Regional water pollution management pathways and effects under strengthened policy constraints: the case of Tianjin, China

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Abstract
In recent years, China has attached great importance to pollution control, and national and many provinces have introduced water pollution management policies in the hope that improvements can be made. However, there is currently a lack of objective and adequate assessment of the effectiveness of water pollution management (WPM) at the regional level, especially a lack of in-depth research on the causes of improvement, key measures, and pathways of action. This paper constructs an evaluation index system based on the driver, pressure, state, impact and response (DPSIR) model and evaluates the WPM performance of Tianjin based on the five aspects comprising the DPSIR model. The results show that WPM performance in Tianjin has been commendable, improving from 76.15 points out of 100 in 2014 to 90.93 points out of 100 in 2018. The score increased more rapidly from 2016 to 2018 after the regional policy was implemented. The main reason for this encouraging phenomenon is the significant improvement in water quality. From 2016 to 2020, the closure of high pollution industrial enterprises and the regulatory management of aquaculture have significantly reduced pollutant emissions. At the same time, under the constraints of the river chief system, pollutant discharge permits, discharge standards, ecological compensation agreements on water pollution and other policies in Tianjin, the effect of pollution source control is obvious, with improved water quality and high public satisfaction.

Keywords Water pollution management (WPM) · Regional water pollution policy · Water pollution management pathways · DPSIR framework

Introduction
Given the importance of water for both economic production and biological life, water pollution is a global concern. Preventing and controlling water pollution is crucial, especially given the current shortage of freshwater resources. Therefore, quantifying the effectiveness of water pollution management (WPM) strategies and measures is a task of great significance. Since the 1980s, China has experienced extensive economic development characterized by a dramatic increase in industrial activity (Zhou et al. 2017), which has been accompanied by a series of environmental problems, such as frequent air pollution, shortage of water resources and poor water quality. Consequently, the environmental quality throughout the country has significantly decreased, resulting in pernicious public health risks (Li 2018; Wang and Yang 2016). Since 2012, the Chinese government has gradually begun to pay attention to ecological and environmental protection. This concern has been demonstrated in the construction of a strict policy system, strong punishments...
for high-pollution events, and the transition towards greener modes of industrial production (Central People’s Government of the People’s Republic of China, 2017).

The promulgation of a series of laws and regulations heralded a new stage of development in WPM. The release of the PRC Environmental Protection Law (Ministry of Ecology and Environment of the People’s Republic of China 2014) and the “Action Plan for Water Pollution Prevention and Control” (Central People’s Government of the People’s Republic of China 2015) improved the responsibility system for water pollution prevention and control and set clear water quality targets. This law outlined ten important tasks and 238 specific measures to address water pollution (Han et al. 2016). The revised “Water Pollution Prevention Law of the People’s Republic of China” has been implemented since 2018 (Ministry of Ecology and Environment of the People’s Republic of China 2018), strengthening restrictions at the legal level. According to China’s Environmental Status Bulletin (Ministry of Ecology and Environment of the People’s Republic of China 2020), the proportion of Class I-III water quality cross-sections increased to 74.9% in 2019 from 65.4% in 2015, reflecting a strict WPM system at the national level. Furthermore, as the entity responsible for WPM and enforcement, local governments in provinces and municipalities actively engage in regional water pollution prevention and control efforts (Wu and Ye 2020). To date, several provinces and cities have issued water pollution prevention and control regulations (Chen et al. 2018) that provide comprehensive and systematic requirements for WPM practices.

Previous scholars have analyzed China’s water pollution prevention and control processes, related laws and regulations, and water pollution control measures from different industry perspectives. Studies have applied difference-in-differences (DID) models to assess the “10-Point Water Plan” effect, showing that the plan has significantly reduced industrial water pollution (Zhou et al. 2021). Similar studies have been conducted on the impact of off-site audits of natural resources on water pollution prevention and control, finding that the implementation of an audit system can effectively reduce water pollution (Ma et al. 2021). Regarding the environmental impact of water pollution prevention in parks, the life cycle assessment approach reveals that chemical and electricity consumption are the leading causes of water pollution (Lyu et al. 2021). In a three-dimensional model of the supporting role of the water environment in the Huaihe River basin, the water pollution prevention and control capabilities were found to have high spatial overlap with the level of economic development (Zhou et al. 2015). Few studies on water pollution prevention and control use specific models for policy assessment. Most of them focus on high-emission industries such as the chemical industry or target national-level policies. Some scholars have examined typical cities for water pollution-related studies. Based on water pollution data and water quality, the water quality changes in Suzhou were analysed and evaluated (Zhang and Guan 2017). The potential impact of Shenzhen city’s promotion of sponge city construction on the water quality of Shenzhen Bay was assessed (Xiong et al. 2021). However, there are relatively few studies constructing water environment-related index systems for quantitative evaluation, especially for evaluating the effects of water pollution policies from regional and municipal perspectives.

Due to differences in natural endowments and production structures, water resources and water pollution vary between different regions of China. This combination of attributes makes the area well suited as a subject for more in-depth research. The “Water Pollution Prevention and Control Regulations of Tianjin” was implemented in March 2016 (Tianjin Municipal People’s Congress 2016). After several revisions, these regulations cover many aspects of water pollution prevention and control, and water quality is showing a good trend (The Bureau of Water Affairs of Tianjin 2019). Furthermore, Tianjin is a typical fast-growing city in China. It is located at the mouth of the sea, with a constrained water supply and a massive WPM burden. In this study, the DPSIR model is used to comprehensively evaluate the effectiveness of Tianjin’s water pollution prevention and control policies. Exploiting the advantage of the model’s circular and closed-loop structure, we assess the overall operational status of water pollution prevention and control to identify weak points and provide substantiative suggestions for the next steps to effectively solve water environment problems.

The structure of this article is as follows: the second section introduces Tianjin’s WPM mechanism. The third section describes the composition of the DPSIR framework and constructs an index system for WPM evaluation based on the framework. The fourth section presents the evaluation results and the effects of WPM. The fifth section discusses the paths of WPM in Tianjin and draws conclusions.

Water pollution management mechanism of Tianjin

Study area

Tianjin lies between 116°43’ E—118°04’ E and 38°34’—40°15’ N. It is a municipality directly under the Central Government of the People’s Republic of China. The largest coastal city in North China, it is located adjacent to Beijing and covers an area of 11,946.88 km², making it slightly smaller than the state of Connecticut in the USA (Fig. 1). At the end of 2018, the resident population was 15.62 million, with a GDP of 1336.292 billion yuan (approximately 188.47 billion USD). In 2018, the water resources per capita was 1971.85 m³ in China (National Bureau of...
Statistics 2019) but only 112.93 m$^3$ in Tianjin, less than one-seventeenth the value for the whole country. This number demonstrates the significant pressure related to both water resources and water pollution in this region.

**Multi-level structure of water pollution management**

WPM agencies in China have a multi-level vertical structure, which extends from the whole country down to provinces, cities, and then districts. In general, high-level government departments are responsible for formulating emission standards and limits, while low-level government departments carry out specific work to meet related expectations.

