population, affluence and technology, while this paper considers more comprehensive influencing factors, including not only common socio-economic factors, but also introducing water use structure and urban development level.

This article is divided into five parts. The second part reviews literature on the impact of water pollution and socio-economic factors on water pollution. Then, the third part introduces the research design, including the definition of variables and their corresponding sustainable development goals, research methods, and data sources. The fourth part describes the development trend of water pollution and the spatiotemporal distribution characteristics of the impact of socio-economic factors on water pollution. The fifth part mainly summarizes the conclusions and proposes some countermeasures for different regions.

2. Literature review

2.1. Water pollution

Water resources are a source of life for human beings and an important element of the Sustainable Development Goals (SDGs), United Nations SDG 6 suggests that civil society organizations should work to keep governments accountable, invest in water research and development, and promote the inclusion of women, youth and indigenous communities in water resources governance. Existing literature mainly focuses on the measurement and influencing factors, hazards, and prevention of water pollution. Regarding the measurement and evaluation of water pollution, The Ukrainian government calls for actions to achieve Sustainable Development Goal 6 and integrate the European Union water legislation (Strokal, 2021). Son et al. (2020) used water quality index and pollution index to evaluate river water quality. On the basis of analyzing the current situation of urban water pollution, Ye (2020) constructed a comprehensive evaluation index system for the ecological restoration effect of urban water pollution based on the multiple quantification method of AHP, and obtained different types of ecological restoration indicators for urban water pollution. An et al. (2022) analyzed point and non-point sources of pollution, and built a simulation system model of urban water pollution from four subsystems: population, industry, cultivated land and livestock and poultry. In terms of the hazards of water pollution, Qu (2020) believes that coastal cities in China have serious water pollution problems. Water pollution is negatively correlated with health outcomes, and the impact of common pollutants in industrial wastewater on health outcomes varies(Wang and Yang, 2016). Agricultural water pollution will worsen health outcomes by increasing incidence rate and reducing body mass index (Lu and Villa, 2022).

In order to prevent and control water pollution, Song and Wu (2022) proposed a new trading mechanism using water credit, called *water quality currency*. Chen et al. (2022) used a three-stage SBM-DEA model to determine the efficiency of water pollution control in a Chinese city from 2003 to 2017. Self-treatment of rural water pollution has no significant impact on farmers' health, and farmers' individualized treatment of rural water pollution significantly reduces the probability of disease (Luo et al., 2022). Water pollution control in Zhejiang has been achieved to a certain extent, but water pollution enterprises still tend to be located in areas with low environmental standards and weak environmental supervision (Xu et al., 2023) The water quality of Beijing Municipal sub-center can be significantly improved by controlling the emission of nuclear power source pollution. Reducing agricultural nitrogen and phosphorus pollution is the key to reducing the concentration of ammonia nitrogen and total phosphorus and improving water quality (Ji et al., 2022). Adequate control of pollution sources in the production process and the development of necessary measures to strengthen inspections should reduce the risk of sudden water pollution (Zhang et al., 2020). An et al. (2023) proposed several measures to reduce water pollution in the Wanquan River, including improving agricultural activities, improving sewage treatment, and strengthening environmental monitoring. In order to effectively monitor groundwater problems, Wu and Zhao (2023) proposes a study on the status and change characteristics of groundwater resource pollution in the Hami area based on sustainable development strategies.

2.2. The impact of socio-economic factors on water pollution

Water pollution is closely related to social and economic development. Taking Zhengzhou City as an example, the average water environmental value loss caused by water pollution from 2000 to 2015 was as high as 5.948 billion yuan (Ling et al., 2018). Dai et al studied the optimal ratio of sewage pollution control amount for a given policy, and proposed the relationship between the optimal ratio of water pollution control amount and the proportion of water pollution control reward and pollution tax rate (Dai et al., 2018). Urban and population pressures directly affect natural resources, ecosystems, freshwater demand, water pollution, and health problems (Noor et al., 2023) The impact of economic activities on environmental pollution continues to worsen, but when the government implements environmental protection and water pricing policies and measures to address environmental pollution caused by economic activities, it will have a significant impact on the reduction of pollution scale (Chou et al., 2021). The increase in agricultural, industrial and domestic pollution has all contributed to the deterioration of water quality, and industry is still the main source of environmental water pollution in China (Xu et al., 2022). Li et al. (2017) found that the exchange of substances between economic sectors caused water pollution to actually shift from downstream industries to upstream industries.

Many literatures have studied the influencing factors of water pollution, mainly including population, economic development level, industrial structure and technological innovation. Overall, the level of economic development and water environment are in a state of high quality coordination, and the pollution of farmland and livestock and poultry breeding accounts for the largest proportion of agricultural pollution (Zhang et al., 2022) Taking China's accession to the World Trade Organization (WTO) as an exogenous impact, the negative causal effect of export liberalization on the cross regional agglomeration of water pollution in China was determined (Chen et al., 2023) Per capita GDP, surface water stock, population and economic structure are all significantly correlated with surface water pollution, among which population has the greatest impact, followed by economic development level (Wang et al., 2019). The spatial effect of population driving factors on water pollution is more prominent than the temporal effect, the economic driving factors are positively correlated with pollution, and the technological driving factors also have significant spatial and temporal heterogeneity (Sheng and Tang, 2021).

