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Ecological Safety Evaluation for Water Resources of China Based on Pressure-State-Response Model: A Case from Zhoushan Archipelago

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ABSTRACT

Water resource ecological safety is a key factor in regional economic and social development. The comprehensive evaluation of water resource ecological safety is an important precondition for realizing regional sustainable development with the increasingly serious water ecological crisis. Zhoushan City of China was taken as an example, and the pressure–state–response model (PSR) was used to evaluate the ecological safety status of regional water resources, improve deficiencies in the existing evaluation index system and evaluation method effectively, and put forward three evaluation subsets (18 evaluation indexes). An evaluation index system was established based on these indexes to evaluate the water resource ecological safety. Combined weights of indexes were calculated using the analytic hierarchy process (AHP) and entropy weight method, and water-resource ecological safety indexes were used to evaluate the water-resource ecological safety status in Zhoushan City during 2010–2019. Results show that the water-resource ecological safety level in Zhoushan City during 2010–2019 presents a rising trend and transformed from a serious warning state into a medium warning state as well as a relatively safe state and safe state. This transformation indicates that the ecological safety status in Zhoushan City gradually improves. The comprehensive evaluation value is the minimum (0.15) under the serious warning state in 2013 and the maximum (0.85) under the safe state in 2019. Ammonia nitrogen and chemical oxygen demand (COD) emissions in industrial wastewater, total water supply throughout the year, and governance area of water and soil loss are the main factors that influence the water resource ecological safety in the city. The ecological safety level of regional water resources can be effectively elevated through key measures, such as increasing the water resource supply throughout the year, reducing the application of pesticides and chemical fertilizers, and reducing the discharge of pollutants, including COD and ammonia nitrogen in industrial wastewater. The water resource ecological safety evaluation model based on the PSR model and AHP–entropy weight method that demonstrates a certain application value can provide a novel idea and method to support the ecological safety evaluation of regional water resources.

INTRODUCTION

Water resources constitute an important material basis for human survival and development, and the development and utilization have a direct bearing on people's life, production development, and ecological environment. Water safety has become a key factor in restricting regional social and economic sustainable development with the increasing global population, rapid economic development and urbanization, and increasingly evident water resource security problems, such as water resource shortage, water environment pollution, and sudden water pollution (Uddameri 2019, Chen et al. 2017). Water resource security problems are caused by the mutual influence and restriction of water, nature, economy, and society. Such problems have attracted considerable attention from global and academic communities, making them an important research topic in many internal conferences held by governments and international organizations. Meanwhile, water resource security problems have driven domestic (Chinese) and foreign scholars and experts to investigate water resource security and related problems from various angles, such as water quality evaluation, water-resource ecological safety evaluation, water environmental management, and sustainable development (Shamir 2017, Cao et al. 2018, Zeng et al. 2016, Kourgialas et al. 2018). The quantification and evaluation of water resource ecological safety, namely, effective evaluation of water safety status of a region or drainage basin, constitutes a fundamental and important part of water safety research. The results determine the scientificity of water resource security evaluation and directly guide the follow-up formation of regional water resource utilization and management countermeasures. Therefore, the objective evaluation of regional water-resource safety status is a necessary precondition for facilitating regional comprehensive, coordinated, and sustainable socioeconomic development as well as maintaining the continuous virtuous cycle of the ecological environment system. Consequently, the regional water-resource safety status has become an important domestic and foreign research topic in the field of water resources.

Water-resource ecological safety evaluation has become a fundamental means for investigating water safety, and scholars have achieved certain progress in the water-resource ecological safety evaluation system and method. Hamilton et al. put forward monitoring approaches with an extensive scope using hazard analysis and critical control point to optimize water-resource safety risk management through a simple mechanism and thus ensure the water resource ecological safety (Hamilton et al. 2006). Dickson et al. established a water security framework for rural, remote, or marginalized communities and evaluated water safety after discussing dimensions and indexes within the framework (Dickson et al. 2016). Norman et al. evaluated the water safety status using the index evaluation method and carried out an empirical demonstration in one community in Canada (Norman et al. 2013). Gain et al. stated that the water resource ecological safety depends not only on the physical availability of freshwater resources relative to water demand but also on social and economic factors, such as sound water resource planning and management method, the ability of institutions to provide water services, and sustainable economic policies (Gain et al. 2016). Jiang et al. used the entropy weight method to establish a complete evaluation system from living water safety, economic water safety, municipal water safety, and ability to prevent water disasters; evaluated the water safety status in the Asia–Pacific region; and demonstrated the optimal water safety status in Australia, New Zealand, Malaysia, and Singapore within the Asia-Pacific Region (Jiang et al. 2015). Zhang et al. formed a water-safety evaluation index system via the analytic hierarchy process (AHP) that can boost the correct evaluation of water safety status in Taizhou City and determine chemical oxygen demand (COD), river pollution percentage, annual precipitation, and municipal water reutilization rate as main factors that influence the water safety status in Taizhou City (Zhang et al. 2017). Shen et al. established a water safety evaluation model through an information entropy-based fuzzy set, determined the water safety evaluation grade by calculating the fuzzy degree of connection and confidence criterion, and evaluated the water safety status in eight administrative regions of Qinghai Province (Shen et al. 2016). Xu et al. used principal component (PCA) and grey relational (GRA) analyses to determine 16 ecological safety evaluation indexes for oasis groundwater in the arid region of Xinjiang and evaluated the groundwater ecological safety status of five irrigation canals through the fuzzy comprehensive evaluation method (Xu et al. 2018). Xu et al. conducted a comprehensive evaluation of water resource sustainability in mainland China using three-layer indexes of water resource quantity, use intensity, and use efficiency and divided China into high, medium, low, and very low regions according to comprehensive evaluation values (Xu et al. 2019). Bui et al. proposed a technical framework for the groundwater-resource ecological safety evaluation based on conventional sustainable development evaluation and AHP methods (Bui et al. 2019). Although foreign studies on the water-resource ecological safety evaluation have achieved considerable progress, the following aspects require further investigation: (1) the evaluation index system fails to reflect correlations among various factors comprehensively and underlying reasons that influence the regional water-resource ecological safety and (2) most scholars have only used single methods to calculate index weights, such as independent application of subjective weighting methods (Olivares et al., 2020; Ren et al., 2019), AHP or objective weighting approaches (Jenifer et al. 2017, Cheng et al. 2019), and entropy weight method. However, errors in index weights determined by single methods will seriously impact the evaluation result.

