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# Evolution of water quality and biota in the Panjiakou Reservoir, China as a consequence of social and economic development: implications for synergies and trade-offs between Sustainable Development Goals

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## Abstract

Water shortages caused by poor water quality severly affect the sustainable social and economic development of Tianjin City and Tangshan City in China. The Panjiakou Reservoir is located in the Luanhe River mainstream and provides water to the public in both cities since 1983. The evolution of water quality and aquatic community structure in the Reservoir and interactions with the social and economic development of its surroundings (Tangshan City and Chengde City) were analyzed. The relations between these changes and the various interrelated Sustainable Development Goals (SDGs) were also evaluated. From 1984 to 2019, the overall trend of total nitrogen (TN), total phosphorus (TP), chemical oxygen demand ($COD_{Mn}$), and ammonia nitrogen ($NH_3$-N) concentrations first increased and then decreased with economic growth. The organisms with strong ecological adaptability and pollution resistance became dominant species in the aquatic community. These included chlorophyta, cyanophyta and bacillariophyta among phytoplankton, copepods among zooplankton, and tubificidae and chironomidae among zoobenthos. The completion of Panjiakou Reservoir satisfied the water demand of Tianjin City and Tangshan City as well as benefited the economic and social development of the surroundings. However, high levels of pollutants produced by cage fish culture, mineral processing, and tourism threatened the water environment, which would in turn harm society and the economy. Therefore, fish cages were removed and other environmental protection measures were implemented to ensure the safety of drinking water. This study demonstrated that considering comprehensively the individual needs inside and across catchments to minimize trade-offs and maximize synergies was of great significance for coordinating the relations among society, economy, and water resources to achieve sustainable development at the sub-national scale.

**Keywords:** Sustainable development, Evolution of Water quality and biota, Society and economy, Synergy and trade-off, Panjiakou Reservoir

## 1. Introduction

The shortage of freshwater resources is an important factor restricting regional economic and social development. As a result, developing the water environment and ecosystem management system is important for the sustainable development of water supplies and the social economy (Li et al. 2020; Biswas 1991). However, in many cities around the world, population growth, rapid socioeconomic development, and global environmental changes, have resulted in a cycle of floods and droughts (Hirabayashi et al. 2008).

Tianjin City, a metropolis with a population more than 15 million, is situated at the confluence of the Haihe River mainstream and its major tributaries. Before 1965, Tianjin's water consumption could be met by the Haihe River. Due to frequent drought disasters, however, the water level of the Haihe River dropped to 0.48 m below sea level, resulting in saline water intrusion and a water supply crisis (Liu 1983). The water consumption of residents dropped from 70 L $d^{-1}$ per capita to 65 L $d^{-1}$ per capita, and part of the water was bitter saltwater containing chloride concentrations greater than 1000 mg $L^{-1}$ (Jowett 1986). People's livelihoods, as well as industrial and agricultural production, have begun to face unprecedented challenges. Between 1965 and 1972, water from Beijing Miyun Reservoir was transferred to Tianjin City to supplement the water supply. However, following a severe drought in 1972, the Miyun Reservoir was unable to support Tianjin City's water supply. As a result, water from the Yellow River had to be transferred to Tianjin City (Jowett 1986), which can only be used as an emergency source of water and cannot solve the problem of water scarcity in a sustainable and perennial way. Furthermore, severe land subsidence in Tianjin City was caused by over-exploitation of groundwater (Yi et al 2011).

Tangshan City, with a population of 7.96 million people, is also a major heavy industrial city in northern China. Tangshan City's water consumption was low before 1952. Tangshan City's water consumption, however, has increased rapidly as a result of the development of industry and agriculture, resulting in a severe shortage of water resources. The average annual per capita water resources of Tangshan is only 305 $m^3$, accounting for 1/8 of the average level in China (Gong et al. 2009). Groundwater was the main supply of water in Tangshan City. Due to long-term over-exploitation of groundwater, groundwater depletion occurred in many places, which caused land subsidence, seawater intrusion, severe land desertification, and salinization, resulting in large economic losses (Liu et al. 2017).

Water resource shortage severely affected the lives of citizens, industrial and agricultural production, and social stability in Tianjin City and Tangshan City. It became a bottleneck for economic and social development. The only way to effectively alleviate the water crisis was to carry out external replenishment (Li and Zheng 2002; Liu and Yang 2002). The Luanhe River, located in the northeastern part of North China, flows directly to Bo Hai Sea with a general direction from northwest to southeast. The total length of the main river channel is 888 km, with a drainage area of 44750 $km^2$ (Figure 1). In 1987, it was considered that the Luanhe River basin had abundant water resources and good water quality (Li and Zheng 2002). For many years the average amount of surface water source was 5.51 billion $m^3$ and the number of groundwater resources was 2.95 billion $m^3$, representing the richest northern water resources (Tian et al. 2019). The State Development Planning Commission of China was instructed to speed up the construction of the Luanhe River water conservancy project in 1973 to alleviate the fundamental imbalance between supply and demand for water in Tianjin City and Tangshan City. Following this, the construction of "Luanhe River Diversion Project" (LRDP) was officially launched.

The Panjiakou and Daheiting Reservoirs, the "Diversion Canal from Luanhe to Tianjin City" (DCLTJ), and the "Diversion Canal from Luanhe to Tangshan City" (DCLTS) are all part of the LRDP (Figure 1). The Panjiakou Reservoir is the water source of the LRDP, and has an area of 33,700 $km^2$, with a total storage capacity of 2.93 billion $m^3$ and an annual average runoff of 2.45 billion $m^3$ (53% of the total runoff in the Luan River basin) (Tian et al. 2019). The reservoir is mainly used to adjust the water volume to supply water to Tianjin City and Tangshan City while preventing flooding and generating electricity. The Daheiting Reservoir, about 30 km downstream of the Panjiakou Reservoir, receives incoming water from upstream and raises the water level for counter-regulation. Together with the Panjiakou Reservoir, it is used to divert water to Tianjin City and Tangshan City through the DCLTJ and DCLTS. The Panjiakou Reservoir began supplying water to Tianjin City and Tangshan City in 1983 and 1985, respectively. By 2020, Panjiakou Reservoir has supplied 19.4 billion $m^3$ of water to Tianjin City, with an average annual supply of 520 million $m^3$, and 5.6 billion $m^3$ to Tangshan City, with an average annual supply of 160 million $m^3$, which has made significant contributions to the Tianjin City and Tangshan City sustainable socio-economic development as well as ecological civilization construction (Wang 2020).

Domestic sewage, industrial and agricultural wastewater were excessively discharged into the reservoir with the development of the economy and society, and a large number of nutrients were imported from cage fish culture, both of which aggravated the pollution load and significantly increased the trophic state of the water body (Domagalski et al. 2007). Some studies revealed that the reservoir's water quality was generally Class V or inferior V (See Table 1 for an explanation of the quality standards), and the trophic state had progressed from oligotrophic to eutrophic (Luo et al. 2011). Furthermore, the community structure of aquatic organisms in the reservoir had changed dramatically in response to changes in water quality. Organisms with strong pollution tolerance became dominant species, while the species with poor ecological adaptability almost disappeared (Li et al. 2012). Water shortage caused by poor overall water quality has become the main factor restricting the sustainable development of water resources, society, and economy in Tianjin City and Tangshan City. As a result, it is urgent to balance the development of the Luanhe River basin’s economy with the effective utilization and protection of the water resources of the Panjiakou Reservoir.

With growing attention to sustainable development issues, the Sustainable Development Goals (SDGs) were put forward in 2015, and include 17 goals, 169 targets, and 231 unique indicators (Allen et al. 2019). However, there are synergies and trade-offs between the goals and targets which cannot be ignored. For instance, dams and reservoirs are built to generate energy (SDG 7), while these infrastructures may harm ecosystems (SDG 15). Only by minimizing trade-offs and maximizing synergies in the process of economic and social development can sustainable development be achieved (Nilsson et al. 2016).

