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Evaluation Methods of Water Environment Safety and Their Application to the Three Northeast Provinces of China

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Abstract: Focusing on the topic of water environment safety of China, this paper has selected the three northeast provinces of China as the research object due to their representativeness in economic development and resource security. By using the Entropy Weight Method, the Grey Correlation Analysis Method, and the Principal Component Analysis Method, this paper has first constructed a water environment safety evaluation system with 17 indicators from the economic, environmental, and ecological aspects. Furthermore, this paper has screened the initially selected indicators by the Principal Component Analysis Method and finally determined 11 indicators as the evaluation indicators. After indicator screening, this paper has adopted the improved Fuzzy Comprehensive Evaluation Method to evaluate the water environment safety of the three northeast provinces of China and obtained the change in water environment safety of different provinces from 2009 to 2017. The results show that the overall water environment safety of the region had improved first but worsened afterward, and that in terms of water safety level, Jilin Province ranked first, followed by Heilongjiang Province and Liaoning Province. The three factors that have the greatest impact on the water environment safety of the three provinces are: Liaoning—Chemical Oxygen Demand (score: 17.10), Per Capita Disposable Income (score: 13.50), and Secondary Industry Output (score: 11.50); Heilongjiang—Chemical Oxygen Demand (score: 18.64), Per Capita Water Resources (score: 12.75), and Concentration of Inhalable Particles (score: 10.89); Jilin—Per Capita Water Resources (score: 15.75), Chemical Oxygen Demand (score: 14.87), and Service Industry Output (score: 11.55). Based on analysis of the evaluation results, this paper has proposed corresponding policy recommendations to improve the water environment safety and promote sustainable development in the northeast provinces of China.

Keywords: water environment safety; the three northeast provinces of China; principal component analysis; fuzzy comprehensive evaluation; sustainable development

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1. Introduction

With the rapid economic growth, increasing population, and surging water consumption, the issue of water environment safety is getting more and more attention from all walks of life. In 1972, the first United Nations Conference on Environment and Development predicted that after the oil crisis, the next crisis would be water crisis [1]. In 2000, the World Ministerial Conference that took place in the Netherlands made "Water Safety in the 21st Century" the main topic of the conference [2]. The topic of water environment safety has become the research hotspot among environment safety research topics [3–5].

It is well known that China is short in water resources. As of 2018, China's total amount of water resources was 2796.00 billion cubic meters, and the per capita water resources was only 2007.57 cubic meters [6], far below the standard for mild water shortage (3000 cubic meters per capita). Most of the water bodies in China have been polluted to varying degrees, and the overall water quality is deteriorating with certain river sections in serious pollution [7–9]. In order to alleviate the water problems China is facing and realize sustainable development of water environment, the "13th Five-Year Plan" has emphasized the requirement of "accelerating the improvement of water infrastructure network, promoting scientific development of water resources, and enhancing the ability of water conservation including appropriate water resource allocation, water-saving, and efficient use of water" [10].

In the study of water environment safety in China, the three northeast provinces are of typical representativeness [11]. On the one hand, with its vast land, abundant resources, and strong industrial base, this region was once a fast-growing region in modern China and the "Cradle of China's Industry" [12]. In the early years of the newly founded China, thanks to the national development policy, the three northeast provinces effectively advanced the industrialization process and attracted large population inflow. On the other hand, rapid industrial development also brought enormous pressure on the resource and environment of the northeast region. Its economy has got into trouble, which is called the "Northeast Phenomenon" [13,14]. In 2017, the per capita water resource of the northeast region was 1214 cubic meters, which makes it a region of moderate water shortage according to international standards [15]. Therefore, it is of great theoretical and practical importance to evaluate water environment safety in the northeast region and explore effective water resource management measures [16,17].

Currently, there is no widely recognized definition of water environment safety. Xia et al. defined water safety as able to supply water that meets water quality requirements for the daily needs of citizens and production needs of various industries with an affordable price under the premise of ecological water utilization [18]. This paper has adopted the definition by Zhong and Geng, i.e., sufficient water resources to satisfy the needs of human society, support economic development, and maintain a healthy ecological environment, emphasizing different amounts of water resources demanded by different goals [19]. Despite the different viewpoints on water environment safety by different scholars, the core and essence are basically the same. From the environmental aspect, water environment safety means the ability of human beings to obtain the amount of water that meets their basic physiological and living needs [20]. From the economic perspective, water environment safety means that the socioeconomic system is able to obtain the amount of water that enables sustainable development [21]. From the ecological aspect, water safety means that the environmental system is able to obtain sufficient amount of water so as to maintain or improve the environment quality [22,23].