Therefore, the water-resource ecological safety problem has gradually become an important topic in domestic and foreign academic investigations that have achieved certain research progress. The pressure–state–response model (PSR) is used in this study to solve problems, such as a weak correlation between evaluation indexes and low accuracy of index weights because it can reflect correlations among evaluation indexes and explore the underlying reasons for changes in the ecological safety status of regional water resources. Meanwhile, the AHP–entropy weight method can evade errors caused by the independent use of objective or subjective weight determination methods and accurately evaluate the ecological safety status of regional water resources. The ecological safety evaluation method of water resources based on the PSR model and AHP–entropy weight method in this study will provide a theoretical basis for establishing and optimizing the research system of water resource ecological safety.

The remainder of this study is organized as follows. The study area of the water-resource ecological safety evaluation and data sources are described in Section Two. The PSR model used in the water-resource ecological safety evaluation was analyzed; pressure, state, and influence indexes were established; comprehensive index weights were solved, and comprehensive evaluation indexes were determined in Section Three. The ecological safety evaluation results of water resources in Zhoushan City were obtained and the water-resource ecological safety status was analyzed and discussed from the four aspects of pressure system, state system, response system, and comprehensive evaluations in Section Four. Finally, the entire study was summarized and conclusions were drawn.

OVERVIEW OF THE STUDY AREA

Zhoushan City is located in the coastal region of Zhejiang Province in southeastern China between east longitude of 121°30′-123°25′ and north latitude of 29°32′-31°04′, with a land area of approximately 1,440.12 km^2 and a sea area of 20,800 km^2. The city is on the western side of the west and low in the north, with a subtropical monsoon climate. Zhoushan is a typical island city and the first to be built on islands. Zhoushan Archipelago is the largest in China consisting of over 4,000 islands. Adjoining large cities, such as Hangzhou and Shanghai, with many geographical advantages, Zhoushan City is an important outward sea portal and channel in the Yangtze River Delta Economic Belt and also a principal port city in China. The geographic location of Zhoushan city is shown in Fig. 1.

Zhoushan Archipelago is an island region and intrinsically deficient in water resources. Its average annual total quantity of water resources is 574,000,000 m^3 and per capita quantity of water resources is 600 m^3, which is only 25.4% that of the entire Zhejiang Province, 23.6% that of China, and one-twelfth that of the world; hence, the archipelago demonstrates the serious shortage of water resources (Qiu et al. 2017). The small average annual precipitation (1,185.85 mm) and evaporation (1,417.59 mm) from the water surface in this region result in a significantly lower runoff volume than that of mainland regions at the same latitude. Moreover, the average annual runoff depth of 550 mm is only equivalent to 58% of the average level of the entire Zhejiang Province. The water transfer and diversion for replenishment are difficult and the freshwater resource shortage worsens due to poor water resource share ability between islands. Meanwhile, the availability of runoffs generated is low and most runoffs are directly discharged into the sea due to special landforms within the archipelago, such as low hills and mountains. Thus, the total impoundage has been insufficient in the archipelago for a long time due to the lack of appropriate reservoir sites for the construction of water storage facilities and the very small catchment area of all reservoirs in this region. Reservoirs may be dried up when a drought occurs. After the national-level Zhoushan Archipelago New District was established by the State Council of China in June 2011, Zhoushan City has been elevated to the national strategic level in the country. Water resources will become an important supporting factor and the water resource ecological safety will suffer extreme challenges in the future all-around development themed by the marine economy, especially under the background of urbanization and high-speed socioeconomic development in the city.