The goals of this study were to 1) investigate the inter-annual variations in water quality and aquatic community structure in the Panjiakou Reservoir, 2) analyze the driving mechanism and interactions with social and economic development in the surroundings of the reservoir, and 3) evaluate the links between these changes and the various interrelated goals and targets of SDGs. Sustainable development can only be achieved by properly coordinating the relationships between water, society, and the economy.

## 2. Materials and methods

### 2.1 Study area and sampling locations

The Panjiakou Reservoir is located on the Luanhe River's mainstream, on the border of Kuancheng Manchu Autonomous County, Chengde City and Qianxi County, Tangshan City. It is located within the Luanhe River basin. Luanhe River basin is located in the northeastern part of the north China plain (115°57'−119°59' E and 39°42'−42°70' N) with a drainage area of 54,400 km$^2$ (Figure 1). It belongs to a typical temperate continental monsoon climate. From 1956 to the present, the average annual temperature of the basin is 5~12°C. The average annual precipitation is 560 mm, and about 70%~80% of the precipitation falls from June to September (Li and Feng 2007).

Samples for water quality and biota (phytoplankton, zooplankton, and zoobenthos) were collected from three sampling locations in the Panjiakou Reservoir, including Yanziyu (118°17′41″E, 40°27′59″N), Reservoir Center (118°17′8″E, 40°25′39″N), and Dam Neighbourhood (118°16′59″E, 40°23′40″N) (Figure 1). Water quality samples were collected monthly (except for the freezing period: December to March) from 1984 to 2019. The sampling periods of phytoplankton, zooplankton and zoobenthos were shown in Tables 2, 3, and 4. Arithmetic average concentrations of water quality indicators at the above three sampling places within a year were used for that year. It was considered by many researchers (e.g., Wang 2020; Xing et al. 2009; Dai et al. 2018) that the selection of these sampling locations was reasonable and the data can represent the water quality and water ecological environment evolution of the Panjiakou Reservoir reliably. In addition, there were no specific sampling locations for the fish community structure because they are mainly affected by the cage fish culture.

## 2.2 Environmental Kuznets Curve

Grossman and Krueger's (1991) study sparked interest in the relationship between economic growth and environmental degradation. They proposed the Environmental Kuznets Curve (EKC) hypothesis after studying the relationship using the Kuznets Curve proposed by American economist Kuznets. This hypothesis held that in the early stage of economic development, environmental quality decreased with the increase of per capita income, while once income reached the inflection point, economic growth would help to improve environmental quality, namely, the two showed an inverted U-shaped relationship. Since the proposal of EKC, an increasing number of scholars have conducted EKC empirical studies on relevant data from various countries or regions (Copeland et al. 2004; Arrow et al. 1995; Cole et al. 1997; Ongan et al. 2021), greatly enhancing ECK's formation theory. In this study, EKC was also applied to simulate the relationship between economic growth and water quality in the Panjiakou Reservoir, to reflect the relationship between social and economic development and quality of the water environment.

At present, there are three types of basic EKC models: quadratic function (1), cubic function (2), and logarithmic function (3) as follows (Ongan et al. 2021):

$$y=a+b_1\times x+b_2\times x^2 \tag{1}$$

$$y=a+b_1\times x+b_2\times x^2+b_3\times x^3 \tag{2}$$

$$\ln y=a+b_1\times \ln x+b_2\times (\ln x)^2+b_3\times (\ln x)^3 \tag{3}$$

Where y is the environmental pressure, usually expressed by environmental quality indicators or pollutant discharges; x is the economic output of the country or region, generally expressed by GDP or per capita GDP; a is a constant; $b_1$, $b_2$, and $b_3$ are model related parameters.

Since Panjiakou Reservoir sits on Luanhe River mainstream and is an open water body, its water quality driving forces are very complex and theoretically numerous from a microscopic point of view. However, water qualities in the reservoir are mainly dependent on several aspects practically and macroscopically, for example, pollutants carried by the Luanhe River mainstream and its tributaries in the upstream of the Panjiakou Reservoir (these areas are mainly administered by Chengde City), pollutants produced by cage fish culture in the reservoir (Panjiakou Reservoir and its close surroundings are mainly administered by Tanshan City), pollutants discharged out with releasing water downstream through the dam and pollutants degraded due to chemical and biological action in the water.

In reality, it is quasi-impossible to find GDP data generated by people and industries located clearly around the Panjiakou Reservoir. The GDP values used in this paper are for Chengde City and Tangshan City, two large surrounding zones of the Panjiakou Reservoir. The former was used to reflect the effect of GDP values from areas upstream of the Panjiakou Reservoir on the water qualities in the reservoir or account for the effect of pollutants generated by various economic activities and carried in by Luanhe River mainstream and its tributaries upstream of the Panjiakou Reservoir and the latter was applied here to explain the effect of GDP values from areas closely around the reservoir, including the GDP generated by cage fish culture in the reservoir. Since Tianjin City is not part of the Luan River Basin and its social and economic development does not affect the water quality of the Panjiakou Reservoir, Tianjin City's GDP was excluded in this study.

### 2.3 Data sources and analysis

The topography and area of the basin were determined by the high-resolution (30 m) digital elevation data from the Digital Elevation Model of the Shuttle Radar Topography Mission (SRTM DEM), using the GCS_Beijing_1954 geographic coordinate system. The water quality, aquatic community structure and inflow of the Panjiakou Reservoir were obtained by referring to published papers. Due to the large number of references cited, they were not listed here but were listed in each section separately for greater clarity. The social and economic development of the surroundings of the reservoir were obtained by consulting statistical yearbooks. In addition, through field research and visiting specialised agencies, the relevant policy changes in the Panjiakou Reservoir and its surroundings were obtained. The relevant policies for Panjiakou Reservoir and its surroundings over the years were shown in Table S1 in the Supplementary Material.

Statistical analyses were performed using the Statistical Program for Social Sciences (SPSS) 11.0 software. The interactions between variables were investigated using regression and correlation analyses, with a *p*-value of 0.05 used to determine significance. All data were graphed and descriptively analyzed using Origin 10.5 software. The map of the study area was created using ArcGIS 11.2. Based on a comprehensive literature review (Nilsson et al. 2016; Mainali et al. 2018; Wiegleb and Bruns; Colloff et al. 2019; Allen et al. 2019; Le et al. 2015) and the research of our project, the figures of relationships between goals and targets of SDGs were drawn with Gephi 0.9.2.

## 3. Results

### 3.1 Inter-annual variation of inflow of the Panjiakou Reservoir

In the past 60 years (1956~2016), the annual inflow of the Panjiakou Reservoir has shown a significant downward trend, from around $40\times10^8$ $m^3$ $a^{-1}$ to $10\times10^8$ $m^3$ $a^{-1}$. The inter-annual variation of the inflow of the reservoir is usually greatly affected by weather patterns and human activities (Scanlon et al. 2007; Jie 2007). As can be seen from Figure 2, the rainfall decreased from 729 mm to 335 mm over the period, with an average of 489 mm. It was essentially consistent with the variation tendency of inflow of the Panjiakou Reservoir, which showed that rainfall was the direct driving factor for inflow (Zeng et al. 2012). Furthermore, human activity had an important impact on the Panjiakou Reservoir's inflow. The average water consumption in the upstream river increased from $1.2\times10^8$ $m^3$ $a^{-1}$ to $6.7\times10^8$ $m^3$ $a^{-1}$, leading to the decrease of the inflow of the Panjiakou Reservoir (Xu et al. 2013). The shortage and spatiotemporal variability of water resources have been exacerbated by the reduction in reservoir inflow. It had a direct impact on the river's ecosystem's physical, chemical, and biological processes, as well as the reasonable allocation, development, and use of water resources (Li and Feng. 2007). Thus, the sustainable economic, social developments and ecological security of the basin were threatened.