In addition, in terms of the impact of industrial structure and technological innovation, there is a long-term relationship between water pollution, industrial agglomeration and economic growth in China, and industrial agglomeration and economic growth play an important role in aggravating water pollution (Huang and Wang, 2022) In the lagging stage, industrial structure upgrading, green technology innovation and water environment pollution are all positively correlated with the current stage (Wang et al., 2021). Industrial structure plays a certain role in promoting water pollution discharge, economic growth can restrain water pollution discharge, and urbanization and foreign investment have inconsistent impacts on the two pollutants discharge (Han et al., 2022).

In order to avoid exacerbating water pollution due to economic development, the increase in trade openness and the import of water intensive products may reduce the level of water pollution (Thompson and Jeffords, 2017). Industrial enterprises should enhance their sense of responsibility for environmental protection, and it is also necessary for the government and enterprises to jointly strengthen the supervision of industrial emissions and strictly control pollution sources (Wu et al., 2018). Moreover, industrial structure upgrading and technological innovation are effective ways to improve industrial water pollution intensity. In areas with low environmental regulation intensity, environmental regulation has a strong inhibition on industrial water pollution intensity (Zhou et al., 2021). The change trend of patent innovation output and innovation input is basically the same, and they are opposite to the change trend of water pollution (Zhang et al., 2022).

Based on above literature, although some scholars have studied the relationship between social and economic development and water pollution, most scholars focus on a single region, without considering the uneven development among regions in China, and analyze it from a national perspective. Therefore, considering the differences between regions, it is of great significance to analyze the spatiotemporal distribution characteristics of the impact of socio-economic factors on water pollution, and formulate prevention and control policies tailored to local conditions to achieve sustainable development of socio-economic and ecological environment.

3. Research design

3.1. Definition of variables

Socio-economic development and water resources are both important elements of the United Nations SDGs. *The China Ecological Environment Status Bulletin* (2022) pointed out that Chemical Oxygen Demand is one of the main indicators of water environmental pollution. Therefore, this study uses Chemical Oxygen Demand (COD) emissions as an indicator to measure water pollution, meaning that the higher the COD emissions, the more severe the water pollution. Based on the SDGs, referring to Noor et al. (2023) and Xu et al. (2022), socio-economic factors are mainly selected as variables that are important for sustainable development, such as population, affluence and level of technological development. The specific indicators selected in this study are as follows: ending permanent population (EPP), urbanization rate (UR), comprehensive production capacity of water supply (CPCOWS), per capita GDP (PCGDP), industrial water consumption proportion (IWCP), and per capita water consumption (PCWC). The variables are shown in Table 1.

Table 1. Water pollution and socio-economic factors variables

Variables	Units	Definition
CODE	10000 tons	Chemical oxygen demand emissions
EPP	10000 people	Ending permanent population
UR	%	Urbanization rate
CPCOWS	10000 cubic meters/day	Comprehensive production capacity of water supply
PCGDP	10000 CNY/person	Per Capita GDP
IWCP	%	Industrial water consumption proportion
PCWC	cubic meters/person	Per capita water consumption

Table 2 shows the sustainable development goals to which the variables correspond. As shown in Table 2, the indicators selected herein capture the content of the United Nations SDGs. For example, CODE corresponds to Good health and well-being (Goal 3) and Clean water and sanitation (Goal 6). Water pollution has a significant impact on human health, and the United Nations has proposed in SDGs to significantly reduce the number of deaths and illnesses caused by hazardous chemicals and air, water and soil pollution by 2030. In addition, expand international cooperation and capacity-building support to developing countries for water- and sanitation-related activities and programmes, including rainwater harvesting, desalination, water use efficiency, wastewater treatment, water recycling and reuse technologies. EPP corresponds to SDG 10: Inequality. Goal 10 calls for the promotion of orderly, safe, regular and responsible migration and population movements, including the implementation of well-planned and well-managed migration policies. Moreover, the indicator of resident population can capture population movements. UR refers to the urbanization rate, which corresponds to Goal 11: Cities. The world is becoming increasingly urbanized. Since 2007, more than half of the world's population has moved to cities. Rapid urbanization is leading to a growing number of problems, including an increase in the number of slum-dwellers and insufficient or overburdened infrastructure and services such as garbage collection, water systems, sanitation systems, roads and transportation. In addition, Goal 11 points to a significant reduction in the number of people killed and affected by disasters, including floods, and a reduction in the per capita negative environmental impact of cities by 2030. CPCOWS and IWCP reflect technological innovation capacity and industrial water use, corresponding to Goal 9: Infrastructure, industrialization. Goal 9 calls for the development of high-quality, reliable, sustainable and disaster-resilient infrastructure, including regional and cross-border infrastructure, to support economic development and enhance human well-being. Technologies to increase water supply capacity can be effective in reducing water pollution. Moreover, promote inclusive and sustainable industrialization. By 2030, significantly increase the share of industry in employment and gross domestic product (GDP), in accordance with national circumstances, and double that share in the least developed countries (LDCs). PCGDP corresponds to the SDGs: No poverty and Economic growth. Goal 1 proposes to increase the resilience of the poor and vulnerable to disasters and reduce their probability of and vulnerability to extreme weather events and other economic, social and environmental shocks and disasters by 2030. Global real GDP per capita growth is projected to slow in 2023, and the challenging economic environment is pushing more workers into informal employment. Accordingly, Goal 8 proposes to sustain per capita economic growth in accordance with national circumstances, in particular by maintaining an annual GDP growth rate of at least 7 per cent in the least developed countries. PCWC corresponds to Goal 6: Clean water and sanitation. Water stress and water scarcity continue to be a concern in many parts of the world. Goal 6 calls for a significant improvement in water use efficiency across all sectors by 2030 to ensure sustainable access to, and supply of, freshwater in order to address water scarcity and significantly reduce the number of people who suffer from water scarcity.