The Tianjin municipal government must comply with relevant national laws and arrange water pollution prevention and control work to ensure the provision of water quality for the whole city. The municipal government can formulate local standards that are more stringent than the national standards; once approval is given by the National Ministry of Ecology and Environment (MEE), local standards can be implemented in Tianjin. The Bureau of Ecology and Environment (BEE) of Tianjin, together with relevant municipal departments, is responsible for compiling Tianjin’s water pollution prevention and control plan. Furthermore, the BEE of Tianjin allocates pollutant emission quotas for all 16 districts and organizes and promotes the implementation of the targets. According to Tianjin’s water pollution prevention and control plan, district governments should formulate
measures and implementation plans to improve the water environment situation within their jurisdiction. After developing pollutant emission quotas, the BEE in district governments implements planned emission controls for key water pollutants within their administrative region (Fig. 2).

Under a vertical management structure, some regions in China have begun to establish river chief systems, which assign specific WPM responsibilities to individual government officials (She et al. 2019) at all levels and impose strict oversight. A river chief system is an important innovation in water resource and water environment management. Using supervision and assessment, this system ensures that individuals remain accountable and operate in a timely manner to achieve high results (Li et al. 2020; Liu et al. 2020). The main tasks stipulated by the policy include the following:

- Strengthen the protection of water resources;
- Support the reasonable development and utilization of water resources;
- Strengthen the management and protection of coastline of rivers and lakes;
- Strengthen the safe construction of flood control and eliminate waterlogging;
- Implement the action plan for water pollution prevention and control;
- Strengthen water environment management;
- Strengthen law enforcement and supervision.

Article 7 of the “Water Pollution Prevention and Control Regulations of Tianjin” stipulates that Tianjin shall establish a four-level river (lake) chief system. Under this system, river chiefs are designed at the city, district, township (street), and village levels. The Tianjin government promulgated and began to implement the river chief system in May 2017. As of July 2019, 5884 river and lake chiefs have been set up at various geographic levels.

**Multi-department collaboration in water pollution management**

WPM affects numerous aspects of a society, its economy, and its citizens’ daily lives. Because of these wide-ranging impacts, it is necessary to coordinate and dispatch pollution management measures from multiple departments.

Generally, the BEE of Tianjin undertakes the core related responsibilities. According to the regulations, the BEE oversees the unified management and supervision of water pollution prevention and control measures. The main duties include organizing the formulation and supervision of related policies, plans and standards; controlling the discharge of water pollution sources and reducing the discharge of pollutants; and supervising and managing the environmental protection of drinking water sources. The Bureau of Water Affairs (BWA) of Tianjin also plays an important role; it is responsible for the protection of water resources and manages and supervises urban drainage and centralized sewage treatment.

The other 12 municipal departments carry out related work within the scope of duties, providing auxiliary support.
for WPM. The detailed coordination mechanisms of industrial water pollution, urban water pollution and rural WPM practices are shown in Fig. 3. Among the industrial pollution management systems, pollutant emissions from industrial sources are the most important indicators; these are supervised by the BEE. Two other departments pay more attention to adjusting the industrial structure and water use efficiency. Urban WPM focuses on sewage treatment and black and odorous water bodies, and the BWA works in cooperation with the Commission of Housing and Construction and the Commission of City Management to address these matters. For rural WPM, the Commission of Agriculture and Rural Affairs undertakes wider responsibilities and coordinates with the BEE and the BWA. The specific contents of departmental collaboration include joint formulation of plans, mutual exchange of data, and unified implementation of actions.

**Evaluation methods**

**DPSIR framework**

DPSIR is a widely recognized analytical framework comprising a sequence of steps for analysing environmental disturbances: driver (D), pressure (P), state (S), impact (I), and response (R). The DPSIR framework was developed from the pressure-state-response (PSR) model that was initially used by the Organization of Economic Cooperation and Development in 1993 (OECD 1993). Then, it was further improved by the European Environmental Agency (European Environment Agency 1999) and scientists into an integrated framework that aimed to inform policymakers on environmental indicators (Gouldson 1996). The framework is primarily used to assess causes, effects, outcomes, and responses, convey causal relationships between society and the environment (Tesfaldet and Ndeh 2022), analyse policy implementation’s effects, and improve public acceptance of policy measures. This purpose is highly consistent with our research purpose. This framework has proven effective in addressing environmental issues at global and sectoral scales (Ramos-Quintana et al. 2018) and has been used widely in research on water resources (Liu et al. 2019; Zare et al. 2019), water quality (Gari et al. 2018), water pollution (Apostolaki et al. 2019) and water accidents (Yang et al. 2020). Therefore, the DPSIR framework is used here to evaluate WPM performance in Tianjin. The results reflect the effects of social, economic, public management and other factors on water pollution management. The coordination of society, economy and water can provide an important foundation for sustainable development (Luo and Zuo 2019). Furthermore, clarifying the driver, pressure, state, impact and response is crucial to identify shortcomings in water pollution prevention and control in Tianjin, thus allowing

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Fig. 3 Multi-department collaboration of water pollution management in Tianjin
valuable policy implications. The details of the five components of the framework are as follows.

**Driver**

Drivers are high-level factors that compel changes in the quality and availability of water in profound and fundamental ways. They usually include factors related to the productivity of the economy and the activities of society. Population growth and demand increases are the most fundamental drivers in this regard.

**Pressure**

Pressures are influences that can be exerted on water pollution and water environment management through numerous different types of human activities. These pressures usually exist in the form of consequences produced in the industrial production and household consumption process and can be divided into water use pressure and water environment pressure.

**State**

States describe the physical attributes of the water environment at different levels of the ecosystem, including hydrological characteristics, water resource sustainability, water quality and other water environment factors.

**Impact**

Impacts include qualitative and quantitative indices that promote changes in water, production, life, and the environment. Generally, socio-economic, ecological, environmental impact and public impacts are significant factors under the framework.

**Response**

Responses are defined as management and control measures enacted to address multiple factors in the water environment, including the driver, pressure, state and impact components. The response component contains the most descriptive indices of governance behavior and comprises environmental and management responses (Posthuma et al. 2019).

There is complex interaction among the five elements of the DPSIR model. The specific influence mechanisms of various components and the contents of the components are shown in Fig. 4. This research requires a comprehensive and systematic analysis and assessment of regional WPM based on the correlation mechanism inherent in the model. We can identify WPM deficiencies and future improvement directions by comparing the scores of different modules, thus providing a valuable reference for developing WPM policies.

**Development of the index system based on the DPSIR framework**

To construct a scientific, representative, and comprehensive evaluation index system, the “Water Pollution Prevention and Control Regulations of Tianjin” (Tianjin Municipal People's Congress 2016) was selected as the policy basis. The proposed index system considered seven chapters of the regional policy. Representative indices were chosen according to the specific requirements of the regulations to reflect the actual situation and facilitate a reasonable evaluation of the regulations.