### 3.2 Inter-annual variation of water quality in the Panjiakou Reservoir

The water quality of the Panjiakou Reservoir was mainly affected by cage fish culture in the reservoir directly and social and ecnomic growth indirectly in its upstream and surrounding areas. The scale of cage fish culture expanded rapidly from 1990 to meet local people’s need of improving living standard (Wang and Liu 2008). Since the reform and opening up in 1987, China attached great importance to economic development (Lu et al. 2019). However, the coastal areas developed first, while the inland areas developed slowly. It was not until after 2000 that the economic development of the surroundings of the Panjiakou Reservoir began to enter the "golden decade" due to the support of China's economic policies (Lin 2011). In addition, China has paid more attention to water environmental protection and issued a number of policies in the past decade, such as the "Opinions on Strengthening Key Environmental Protection Work" issued by China State Council in 2011, "The Action Plan for Water Pollution Prevention and Control" issued by China State Council in 2015, and "The comprehensive improvement of the rural environment in the 13th Five-Year Plan" issued by National Development and Reform Commission and Ministry of Housing and Urban-Rural Development in 2016. The water environment management has been strengthened continuously (Xie 2020). Besides, fish cages began to be removed at the end of 2016 and fully removed in May, 2017 to ensure the safety of the water source (Wang 2020). Taking these factors into consideration, this study analyzed variation of main pollutants in the Panjiakou Reservoir from 1984 to 2000, 2001 to 2010, 2011 to 2015, and 2016 to 2019.

In this study, the four most representative pollution indicators, namely total nitrogen (TN), total phosphorus (TP), chemical oxygen demand ($COD_{Mn}$), and ammonia nitrogen ($NH_3$-N), were selected to represent the inter-annual variation of water quality in Panjiakou Reservoir. These indicators were closely related to the economic and social activities in the Panjiakou Reservoir, its surroundings and upstream of the Panjiakou Reservoir. To be more specific, quite a large amount of fish food containing organic matter, nitrogen and phosphorus were utilized to feed carnivorous and omnivorous fish in the reservoir. As a result, fish food residues and excreta contribute significantly to nutrient contaminants (Degefu et al. 2011, Huang and Xiang 2015). Furthermore, sewage discharged from both industrial and residential operations had high levels of ammonia nitrogen and organic contaminants (Wang 2020). Figure 3 displays changes in the concentrations of these four indicators in the Panjiakou Reservoir from 1984 to 2019. From the initial use of the reservoir in 1984 to 2000, TN concentrations exceeded 2.00 mg $L^{-1}$ in 1984 and 1989, which could not meet Class V of the Chinese Environmental Quality Standards for Surface Water (EQS). While in the remaining years they were relatively stable, maintaining a level below 1.50 mg $L^{-1}$, which could meet EQS Class IV. TP concentrations were relatively high in 1991, at 0.075 mg $L^{-1}$, while its average value in other years was 0.034 mg $L^{-1}$, which was in line with EQS Class III. $COD_{Mn}$ concentrations decreased from 3.38 mg $L^{-1}$ to 0.81 mg $L^{-1}$ from 1984 to 1995, which upgraded from EQS Class II to EQS Class I. However, it increased continuously with a maximum value of 3.16 mg $L^{-1}$ from 1995 to 2000, which could meet EQS Class II. $NH_3$-N concentrations ranged from 0.01 to 0.46 mg $L^{-1}$, with an average value of 0.143 mg $L^{-1}$, which could meet EQS Class II.

During the first decade of the 21st century, TN concentrations showed an increasing trend and reached a maximum value of 5.3 mg $L^{-1}$, which could not meet the EQS Class V. TP concentrations increased slowly with a range of 0.020 ~ 0.091 mg $L^{-1}$ and an average value of 0.043 mg $L^{-1}$, which met EQS Class III. $COD_{Mn}$ concentrations varied from 2.29 mg $L^{-1}$ to 3.58 mg $L^{-1}$ with an average of 3.03 mg $L^{-1}$, which could reach EQS Class II. $NH_3$-N concentrations varied from 0.09 mg $L^{-1}$ to 0.82 mg $L^{-1}$, which could meet EQS Class III.

From 2011 to 2015, TN concentrations decreased to 3.16 mg $L^{-1}$, while TP concentrations gradually increased to 0.179 mg $L^{-1}$, both of which were below the class V of EQS. The concentrations of $COD_{Mn}$ ranged from 3.35 mg $L^{-1}$ to 4.40 mg $L^{-1}$, with an average value of 4.03 mg $L^{-1}$, which could meet EQS Class III. $NH_3$-N decreased continuously and dropped to 0.40 mg $L^{-1}$, which met EQS Class II.

Removal of the fish cages in the Panjiakou Reservoir started at the end of 2016 and all fish cages in the reservoir and its upstream were removed, resulting in a significant drop in the concentrations of TP, $NH_3$-N, $COD_{Mn}$. In 2019, the concentrations of TP, $NH_3$-N, and $COD_{Mn}$ were 0.060 mg $L^{-1}$, 0.057 mg $L^{-1}$ and 2.0 mg $L^{-1}$, respectively, which were in line with EQS Class III, I, and I, respectively. However, TN showed a slight upward trend, rising to 4.11 mg $L^{-1}$ in 2019, which was lower to EQS Class V. The classification of water quality is shown in Table 1.

## 3.3 Inter-annual variations of aquatic community structure

### 3.3.1 Inter-annual variations of phytoplankton community structure

The six phytoplankton community structure data of the Panjiakou Reservoir for the years 1987~1988, 2001~2002, 2009, 2010, 2015, and 2019 are shown in Table 2. It can be seen that the diversity and density of phytoplankton species in the Panjiakou Reservoir varied greatly over time. From 1987 to 2019, the overall trend of phytoplankton species diversity in the reservoir gradually declined, from 83 genera to 47 genera. According to the data, the species diversity was relatively stable after 2000, while the phytoplankton density increased from $1.88\times10^6$ cells $L^{-1}$ in 1987 to $113.6\times10^6$ cells $L^{-1}$ in 2015, an approximately 60 fold increase. However, in 2019, the phytoplankton density decreased to $35.1\times10^6$ cells $L^{-1}$.

The phytoplankton community structure of the Panjiakou Reservoir was also varying constantly. The community structure was bacillariophyta type for the years of

1987~1988 and 2001~2002, but changed to cyanophyta-chlorophyta type both in 2009 and 2010. The community structure converted into chrysophyta-cyanophyta type by 2015, but altered into chlorophyta-bacillariophyta in 2019. It can be seen that there was a trend of transformation from a single bacillariophyta to chlorophyta, cyanophyta, and bacillariophyta in the Panjiakou Reservoir, which was discussed in detail in Section 4.1.

### 3.3.2 Inter-annual variations of zooplankton community structure

The inter-annual variations of the zooplankton community structure in the Panjiakou Reservoir and sampling periods are shown in Figure 4 and table 3 for the years 2001~2002, 2010 and 2015. In terms of species diversity, the highest number of species was 194 in 2010 and the lowest was 22 in 2015. The zooplankton density did not alter significantly over time, with an average of 525.7 ind $L^{-1}$. Protozoon and rotifers dominated the species composition in 2001 and 2002, and rotifers dominated in 2010 and 2015. However, copepoda was always the dominant species in terms of density composition.