Table 2. Variables and Sustainable Development Goals

Variables	Sustainable Development Goals
CODE	Good health and well-being (Goal 3)
	Clean water and sanitation (Goal 6)
EPP	Inequality (Goal 10)
UR	Cities (Goal 11)
CPCOWS	Infrastructure, industrialization (Goal 9)
PCGDP	No poverty (Goal 1)
	Economic growth (Goal 8)
IWCP	Infrastructure, industrialization (Goal 9)
PCWC	Clean water and sanitation (Goal 6)

The descriptive statistics of the variables are shown in Table 3, as can be seen from Table 3, CODE values range from 1.40 to 198.25, with an average value of 51.93.

Table 3. Descriptive statistics of the initial indicators by provinces

Variables	Min	Q_1	Median	Mean	Q_3	Max
CODE	1.40	17.82	37.40	51.93	74.60	198.25
EPP	280.00	2434.00	3823.00	4384.00	6084.00	12684.00
UR	20.71	44.97	53.87	54.84	62.65	89.58
CPCOWS	17.00	380.60	685.00	922.10	1225.30	4231.70
PCGDP	0.52	2.32	3.81	4.41	5.58	18.75
IWCP	1.51	11.20	18.31	20.75	27.57	67.64
PCWC	161.20	267.60	441.10	524.00	559.40	2657.40

3.2. Research methodologies

This study used the geographically and temporally weighted regression (GTWR) model to study the spatiotemporal heterogeneity of the impact of socio-economic factors on water pollution. In existing research, geographically weighted regression (GWR) and temporally weighted regression (TWR) are commonly used to address the issues of spatial and temporal heterogeneity. However, both models have limitations and cannot simultaneously analyze temporal and spatial heterogeneity. Huang et al. (2010) proposed the GTWR model, which is an improvement on the GWR and TWR models and applies panel data regression. Bai et al. (2016) validated that GTWR outperforms GWR method in regression analysis. The calculation formula for the GTWR method is:

$$y_i = \beta_0(u_i, v_i, t_i) + \sum_{k=1}^{P} \beta_k(u_i, v_i, t_i)x_{ik} + \varepsilon_i \quad (1)$$

where u_i and v_i are the longitude and latitude coordinates of the observation point respectively; (u_i, v_i, t_i) is the space-time coordinates of the *i*-th sample point; β_0 is the regression constant of sample point *i*, that is, the constant term of GTWR; β_k is the *k*-th regression parameter of point *i*, and x_{ik} is the value of independent variable x_k at point *i*, that is, the value of each explanatory variable in the GTWR model.

3.3. Data sources

The research area of this study is the administrative division of China. According to the definition of the National Bureau of Statistics, China's 34 provincial-level administrative units can be divided into 5 regions, namely the East, Central, West, Northeast, and Hong Kong, Macao, and Taiwan. The data is sourced from the *China Statistical Yearbook* released by the National Bureau of Statistics of China, covering 31 provinces in China from 2005 to 2021 (excluding Hong Kong, Macau, and Taiwan). Due to the lack of data in some regions, the study area is divided into the eastern, central, western, and northeastern regions. The data type is panel data, where the dependent variable is CODE and the other socio-economic factor variables are independent variables. Due to some missing data, the mean interpolation method has been used for processing.

4. Results and discussion

4.1. Development trend of water pollution

The average values of CODE in eastern, central, western and northeastern China from 2005 to 2021 are shown in Table 4. The CODE values mentioned in this section are the average values of corresponding years in different regions, and the data visualization is shown in Figure 1. Figure 1 shows that the temporal evolution of CODE in different regions is highly consistent. From a national perspective, although CODE decreased from 2011 to 2016, it rapidly increased in 2019 and reached its highest point during the inspection period in 2020. In the eastern region, the value of CODE was 88.78 in 2011, which was the maximum value during the period examined. Between 2005 and 2019, CODE in the eastern region is consistently higher than the national average, and only in 2020 and 2021 is it lower than the national average. In the central region, CODE values have consistently been among the highest in all regions for all years except 2011 through 2015. In the western, CODE has consistently been at the lowest level of all regions each year. In the Northeast, just the opposite of the central region, CODE was at its highest level from 2011 through 2015. In addition, CODE values for all regions were at their lowest levels in 2019.