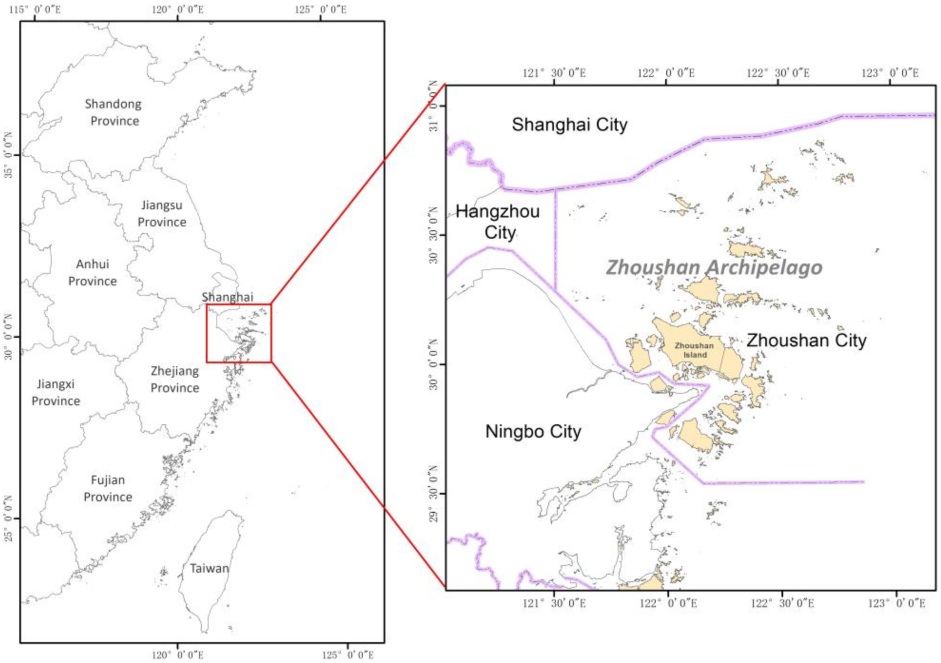

Fig. 1: Geographic location of Zhoushan city.

MATERIALS AND METHODS

Research Data

Original data used in this study were derived from Zhejiang Statistical Yearbook, Zhoushan Statistical Bulletin of National Economy and Social Development, Zhoushan Statistical Yearbook, Zhoushan Environmental Conditions Bulletin, and Zhoushan Water Resources Bulletin from 2010 to 2019 along with other existing water resource-related results in Zhoushan City. Ten years of water resource data of Zhoushan City (2010-2019) were selected to evaluate its water-resource ecological safety status.

PSR Model and Evaluation Indexes

The PSR model was initially proposed by Canadian statisticians, such as Rapport. This model has gradually been applied to studies on various ecological problems and become a framework system for the discipline of environmental quality assessment with the mutual development of United Nations Environment Programs and Organization for Economic Cooperation and Development toward the end of the twentieth century. The PSR model is commonly used in the field of ecological environmental evaluation due to its unique comprehensiveness, flexibility, and strong causal logic relations in the aspect of index selection (Sun et al. 2019, Shi et al. 2018, Bahraminejad et al. 2018, Wang et al. 2018).

The evaluation index system established via the PSR model includes not only the pressure imposed by human beings on the water ecosystem (such as discharge of industrial and domestic wastewater and agricultural irrigation) and human protection of the water ecosystem (such as popularization of water-saving appliances and centralized wastewater treatment) but also the status (such as groundwater resource quantity and water quality and health status) of water resources themselves. Therefore, the PSR model can realize the complete and thorough evaluation of water ecological safety. Water resource characteristics of Zhoushan City were combined according to index selection principles of pertinence, representativeness, dynamics, feasibility, and systematicness to establish the ecological-safety evaluation index system of water resources consisting of the target, criterion, and index layers based on the PSR model, as given in Table 1.

Table 1: Safety evaluation index system of water resources of Zhoushan City.

Target layer	Factor layer	Index layer	Index explanation
Comprehensive water resource safety index	Pressure	P1 Annual total wastewater discharge/10,000 t	Annual total wastewater discharge in the evaluation area
		P2 Annual total industrial wastewater discharge/10,000 t	Annual total industrial wastewater discharge
		P3 Annual COD emission in industrial wastewater/t	Annual total COD emission in industrial wastewater
		P4 Annual ammonia nitrogen emission in industrial wastewater/t	Annual total ammonia nitrogen emission in industrial wastewater
		P5 Application of agrochemical fertilizers/t	Annual total application of chemical fertilizers
		P6 Application of agricultural pesticides/t	Annual total application of agricultural pesticides
		P7 Annual total water consumption/10,000 m^3	Annual total water consumption in the evaluation area
	State	S1 Surface water resource quantity/100 million m^3	Total surface water resource quantity in the evaluation area
		S2 Groundwater resource quantity/100 million m^3	Total groundwater resource quantity in the evaluation area
		S3 Per capita water resource quantity/m^3	Total water resource quantity/total population in the evaluation area
		S4 Water qualification rate in water function zone/%	Water quality in the evaluation area reaches above Class II water quality standard
		S5 Water quantity converted from annual precipitation/100 million m^3	Water resource quantity converted from annual precipitation in the evaluation area
	Response	R1 Governance area of water and soil loss/1,000 ha	Total governance area of water and soil loss
		R2 Water quantity diverted from the mainland/100 million m^3	Annual water quantity diverted from the mainland in the evaluation area
		R3 Reservoir water storage capacity/10,000 m^3	Annual reservoir water storage in the evaluation area
		R4 Annual total water supply/10,000 m^3	Annual total water supply in the evaluation area
		R5 Quota of pollutant discharge fee/10,000 yuan	Pollutant discharge fee annually levied in the evaluation area
		R6 Flood embankment length/km	Flood embankment length in the evaluation area

Determination of Index Weights

Index weight plays a significant role in the ecological safety evaluation result of water resources. AHP, correlation coefficient method, PCA, and entropy weight method are primarily used to determine index weights (Mohammad et al. 2013, Liu et al. 2019). According to the mode of weight assignment, methods can be divided into AHP-represented subjective weight and entropy weight-represented objective assignment methods. If only one of these methods is used in the actual assessment process, the assessment conclusions may be subject to excessively strong subjectivity or objectivity restrictions, leading to a certain deviation from the actual situation. This problem can be effectively solved by calculating comprehensive index weights through the AHP-entropy weight method.