Additionally, relevant literature was investigated (Lu et al. 2019; Sun et al. 2018; Vannevel 2018; Zare et al. 2019). Based on the literature review of water management indices (Apostolaki et al. 2019; Liu et al. 2018; Xiao et al. 2019; Yang et al. 2018) and the specific situation of Tianjin’s WPM, the final index system was determined through on-site investigation and demonstrations by many experts in the field. The system comprised four layers (target layer, component layer, factor layer, and index layer) and thirty indices (Table 1).
| Target layer | Component layer | Factor layer | Index layer | Unit | References | Corresponding regulation |
|-------------|----------------|--------------|-------------|------|------------|--------------------------|
| Performance of water pollution management (WPM) in Tianjin | Driver ($C_1$) | Economy ($F_1$) | Annual GDP growth rate ($I_1$) | % | Lu et al. (2019) | Article 14: “…Economic and social development…” |
| | | | Natural population growth rate ($I_2$) | % | Sun et al. (2016) | |
| | | | Growth rate of water resources per capita ($I_3$) | % | | |
| | Pressure ($C_2$) | Water use ($F_3$) | Total water consumption ($I_4$) | $10^6$ m$^3$ | Zare et al. (2019) | Article 40: “…Save water…” |
| | | | Water consumption for industrial output value of 10,000 yuan ($I_5$) | m$^3$ | Xiao et al. (2019) | |
| | | | Effective utilization coefficient of farmland irrigation water ($I_6$) | - | Ramos-Quintana et al. (2018) | |
| | Water environment ($F_4$) | | Discharge of domestic wastewater from urban residents ($I_7$) | $10^6$ t | | Article 13: “…Control water pollutant discharge concentration and total discharge of key water pollutants…” |
| | | | Discharge of waste water from Industry and Construction Industry ($I_8$) | $10^6$ t | | |
| | | | Discharge of Chemical Oxygen Demand (COD) in wastewater ($I_9$) | $10^4$ t | | Article 58: “…Encourage watersaving irrigation…” |
| | | | Discharge of Ammonia Nitrogen ($NH_3$-N) in wastewater ($I_{10}$) | $10^4$ t | | |
| | State ($C_3$) | Water state ($F_5$) | Proportion of Class I-III water quality sections in National Examination Sections ($I_{11}$) | % | Liu et al. (2019) | Article 4: “…Protect and improve water environment quality…” |
| | | | Penetration rate of urban water ($I_{12}$) | % | Sun et al. (2018) | |
| | | | Growth rate of total water storage of large and medium-sized reservoirs at the end of the year ($I_{13}$) | % | | Article 18: “…Improve the carrying capacity of environmental resources in river basins…” |
| | | | Compliance rate of water functional zone evaluation based on full indicators ($I_{14}$) | % | | Article 4: “…Protect and improve water environment quality…” |
| Target layer                        | Component layer | Factor layer | Index layer                                                                 | Unit            | References                                           | Corresponding regulation                                                                 |
|------------------------------------|-----------------|--------------|-------------------------------------------------------------------------------|-----------------|------------------------------------------------------|------------------------------------------------------------------------------------------|
| Impact (C₄)                        | Socio-economic impact (F₆) | GDP per cubic meter of water (I₁₆) | Average utilization rate of water resources (I₁₅)                              | %               | Wei et al. (2019)                                    | Article 34: “...Increase water reuse rate...”                                               |
|                                    | Ecology and environment impact (F₇) | Green coverage rate of built-up areas (I₁₇) | GDP per cubic meter of water (I₁₆)                                         | yuan/m³         | Gari et al. (2018)                                  | Article 40: “...Save water...”                                                             |
|                                    |                  | Water supplement to ecology and environment (I₁₈) | Green coverage rate of built-up areas (I₁₇)                                  | %              |                                                      | Article 18: “...Ecological environment governance and protection project...”               |
|                                    | Public impact (F₉) | Public satisfaction with water environment management (I₁₉) | Water supplement to ecology and environment (I₁₈)                           | 10⁶ m³         |                                                      | Article 18: “...Carrying capacity of river basin environmental resources...”               |
| Response (C₃)                      | Environment response (F₉) | Centralized treatment rate of sewage (I₂₀) | Public satisfaction with water environment management (I₁₉)                | %              | Ding et al. (2019)                                   | Article 10: “...Public participation...”                                                    |
|                                    |                  | Water quality compliance rate of discharged sewage (I₁₁) | Centralized treatment rate of sewage (I₂₀)                                 | %              | Liu et al. (2018)                                    | Article 46: “...Increase the treatment rate of urban sewage...”                            |
|                                    |                  | Compliance rate of discharged industrial wastewater (I₁₂) | Water quality compliance rate of discharged sewage (I₁₁)                   | %              | Pires et al. (2017)                                  |                                                                                           |
|                                    |                  | Sewage reuse rate (I₁₃) | Compliance rate of discharged industrial wastewater (I₁₂)                   | %              | Hazarika and Nitivattananon (2016)                   |                                                                                           |
|                                    | Management response (F₁₀) | Growth rate of Pollution Discharge Permits issued by Environmental Protection Department to enterprises (I₂₃) | Sewage reuse rate (I₁₃)                                                     | %              |                                                          | Article 50: “...Ensure that the effluent water quality meets relevant emission standards...” |
|                                    |                  | Growth rate of urban drinking water sources (I₁₄) | Growth rate of Pollution Discharge Permits issued by Environmental Protection Department to enterprises (I₂₃) | %              |                                                      | Article 43: “...Construct centralized sewage treatment facilities and install automatic online monitoring facilities...” |
|                                    |                  | Soundness of laws and standards related to water pollution prevention and control (I₁₅) | Growth rate of urban drinking water sources (I₁₄)                           | %              |                                                      | Article 9: “...Encourage reuse of water...”                                                  |
|                                    |                  |                                                          | Soundness of laws and standards related to water pollution prevention and control (I₁₅) | -              |                                                      | Articles 35 to 39: “...Protect drinking water sources...”                                   |
|                                    |                  |                                                          | Soundness of laws and standards related to water pollution prevention and control (I₁₅) | -              |                                                      | Article 16: “...Pollution discharge permit management system...”                            |
|                                    |                  |                                                          | Soundness of laws and standards related to water pollution prevention and control (I₁₅) | -              |                                                      | Article 46: “...Strengthen the planning and construction of urban sewage centralized treatment facilities and pipe networks...” |
|                                    |                  |                                                          | Soundness of laws and standards related to water pollution prevention and control (I₁₅) | -              |                                                      | Article 11: “...Formulate environmental management measures, implementation plans and local standards...” |
Quantitative evaluation steps of the index system

After establishing the index system, a series of assessment tasks were undertaken according to the following stepwise procedure.

Step 1—Data procurement

To reflect the actual effects of the “Water Pollution Prevention and Control Regulations of Tianjin” implemented in March 2016, we evaluated the WPM performance in Tianjin on the basis of the regional policy during the 2014–2018 period. Annual data were mainly obtained from the websites of the China National Bureau of Statistics, the Statistical Yearbook of Tianjin, and the Water Resources Bulletin of Tianjin. The exact sources of the index data are enumerated in Table 2.

Additionally, we visited major reservoirs, rivers and lake basins in Tianjin and interviewed staff of the Tianjin Water Bureau and BEE in April 2019. We obtained internal data and obtained insight into the staff’s perspectives.