The evolution of CODE in different regions can be divided into four phases: 2005-2010,2010-2015,2015-2020, 2020-2021. The first phase of CODE was characterized by a slow decline. In the second phase, CODE increased rapidly from 2010 to 2011 and then declined in different regions in 2011 and 2015. In the second phase, CODE increased rapidly from 2010 to 2011, followed by a decline in CODE values of varying magnitude in all regions from 2011 to 2015.The third phase is characterized by a U-shape, and the CODE values in the different regions between 2016 and 2019 are at the lowest level during the study period. In the fourth phase, except for the decline of CODE in the west and northeast, the rest of the regions showed a rise of different amplitude.

Table 4. Average CODE for different regions from 2005 to 2021

Year	Eastern	Central	Western	Northeast	Nationwide
2005	51.05	58.67	33.02	51.83	45.62
2006	50.67	59.78	33.84	51.87	46.07
2007	48.80	58.22	32.73	50.53	44.57
2008	46.18	55.98	31.66	47.80	42.60
2009	44.15	54.22	31.01	46.20	41.21
2010	42.09	52.75	30.58	44.60	39.94
2011	88.78	100.96	52.66	124.82	80.64
2012	85.72	98.22	51.50	119.74	78.19
2013	82.63	96.00	50.36	115.37	75.89
2014	79.78	93.80	49.63	112.80	74.02
2015	76.77	91.21	48.34	109.48	71.73
2016	26.24	30.53	14.00	14.83	21.23
2017	24.93	27.78	12.69	13.58	19.64
2018	23.44	27.39	12.37	12.35	18.85
2019	22.47	26.75	12.11	12.21	18.29
2020	72.41	121.22	65.27	110.06	82.73
2021	73.80	125.27	63.33	93.77	81.64

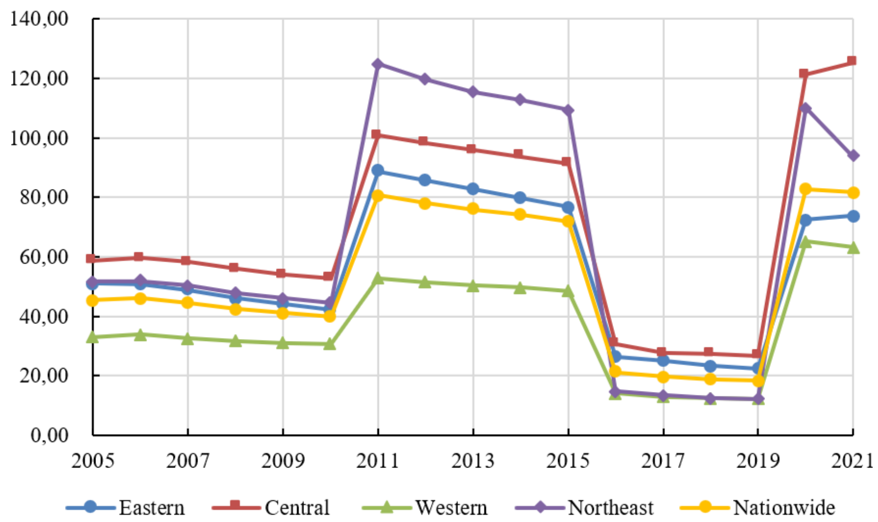

Figure 1. Trends in average CODE for different regions from 2005 to 2021

4.2. The spatiotemporal distribution of factors affecting water pollution

By comparing the fitting effects of OLS, TWR and GWR, it is demonstrated that the GTWR model has high accuracy and applicability in the study of influencing factors of CODE in China. Specifically, the adjusted R-squared for OLS, TWR, and GWR are 0.46, 0.76, and 0.47, respectively, while the adjusted R-squared value for GTWR is 0.81. In summary, TWR considering temporal non-stationary is better than OLS, and GWR considering spatial non-stationary is also better than OLS. In addition, the above criteria for judging the usefulness of model fitting reflect that GTWR, which considers both temporal and spatial non-stationary factors, has the best accuracy and applicability compared to other criteria.

Table 5 presents descriptive statistics of the regression coefficient estimation results calculated by GTWR. For example, on average, EPP, UR, CPCOWS, and PCWC are positive influences on CODE, while PCGDP and IWCP are negative influences. Therefore, there is a need to further investigate the spatial and temporal differences in the impact of socioeconomic factors on CODE.

Figure 2 shows the trend of time evolution of the impact of socio-economic factors on CODE. Overall, the impact of the different variables fluctuated, with the largest fluctuation being in PCGDP. PCGDP has a positive impact on CODE only in 2009-2011 and 2019, with a negative impact in the remaining years and a maximum impact in 2010. The fluctuation of PCWC is the smallest, and the influence is positive during the study period. The impact direction of other variables has changed multiple times during the inspection period. For example, EPP only had a negative impact on CODE in 2015 and 2016, while the impact in other years was positive. UR has a negative impact on CODE in 2009-2011, 2017 and 2021, and a positive impact in the remaining years. CPCOWS only had a positive impact on CODE from 2009-2013 and a negative impact the rest of the time. The impact of IWCP fluctuates the most in 2017-2018 and approaches zero in 2021. it is therefore necessary to further analyze the spatial heterogeneity of the variable's impact in the context of regional differences.