AHP-based weight determination: The AHP method was first proposed by T. L. Saaty, a famous mathematical specialist from the American University of Pittsburgh, in his famous work The Analytic Hierarchy Process in the 1970s. Since then, the AHP method has gradually matured and been widely used by Chinese and foreign scholars.

AHP is a decision-making mode of thinking that decomposes a complicated problem into component factors, which are then combined in a grouped way to form an appropriately ordered hierarchical structure according to memberships. The importance of every two indexes is then compared via expertise to determine the importance ranking (weight value) of each factor to the decision-making objective. This process is generally carried out in five steps, namely, the establishment of hierarchical structure, construction of importance judgment matrix, single hierarchical arrangement of indexes, consistency check, and total index ranking (Canan et al. 2018, Myronidis et al. 2016).

Weight solving through the entropy weight method: The concept of entropy was put forward by the German physicist Rudolf Clausius in 1850. Entropy was then introduced by the American mathematician Shannon into information theory in 1948 to propose the concept of "information entropy," which is the uncertainty measurement of a random variable and used to describe the occurrence probability or uncertainty of a signal in the information source (Reinaldo et al. 2013, Mohamed et al. 2011). High information entropy indicates high uncertainty. Information entropy is expressed as follows:

$$H(p_1, p_2, \cdots, p_n) = -\sum_{i=1}^{n} p_i \log_2 p_i \qquad \ldots(1)$$

Where, $H(p_1, p_2, \ldots, p_n)$ is the information entropy and p_i is the occurrence probability of the event i.

The discrete degree of an evaluation index can be assessed using entropy. Small entropy indicates the large information quantity provided by this index, high discrete degree, and strong influence on the overall objective and weight value. Therefore, the entropy weight method, which is an objective weighting tool, can be used to determine the weight of each index and delete indexes with minimal contribution to the evaluation result, while the entropy coefficient is applied to correct the weight of each index and finally obtain objective index weights (Gu et al. 2020, Chen et al. 2019) and provide a basis for the multi-index comprehensive evaluation.

The following initial data factor matrix $B = (b_{ij})_{mxn}$ is composed of m evaluation objects and n concrete evaluation indexes:

$$B = (b_{ij})_{m\times n} = \begin{pmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{m1} & \cdots & b_{mn} \end{pmatrix} \qquad \ldots(2)$$

Where b_{ij} is the evaluation value of the object i at the j^{th} index layer. The calculation steps of each index weight are as follows:

1. Calculate p_{ij}, which is the ratio of the j^{th} evaluation index value under the index i, as follows:

$$p_{ij} = \frac{b_{ij}}{\sum_{j=1}^{n} b_{ij}} (i = 1, 2, 3, \cdots, n; j = 1, 2, 3, \cdots, m) \qquad \ldots(3)$$

If $p_{ij} = 0$, then we define the following:

$$\lim_{p_{ij}\to 0} p_{ij} \ln p_{ij} = 0 \qquad \ldots(4)$$

2. Calculate entropy E_i of index as follows:

$$E_i = -\frac{\sum_{j=1}^{n} p_{ij} \ln p_{ij}}{\ln(n)} (i = 1, 2, 3, \cdots, n) \qquad \ldots(5)$$

3. Calculate the entropy v_i (objective weight value) of the index i according to E_i as follows:

$$v_i = \frac{1 - E_i}{\sum_{i=1}^{m} (1 - E_i)} (i = 1, 2, 3, \cdots, n) \qquad \ldots(6)$$

Comprehensive weight solving method: The comprehensive index weight z_i is generally obtained by integrating proportional, simple multiplication, mean value, and minimum relative information entropy methods with AHP-obtained subjective w_i and entropy weight-determined objective v_i weights. Simple multiplication and mean value methods were selected in this study to solve the comprehensive weight of the water-resource ecological safety index with consideration for scientific rigour and operation convenience as follows:

$$z_i = \frac{w_i v_i}{\sum_{j=1}^{n} w_i v_i} \qquad \ldots(7)$$

Table 2: Water ecological safety status grade in Zhoushan City.

Comprehensive index value	Water ecological safety status
0–0.2	Serious warning
0.2–0.4	Medium warning
0.4–0.6	Prewarning
0.6–0.8	Relatively safe
0.8–1	Safe

Calculation of Comprehensive Water Ecological Safety Evaluation Index

The obtained comprehensive weight z_i was used to solve the following ecological safety evaluation indexes of comprehensive water resources I in Zhoushan City for different years after index standardization:

$$I = \sum_{j=0}^{p} Z_i Y_{ij} \qquad \ldots(8)$$

Where Y_{ij} is the index value after the standardization processing and z_i is the comprehensive weight value solved.

Grading of the Water-Resource Ecological Safety Status

The water-resource ecological safety evaluation is graded to reflect the current water ecological safety status. The water ecological safety level should be graded and the evaluation value is then associated with the evaluation grade because the comprehensive value of ecological safety evaluation of water resources fails to incorporate the water ecological safety status directly. Current natural conditions and the social development status in Zhoushan City were combined to grade the level of water ecological safety status (Table 2) according to ecological safety prewarning criteria and existing research results (Sun et al. 2018, Wang et al. 2019).