### 3.3.3 Inter-annual variation of zoobenthos community structure

According to the data from the community structure of zoobenthos in the Panjiakou Reservoir for the years 1986~1987, 1997, 1999~2000, 2001~2002, and 2015 (Table 4), it can be seen that the maximum species richness occurred in 2001, while the minimum appeared in 2015. The density of zoobenthos exceeded 2000 ind $m^{-2}$ in

1999~2000 and 2015, while it was around 1500 ind $m^{-2}$ in other years. The dominant species were tubificidae (oligochaete) and chironomidae with strong ecological adaptability and pollution tolerance. Also, the Goodnight-Whitley Index (GI) was employed to assess the water environment. GI was expressed as the ratio of oligochaete densities and zoobenthos densities. The different GI indicated different water quality status. When GI is lower than 60%, it indicates that the water body is in good condition, between 60% and 80% moderately polluted, and larger than 80% seriously polluted. As can be seen from Table 4, GI for 1986~1987, 1997, 1999~2000, 2001~2002, and 2015 was 37%, 39%, 55%, 83%, and 97%, respectively, showing a gradually increasing trend of pollution.

### 3.3.4 Inter-annual variations of fish community structure

Cage culture had a significant impact on the fish community structure of the Panjiakou Reservoir (see 3.5 for the development of cage fish culture). Cage fish culture in the Panjiakou Reservoir began in the late 1980s. Initially, only a small amount of filter-feeding fish such as silver carp and bighead carp were bred in cages at the entrance of the upstream river of the reservoir. In the early 1990s, the scale of breeding began to rapidly expand, from a few hundred cages to tens of thousands of cages. Breeding species were also gradually increasing, and feed-eating fish such as carp and crucian appeared (Wang and Liu 2008). In the 1990s, about 20 species of fish were discovered in the reservoir, primarily carp, crucian carp, silver carp, bighead carp, grass carp, catfish, and so on (Kang et al. 2020). Food-eating fishes like carp and grass carp, as well as filter-feeding fishes like white carp and silver carp, dominated the fish community structure (Liu et al. 2019).

### 3.4 Economic development changes in the surroundings of the Panjiakou Reservoir

The rate of economic development in the surroundings of Panjiakou Reservoir accelerated with the completion and use of the Panjiakou Reservoir. From 1984 to 2019, the GDP of Chengde City and Tangshan City increased significantly, from $0.13 \times 10^6$ ten thousand yuan to $16.61 \times 10^6$ ten thousand yuan and $0.48 \times 10^6$ ten thousand yuan to $75.04 \times 10^6$ ten thousand yuan, respectively (Figure 5). The primary, secondary, and tertiary industries, particularly the secondary and tertiary industries, grew very rapidly. The proportion of the prodution value of the secondary and tertiary industries in GDP has increased significantly. Chengde City and Tangshan City's per capita GDP has also shown a clear upward trend. The per capita GDP of Chengde City increased from 410 yuan to 46,800 yuan, and that of Tangshan City from 790 yuan to 95,800 yuan. People's living standards significantly improved.

### 3.5 Development and changes in cage fish culture

At the beginning of the construction of the Panjiakou Reservoir, 153 residential groups in 20 administrative villages and 4 townships were submerged, and 28,000 people were relocated. The residents who remained in the reservoir area had only 80 $m^2$ per capita of steep slope land. In the 1980s, the government encouraged residents in the reservoir area to develop cage fish culture, which was a type of high-cost, high-output fishery culture mode, to help them solve their basic livelihood problems (Kang et al. 2020). The cage fish culture was easy to manage and resulted in significant social and economic benefits.

A small amount of cage fish culture was initially tested at the upstream river's entrance. It began to be fully promoted in the 1990s and became one of the main economic development modes in the reservoir area (Wang and Liu 2008). Figure 6 shows the situation of cage fish culture in Qianxi County, Tangshan City and Kuancheng Manchu Autonomous County, Chende City, where the Panjiakou Reservoir was located. From 1991 to 2006, the area of cage fish culture in Qianxi County gradually increased from $0.16\times10^8$ $m^2$ to $0.38\times10^8$ $m^2$, the cage fish culture production increased from $0.08\times10^4$ t $a^{-1}$ to $1.91\times10^4$ t $a^{-1}$, and the cage fish culture production value surged from $0.03\times10^4$ ten thousand yuan to $1.27\times10^4$ ten thousand yuan.

In 2007, there was a large area of dead fish that materialised in the Panjiakou Reservoir, with more than 9,000 boxes of dead fish. The culture area in Qianxi County was reduced to $0.06\times10^8$ $m^2$, which led to a decrease in production and production value. After 2007, the production and production value of Qianxi County resumed an upward trend. The maximum production and maximum production value appeared in

2015, reaching $3.41 \times 10^4$ t $a^{-1}$ and $4.77 \times 10^4$ ten thousand yuan, respectively (Tangshan City Statistical Yearbook 1990~2016). The area of cage fish culture in Kuancheng Manchu Autonomous County was stable at $0.23 \times 10^8$ $m^2$ from 2013 to 2016, while the culture production increased from $1.50 \times 10^4$ t $a^{-1}$ to $1.90 \times 10^4$ t $a^{-1}$, and the production value increased from $1.72 \times 10^4$ ten thousand yuan to $1.95 \times 10^4$ ten thousand yuan (Chengde City Statistical Yearbook 2013~2016). Cage fish culture had become the main source of income for residents in the reservoir area.

However, the number of fish cultured cages grew uncontrollably due to the significant economic benefits generated by this activity. Large amounts of exogenous food were used to boost fishery production, posing a serious threat to the water environment of the reservoir. From the end of 2016, Qianxi County and Kuanchang Manchu Autonomous County began removing the cages to ensure the safety of the water source. By May 20, 2017, a total of 86,463.5 t of fish and 79,687 cages in the Panjiakou Reservoir and its upstream main river had been removed completely (Wang 2020).

## 4. Discussion

### 4.1 Factors influencing inter-annual variations of aquatic community structure

Because aquatic organisms are more sensitive to changes in water quality, species diversity, dominant species, and density are important indicators of water pollution and trophic states (Zhou et al. 2014a). The current status of the Panjiakou Reservoir's aquatic ecological environment was further clarified in this study by examining inter-annual variations in phytoplankton, zooplankton, and zoobenthos community structures.

From the reservoir's operation in 1987 to 2019, the overall trend of reservoir's phytoplankton species diversity gradually decreased, from 83 genera to 47 genera, while the density increased from $1.88\times10^6$ cells $L^{-1}$ in 1987 to $35.1\times10^6$ cells $L^{-1}$ in 2019. This could be due to the impact of paper mills and dyeing plants upstream of the reservoir, which wiped out some species that were less resistant to organic pollution (Li et al. 2010). Because of the decrease in species diversity, a single species developed a competitive advantage under favorable conditions, resulting in bloom (Carstensen and Conley 2004). Furthermore, the phytoplankton community structure of the Panjiakou Reservoir tended to change from a single bacillariophyta to chlorophyta, cyanophyta, and bacillariophyta, according to the study. Since cyanophyta and chlorophyta tended to become dominant phylum in eutrophic waters (Wei et al. 2019), the change of phytoplankton community structure reflected the increase of trophic state in the Panjiakou Reservoir.

The zooplankton species richness in the Panjiakou Reservoir was highest in 2010 and lowest in 2015. This could be because some species with low pollution resistance became extinct as pollution became more intense, while rotifers, which were highly adaptable, became the dominant species. There was no significant change in zooplankton density, and copepods were always the dominant species (Feng et al. 2011; Zhang et al. 2016). This could be due to the Panjiakou Reservoir's intensive cage fish culture, where fish predation activities directly affected the zooplankton community structure, making copepod the dominant species (Korponai et al. 1997; Yang et al. 2005). Moreover, it was found that copepods dominate easily in eutrophic water. In particular, the appearance of cyanobacteria blooms was conducive to copepods to become a dominant species (Geng et al. 2005; Hogfors et al. 2014). With the increase of trophic states in the Panjiakou Reservoir, cyanobacteria became the dominant species, which may also be one of the reasons for the dominance of copepods in the reservoir.