Table 5. Description statistics of GTWR results

Variables	Min	Q_1	Median	Mean	Q_3	Max
Intercept	-810.91	-46.68	-15.01	-20.96	2.38	542.02
EPP	-6551.23	81.58	135.92	129.69	206.74	3484.87
UR	-1047.75	-8.03	29.87	28.83	76.17	1579.53
CPCOWS	-1475.98	-45.79	5.95	16.96	42.50	2291.53
PCGDP	-983.52	-161.15	-63.39	-40.96	20.07	1841.00
IWCP	-3826.63	-40.10	-2.61	-12.88	17.53	3593.85
PCWC	-707.92	36.77	107.05	132.14	194.66	1602.53

4.2.1. The influence of EPP on CODE

As shown in Figure 3 (a), EPP had a positive impact on CODE in 2005, 2013, and 2021. For the eastern, central and northeast regions, the impact of EPP in 2021 is lower than in 2013, but still on the rise compared to 2005. In the western region, the impact of EPP on CODE generally maintains an upward trend.

The above phenomenon shows that population is still an important factor causing water pollution, and it remains consistent in different regions. Therefore, in order to reduce water pollution caused by the population, it is necessary to increase domestic sewage treatment in every region, improve the level of harmless treatment of domestic garbage, and reduce water pollution.