RESULT ANALYSIS AND DISCUSSION

Research Results

Subjective and objective weights were solved via AHP and entropy weight method, respectively, in the processing and analysis of research data. Equation (5) was then utilized to solve ecological safety evaluation indexes of comprehensive weights of water resources (Table 3).

Equation (6) was used to solve comprehensive evaluation values of water resource ecological safety in Zhoushan City during 2010-2019. Table 4 presents the assessment of ecological safety status grades of water resources according to Table 2.

Table 3: Entropies, subjective weights, objective weights, and comprehensive weights of ecological safety evaluation indexes of water resources in Zhoushan City.

Index layer	Entropy E_i	Subjective weight w_i	Objective weight v_i	Comprehensive weight z_i
P1 Annual total wastewater discharge/10,000 t	0.7449	0.0156	0.0908	0.024
P2 Annual industrial wastewater discharge/10,000 t	0.8102	0.042	0.0676	0.047
P3 Annual COD emission in industrial wastewater/t	0.704	0.109	0.1054	0.191
P4 Annual ammonia nitrogen emission in industrial wastewater/t	0.682	0.1388	0.1132	0.261
P5 Application of agrochemical fertilizer/t	0.8441	0.04	0.0555	0.037
P6 Application of agricultural pesticides/t	0.9225	0.1002	0.0276	0.046
P7 Annual total water consumption/10,000 m^3	0.8467	0.0305	0.0546	0.028
S1 Surface water resource quantity/100 million m^3	0.8916	0.012	0.0386	0.008
S2 Groundwater resource quantity/100 million m^3	0.8902	0.0084	0.0391	0.005
S3 Per capital water resources/m^3	0.8759	0.0389	0.0442	0.029
S4 Water qualification rate in water function zone/%	0.8369	0.004	0.0581	0.004
S5 Water quantity converted from annual precipitation/100 million m^3	0.8902	0.0084	0.0391	0.005
R1 Governance area of water and soil loss/1,000 ha	0.893	0.126	0.0381	0.080
R2 Water quantity diverted from the mainland/100 million m^3	0.8738	0.0495	0.0449	0.037
R3 Reservoir water storage capacity/10,000 m^3	0.8641	0.1034	0.0484	0.083
R4 Annual total water supply/10,000 m^3	0.891	0.1297	0.0388	0.084
R5 Quota of pollutant discharge fee/10,000 yuan	0.9001	0.0264	0.0356	0.016
R6 Flood embankment length/km	0.8294	0.0172	0.0607	0.017

Table 4: Water safety evaluation results of Zhoushan City during 2010-2019.

Year	Evaluation value				Water ecological safety status
	Pressure	State	Response	Comprehensive	
2010	0.27	0.02	0.01	0.30	Medium warning
2011	0.24	0.01	0.06	0.30	Medium warning
2012	0.08	0.04	0.09	0.21	Medium warning
2013	0.07	0.01	0.08	0.15	Serious warning
2014	0.05	0.01	0.17	0.24	Medium warning
2015	0.05	0.03	0.24	0.32	Medium warning
2016	0.07	0.03	0.22	0.32	Medium warning
2017	0.46	0.02	0.25	0.73	Relatively safe
2018	0.54	0.01	0.27	0.83	Safe
2019	0.58	0.05	0.22	0.85	Safe

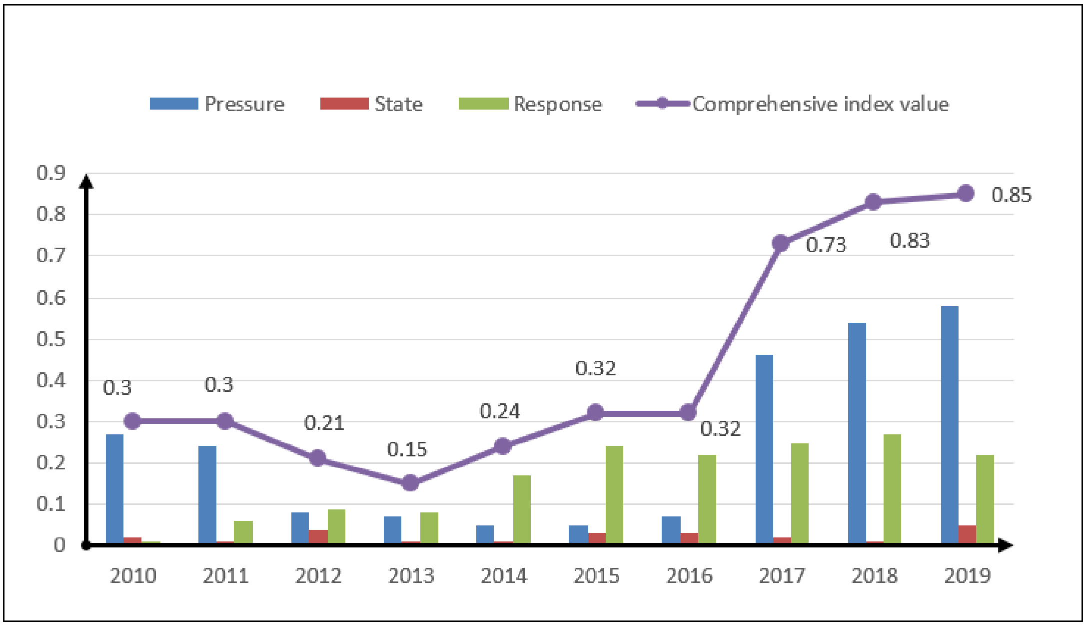

Fig. 2: Variation trend of water resource ecological safety in Zhoushan City (2010-2019).