In the policy implementation survey, we focused not only on tangible effects but also on public satisfaction and opinion (Fu and Geng 2019; Li et al. 2018). To this end, we developed a public opinion survey that asked questions about the levels of public satisfaction with WPM in Tianjin. A total of 345 valid submissions were collected, and the complete questionnaire is provided in Appendix A.

Step 2—Calculation of indicator score

Because of the distinctive indicator measuring units, it is necessary to transfer and calculate the original data for subsequent assessments. Due to the differences between the properties of different indicators, we divided the thirty indicators into three types. The indicator score for each type was generated using different methods, and for each indicator, the way their scores are calculated is described in Table 2.

• Graded scoring method

The graded scoring method sets four grades (grades I/II/III/IV) for the performance of the indicators. The boundary values for the four grades are decided according to relevant laws, regulations and regional targets as well as the literature (Yang et al. 2018). We then compare index data with four boundary values, determine the grade of each index, and calculate the exact score as follows:

$$S_i = \frac{X_i - X_{ib}}{X_{ib}^{max} - X_{ib}^{min}} \cdot P_{ib} + S_{ib}^{min}$$  (1)
where $S_i$ is the score of the $i$th index ($I_i$); $X_i$ is the actual data of $I_i$; $b$ is grade number ranks 1 to 4, and the value of $X_i$ belongs to grade $b$; $X_{ib}^{\text{min}}$ is the minimum value of grade $b$ of $I_i$; $X_{ib}^{\text{max}}$ is the maximum value of grade $b$ of $I_i$; $P_{ib}$ is the score interval of grade $b$; and $S_{ib}^{\text{min}}$ is the minimum score of grade $b$.

| Index layer | Weight (relative to the component layer) | Weight (relative to the target layer) | Positive or negative | Grading standard | Data source |
|-------------|----------------------------------------|----------------------------------------|----------------------|-----------------|-------------|
| $I_1$       | 0.2857                                 | 0.0244                                 | P                    | $< 0$           | 5–10        | ≥ 10        | C           |
| $I_2$       | 0.2857                                 | 0.0244                                 | P                    | $0$             | 0.5–1       | ≥ 1         | C           |
| $I_3$       | 0.4286                                 | 0.0366                                 | P                    | $< -40$         | 0–40        | ≥ 40        | C           |
| $I_4$       | 0.1208                                 | 0.0190                                 | N                    |                 | Median-based standardized calculation method | D |
| $I_5$       | 0.1453                                 | 0.0228                                 | N                    | $> 20$          | 20–10      | ≤ 5         | D           |
| $I_6$       | 0.0996                                 | 0.0156                                 | P                    | $0.64–0.68$     | 0.68–0.72   | ≥ 0.72      | F           |
| $I_7$       | 0.1208                                 | 0.0190                                 | N                    |                 | Median-based standardized calculation method | D |
| $I_8$       | 0.1577                                 | 0.0248                                 | N                    |                 | Median-based standardized calculation method | D |
| $I_9$       | 0.1779                                 | 0.0279                                 | N                    |                 | Median-based standardized calculation method | A |
| $I_{10}$    | 0.1779                                 | 0.0279                                 | N                    |                 | Median-based standardized calculation method | A |
| $I_{11}$    | 0.2230                                 | 0.0558                                 | P                    | $< 15$          | 15–25      | ≥ 40        | C           |
| $I_{12}$    | 0.1609                                 | 0.0403                                 | P                    | $< 90$          | 90–95      | 95–100     | 100         | A           |
| $I_{13}$    | 0.1982                                 | 0.0496                                 | P                    | $< 0$           | 0–5        | 5–10       | ≥ 10        | D           |
| $I_{14}$    | 0.2356                                 | 0.0590                                 | P                    | $< 5$           | 5–20      | 20–40     | ≥ 40        | D           |
| $I_{15}$    | 0.1823                                 | 0.0456                                 | P                    | $< 90$          | 90–95      | 95–100     | ≥ 100       | G           |
| $I_{16}$    | 0.2128                                 | 0.0426                                 | P                    | $< 500$         | 500–600    | 600–800    | ≥ 800       | F           |
| $I_{17}$    | 0.2374                                 | 0.0475                                 | P                    | $< 25$          | 25–35      | 35–45       | ≥ 45        | A           |
| $I_{18}$    | 0.2653                                 | 0.0531                                 | P                    |                 | Median-based standardized calculation method | D |
| $I_{19}$    | 0.2844                                 | 0.0569                                 | P                    | Expert scoring evaluation method | I |
| $I_{20}$    | 0.0738                                 | 0.0227                                 | P                    | $< 80$          | 80–90      | 90–98      | ≥ 98        | C           |
| $I_{21}$    | 0.0894                                 | 0.0275                                 | P                    | $< 80$          | 80–90      | 90–98      | ≥ 98        | E           |
| $I_{22}$    | 0.0983                                 | 0.0302                                 | P                    | $< 60$          | 60–80      | 80–100     | ≥ 100       | G           |
| $I_{23}$    | 0.0808                                 | 0.0248                                 | P                    | $< 15$          | 15–30      | 30–40       | ≥ 40        | D           |
| $I_{24}$    | 0.1078                                 | 0.0331                                 | P                    | $< 90$          | 90–95      | 95–100     | ≥ 100       | B&C         |
| $I_{25}$    | 0.0706                                 | 0.0217                                 | P                    | $< 0$           | 0–50       | 50–100     | ≥ 100       | G           |
| $I_{26}$    | 0.0867                                 | 0.0266                                 | P                    | $< 0.4$         | 0.4–1.2    | 1.2–2      | ≥ 2         | C           |
| $I_{27}$    | 0.1058                                 | 0.0325                                 | P                    | Expert scoring evaluation method | H |
| $I_{28}$    | 0.1058                                 | 0.0325                                 | P                    | Expert scoring evaluation method | H |
| $I_{29}$    | 0.0855                                 | 0.0263                                 | P                    | $< 1$           | 1–1.5     | 1.5–3       | ≥ 3         | C           |
| $I_{30}$    | 0.0957                                 | 0.0294                                 | P                    | Expert scoring evaluation method | H |

*Data source:
A. Website of China National Bureau of Statistics
B. Website of Tianjin Eco-Environment Bureau
C. Statistical Yearbook of Tianjin (2013–2018)
D. Water Resources Bulletin of Tianjin (2013–2018)
E. Environmental Status Bulletin of Tianjin (2013–2018)
F. Calculated from statistical yearbook data
G. Obtained from relevant government departments
H. Scored by experts
I. Scored according to Public Satisfaction Questionnaire Survey
Twenty of the thirty indicators used in the index system are calculated according to this method.

- **Median-based standardized calculation method**

The median-based standardized calculation method calculates the median score for the five-year period. This method is applied to six of thirty indicators in the index system. Due to differences in natural resource endowment, population, economic development level and other factors, these values cannot be directly compared with the national and global average levels. Therefore, it is deemed more appropriate to reflect the growth or decline of the data obtained for Tianjin across a sample of multiple different years. The specific calculation method is as follows:

\[
S_i = S_0 \cdot \left(1 \pm \frac{X_i - X_i^{\text{median}}}{X_i^{\text{median}}} \right)
\]

where \(X_i^{\text{median}}\) is the median of \((I_i)\) from 2014–2018; set \(S_0 = 80\) when the index is positive, use “+” from “±”; when the index is negative, use “−” from “±”; when the value of \(S_i > 100\), set \(S_i = 100\).