Tubificidae and chironomidae of the zoobenthos, with strong ecological adaptability and pollution resistance, tended to dominate in areas rich in organic matter, indicating the presence of organic pollution in the Luanhe River basin (Nijboer et al.2004; Nogaro and Burgin 2014). Furthermore, the GI of the Panjiakou Reservoir was rising, indicating that water pollution was gradually increasing and the water body was vulnerable to eutrophication.

### 4.2 Impact of economic growth of the surroundings of the Panjiakou Reservoir on the variation of water quality

The per capita GDP of Chengde City and Tangshan City from 1984 to 2019 was chosen as the independent variable, the average concentrations of TN, TP, $NH_3$-N, and $COD_{Mn}$ of the Panjiakou Reservoir during the same period were chosen as the dependent variable, to better explain the influence of economic growth on variations of water qualities. The EKC theory's mathematical model was used to run regression simulations, and a polynomial model was created to fit the data. The optimal result with a good degree of fit was selected. Table 5 showed that the fitting $R^2$ of the four main pollutants in Chengde City and Tangshan City were all greater than 0.75, and the *p*-value was always less than 0.05, indicating that the regression equations were effective and had a good fitting degree, which was of sufficient statistical significance for EKC and could explain the relationship between water pollution and per capita GDP.

In this study, the simulated trends of the econometric models in Chengde City and Tangshan City were shown to be similar. The relationship between selected water quality indicators and per capita GDP all presented a typical "inverted U-shaped" curve (Fig. 7), that is, the pollutant concentration first increased and then decreased with economic growth, which conformed to the general rule of the relationship between economic development and environmental quality. People paid more attention to the growth rate of GDP in the early stages of economic development to meet basic living needs, even if it was based on the over-exploitation of natural resources (Partow 1989). From the initial use of the reservoir in 1984 to 2000, the per capita GDP of Chengde and Tangshan City increased from 416 yuan to 4486 yuan and from 797 yuan to 13,129 yuan, respectively. During this stage, the TN, TP, and $NH_3$-N concentrations changed little and were relatively low, indicating that input of the nitrogen and phosphorus loads to the water environment by economic activities were relatively low. However, $COD_{Mn}$, during this period, showed a significant upward trend from 1995. The source of this load was industrial wastewater from paper mills and dyeing plants upstream of the reservoir, which had only received basic treatment (Huang and Xiang 2015).

For the first decade of the 21st century, the industry and agriculture developed rapidly, with the per capita GDP growth of Chengde City and Tangshan City ranging from 4,979 yuan to 25,698 yuan and 14,379 yuan to 59,389 yuan, respectively. The economic development brought a lot of nutrients, and the concentrations of TN, TP, $NH_3$-N, and $COD_{Mn}$ all showed an obvious trend of increase. Monitoring data in 2010 showed that the water quality of the Panjiakou Reservoir was classified as Class V. In fact, not only China, but many countries pursued economic development at the expense of the environment. For example, many countries such as Indonesia, Brazil, Thailand, Congo, Madagascar, had ignored the cost of soil erosion and timber extraction in pursuit of GDP growth (Sorrell 2010). The United States also pursued GDP without considering the cost of ozone degradation (Salih 2003). However, this mode of economic growth at the expense of the natural environment is not sustainable.

With the growth of per capita GDP, people were no longer limited to material satisfaction as per capita GDP increased, and they began to pay more attention to environmental protection. Generally speaking, they needed clean air and water and pursued sustainable development (Grossman 1993). The protection of the natural environment was considered a part of the cost of economic development in Tianjin City and Tangshan City to achieve sustainable development and ensure water safety (Yang et al. 2014). More environmental protection funds were invested, resulting in a downward trend in the concentrations of major pollutants. From 2011 to 2015, TN, $NH_3$-N, and $COD_{Mn}$ concentrations in the Panjiakou Reservoir were decreasing. According to EKC, the inflection points of TN and $NH_3$-N concentrations in Chengde City occurred when the per capita GDP reached 25,211 yuan and 24,718 yuan respectively (Fig. 7a, c), and the inflection points of TN and $NH_3$-N concentrations in Tangshan City appeared when the per capita GDP reached 59,455 yuan and 68,957 yuan respectively (Fig. 7e, g), both were in 2011. The concentration of $COD_{Mn}$ also first rose and then decreased with economic growth after 2011, when the per capita GDP of Chengde and Tangshan City was 29,715 yuan and 61,823 yuan, respectively, the inflection points appeared (Fig. 7d, h). This is probably because many policies of environmental protection were issued (as mentioned above) and more funds were invested in environmental protection since 2011. As can be seen from Figure 3, $NH_3$-N and $COD_{Mn}$ did show an obvious downward trend after 2011, which was consistent with the fitting results of EKC curve. However, TN showed a minor increase trend after 2017 due to the release of nitrogen maybe from the bottom sediment, but it was still lower than the concentration before 2011. Therefore, EKC curve can reflect the general trend of the relationship between environmental status and economic growth and have a certain reference value.

In 2016, the fish cages started to be removed in the Panjiakou Reservoir and its upstream mainstream to further improve the water quality, which significantly reduced the concentration of TP. According to EKC, TP concentrations in Chengde City and

Tangshan City crossed the inflection point in 2015, later than other indicators. At this time, the per capita GDP of Chengde City and Tangshan City was 37,018 yuan and 76,857 yuan, respectively (Fig 7b, f). However, from Fig 3a, peak values of TP concentrations were reached in 2016 and 2017 and a sharp drop of TP concentrations happened in 2018 and 2019 due to the complete removal of the fish cages. This showed the EKC theory's limitation to some extent.

### 4.3 Impact of cage fish culture and agricultural development (primary industry) on the water quality

Water pollution was gradually worsening as the scale and intensity of cage fish culture grew (Guo and Li 2003). Many studies had assessed the impact of cage aquaculture on the water environment quantitatively. Penczak et al. (1982) discovered that every kilogram of rainbow trout produced in Lake Glebokie in Poland would input 0.75 kg C, 0.023 kg P, and 0.10 kg N to the lake. Huang and Xiang (2015) calculated that the annual N and P loads generated by aquaculture in the Panjiakou Reservoir were about 8,700 t and 1,300 t respectively. Uneaten fish food, fertilizer, and fish excrement were the main sources of pollution.

As the scale of cage fish culture expanded, a large amount of fish food was thrown into the water. Phillips et al. (1986) found that the fish food utilization rate was usually low, only 25%~35% was used to increase the weight of fish, and the remaining 65%~75% was left in the water environment. Wu (1995) found that 85% P, 80%~88% C, and

52%~95% N of the fish food were added into the water environment due to excessive feed. Organic and inorganic fertilizers were discharged into the water body in addition to fish food, promoting the growth of plankton and aquatic plants, providing natural nutrition for filter-feeding fish (Degefu et al. 2011). Unfortunately, these fertilizers contained a variety of pollutants, including organic matter, nitrogen, phosphorus, and suspended solids, resulting in significant water pollution. Furthermore, the impact of fish excrement on the water environment cannot be ignored. Reid et al. (2009) found that 15% of salmon feed was excreted in the form of excrement. Hakanson (1988) calculated that 15% N and 70% P of fish food were lost by fish excrement. Overall, the development of cage fish culture resulted in an excess of nutrients, which posed a serious threat to the water's ecological environment and hastened the eutrophication process.