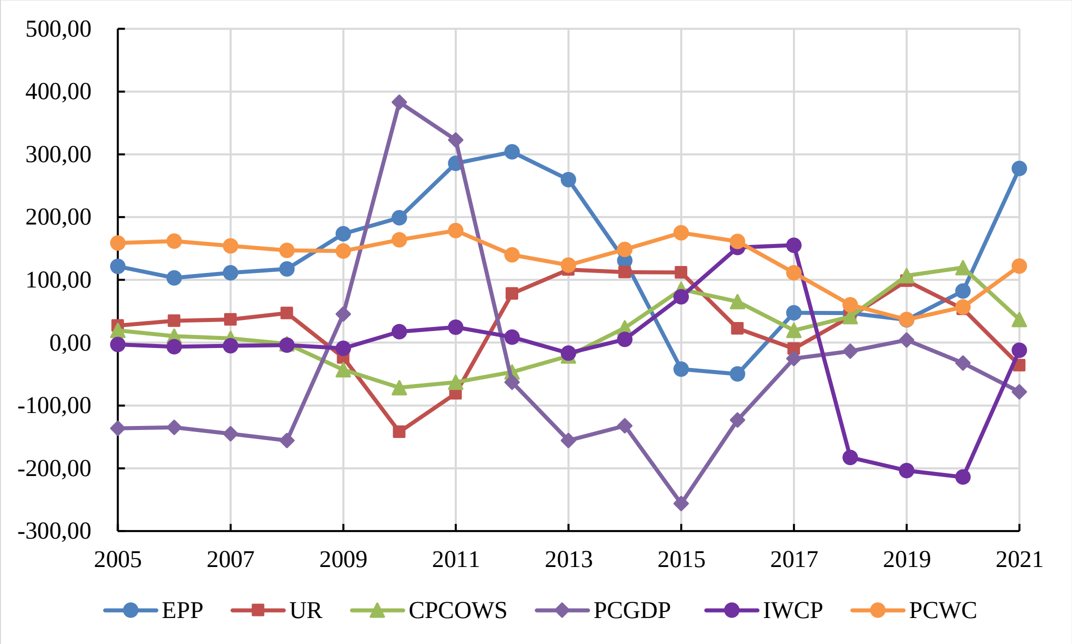

Figure 2. Temporal evolution of socio-economic factors on the impact of CODE

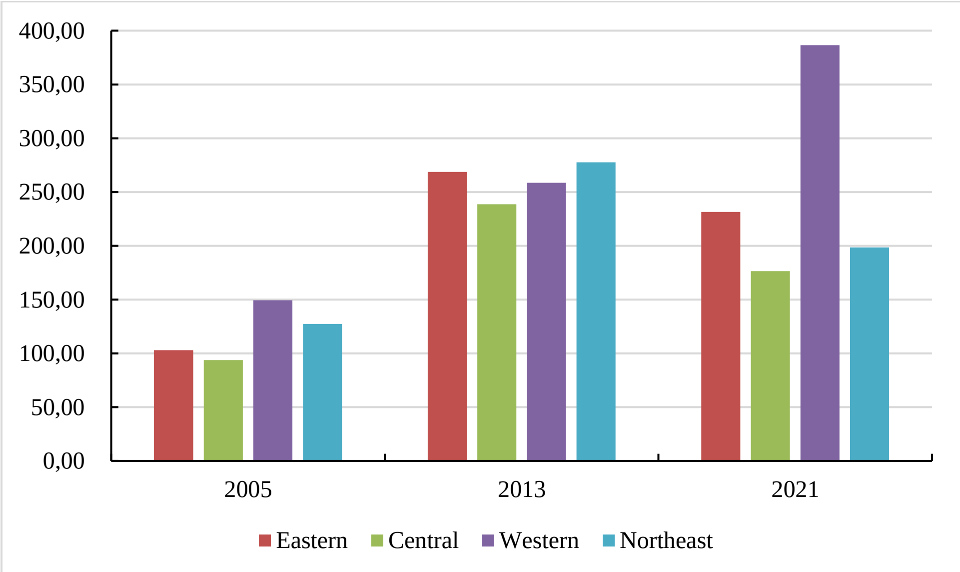

Figure 3 (a). The influence of EPP on CODE

4.2.2. The influence of UR on CODE

As shown in Figure 3(b), UR has a positive impact on CODE in both 2005 and 2013, while exhibiting strong regional heterogeneity in 2021. For the eastern region, the coefficients of the urbanization rate are only 3.57 and 2.50 in 2005 and 2021, which has a smaller impact. In the central and western regions, the impact of UR turns negative in 2021, indicating that the development of urbanization will not exacerbate the level of water pollution. However, in the Northeast, the impact of UR is increasing, and with higher rates of urbanization, water pollution is more severe.

The impact of UR on CODE has spatiotemporal heterogeneity, and one possible explanation is that the urbanization development process varies in different regions. For example, the high rate of urbanization in the east and northeast of the country, the expanding size of the urban population, urban life and the large number of pollutants discharged from products produced to sustain urban life and consumption will have a significant impact on the water environment. In the process of urban development, it is necessary to balance the relationship between urban development and water pollution, and consider carrying out special actions to rectify water pollution in cities in the Northeast region.

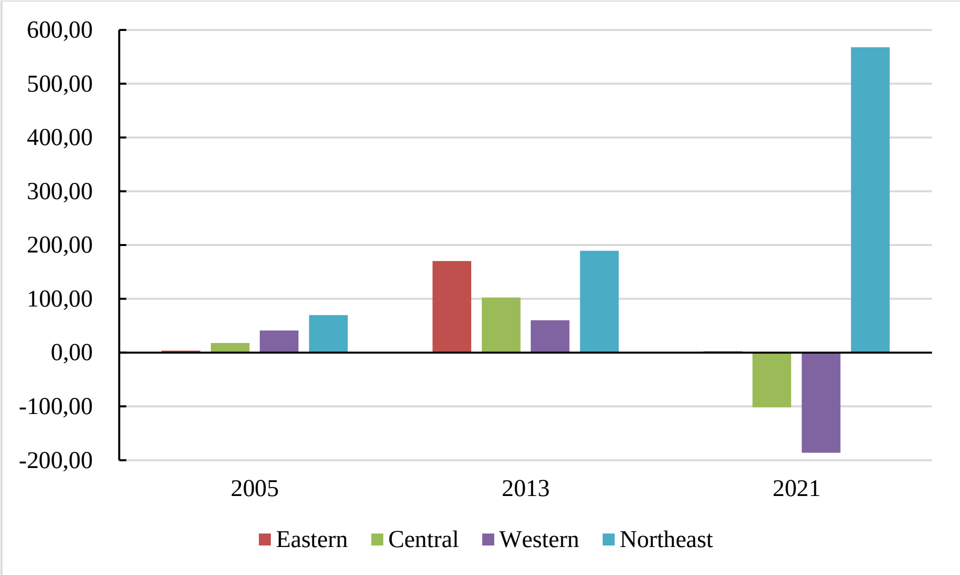

Figure 3 (b). The influence of UR on CODE

4.2.3. The influence of CPCOWS on CODE

As shown in Figure 3 (c), the impact of CPCOWS on CODE exhibits spatial heterogeneity at different times. In the eastern, western and northeast regions, the impact of CPCOWS turned negative in 2013 and remained negative in 2021. In contrast to other regions, the impact of CPCOWS in the western region was negative in 2005 and 2013, while it was positive in 2021.

CPCOWS includes a capability assessment of the water purification process, reflecting the level of technological development. The eastern, central and northeast regions have a rapid economic development, so they have a greater demand for water resources and a higher requirement for technical level. The results show that the eastern, central and northeast regions need to improve the technical level and enhance the water purification capacity.