- **Expert scoring method**

In addition to the two calculation methods above, there are four indicators related to the perfection of the WPM system and public satisfaction in the proposed index system, which need to be assigned quantitatively. According to the expert scoring method, indicator values are decided by numerous experts in the water management field based on extensive and in-depth investigation and supporting materials.

**Step 3—Calculation of indicator weight**

The relative weighting of different indicators can have a significant impact on the overall index ranking of the study area and on subsequent policy decisions. This is because relative indicator weights may significantly differ depending on the chosen weighting procedure (Mikulić et al. 2015). According to the results of most studies, common weighting methods can be segregated into two categories: subjective weighting and objective weighting. To address the presence of extreme values for several indicators in various years without unduly skewing the overall results, we choose the analytic hierarchy process (AHP) to calculate each indicator’s weight.

Created by Saaty (2004), the AHP is a methodology in which an importance level is selected according to a comparison between parameters (Sun et al. 2016). The AHP provides a framework to handle decisions without making assumptions about the independence of higher-level elements from lower-level elements or about the independence of the elements within a level (Do et al. 2013; Saaty 2008).

In this paper, we conduct AHP twice among the component layer and the index layer in the same component layer. The importance levels were chosen by water management experts according to requirements in water pollution prevention and control. The main calculation processes are as follows:

First, construct an evaluation matrix. In n-criteria evaluation matrix \(A\), every element \(a_{ij}(i, j = 1, 2, \ldots, n)\) is the quotient/ratio of the preference values attached to the criteria, as shown in the following matrix (Gao and Hailu 2013):

\[
A = \begin{pmatrix}
1 & \cdots & a_{in} \\
\vdots & \ddots & \vdots \\
a_{n1} & \cdots & 1
\end{pmatrix}
\]

where \(a_{ij} > 0; a_{ii} = 1/a_{ii}\); and \(a_{ii} = 1\).

Next, derive the criteria weight. The consistency index (CI) is used to determine whether and to what extent decisions violate the transitivity rule, and the equation provides optimal results when CI < 0.1 (Feng et al. 2014; Saaty 2006):

\[
\text{CI} = (\lambda_{\text{max}} - n) / (n - 1)
\]

where \(\lambda_{\text{max}}\) is the largest eigenvalue of matrix \(a\), \(n\) is the order of matrix \(A\), and \(\lambda_{\text{max}}\) is calculated as follows (Feng et al. 2014):

\[
\lambda_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n} \frac{(A\omega)_i}{\omega_i}
\]

The weight of an index is calculated using the importance scales in the second and fourth layers. For this process, the square-root method is used as follows (Feng et al. 2014; Saaty 2006; Sun et al. 2016):

\[
m_i = \prod_{j=1}^{n} a_{ij}, i = 1, 2, \ldots, n
\]

\[
\bar{\omega}_i = \sqrt[n]{m_i}, i = 1, 2, \ldots, n
\]

\[
\omega_i = \frac{\bar{\omega}_i}{\sum_{k=1}^{n} \bar{\omega}_k}
\]

The calculation result of the indicator weight can be checked in Table 2. The above results pass the consistency test.

**Step 4—Calculation of annual WPM scores in Tianjin**

After indicator weights are computed according to the AHP method, the annual WPM scores in Tianjin are calculated. It is inevitable for missing values to occur in the
underlying data supporting such an index system, and there are three missing values for every 150 data points. Consequently, we calculate the scoring rate as a reasonable approach to avoid imbalance due to blank values for specific years and indicators. Finally, we regard the calculated rate as the annual scores for regulation implementation.

\[ S_{new} = \sum_{i=1}^{n} \frac{S_i + W_{ic} + W_{ct}}{100 + W_{ic} + W_{ct}} \times 100\% \quad \text{if} \text{isnotmissingvalue} \]  

where \( W_{ic} \) is the weight of the \( i \)th index relative to the component layer; \( W_{ct} \) is the weight of the \( c \)th component relative to the target layer; and \( n \) is the number of indicators.

**Results**

**Results of indicator system assessment**

**Results for factor layer**

The results for the factor layer and component layer are shown in Figs. 5 and 6. When analysed according to sub-element layers, the factors in different element layers have differentiated performance. Starting with the response, there was a significant difference between the environmental response and management response scores in the early stage. However, after four years of growth, the final results of the two are similar at 91 and 90.4, respectively, and the management response exceeds the environmental response. This reveals that the environmental requirements of Tianjin city are high in terms of water pollution treatment, and the implementation of relevant policies has dramatically promoted management-level reform. Regarding the impact, the scores of all three factors show a continuous growth trend, but the final score of public impact is only 85, leaving room for growth. For the state, the water state assessment score increased from 74.6 to 96, which is the highest score among all factor layers. This significant increase indicates that Tianjin’s water quality and quantity have improved significantly, and water pollution prevention has had a significant effect. Next, for the pressure component, water use and water environment are evaluated. Although there has been some improvement in water conservation and emission reduction, Tianjin is slightly inferior in these two areas compared to the other factors. The performance of the factors in the drive component is also noteworthy. First, the economic score decreases yearly, from 100 in 2014 to 74.4 in 2018. The economic development of Tianjin needs to be improved. Second, the society score fluctuates, increasing and decreasing and reaching a peak in 2016. The score in 2018 reached 94.2 points, much higher than the score of 80.5 points in the initial year. This indicates that the social aspect is also subject to greater inter-annual variability due to a higher number of factors.

**Results of the component layer and interaction between components**

The component layers help explain the changes in scores. The score of the driver component (\( C_1 \)) fluctuated wildly from 2014 to 2018, with a maximum value of 95.67 in 2016 and a minimum value of 77.82 in 2017. The performance of the pressure component (\( C_2 \)) increased gradually during the study period. In 2014 and 2015, its scores were nearly the same, at 75 and 76. Then, the scores improved and finally reached 85.81 in 2018. Similarly, the state component (\( C_3 \)) increased greatly over time, from 74.58 in 2014 to 96.02 in 2018. For the impact component (\( C_4 \)), the highest scores of 89.88 was achieved in 2018, and scores improved by 1.01, 4.00, 6.55 and 2.75 in 2015, 2016, 2017 and 2018.
respectively. Responses consist of two factors and eleven indicators and account for nearly 30% of the total weight within the whole index system.

The association can be fed back to their corresponding index scores because of the interaction among the five components in the DPSIR model. The interaction path between DPSIR components (see Fig. 4) can explain the index scores.

- The economic and social indicators in the Driver component ($C_1$) drive the variation in the Pressure component ($C_2$). Due to fluctuations in the Driver component ($C_1$) scores for water resources per capita, and despite the government’s efforts to regulate water use and the water environment, the Pressure component ($C_2$) score was still generally below 85. Its growth slowed during 2017, reflecting the pressure on water use and pollutant discharge.