The government issued a ban on cage fish culture in the Panjiakou Reservoir in November 2016, forcing the removal of all cages within a few months, to protect the water environment and ensure access to safe drinking water in downstream cities. Figure 8 shows the changes in the concentrations of TN, TP, and $COD_{Mn}$ in the Panjiakou Reservoir before (in 2015) and after (in 2018) the cages were removed. It was found that after the cages were removed, the average concentration of TP decreased from 0.18 mg $L^{-1}$ to 0.10 mg $L^{-1}$, and the average concentration of $COD_{Mn}$ decreased from 4.13 mg $L^{-1}$ to 3.13 mg $L^{-1}$. The quality of the water showed a significant improvement, indicating that the removal of the fish cages had an obvious, immediate impact on improving the ecological environment of the Panjiakou Reservoir. However, after the cages were removed, the concentration of TN in the water increased slightly, with the average concentration rising from 3.13 mg $L^{-1}$ to 3.90 mg $L^{-1}$, possibly due to the release of nitrogen from the sediment and input form atmosphere. It was estimated that the TN release flux in the sediment of the Panjiakou Reservoir was 68 mg $m^{-2}$ $d^{-1}$ (Yao and Guo 2020). These nutrients were transferred from the bottom waters to the photic zone as the reservoir turned over (Rueda et al. 2007), further affecting the water quality and the growth of algae. Therefore, it can be estimated that the reduction in TN concentration after removing the fish cages may take several years to become apparent.

Agricultural activities have a substantial impact on the Panjiakou Reservoir's water quality. A large number of nitrogen fertilizers and organophosphorus pesticides were applied to the agricultural land at the upper basin of the Panjiakou Reservoir (Wang and Xing 2002). Furthermore, serious soil erosion exists in some regions in the upper basin of the Panjiakou Reservoir (Zhou et al. 2014b), causing fertilizers, pesticides, and silt to enter the Luanhe River's mainstream and tributaries with rainstorm runoff, and then flow into the reservoir, increasing the reservoir's degree of eutrophication. Therefore, agricultural non-point source pollution also increased the concentrations of TN, TP, and $NH_3$-N in the reservoir. Wang et al. (2009) found that the mainstream of Luanhe River imported 3,467 tons of TN and 68 tons of TP into the Panjiakou Reservoir in 2005 due to non-point source pollution.

## 4.4 Impact of the secondary and tertiary industries in the surroundings of the Panjiakou Reservoir on the water quality

There are many mineral processing enterprises, which are the pillar industries of the secondary industry, due to the abundant mineral resources around the Panjiakou Reservoir and the upstream area. As of 2019, there are 103 mineral processing enterprises around the Panjiakou Reservoir, with 7.5 million t $a^{-1}$ of ore processed, and 1.44 billion t $a^{-1}$ of water consumption (Wang 2020). However, most enterprises did not have sewage treatment facilities. Yao and Guo (2020) found that these mineral processing enterprises discharged 130 million t $a^{-1}$ sewage, including 190,000 t $a^{-1}$ COD and 3,800 t $a^{-1}$ $NH_3$-N, far exceeding the water body's pollution holding capacity. Zhou et al. (2014b) found that the Qinghe River, which had been heavily polluted by mineral processing before it merged with the Luanhe River, contained suspended solids larger than 10,000 mg $L^{-1}$. Besides, there are 22 tailings around the Panjiakou Reservoir, which have accumulated about 10 million $m^3$ of tailings so far. These tailings are stacked around the reservoir along the river (Yao and Guo 2020). In the event of a major flood, the tailings will be discharged with the water and will fill the reservoir, putting the reservoir's capacity at risk. According to statistics, the current tailings have occupied 5.69 million $m^3$ of reservoir capacity (Yao and Guo 2020). To increase the sustainability of the mining processing industry, the construction of urban centralized sewage treatment plant should be accelerated in the future to achieve the standard discharge of industrial wastewater, and the reuse rate of industrial wastewater should also be improved to reduce the use of water resources. Furthermore, to avoid threats to reservoir capacity, random stacking of tailings along the river should be prohibited.

Among the three major industries in the economic structure, the tertiary industry has the least impact on the environment (Grossman 1993), but the pollution load brought by tourism in the Panjiakou Reservoir cannot be overlooked. Due to removing of the fish cages, the living income of more than 30,000 residents in the reservoir area dropped sharply. Therefore, the local government encouraged the development of tourism to increase households′ income. Qianxi County of Tangshan City has been designated as "regional tourism model county", and Kuancheng Manchu Autonomous County and Xinglong County of Chengde City have also taken the Panjiakou Reservoir tourism as an important development project (Xie 2020). At present, there are more than 70 tourist service places around the reservoir, such as various sanatoriums, resorts, agritainment, floating restaurants, and so on, and the number of tourist service places keeps increasing every year (Wang 2020). Furthermore, the wastewater was essentially directly discharged into the Panjiakou Reservoir, with an inflow of 32.88 million t $a^{-1}$ sewage, including 2,895 t $a^{-1}$ COD and 42 t $a^{-1}$ $NH_3$-N (Yao and Guo 2020). This resulted in an excessive pollution load to the water body. It is well known that good environmental quality is the material basis for the healthy development of tourism. As a result, in the future, the relationship between environmental protection and tourism development should be coordinated to achieve sustainable tourism development. First and foremost, the layout of tourist facilities in the Panjiakou Reservoir must be carefully planned. Large tourist facilities should be built outside the reservoir protection area. Only a few simple and locally distinctive rest and accommodation facilities should be constructed in the area, which is environmentally friendly. At the same time, the discharge of domestic sewage to a high standard should be applauded.

## 4.5 Potential synergies and trade-offs among the SDGs during the development of the Panjiakou Reservoir

Based on a comprehensive literature review, this study analyzed qualitatively the interactions between various factors before and after the construction of the Panjiakou Reservoir and after the prohibition of cage fish culture, and mapped them to the relevant goals and targets of SDGs. It should be noted that the SDGs were proposed in 2015, however, the economic and social activities of the Panjiakou Reservoir and its surrounding areas in the above three periods can still be linked to the relevant goals and targets today. Social and economic activities consistent with the goals and targets of SDGs were considered as positive factors. Conversely, social and economic activities contrary to the goals and targets of SDGs were considered as negative factors. The synergies and trade-offs between all the factors were also analyzed in detail.

Before the construction of the Panjiakou Reservoir, the Luanhe River had good water quality (Target 6.3, SDG 6) and abundant species (Target 15.5, SDG 15). However, it faced slow economic development (Target 8.1, SDG 8), low levels of urbanization (Target 11.1, SDG 11) and low energy supply (Target 7.1, SDG 7), which may have generated potential synergies and trade-offs with the water environment. In addition, there were frequent floods in the basin (Target 11.5, SDG 11), but the lack of flood control infrastructure was difficult to cope with climate change (Target 13.1, SDG 13), which had obvious trade-off relationships with the water environment (Fig. 9a).

The Panjiakou Reservoir started being built in 1973 to solve the water shortage in Tianjin City and Tangshan City. It was difficult for local residents to make their living because a lot of farmland was submerged due to the construction of the reservoir. Thus, the government encouraged the development of cage fish culture to solve the basic livelihood problem of residents (Target 2.1, SDG 2).With the completion of the Panjiakou Reservoir in 1983 and the support of China's economic policies after 2000, the level of industrial (Target 9.2, SDG 9) and agricultural productivity (Target 2.3, SDG 2) improved, which benefited the economic development (Target 8.1, SDG 8) and urbanization (Target 11.1, SDG 11), that is, there were synergies between them. At the same time, the Panjiakou Reservoir also played a role in flood prevention and power generation (Target 11.5, SDG 11), thereby strengthening resilience to climate change (Target 13.1, SDG 13) and contributing to social and economic development (Target 8.1, SDG 8).