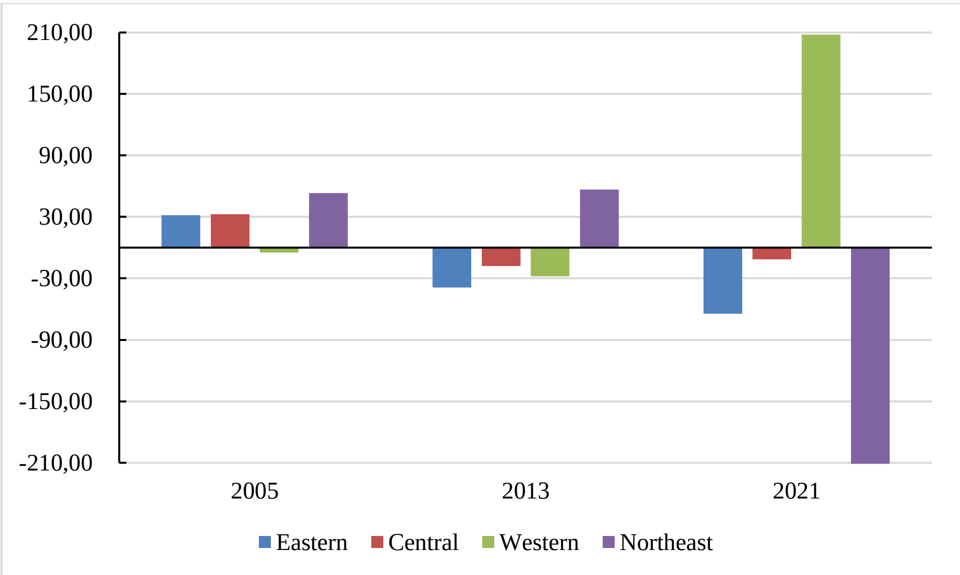

Figure 3 (c). The influence of CPCOWS on CODE

4.2.4. The influence of PCGDP on CODE

As shown in Figure 3(d), PCGDP has a negative impact on CODE in 2005, 2013 and 2021. The impact of PCGDP in both the eastern and central regions increased in 2013 and decreased in 2021. The impact of PCGDP on CODE in the western region continued to decrease in 2013 and 2021, while it continued to increase in the northeast region.

PCGDP has a consistent direction of influence on CODE across regions. The results show that the better the economic development of the city, the less water pollution. The possible reasons for this are that the better the economic development, the funds invested in water pollution control remain sufficient, the means of control for water pollution are more mature, and there are more personnel for water pollution control, which makes the level of water pollution lower.

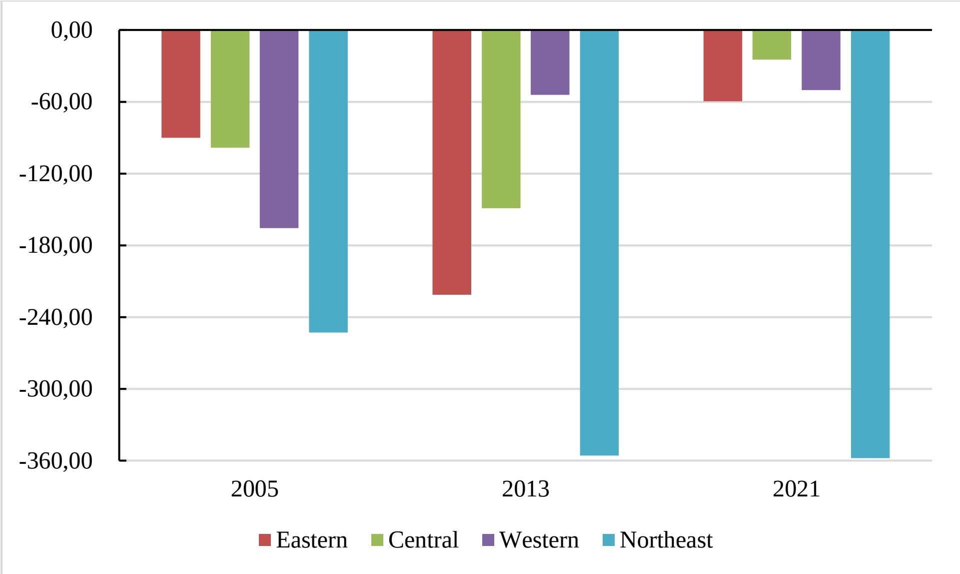

Figure 3 (d). The influence of PCGDP on CODE

4.2.5. The influence of IWCP on CODE

As shown in Figure 3 (e), the impact of IWCP on CODE exhibits strong spatiotemporal heterogeneity. In the eastern, the IWCP has a negative impact in both 2005 and 2013, with a regression coefficient of only 0.77 in 2021. The impact of IWCP on CODE in the central region is negative in 2005 and 2013, and positive in 2021. In addition, the IWCP effect changes in the opposite direction in the western and northeast regions. The influence of IWCP on CODE is positive in the western region, but negative in the northeast region.

The IWCP reflects the structure of water use and to some extent the level of industrial development. For the central and western regions, as the proportion of industrial water use increases, the more serious water pollution becomes. In order to control water pollution while developing industry, water pollution prevention in industrial parks should be deepened. It can be considered in the central and western regions to establish centralized sewage treatment facilities for industrial parks to solve problems such as imperfect sewage pipe networks.