DISCUSSION

1. Pressure system evaluation: According to the research results (Table 4 and Fig. 2), the evaluated value of water resource safety pressure in Zhoushan City first reduced and then increased during 2010-2019. These values were divided into the following phases: the mean value was (1) approximately 0.255 during 2010-2011, (2) 0.064 during 2012-2016, and (3) 0.527 during 2017-2019. These findings indicated that the pressure faced by the ecological safety system of water resources in Zhoushan City presented a declining–increasing–declining trend. The water-resource ecological safety pressure from 2012 was significantly elevated in Zhoushan City, with the evaluation value declining from 0.24 to 0.08 mainly because the city was accredited as a national-level marine development demonstration area, followed by large-scale social construction and entrance of various industries in a fast development period. Indexes, such as total wastewater discharge, annual industrial wastewater discharge, and COD and ammonia nitrogen emissions in industrial wastewater, continued to increase annually or remained at high levels during this period of rapid development. Although the consumption of agrochemical fertilizers reduced (from 15,697 t to 11,848 t) and the application of agricultural pesticides

reduced to a certain degree, the water ecological safety pressure failed to weaken. Hence, the pressure borne by water ecology in Zhoushan City during this period, mainly came from the indirect water pollution triggered by industrial wastewater discharge and agricultural production in human society.

The evaluation value of water resource ecological pressure in Zhoushan City during 2016-2019 increased from 0.07 to 0.58, and the pressure tolerated by the water ecosystem in this phase gradually remitted mainly because the city experienced a large-scale construction phase with a stable social industrial structure. The annual water consumption gradually increased in Zhoushan (from 155,450,000 m^3 to 162,050,000 m^3). However, the industrial wastewater discharge (from 22,020,000 t to 11,380,000 t), COD (from 6,466 t to 754 t) and ammonia nitrogen (from 238 t to 62 t) emissions in industrial wastewater, and application of agricultural pesticides (from 501 t to 444 t) all declined annually and remitted the pressure faced by the water ecological safety in Zhoushan City to a certain extent with the progress in energy-saving technologies and wastewater treatment means. The variation trend chart of the pressure index is shown in Fig. 3.

2. State system evaluation: The state evaluation value represents the contribution of the current water resource status to water ecological safety. Fig. 4 shows that the variation trend of the state evaluation value is unclear but slightly fluctuating from 2010 to 2019. Values of the water resource ecological state in 2011, 2013, and 2014 were all 0.01, which was relatively small, while those in 2012, 2015, 2016, and 2019 were relatively large at 0.04, 0.03, 0.03, and 0.05, respectively. The ecological safety status value of water resources in Zhoushan City

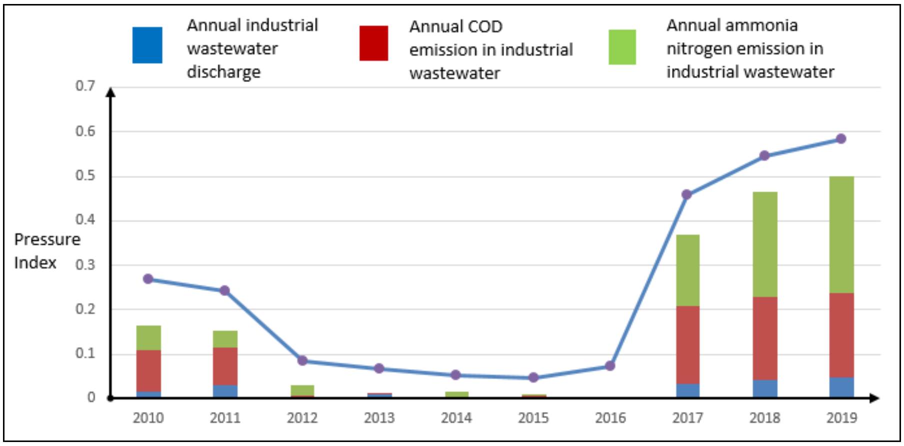

Fig. 3: Variation trend chart of the pressure index.

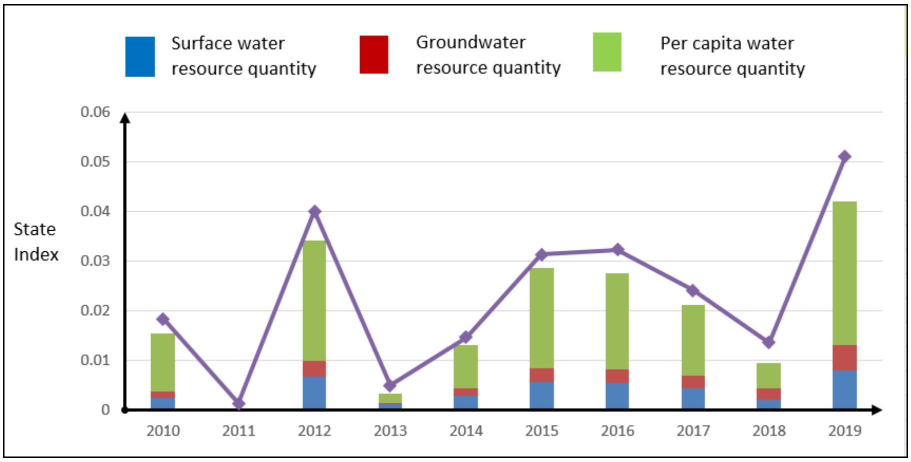

Fig. 4: Variation trend chart of the state index.