Unfortunately, there were also obvious trade-offs in the process of social and economic development. Although cage fish culture produced great economic benefits, intensive development of aquaculture without proper management generated large amounts of unutilized food, fertilizer, and fish excrement and caused serious water pollution from pollutants such as suspended solids, nitrogen, and phosphorus. Moreover, large amounts of solid waste (Target 11.6, SDG 11) and sewage (Target 6.3, SDG 6) generated by social and economic development were discharged due to a lack of effective water resource management. These pollutants from cage fish culture and economy development caused water pollution (Target 6.3, SDG 6), unsustainable use of freshwater resources (Target 15.1, SDG 15), destruction of natural habitats and biodiversity (Target 15.5, SDG 15), and affected ecosystem services (Target 15.5, SDG 15). The negative effects on the environment would in turn harm society and the economy, including adverse impacts on agricultural (Target 2.3, SDG 2) and industrial productivity (Target 9.2, SDG 9), economic growth (Target 8.1, SDG 8), increasing conflicts between upstream and downstream (Target 6.5, SDG 6), and so on (Fig. 9b).

To address this urgent issue, cage fish culture was banned from the end of 2016 to force the removal of all the cages within a couple of months (Target 2.1, SDG 2), which aimed to improve the water quality (Target 6.3, SDG 6) and protect water-related ecosystems (Target 6.6, SDG 6). However, suddenly stopping local economic activities had affected the livelihoods of aquaculture farmers (Target 8.3, SDG 8), which had trade-offs with the eradication of poverty (Target 1.b, SDG 1) and inequalities (Target 10.4, SDG 10). Therefore, the local government encouraged the development of tourism to increase income (Target 12.b, SDG 12). Furthermore, with rising environmental awareness (Target 12.8, SDG 12), the wastewater treatment system (Target 6.3, SDG 6) and solid waste management (Target 11.6, SDG 11) will be improved in the future, allowing for the sustainable use of water resources (Target 15.1, SDG 15) (Fig. 9c). Besides the policies had already been implemented, the cross-provincial ecological compensation mechanism should be established and effectively implemented in the future, so as to compensate the residents neighbour the Panjiakou Reservoir for protecting the water quality at the expense of the local economy (Cage fish culture), thus minimizing the trade-off.

Some lessons can be drawn from the actual case of the Panjiakou reservoir. Looking back at the development process of the Panjiakou Reservoir and its surroundings, the area initially only focused on economic development and vigorously developed cage fish culture, which solved the livelihood problem of local residents. However, excessive fish food has caused serious pollution of the water environment. Water quality degradation can compromise the supply of safe water to downstream Tianjin City and Tanshan City (actually, in some years neither would like to buy the water because of heavy pollution). In order to solve this problem, the local government strived to find an environment-friendly way to develop the economy. Consequently, cage fish culture had been completely removed and replaced by the development of tourism with a relatively small environmental impact. This is a typical case of minimizing trade-offs and maximizing synergies. To prevent these trade-offs in the future, the Panjiakou Reservoir's water resources management should take into account the individual needs inside and across catchments to accomplish long-term social, economic, and environmental development at the subnational level. To be more specific, policymakers must prioritise environmental protection while developing the economy to assure the security of water supplies. For example, domestic sewage and industrial wastewater should be discharged after reaching specific quality standards, large-scale tourism facilities should be built outside the reservoir protection area, and so on. Simultaneously, a cross-provincial ecological compensation mechanism can be devised and successfully executed to ensure that local citizens' livelihoods are not jeopardized (Xu et al. 2021). Properly dealing with the trade-off and synergy between the SDGs is not only beneficial to the sustainable development of the catchment, but also plays a positive role in the sustainable development of areas (such as Tianjin City and Tangshan City) outside the catchment.

## 5. Conclusions

This study partly reflected the real socio-economic and environmental situation of the Panjiakou Reservoir by analyzing the existing data from a macroscopic point of view. The concentrations of TN, TP, $NH_3$-N, and $COD_{Mn}$ in the Panjiakou Reservoir have followed an overall trend of increasing first and then decreasing with economic growth and cage fish culture development (to 2016) and removal (after 2016) from the reservoir's inception to the present. From 1984 to 2000, TN, TP and $NH_3$-N concentrations were rarely affected by economic development, while $COD_{Mn}$ concentration increased with economic growth. For the first decade of the 21st century, cage fish culture and economic activities imported a lot of nutrients, leading to an obvious increase in TN, TP, $NH_3$-N, and $COD_{Mn}$ concentrations. From 2010 to 2016, sustainable development was pursued, and the concentration of TN, $NH_3$-N, and $COD_{Mn}$ reduced constantly. After the removal of fish cages in 2017, TP concentration declined while TN concentration rose slightly.

In the aquatic community structure, organisms with high ecological adaptability and pollution resistance, such as chlorophyta, cyanophyta, and bacillariophyta among phytoplankton, copepods among zooplankton, and tubificidae and chironomidae among zoobenthos, became dominant. Cage fish culture had the greatest impact on fish population, which ranged from filter-feeding fishes like silver carp and bighead carp to feed-eating fishes like carp, grass carp, and filter-feeding fishes like white carp and silver carp.

Mineral processing companies dominated the secondary industry, which produced a lot of sewage and tailings. Tourism, which produced a lot of domestic sewage, dominated the tertiary industry. Economic development would put a lot of strain on the environment if it wasn't managed properly.

The completion of Panjiakou Reservoir had solved the water shortage problem in Tianjin City and Tangshan City. At the same time, the power generation and irrigation using the reservoir as well as cage fish culture in the reservoir were beneficial to the economic and social development of the surroundings. However, a great deal of pollution brought by cage fish culture and other social and economic activities posed environmental risks such as water pollution, unsustainable water resource use, ecological destruction, and so on, all of which would in turn harm society and the economy. Therefore, cage fish culture was removed and the wastewater treatment system and the solid waste management were improved to ensure the safety of drinking water. Futhermore, the development of tourism was encouraged and the cross-provincial ecological compensation mechanism should be established and effectively implemented to maintain livelihood of local residents. The actual case here demonstrated that individual needs inside and across catchments must be considered comprehensively in the integrated water resources management process to minimize trade-offs and maximize synergies, so as to achieve long-term sustainability at the sub-national scale.

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## Author contributions

Suiliang Huang and Mengjiao Wei conceived and designed the research; Mengjiao Wei, Ling Li, Tianqi Zhang collected the data; Suiliang Huang, Mengjiao Wei, Ling Li, Tianqi Zhang analyzed the data; Mengjiao Wei, Suiliang Huang wrote the article; Fabrice G. Renaud oversaw the section on the SDGs; Fabrice G. Renaud, Suiliang Huang, Zobia Khatoon, Waseem Akram edited the manuscript. Fabrice G. Renaud and Suiliang Huang supervised and edited the manuscript. All authors read and approved the final manuscript. All authors agreed to authorship and submission of the manuscript for peer review.

## Conflict of interest

The authors declare no competing financial interests.

## Statement of informed consent, human/animal rights

No conflicts, informed consent, human or animal rights applicable.