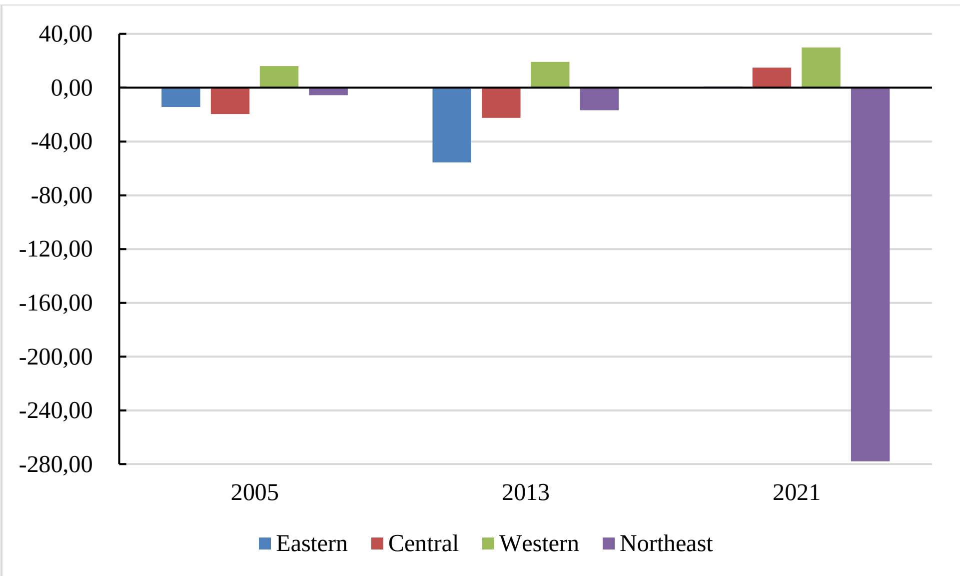

Figure 3 (e). The influence of IWCP on CODE

4.2.6. The influence of PCWC on CODE

As shown in Figure 3(f), the impact of PCWC on CODE is spatially heterogeneous in 2021. The impact of PCWC on CODE within different regions was positive in both 2005 and 2013. For the western and northeastern regions, the impact of PCWC on CODE turned negative in 2021, while PCWC maintained a positive impact in both the eastern and central regions.

One possible explanation is that the higher the per capita water consumption, the greater the pressure on water pollution control. On the basis of ensuring an adequate supply of water resources, the eastern and central regions can then consider carrying out regional recycled water recycling pilot projects in some cities, and actively promote the delineation of centralized drinking water source protection zones at the township level.

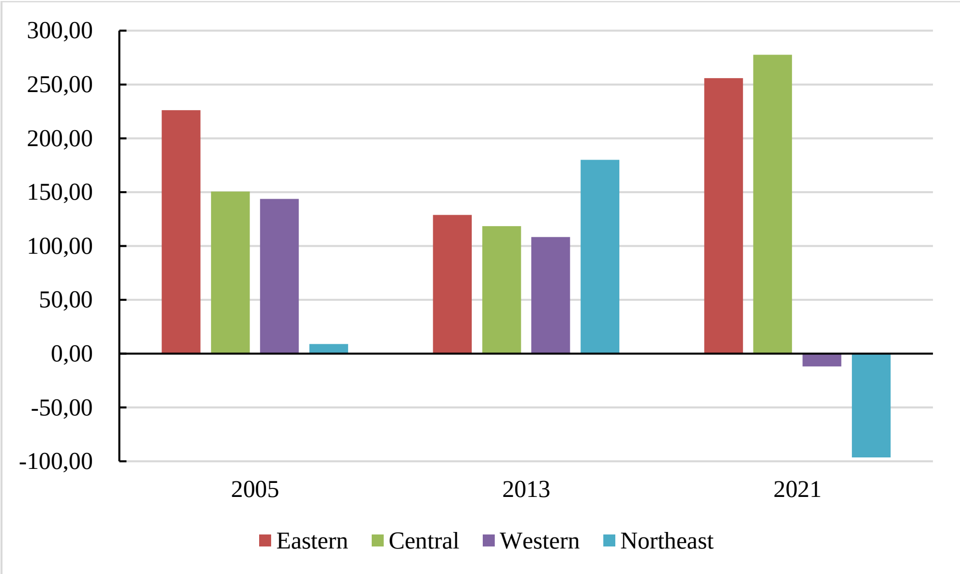

Figure 3 (f). The influence of PCWC on CODE

5. Conclusions

This paper takes the United Nations SDGs as the starting point to study the impact of socio-economic factors on water pollution using data from 31 provinces in China (excluding Hong Kong, Macao and Taiwan) from 2005 to 2021. The conclusion are as follows. First, the temporal evolution of CODE in different regions is highly consistent, with the order of water pollution severity being central, northeast, eastern, and western. Second, the influence of each factor on water pollution is different, and the variables show different influences in different periods. To be specific. The influence of PCWC fluctuated the least and was all positive during the study period. The influence direction of the other variables changed several times during the study period, among which the influence of PCGDP fluctuated the most. Third, there is significant spatial and temporal heterogeneity in the impacts of some variables. Among them, the direction of the impact of EPP and PCGDP on CODE remains consistent across regions. The impact of UR is mainly in the northeast, the impact of CPCOWS is mainly in the eastern, central, and northeast, the main impact of IWCP is in the central and western, and the impact of PCWC is mainly in the eastern and central.

Based on this, the following practical and feasible policy recommendations are proposed for different regions. In the eastern region, improve water purification capacity and carry out pilot projects for regional recycled water recycling in some cities to protect water sources from pollution. In the central region, improve the level of technology, focus on solving the problem of industrial sewage, and actively promote the demarcation of centralized drinking water protection areas. In the western region, more efforts will be made to rectify industrial water pollution and balance the relationship between industrial development and water environmental protection. In the northeastern region, it is necessary to carry out special actions for cities to rectify water pollution, and to promote the process of urbanization and construction, paying attention to the protection of the water environment. In addition, every region should take measures to increase the treatment of domestic sewage and reduce domestic water pollution.

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