In the evaluation of water environment safety, Fuzzy Comprehensive Evaluation Method has been widely used [24,25]. For the Fuzzy Comprehensive Evaluation Method, the key is to determine appropriate weights [26]. The traditional comprehensive evaluation method is based on individual evaluation object [27]. When the number of evaluation objects gets huge, it would greatly increase the amount of calculation. Moreover, during the calculation, this method ignores the interactions between indicators [28].

In order to solve above issues, some scholars have proposed new methods, especially the Entropy Weight Method and Fuzzy Comprehensive Evaluation Method, for calculating the weights. Sun et al. established a Fuzzy Comprehensive Evaluation Model for urban water resources safety from the perspective of a complex system, considering the complexity and uncertainty of water resource safety, and determined the comprehensive weights by using the Entropy Weight Method and Subjective Weighting Method [29]. Ilic et al. estimate the influence on water resources from climatic parameters such as air temperature, vapor pressure, and humidity. By neuro-fuzzy approach, they constructed the process model to predict the influence of such climatic parameters and found that their results could be used to improve water resources management [30]. Lu et al. used the fuzzy clustering method for water conservancy project bidding evaluation. Treating the evaluation as a multi-target group decision-making process, they chose the most suitable contractor for the project by determining the score matrix and index weight vector of all the bidders concerned [31]. Milan et al. established a linear fuzzy optimization model to decide the optimal surface and groundwater withdrawal for sustainable water resource management. For replacing the numerical optimization methods, they developed a Fuzzy Inference System to calculate the groundwater withdrawal level in the Astaneh-Kouchesfahan Plain. They found the value of the best solution for the fuzzy optimization model and predicted the optimal value of groundwater withdrawal based on the predictor variables [32]. Moreover, using Fuzzy Inference System, Tiri et al. selected three stations and ten parameters to establish a surface water quality index. They found that calcium and sulfate are the dominate ions, and there are no significant differences for all parameters except Ca and K. The results also showed that the surface water quality is mainly influenced by the water-rock interactions and anthropogenic process [33]. By combining the data characteristics and the traditional method of Relative Membership Degree, Fang et al. improved the widely applied variable fuzzy sets theory for water quality evaluation. They proved that the new model simplified the calculation process and improved the calculation accuracy of Relative Membership Degree [34].

The above studies could avoid the influence of subjective factors, but they did not take into account the interactions between indicators. In addition, the commonly used maximum-minimum algorithms and the maximum membership principle of the Fuzzy Comprehensive Evaluation Method would cause certain information loss and lead to evaluation results with low distinguishability that cannot truly reflect the difference between research objects [35].

Taking these issues above into account, this paper has first constructed an integrated weighting model based on the Entropy Weight Method, the Grey Correlation Analysis Method, and the Principal Component Analysis Method in order to utilize the advantages of various methods [36–38]. Secondly, based on the weighted average principle [39], this paper has adopted an improved Fuzzy Comprehensive Evaluation Method. After that, this paper has evaluated the water environment safety of the northeast provinces using such improved method. Based on the analysis of the evaluation results, this paper has determined the top three indicators that have the greatest impact on the water safety of the northeast provinces by using the Graded Scoring Method in order to find out the principal influencing factors. Finally, this paper has provided a few policy recommendations.

2. Materials and Methods

2.1. Selection of Evaluation Indicators and Data Source

Based on existing researches in the academia, and by referring to the definition of water environment safety [40], this paper has established an evaluation indicator system for the water environment safety of the northeast region after preliminary screening of indicators. This evaluation indicator system covers 17 indicators in total, involving the socioeconomic, water quality, and ecological aspects. The raw data of the indicators are from the China Statistical Yearbook [15], the Annual Statistic Report on Environment in China [41], and the Water Resource Bulletin of Liaoning [42], Jilin [43], and Heilongjiang Provinces [44], respectively. The study period is from 2009 to 2017.

Based on the preliminarily selected indicators, this paper has conducted indicator screening by the Principal Component Analysis Method. This is a method for analyzing and simplifying data sets, which could effectively reduce the dimension of data while maintaining their contribution to the variance. The basic idea is to restructure the original indicators with certain correlation to each other into a new set of mutually independent comprehensive indicators to replace the original indicators. By calculating the loading factor of individual indicators to the overall data variance and removing indicators with small loading factors, this paper keeps those indicators with large loading factors to reflect the overall characteristics of the data [45,46].