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**Table 1.** Chinese Environmental Quality Standards for Surface Water (National Standards of the People's Republic of China 2002).

| Level | TN (mg $L^{-1}$) | TP (mg $L^{-1}$) | $COD_{Mn}$ (mg $L^{-1}$) | $NH_3$-N (mg $L^{-1}$) | Application |
|---|---|---|---|---|---|
| I | ≤ 0.2 | ≤ 0.01 | ≤ 2 | ≤ 0.15 | ● Source water, national nature reserves |
| II | ≤ 0.5 | ≤ 0.025 | ≤ 4 | ≤ 0.5 | ● First-level protection zone for centralized surface water source of drinking water<br>● The habitat of rare aquatic organisms<br>● The production of fish and shrimp |
| III | ≤ 1 | ≤ 0.05 | ≤ 6 | ≤ 1 | ● Second-level protection zone for centralized surface water source of drinking water<br>● Wintering ground, migration channels, aquaculture areas of fish and shrimp<br>● Swimming |
| IV | ≤ 1.5 | ≤ 0.1 | ≤ 10 | ≤ 1.5 | ● General industrial water<br>● Recreational water that are not in direct contact with human bodies |
| V | ≤ 2 | ≤ 0.2 | ≤ 15 | ≤ 2 | ● Agricultural water<br>● General landscape requires water |

**Table 2.** Inter-annual variations of phytoplankton community structure in the Panjiakou Reservoir (data source: Luanhe River Diversion Project Management Bureau, Haihe Water Resources Commission 1989, 2020; Wang et al. 2004; Gao et al. 2012; Li et al. 2012; Zhang et al. 2016).

| Sampling time | Sampling periods | Species | Density ($10^6$ cells $L^{-1}$) | Community structure |
|---|---|---|---|---|
| 1987~1988 | Monthly | 83 genus | 1.88 | Bacillariophyta |
| 2001~2002 | Sept. 2001, Apr. 2002 | 52 genus<br>76 species | 1.10 | Bacillariophyta |
| 2009 | May to Nov.: monthly | 37 genus | 6.69 | Cyanophyta, Chlorophyta |
| 2010 | May to Nov.: monthly | 41 genus | 32.6 | Cyanophyta, Chlorophyta |
| 2015 | May | 52 genus | 113.6 | Chrysophyta, Cyanophyta |
| 2019 | Monthly | 47 genus<br>58 species | 35.1 | Chlorophyta<br>Bacillariophyta |

**Table 3.** Sampling periods of zooplankton in the Panjiakou Reservoir (data source: Wang et al. 2003; Feng et al. 2010; Zhang et al. 2016).

| Sampling time | Sampling periods |
|---|---|
| 2001~2002 | Sept. 2001, Apr. 2002 |
| 2010 | May to Nov.: every 15 days |
| 2015 | May |

**Table 4.** Inter-annual variations of the density of zoobenthos in the Panjiakou Reservoir (data source: Ji et al. 2005; Zhang et al. 2016).

| Sampling time | Sampling periods | Species | Tubificidae (ind m$^{-2}$) | Chironomidae (ind m$^{-2}$) | Mollusk (ind m$^{-2}$) | Other (ind m$^{-2}$) | Total (ind m$^{-2}$) | GI |
|---|---|---|---|---|---|---|---|---|
| 1986~1987 | Sept. and Nov. 1986, Apr. and Jul. 1987 | 38 species | 587 | 942 | 51 | - | 1580 | 37% |
| 1997 | Apr., Jul., Sept. and Nov. 1997 | 25 species | 597 | 621 | 327 | - | 1545 | 39% |
| 1999~2000 | Sept. and Nov. 1996, Apr. and Jul. 2000 | 28 species | 1635 | 1300 | 16 | 42 | 2993 | 55% |
| 2001~2002 | Sept. and Nov. 2001, Apr. and Jul. 2002 | 57 species | 1285 | 167 | - | 105 | 1557 | 83% |
| 2015 | May | 15 species | 2552 | 122 | - | - | 2674 | 97% |

**Table 5.** Simulation results of economic growth and main pollutant concentrations of the Panjiakou Reservoir.

| City | Main pollutants | Optimal regression equation | $R^2$ | *p* | Curve type |
|---|---|---|---|---|---|
| Chengde | TN | $y=9*10^{-14}\times x^3-1*10^{-8}\times x^2+0.0004\times x+0.38$ | 0.77 | 0.00 | Inverted U |
| | TP | $y=-1*10^{-14}\times x^3+8*10^{-10}\times x^2-9*10^{-6}\times x+0.05$ | 0.80 | 0.00 | Inverted U |
| | $NH_3$-N | $y=-2*10^{-14}\times x^3+4*10^{-9}\times x^2+2*10^{-5}\times x+0.07$ | 0.78 | 0.00 | Inverted U |
| | $COD_{Mn}$ | $y=-7*10^{-14}\times x^3+1*10^{-9}\times x^2+0.0001\times x+1.16$ | 0.84 | 0.00 | Inverted U |
| Tangshan | TN | $y=2*10^{-15}\times x^3-1*10^{-9}\times x^2+0.0002\times x+0.62$ | 0.82 | 0.00 | Inverted U |
| | TP | $y=-1*10^{-15}\times x^3+2*10^{-10}\times x^2-4*10^{-6}\times x+0.05$ | 0.76 | 0.00 | Inverted U |
| | $NH_3$-N | $y=-4*10^{-15}\times x^3+4*10^{-10}\times x^2+2*10^{-5}\times x+0.10$ | 0.75 | 0.00 | Inverted U |
| | $COD_{Mn}$ | $y=-9*10^{-15}\times x^3+3*10^{-10}\times x^2+6*10^{-5}\times x+1.13$ | 0.81 | 0.00 | Inverted U |

$R^2$ takes a value between 0-1, and is a coefficient indicating the degree of fit. The larger the value, the better fit of the equation. *p* represented the significance probability. When it was less than 0.05, the regression equation was valid.

**Figure legends:**

**Figure 1.** Location of the Luanhe River basin and the sampling locations in the Panjiakou Reservoir (own figure)

**Figure 2.** The annual inflow, water consumption and rainfall of the Panjiakou Reservoir in the Luanhe River basin from 1956 to 2016 (data source: Li et al. 2019; Li and Feng 2007; Zeng et al. 2012; Tian and Zhang 2011; China Meteorological Administration (https://data.cma.cn/))

**Figure 3.** Inter-annual variations of (a) total nitrogen (TN) and total phosphorus (TP), (b) chemical oxygen demand ($COD_{Mn}$) and ammonia-nitrogen ($NH_3$-N) in the Panjiakou Reservoir from 1984 to 2019 (data source: Wang 2020; Xing et al. 2009)

**Figure 4.** Inter-annual variations of (a) species and (b) density of zooplankton in the Panjiakou Reservoir (data source: Wang et al. 2003; Feng et al. 2010; Zhang et al. 2016)

**Figure 5.** Economic growth trends of (a) Chengde City and (b) Tangshan City (data source: Statistical Yearbook of Chengde City and Tangshan City 1984~2019)

**Figure 6.** Cage fish culture of the Panjiakou Reservoir in (a) Qianxi County, Tangshan City and (b) Kuancheng Manchu Autonomous County, Chende City (data source: Tangshan City Statistical Yearbook 1990~2016, Chengde City Statistical Yearbook 2013~2016)

**Figure 7.** EKC fitting curves of main pollutants and per capita GDP in (a-d) Chengde City and (e-h) Tangshan City

**Figure 8.** Comparisons of pollutant concentrations before (in 2015) and after (in 2018) the fish cages were removed in the Panjiakou Reservoir (data source: Liu et al. 2019)

**Figure 9.** The SDG synergies and trade-offs in the Panjiakou Reservoir and its surroundings (a) before and (b) after the construction of the Panjiakou Reservoir and (c) the prohibition of cage fish culture. Green nodes represent factors which consistent with the goals and targets of SDGs, and red nodes represent factors which contrary to the goals and targets of SDGs. Each line with an arrow indicates a causal link between the paired factors. The grey lines represent a potential trade-off, the yellow lines represent a potential synergy, and the blue lines represent a link that can be either a trade-off or a synergy. The number of links a node has is reflected in its size