- It is encouraging to note that the slow growth in Pressure component ($C_2$) led to a significant improvement in the State component ($C_3$), which was related to the increased focus on water quality and compliance and usage rates by the government and the public in assessing water pollution.

- Further, the State component ($C_3$) contributed to the improvement in the Impact component ($C_4$), and there was a significant year-on-year increase in the Response component ($C_5$).

- In fact, in the Response component ($C_5$), both environmental and policy management responses dynamically influenced the other four components. Thus, under the dynamic model architecture of interaction, the water pollution work in Tianjin continues to progress.

**Inter-annual variation in target layer scores**

Finally, a comprehensive assessment was undertaken to evaluate the overall change in WPM scores in Tianjin across the study years (Table 3). With scores of 76.15 in 2014 and 76.62 in 2015, the water pollution situation improved slightly, and the rate of this improvement was calculated as 0.47 units per year. However, after the implementation of the “Water Pollution Prevention and Control Regulations of Tianjin”, sharp growth occurred in 2016, which was followed by sustained increases in scores. Finally, the overall score in 2018 was 90.93. During 2016—2018, the rate of improvement was 4.36 units per year, nearly ten times that during the 2014 to 2015 period. In general, the implementation of the “Water Pollution Prevention and Control Regulations of Tianjin,” together with water management efforts during these years, was effective.

**Actual improvement in water pollution**

The results presented in Fig. 6 show that the water state ($F_3$) layer index score emerged as the most prominent component. Diverging from the inter-annual fluctuation of scores in other index layers, the water state component scores maintained a
growth trend of more than 5 points per year starting in 2016 and reached 96.0 by 2018. This outstanding performance is mainly attributed to the improvement in water pollution in Tianjin. In fact, the 2019–2020 period showed further improvement in water quality and the water environment.

Changes in water quality are closely related to the source discharge of pollutants. Industry and construction activities are currently the main sources of wastewater in Tianjin, accounting for more than 40% of the city’s total wastewater emissions during the study years (Table 4). In terms of industrial pollutant emissions, the chemical oxygen demand (COD) and ammonia nitrogen showed similar trends of change. They both plummeted to less than 40% from the previous year in 2016 and maintained significant declining trends thereafter. The specific pollutant data are presented in Table 5.

The “Proportion of Class I-III water quality sections in National Examination Sections” is an important indicator of water quality in China, which includes the pH value, COD, BOD, ammonia nitrogen, total phosphorus, heavy metal concentration, etc. Water with the highest quality is categorized into Class I, and water with the poorest quality is categorized as Class III. The use of this indicator grew over the five-year period from 2016 to 2020, and the specific data can be seen in Table 6. By 2020, according to the different categories of water quality measurement standards, 55% of water bodies had reached the standard of “secondary protected areas of centralized surface water sources for living drinking water, fish and shrimp overwintering grounds, swimming channels, aquaculture areas and other fishing waters and swimming areas”. Thus, the water met the production and living water needs of Tianjin residents.

Meanwhile, the indicators “Penetration rate of urban water”; “Growth rate of total water storage of large and medium-sized reservoirs at the end of the year”; “Compliance rate of water functional zone evaluation based on full indicators”; and “Average utilization rate of water resources” also showed improvements in the study years, indicating that water pollution control in Tianjin has indeed achieved good results.

### Discussion

Based on the evaluation results of the index system under the DPSIR model, this paper has identified several deep-seated challenges related to WPM that are worth analysing further. The findings reveal the reasons for the improvement in the state component \( (C_3) \), the WPM situation, as well as public satisfaction and participation. Furthermore, as a representative of cities in China or cities in other developing countries that are experiencing water shortages and related pressures, Tianjin’s experience with implementing WPM measures has particular research value.

### Key measures to reduce emissions and improve water quality

#### Closure and remediation of industrial high-pollution and high-emission enterprises

Pollutants discharged from industrial sources have been reduced significantly, and the main paths of source emissions reductions in Tianjin are clear.

To achieve these gains, the Tianjin municipal government shut down and renovated several industries and developed centralized sewage treatment plants within industrial agglomeration areas. In response to the national requirements, the Tianjin municipal government completely banned 10 types of small-scale industries, including miniature paper making, leather making, printing and dyeing, dyes, coking, sulphur refining, arsenic refining, oil refining, electroplating, and pesticides. At

### Table 4 Discharge of wastewater from different sources in Tianjin

| Source                      | 2015          | Proportion (%) | 2016          | Proportion (%) | 2017          | Proportion (%) | 2018          | Proportion (%) |
|-----------------------------|---------------|----------------|---------------|----------------|---------------|----------------|---------------|----------------|
| From urban residents        | 1.8463        | 30.8           | 2.3382        | 34.5           | 2.4308        | 34.5           | 2.7935        | 35.6           |
| From industry and construction | 3.3996      | 56.8           | 3.5969        | 53.2           | 3.5510        | 50.3           | 3.4764        | 44.2           |
| From tertiary industry      | 0.7406        | 12.4           | 0.8315        | 12.3           | 1.0703        | 15.2           | 1.5882        | 20.2           |
| From the whole city         | 5.9865        | 100.0          | 6.7666        | 100.0          | 7.0521        | 100.0          | 7.8584        | 100.0          |

*Data source: Water Resources Bulletin of Tianjin (2013–2018)*
the same time, the government formulated special treatment plans for the industries of paper making, coking, nitrogen fertilizer, non-ferrous metals, printing and dyeing, leather making, etc., and implemented cleaner renovation for such enterprises. From 2015 to 2019, more than 21,900 scattered and high-pollution enterprises were comprehensively reformed, an effort that significantly contributed to the overall progress of the region’s WPM programme. To promote centralized wastewater treatment, the Tianjin municipal government encouraged scattered enterprises to move into industrial parks, which is common in China. This centralization makes supervision more convenient and makes it easier to meet the requirements of relevant standards (Amiri et al. 2019). By the end of 2016, a total of 60 national and municipal industrial clusters in Tianjin had completed the construction of centralized sewage treatment facilities and installed automatic online monitoring devices, leading to improved discharge performance.

**Regulatory management of agricultural aquaculture**

After the promulgation of the Water Pollution Prevention Regulations of Tianjin, emissions from agricultural sources decreased rapidly through livestock and poultry excrement pollution management and aquaculture pollution controls, similar to other regions in China (Sun et al. 2019; Zou et al. 2020). According to the Tianjin Statistical Yearbook, the discharge of COD and ammonia nitrogen from agricultural sources dropped sharply in 2016, with the emissions of COD reaching only 14.93% of their 2015 level and ammonia nitrogen emissions reaching only 1.74% of their 2015 level. Relevant departments have carried out a great deal of work. Tianjin designated a livestock and poultry breeding exclusionary zone in 2016, closed or relocated livestock and poultry farms in the exclusionary zone, and assisted farms with pollution treatment. By 2018, the matching rate of excrement treatment facilities for large-scale livestock and poultry farms in Tianjin reached 75%, and the utilization rate of excrement resources reached 76.5%. For aquaculture pollution control, more than 66.7 million m² of freshwater aquaculture ponds were renovated, and individual aquaculture farmers who failed to meet the sewage treatment standards were shut down or relocated in 2016. The municipal government actively promoted the recycling of aquaculture wastewater, which can be discharged only after it reaches permissible quality standards, thus greatly reducing pollutant discharge.