was mainly affected by surface water resource quantity, groundwater resource quantity, and water quantity converted from annual precipitation, which exerted the maximum influence. Water resource quantities converted from annual precipitation in the city were 13.7802, 14.7405, and 17.8481 m^3 in 2011, 2013, and 2014, respectively, during which the city experienced three years of minimum precipitation within 2010-2019, with minimum status evaluation values of water resources (0.01). Water resource quantities converted from the annual precipitation in Zhoushan City were 22.6386 and 27.1485 m^3 in 2012 and 2019, respectively, with large evaluation values (0.04 and 0.05). The water qualification rate in the water function zone of the city during 2010-2019 was stable and presented an increasing trend (from 44% in 2014 to 57% in 2019), and water environmental indexes improved to a certain extent. Therefore, water resource quantity converted from precipitation, surface water resource quantity, groundwater resource quantity, and per capita water resources, except for the water qualification rate in the water function zone, exert certain influences on the level of water ecological safety status in Zhoushan City, which is an island region.

3. Response system evaluation: The response evaluation value reflects the effort level made by human society to the protection of the water ecosystem. Fig. 5 shows that the response curve is rapidly rising (from 0.01 in 2010 to 0.22 in 2019) during 2010–2019, thereby indicating that the Zhoushan municipal government made considerable efforts into the improvement of the water ecological safety level after being made aware of the importance of water ecological safety. The municipal government applied effective measures for water resource protection, which reduced not only the water consumption in life and production but also enhanced the development and utilization of unconventional water resources, such as water diversion from the mainland, with the increase in the governance area of water and soil loss, reservoir water storage capacity, annual total water supply, and flood embankment length and the change in pollutant discharge fees. Thus, "increasing water sources and reducing water consumption" was realized. The governance area of water and soil loss increased from 23.46 ha in 2010 to 56.57 ha in 2019, with a growth rate of 141.1%. The annual total water supply elevated from 137,070,000 m^3 in 2010 to 162,050,000 m^3 in 2019, with a growth rate of 18%. The amount of pollutant discharge fees increased from RMB 17,690,000 in 2010 to RMB 30,050,000 in 2019 by 69.9%. The flood embankment length increased from 453 km in 2010 to 939 km in 2019 by 107.3%.

   The response system contributed to achieving the maximum progress in the PSR evaluation system and was an important link to guaranteeing the water resource ecological safety in Zhoushan City during 2010-2019.

4. Comprehensive evaluation: The results in Table 4 showed that the water resource ecological safety is basically under the medium warning status in Zhoushan City during 2010–2016 and comprehensive evaluation indexes are 0.3, 0.3, 0.21, 0.15, 0.24, 0.32, and 0.32. Compared with that in 2012, the annual precipitation

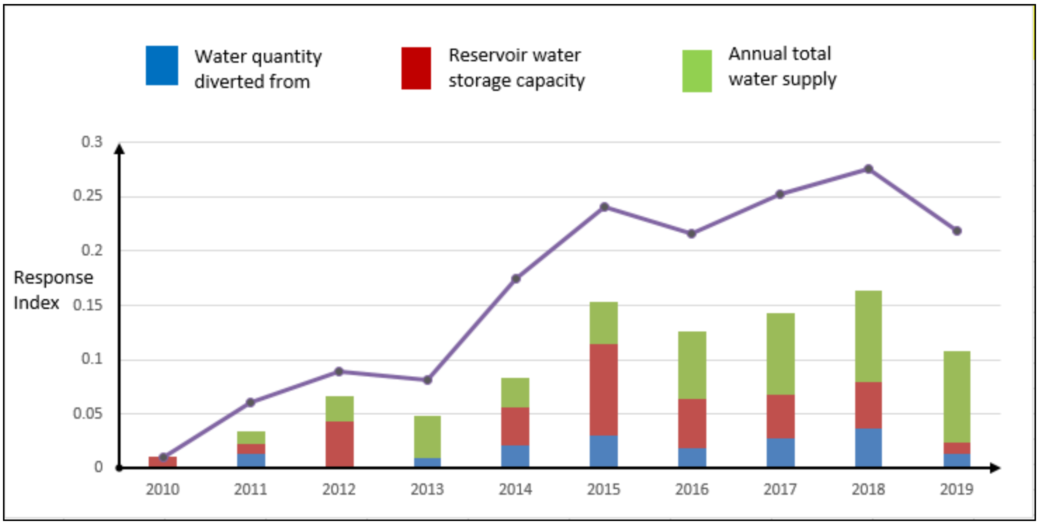

Fig. 5: Variation trend chart of the response index.