The top 5 eigenvalues by Principal Component Analysis on the 17 preliminarily selected indicators are 5.63, 4.38, 2.04, 1.23, and 0.77, respectively, which have cumulatively contributed 90.38% to overall data variance. Therefore, these five eigenvalues should be able to reflect the overall data characteristics. Let the eigenvectors corresponding to the five eigenvectors be u1, u2, u3, u4, and u5. Then this paper calculates the loading matrix and selects the indicators whose loading factor value (absolute value) is above 0.6. In this way, this paper could ensure that the selected indicators play a significant role in the comprehensive evaluation. The screening result is shown in Table 1 below:

Table 1. Selected Evaluation Indicators and Their Loading Factor by Principal Component Analysis Method.

Indicator	Principal Component 1	Principal Component 2	Principal Component 3	Principal Component 4	Principal Component 5	Screening Result
Percentage of Urban Population by End of Year (%)	0.136	0.231	0.462	−0.489	−0.430	Drop
Natural Population Growth Rate (%)	−0.003	−0.118	−0.166	0.454	0.315	Drop
Per Capita Water Resources (m^3 per Person)	0.197	−0.414	−0.704	0.592	0.685	Keep
Regional GDP (100 Million RMB)	0.168	0.375	0.480	−0.597	−0.445	Drop
Secondary Industry Output (100 Million RMB)	0.142	0.401	0.446	−0.607	−0.335	Keep
Service Industry Output (100 Million RMB)	0.125	0.179	0.322	−0.626	−0.304	Keep
Per Capita Disposable Income by Region (RMB)	−0.024	0.080	0.221	−0.732	−0.269	Keep
Proportion of Water of Quality Level 1–3 (%)	−0.156	−0.242	−0.453	0.415	0.248	Drop
Proportion of Water of Poor Quality Below Level 5 (%)	−0.267	−0.009	−0.002	−0.211	0.054	Drop
Waste Water Emission (100 Million Tons)	0.216	0.409	0.563	−0.333	−0.565	Drop
Chemical Oxygen Demand (COD) (10,000 Tons)	0.802	0.609	−0.171	0.070	0.142	Keep
NH3−N Emissions (10,000 Tons)	0.652	0.579	0.083	−0.072	−0.056	Keep
Forest Coverage Rate (%)	0.278	−0.378	−0.827	0.201	1.000	Keep
Percentage of Days with Good Water Quality (%)	−0.006	−0.175	−0.282	0.729	0.201	Keep
Concentration of Sulfur Dioxides (mg/m^3)	−0.426	0.297	0.349	−0.282	−0.827	Keep
Concentration of Nitrogen Oxides (mg/m^3)	0.529	0.689	0.297	−0.175	−0.378	Keep
Concentration of Inhalable Particles (mg/m^3)	0.639	0.529	−0.426	−0.006	0.278	Keep

2.2. Evaluation Standards of Water Environment Safety

Based on the basic facts of water resources in northeast China and the economic and social development level of the country as well as the three northeast provinces, this paper has classified the water environment safety into five levels: Very safe, safe, neutral, unsafe, and very dangerous (see Table 2) according to previous studies [47,48]. Based on the data sources mentioned in 2.1, this paper has consolidated the raw data and graded the indicators including the Regional GDP Growth Rate, Natural Population Growth Rate, Percentage of Urban Population by End of Year, Service Industry as a Percentage of GDP, Proportion of Water of Quality Level 1–3, Per Capita Water Resources, Percentage of Days with Good Water Quality, Secondary Industry as a Percentage of GDP, etc.

Table 2. Evaluation Standards of Water Environment Safety.

Focus	Indicator	Very Safe	Safe	Neutral	Unsafe	Very Dangerous
Economic	Percentage of Urban Population by End of Year (%)	0.84	0.79	0.69	0.5	0.47
Economic	Natural Population Growth Rate (%)	6.3	5	4.1	3.5	2.5
Economic	Regional GDP Growth Rate (%)	6.75	7	7.25	7.75	8.25
Economic	Secondary Industry as a Percentage of GDP (%)	0.693	−0.063	0.364	−0.006	−0.097
Economic	Service Industry as a Percentage of GDP (%)	65	60	51.4	46	35.4
Economic	Per Capita Disposable Income by Region (RMB)	0.975	−0.183	0.072	0.029	0.017
Environmental	Proportion of Water of Quality Level 1–3 (%)	80	70	60	50	40
Environmental	Percentage of Days with Good Water Quality (%)	−0.692	−0.029	−0.616	0.139	0.300
Ecological	Per Capita Water Resources (m^3 per Person)	2300	1700	1100	700	500