**Pathways and policies for water pollution management**

According to the results presented in Fig. 5, the scores for management response ($F_{10}$) also exhibited a significant positive growth trend. In 2014–2016, the scores were only slightly higher than 70 points, while in 2017 and 2018, they were significantly higher. By 2018, the score was 89.3, which means that there is still room for improvement in response to WPM. Nevertheless, Tianjin has introduced many important management policies for water pollution prevention and control since 2017. Prominent among them are the river chief system, the issuance of pollutant discharge permits for heavy pollution industries, the development of relevant discharge standards, and ecological compensation agreements. A detailed discussion of these specific management policies is provided in the following sections.

**Emission control at the source**

Currently, for the management of water pollution in Tianjin and China as a whole, source control is regarded as the most effective and fundamental means. There are relevant pollutant discharge standards and discharge permits and administrative orders in place. In addition to the aforementioned shutdowns and standardization, the raised standards in Tianjin in recent years have laid a solid institutional foundation for good control at the source. In July 2017, the MEE issued a List of Classified Management of Pollutant Discharge Permits for Fixed Pollution...
Sources, stipulating the classified management and orderly issuance of such permits nationwide. Additionally, the list restricted the duration of issued pollutant discharge permits for different industry categories. As one of the key cities, Tianjin completed the issuance of pollutant discharge permits for enterprises in ten industries with high pollution, such as paper making and coking, in 2017 and in 20 industries, such as starch and built-up area sewage treatment plants, by the end of 2018. Furthermore, pollutant discharge permits have covered all fixed pollution sources since 2020 in Tianjin.

In terms of discharge standards, Tianjin issued its Urban Sewage Treatment Plants Pollutant Discharge Standard (DB12/599–2015) in October 2015. Considering the requirements of water functional areas, differentiated emission limits are determined depending upon the design throughput of sewage treatment plants and the normal concentrations of general pollutants in the wastewater stream (categorized on an A/B/C level). The standard has been implemented in existing sewage treatment plants since 2018, and 108 sewage treatment plants were renovated by the end of 2018. In 2018, Tianjin revised the local Comprehensive Sewage Discharge Standard (DB12/356–2008) implemented in 2008, greatly reducing the permissible emission rates for several major pollutants. For example, the limit of CODCr in the first-class standard was adjusted from 50 mg/L to 30 mg/L; ammonia nitrogen (calculated by N) was adjusted from 5 mg/L to 3 mg/L. In addition, similar reductions have been proposed for other pollutants (such as volatile phenol and sulphide). After the implementation of the above two standards, black and odorous surface waters were effectively eliminated, with distinct improvements in overall water environment quality throughout the city.

Upstream water quality control

The upstream and downstream transfer of pollutants cannot be avoided, and as a downstream city, Tianjin’s water pollution is closely linked to the discharge of upstream cities.

Ecological compensation agreements on water pollution have been established to promote the upstream and downstream cooperative management process, which means that once upstream provinces meet the agreed-upon water quality requirements, downstream provinces and even the central government pay them fees (Cheng et al. 2020; Wang et al. 2019). This type of compensation has been used as a tool in WPM programmes in other areas of China in recent years (Gao et al. 2019). As an important drinking water source of Tianjin, the Yuqiao Reservoir’s water quality is affected by Hebei province upstream. To improve the water quality in this reservoir, a three-year ecological compensation agreement was established in 2016. With a total of 1.5 billion yuan invested by the national government, Tianjin’s municipal government and Hebei’s provincial government in 2016–2018, water source protection and water pollution prevention projects were conducted in Panjiakou, the Daheiting River Basin, and the upper reaches along the Luanhe River. Two provincial monitoring stations were set up to measure the concentration levels of pollutants such as permanganate and to measure pH levels. From 2016 to 2018, both sections met the requirements for drinking water sources, proving that water quality had significantly improved (Central People’s Government of the People’s Republic of China, 2019).

In addition to ecological compensation between provinces, Tianjin formulated the Measures for the Monthly Ranking of Surface Water Environmental Quality in Districts, ranking the surface water quality within each district on a monthly basis. Lower-ranking districts need to pay money to compensate the top-ranking districts, forcing the upper- and lower-level districts to protect the river and reduce water pollution jointly.

Conclusions

The DPSIR framework was used to evaluate the performance of WPM. According to the evaluation results, the WPM situation improved little from 2014 to 2015. However, after the implementation of the regional policy, sharp growth occurred in 2016, followed by a sustained increase; finally, the score in 2018 reached 90. In general, the implementation of the “Water Pollution Prevention and Control Regulations of Tianjin”, together with water management efforts made these years, were effective.

Through the analysis of regional water pollution control policies, pathways and measures, we reveal that good results have been achieved in controlling industrial and agricultural pollution sources. Additionally, we clarified the main paths of emission reduction in Tianjin, including renovating industrial clarify with high pollution discharge, conducting strict livestock and poultry excrement pollution management, and controlling aquaculture pollution. The analysis of the reasons for improvement proves the effectiveness of the regulations and government work and provides a reference for other countries and regions committed to promoting WPM. The shortcomings and deficiencies identified through the evaluation of the index system, such as an inadequate public participation mechanism, should be a focus of the government and scholars in the future.

The index system set up in this paper has comprehensive, systematic, and scientific characteristics based on a comparison with the contents of the “Water Pollution Prevention and Control Regulations of Tianjin”. It is meaningful for the evaluation of regional water pollution control policies. At the same time, this study has limitations, such as the use of subjective factors in index selection and weight determination. The index setting is worthy of further discussion and refinement. In the future, different evaluation methods can
be adopted to analyse the effects of policy implementation, and the credibility of the evaluation results can be improved through a comprehensive and multi-faceted assessment.

Appendix A

1. Age:
☐ Under 20 ☐ 20-40 ☐ 41-60 ☐ 60 and above
2. Gender: ☐ Male ☐ Female
3. Level of education: ☐ Primary school and junior high school ☐ Senior high school and technical secondary school ☐ Undergraduate ☐ Postgraduate and above
4. Occupation: ☐ Government staff ☐ College and public institution staff ☐ Enterprise staff ☐ Students ☐ Unemployed and retired staff