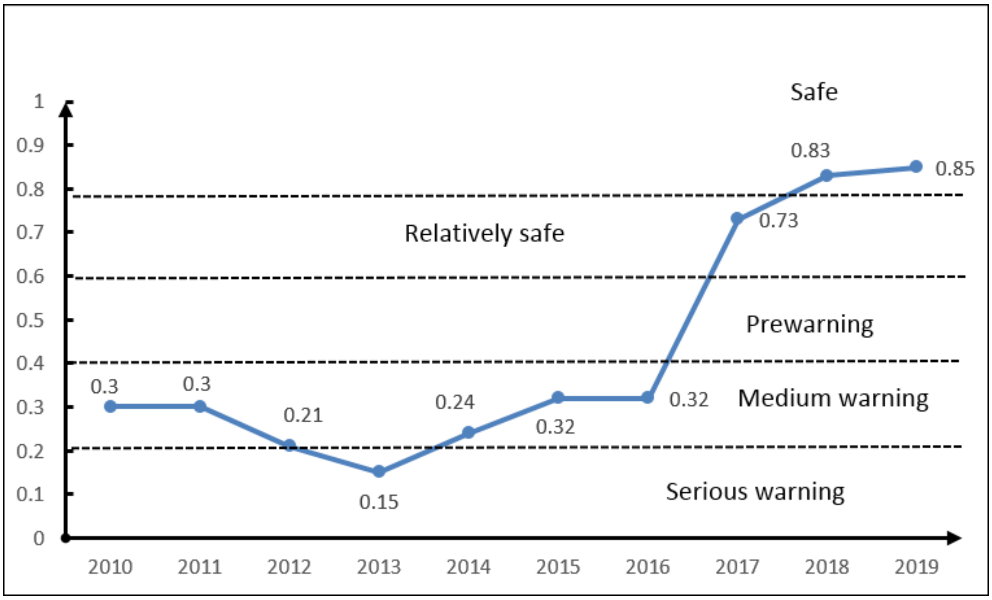

Fig. 6: Comprehensive evaluation results of water resource safety in Zhoushan City during 2010–2019

in the city reduced by 34.1% at only 1,186.4 mm in 2013, which was also the same year that experienced minimum precipitation within the study period. The reduced precipitation seriously impacted the water resource quantity and safety status in the city. Hence, the comprehensive evaluation index of water resource ecological safety reached the minimum value in 2013 at only 0.15 within the 10 years. Comprehensive evaluation indexes of water resource ecological safety presented a rising trend in Zhoushan at 0.73, 0.83, and 0.85 and the overall water ecosystem was under relatively safe and safe statuses during 2017-2019. As shown in Fig. 6, the general curve of comprehensive evaluation indexes first reduced and then increased during 2010-2019. However, the general rising trend of the curve indicated that the water ecological safety status of Zhoushan City was in the process of improvement and optimization.

The water ecological safety status in the city upgraded from a medium warning state to a relatively safe state in 2017 and then realized the transformation from a relatively safe state to a safe state in 2018 after reaching the minimum point in 2013. Relative to 2010, the pressure system somehow deteriorated in 2019. However, the deteriorating trend was curbed already and the pressure borne by the water ecosystem was significantly relieved by the optimization of indexes, such as industrial wastewater discharge, COD and ammonia nitrogen emissions in industrial wastewater, and the application of agricultural pesticides. Notably, wastewater discharge will continue to be a major problem faced by the water ecological safety in Zhoushan. The state system fluctuated to some degree because of the effect of the change in the water resource quantity converted from precipitation. However, indexes, such as water qualification rate, continued to steadily progress and the health status of the water ecosystem gradually improved. The improvement of the response system primarily caused the upgrading of water ecological safety status, governance area of water and soil loss, reservoir water storage capacity, annual total water supply, pollutant discharge fees, and flood embankment length, which were optimized to different degrees. This finding indicated that the capability of Zhoushan City in guaranteeing water ecological safety was comprehensively enhanced.

CONCLUSION

The water resource safety evaluation in the island area of Zhoushan City in China was taken as the research object to clarify influences of factors, such as pressure, state, and response on the water resource safety status and reveal their mutual relationships. Comprehensive weights of different indexes were calculated through the AHP–entropy weight method based on the constructed evaluation index system, influence degrees of different factors on water resource safety status were analyzed via the PSR model, and measures facilitating the sustainable utilization of water resources were proposed. The following conclusions were drawn from this study.

1. The water ecological safety evaluation of Zhoushan City during 2010–2019 demonstrated that the PSR model can evade not only the one-sidedness in the

evaluation of water resource environmental status but also accurately reflect correlations among water ecological safety factors starting from the mutual influence and association between social development and the natural environment. Accordingly, water ecological safety can be evaluated through the PSR-based evaluation system.

2. The weight solving method that integrates the AHP and entropy weight method avoids not only the subjective influence of human preferences but also mitigates the limitation of discrepancy with the real situation caused by variable data deviations in the entropy weight method. Hence, this approach can provide a certain reference for weight determination.
3. The subsystem analysis demonstrated that COD and ammonia nitrogen emissions are the main influencing factors of the pressure subsystem, while water resource quantity converted from precipitation and the water qualification rate in the water function zone are primary influencing factors of the state subsystem. The water-resource ecological safety level can be effectively elevated by increasing the governance area of water and soil loss, reservoir water storage capacity, annual total water supply, and amount of pollutant discharge fees to accelerate reclaimed water engineering construction, such as seawater desalination, and develop and utilize unconventional water resources.

Therefore, the status of regional water resource safety was evaluated using the PSR model; influence degrees of pressure, state, and response on the water resource safety status were determined, and correlations among different influence factors were analyzed to provide a theoretical basis for evaluating the regional water-resource safety status and formulating water-resource sustainable utilization measures. Improving the water resource safety level is important to reduce the industrial wastewater discharge, enhance the reclaimed water engineering construction, and develop and utilize unconventional water resources in the island area. Regional water supply and wastewater recycling can be the focus of future investigations. Meanwhile, the factor of driving force can be further considered in the safety evaluation index system of water resources to realize the comprehensive evaluation of water resource ecological safety.

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