2.3. Improved Fuzzy Comprehensive Evaluation Method

This paper has adopted the improved Fuzzy Comprehensive Evaluation Method to analyze the water environment safety in the northeast provinces. The detailed steps are as follows:

2.3.1. Membership Function Calculation

According to the water environment safety evaluation standards, this paper has calculated the Membership Function based on single environmental indicator data, which is calculated as follows using the linear function:

(1) The Membership Function belonging to Level 1 is:

$$r_{1j} = \begin{cases} 1 & x \leq c_1 \\ \frac{c_2 - x}{c_2 - c_1} & c_1 < x < c_2 \\ 0 & x \geq c_2 \end{cases} \tag{1}$$

(2) The Membership Functions belonging to Level 2, 3, and 4 are:

$$r_{kj} = \begin{cases} 0 & x \leq c_{k-1} \\ \frac{c_{k-1} - x}{c_{k-1} - c_k} & c_{k-1} < x < c_k \\ \frac{c_{k+1} - x}{c_{k+1} - c_k} & c_k \leq x < c_{k+1} \\ 0 & x \geq c_{k+1} \end{cases} \quad k = 2, 3, 4 \tag{2}$$

(3) The Membership Function belonging to Level 5 is:

$$r_{5j} = \begin{cases} 0 & x \leq c_4 \\ \frac{c_4 - x}{c_4 - c_5} & c_4 < x < c_5 \\ 1 & x \geq c_5 \end{cases} \tag{3}$$

where r_{ij} represents the membership degree of the j^{th} factor to Level i, while c_k represents the standard concentration of the j^{th} pollution factor for water quality Level k. For some factors, the lower the factor concentration, the safer the water environment is. Then for these factors, this paper uses Equations (1)–(3) to calculate their membership degrees. For other factors, the higher the factor concentration, the safer the water environment is. Then for these factors, this paper calculates their membership degrees by replacing the ≤ in Equations (1)–(3) with ≥.

2.3.2. Weight Determination

This paper has integrated multiple methods including the Entropy Weight Method [49], the Grey Correlation Analysis Method [50], and the Principal Component Analysis Method [51] to determine the weights as well as calculate the evaluation results. Then this paper tests the consistency of the results by the three methods by using the *Kendall* coefficient of concordance [52,53]. If the result passes the test, this paper will reach a final evaluation result.

2.3.3. Overall Evaluation

In order to avoid information loss, this paper has adopted the weighted average principle and views levels as relative positions which are continuous. Let 1, 2, 3, 4, and 5 represent each level and call them the Rank of respective levels. From the first step, we could obtain a 5×13 Membership Matrix (R). The jth column of R represents the membership degree of the jth influencing factor (C_j) to different levels. The water environment safety level can be expressed as:

$$C = \sum_{j=1}^{13} \omega_j * \sum_{i=1}^{5} r_{ij} * i \quad (4)$$

where r_{ij} represents the membership degree of the jth influencing factor to Level i; w_j is the weight coefficient of the jth factor; C represents the relative level of water environment safety.

According to the above Equation, the water environment safety level (C) ranges from 1 to 5, with a smaller C value representing a safer water environment. When all indicators have reached their Level 1 standards, $C = 1$; when all the indicators have reached their Level 5 standards or even beyond, $C = 5$; in other cases, $1 < C < 5$.

3. Results

With the water environment of the three northeast provinces being the research object, this paper calculates the evaluation results for this region from 2009 to 2017.

3.1. Evaluation of Water Environment Safety

By integrating the Entropy Weight Method, the Grey Correlation Analysis Method, and the Principal Component Analysis Method (please refer to the "Weight Determination" of Part 2.3), this paper has obtained the weight of various indicators as shown in Table 3. The weights obtained by these three methods for each indicator are slightly different from one another. In order to test the concordance of the weight values from different methods, this paper has further adopted the *Kendall* test for coefficient of concordance. As the test results show, the coefficient of concordance is 0.913, the Chi-Square value is 89, and the p-value is 0.006, which indicates that the coefficient of concordance is significant and the weight values are appropriate. This paper has calculated the weighted average value respectively based on the weights from these three methods and obtained three weight values: 0.0955 under the Entropy Weight Method, 0.0840 under the Principal Component Analysis Method, and 0.0874 under the Grey Correlation Method. It can be seen that the difference in weight values by different methods is below 0.01 and that the approximation degree of the result is significant and above 0.99.