Part 2: Public assessment of water environment
1. Are you concerned about water pollution in daily life?
☐ Very concerned ☐ Concerned ☐ A little concerned ☐ Never concerned
2. Do you think the water pollution in Tianjin is serious this year?
☐ Very serious ☐ Serious ☐ A little serious ☐ Not serious at all
3. Does the water pollution in Tianjin and surrounding areas affect your daily life?
☐ Cause serious impact ☐ Cause slight impact ☐ Almost no impact
4. If water pollution seriously affects your daily life, what measures will you most likely to take?
☐ Complain to local government ☐ Negotiate with pollution enterprises ☐ Seek help from media ☐ Others
5. What do you think of the current water pollution situation in Tianjin compared with previous years?
☐ More serious ☐ Nearly the same ☐ Better ☐ Much better
6. Do you know the river chief policy in Tianjin?
☐ Understand and pay close attention ☐ Have heard about ☐ Never heard about
7. What do you think of the effect of the river chief policy in Tianjin?
☐ Pretty good ☐ Good, and still need improvement ☐ Almost no effect ☐ Don’t understand
8. Do you think Tianjin’s drinking water reserves should be open to the public?
☐ Should be open, for better public participation ☐ Should not be open, for better protection of water resources ☐ Both is OK
9. What do you think of the attitude of Tianjin government towards water environment management?
☐ Pay more attention to final result ☐ Pay more attention to formalism ☐ Lack of attention
10. Are you satisfied with the water environment management work of Tianjin government?
☐ Very satisfied (Scored 86-100) ☐ Satisfied (Scored 76-85) ☐ Not very satisfied (Scored 60-75) ☐ Unsatisfied (Scored under 60)
11. Are you satisfied with the water environment management effect of rivers and lakes in Tianjin?
☐ Very satisfied (Scored 86-100) ☐ Satisfied (Scored 76-85) ☐ Not very satisfied (Scored 60-75) ☐ Unsatisfied (Scored under 60)
12. What effects do you think Tianjin government has achieved in water environment management in recent years?
☐ Less peculiar smell ☐ Clearer water ☐ Less flotage and suspended matter ☐ Better greening of river banks ☐ Others
13. What are the deficiencies in the water environment management in your region?
☐ Relevant laws and regulations need to be improved ☐ Law enforcement needs to be strengthened ☐ Law punishment needs be strengthened ☐ Public propaganda needs to be improved ☐ Public participation mechanism is not good enough ☐ Others
14. Are you willing to participate in water environment management?
☐ Yes ☐ No
15. What do you think are feasible ways for public to participate in water environment management?
☐ Participate in public hearings and relevant meetings ☐ Participate in relevant public welfare activities ☐ Report adverse activities ☐ Express opinions through questionnaires ☐ Others
Appendix B

Results of public satisfaction questionnaire.

Table 7 Composition of respondents

| Gender             | Male   | 43.77% | Female | 56.23% |
|--------------------|--------|--------|--------|--------|
| Age structure      | Under 20 | 9.28%  | 20–40  | 49.86% |
|                    | 41–60  | 20.87% | 60 and above | 20%    |
| Education          | Primary school and junior high school | 7.83% | Senior high school and technical secondary school | 13.04% |
|                    | Undergraduate | 37.97% | Postgraduate and above | 41.16% |
| Occupation         | Government staff | 16.23% | College and public institution staff | 24.64% |
|                    | Enterprise staff | 16.23% | Students | 26.67% |
|                    | Unemployed and retired staff | 16.23% |

Table 8 Public assessment of water environment

| Questions                                                                 | Results                          | Proportion |
|---------------------------------------------------------------------------|----------------------------------|------------|
| Are you concerned about water pollution in daily life?                    | Very concerned                   | 48.7%      |
|                                                                            | Concerned                        | 42.32%     |
|                                                                            | A little concerned               | 8.99%      |
|                                                                            | Never concerned                  | 0%         |
| Do you think the water pollution in Tianjin is serious this year?         | Very serious                     | 26.96%     |
|                                                                            | Serious                          | 59.71%     |
|                                                                            | A little serious                  | 5.22%      |
|                                                                            | Not serious at all               | 8.12%      |
| Does the water pollution in Tianjin and surrounding areas affect your daily life? | Cause serious impact              | 14.2%      |
|                                                                            | Cause slight impact              | 66.38%     |
|                                                                            | Almost no impact                 | 19.42%     |
| If water pollution seriously affects your daily life, what measures will you most likely to take? | Complain to local government | 53.62% |
|                                                                            | Negotiate with pollution enterprises | 3.19%     |
|                                                                            | Seek help from media             | 15.94%     |
|                                                                            | Others                           | 27.25%     |
| What do you think of the current water pollution situation in Tianjin compared with previous years? | More serious                     | 8.12%      |
|                                                                            | Nearly the same                  | 19.42%     |
|                                                                            | Better                           | 56.23%     |
|                                                                            | Much better                      | 16.23%     |
| Do you know the river chief policy in Tianjin?                            | Understand and pay close attention | 8.99%      |
|                                                                            | Have heard about                 | 51.01%     |
|                                                                            | Never heard about                | 40%        |
| What do you think of the effect of the river chief policy in Tianjin?     | Pretty good                      | 29.95%     |
|                                                                            | Good, and still need improvement | 54.11%     |
|                                                                            | Don’t understand                 | 15.94%     |
| Do you think Tianjin’s drinking water reserves should be open to the public? | Should be open, for better public participation | 52.46%     |
|                                                                            | Should not be open, for better protection of water resources | 43.19%     |
|                                                                            | Both is OK                       | 4.35%      |
| What do you think of the attitude of Tianjin government towards water environment management? | Pay more attention to final result | 45.51%     |
### Table 7 and 8 (continued)

| Questions                                                                 | Results                        | Proportion |
|---------------------------------------------------------------------------|-------------------------------|------------|
| Are you satisfied with the water environmental work of Tianjin government? | Very satisfied (Scored 86–100) | 9.57%      |
|                                                                            | Satisfied (Scored 76–85)      | 48.41%     |
|                                                                            | Not very satisfied (Scored 60–75) | 39.42% |
|                                                                            | Unsatisfied (Scored under 60) | 2.61%      |
| What effects do you think Tianjin government has achieved in water environmental management in recent years? | Clearer water | 32.46% |
|                                                                            | Less flotage and suspended matter | 48.7%    |
|                                                                            | Better greening of river banks | 54.49%   |
|                                                                            | Others                        | 2.61%     |
| What are the deficiencies in the water environmental management in your region? | Relevant laws and regulations need to be improved and Law punishment needs to be strengthened | 48.7% |
|                                                                            | Law enforcement needs to be strengthened | 55.94% |
|                                                                            | Public propaganda needs to be improved | 50.43% |
|                                                                            | Public participation mechanism is not good enough | 51.3% |
|                                                                            | Others                        | 2.32%     |
| Are you willing to participate in water environment management?            | Yes                           | 95.07%    |
|                                                                            | No                            | 4.93%     |
| What do you think are feasible ways for public to participate in water environment management? | Participate in public hearings and relevant meetings | 55.07% |
|                                                                            | Participate in relevant public welfare activities | 73.62% |
|                                                                            | Report adverse activities      | 58.84%    |
|                                                                            | Express opinions through questionnaires | 57.97% |
|                                                                            | Others                        | 4.64%     |

### Author contribution
All authors contributed to the study conception and design. Mo Zhang and Meiting Ju contributed the central idea and design the research. Material preparation, data collection and analysis were performed by Yujia Wang, Yan He, Chonggang Yang. The first draft of the manuscript was written by Yujia Wang. Chonggang Yang worked very hard during the revision process. All authors read and approved the final manuscript.

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### Data availability
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

### Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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