Since the calculation results of the three methods are consistent, the research framework of this paper has been proved scientific. Furthermore, this paper has obtained the evaluation results under different methods by summing up the product of various indicators and their corresponding weights under respective methods. Let s_i be the evaluation result of the jth method, then the final evaluation result is $s = (s_1 + s_2 + s_3)/3$. The evaluation results are shown in Figure 1.

Table 3. Evaluation Indicator Weights Obtained by Three Different Methods.

Indicator	Entropy Weight Method	Principal Component Analysis Method	Grey Correlation Method
Per Capita Water Resources (m^3 per Person)	0.3537	0.1771	0.1525
Secondary Industry as a Percentage of GDP (%)	0.0813	0.0596	0.0961
Service Industry as a Percentage of GDP (%)	0.1158	0.1217	0.1250
Per Capita Disposable Income by Region (RMB)	0.1282	0.1504	0.1332
Chemical Oxygen Demand (COD) (10,000 Tons)	0.1585	0.2078	0.1791
NH3-N Emissions (10,000 Tons)	0.0124	0.0426	0.0306
Forest Coverage Rate (%)	0.0066	0.0032	0.0055
Percentage of Days with Good Water Quality (%)	0.0329	0.0147	0.0699
Concentration of Sulfur Dioxides (mg/m^3)	0.0102	0.0283	0.0292
Concentration of Nitrogen Oxides (mg/m^3)	0.0576	0.0414	0.0876
Concentration of Inhalable Particles (PM_{10}) (mg/m^3)	0.0935	0.0771	0.0525

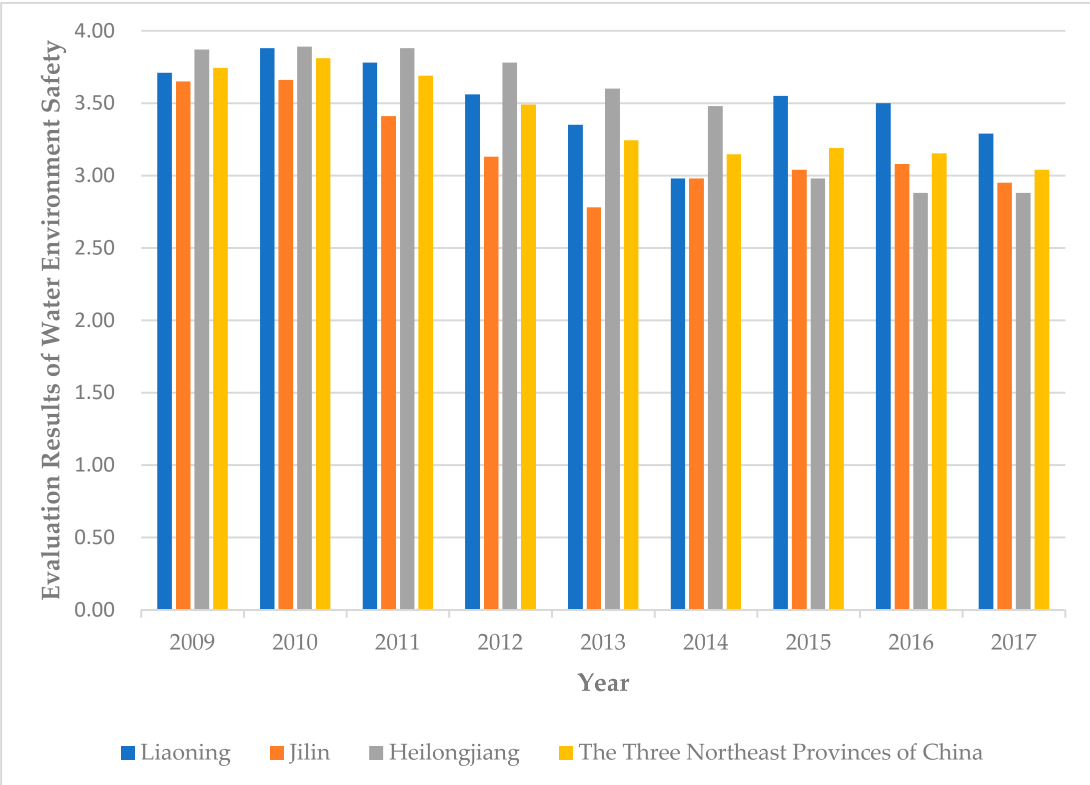


Figure 1. Evaluation Results of Water Environment Safety in the Three Northeast Provinces of China.

It can be seen from Figure 1 that in terms of water environment safety, Jilin Province was generally better than Heilongjiang Province, and Heilongjiang Province was better than Liaoning Province. As can be seen from the weighted average of the 9-year data:

(1) From 2009 to 2017, Jilin Province's water environment safety score was basically in the Level 3 range, with an average level number of 3.1. From 2009 to 2011, the water environment safety score of this province was at Level 4, with an average level number of 3.6; in 2013, 2014, and

2017, the water environment safety score of Jilin Province was at Level 2, with an average level number of 2.48. Therefore, overall speaking, there has been an improvement trend in the water environment of Jilin Province, which was deteriorating since 2013 but improving since 2017.

(2) From 2009 to 2017, Heilongjiang Province's water environment safety score was basically in the Level 4 range, with an average level number of 3.5. From 2015, its water environment safety score had improved to Level 3, with an average level number of 2.9. Therefore, overall speaking, there has been an improvement trend in the water environment of Heilongjiang Province, and its water environment safety score has been around Level 3 since 2014.

(3) From 2009 to 2017, Liaoning Province's water environment safety score was basically in the Level 4 range, with an average level number of 3.6. Within the study period, its water environment safety score reached its best level of 3.4 in 2014, which belonged to Level 3. For the rest of the years, its water environment safety scores were all in the Level 4 range, with an average level number of 3.75. Therefore, overall speaking, Liaoning Province's water environment safety score belonged to Level 4 during the study period, and since 2013, its water environment safety level has improved first and then worsened, showing an overall improvement trend.

(4) During the study period of 2009–2017, the overall water environment safety level of the three northeast provinces has shown an improvement trend and has become more stable, with the water safety score improving between 2009 and 2014, and fluctuating around a certain level since 2014. Since 2013, the overall water environment safety level of these northeast provinces has been in Level 3, with an average level number of 3.15. Although the safety score sometimes moves close to the Level 4 range, most of the time it falls in the Level 3 range.

3.2. Indicator Influence Analysis

It can be seen from Part 2.3 that the smaller the C value, the safer the water environment. This paper has further scored the 11 indicators by using the Graded Scoring Method. Because the safety level and the water environment safety level are in opposite directions, this paper has let $K = 1/C$, and obtained the total score of all indicators by multiplying the weighted average weight and corresponding grading coefficients, as shown in Figure 2:

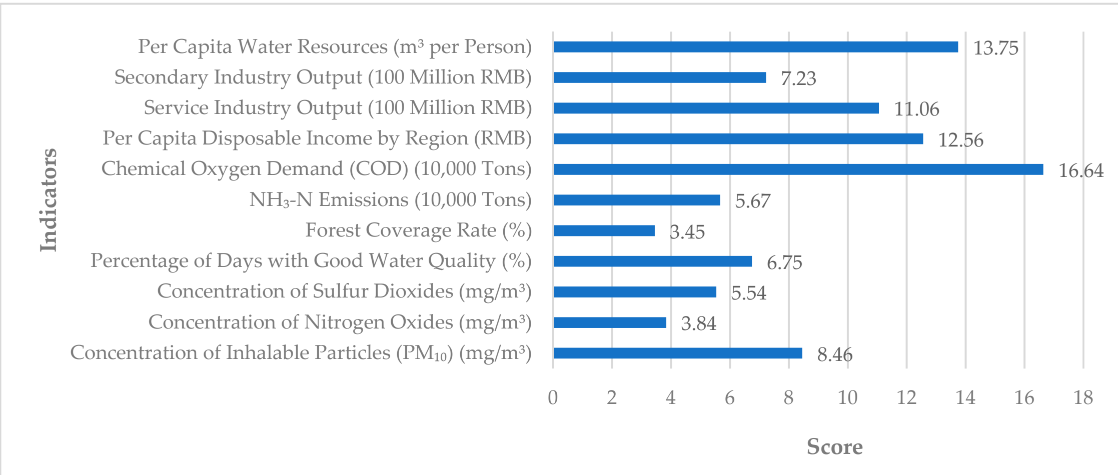
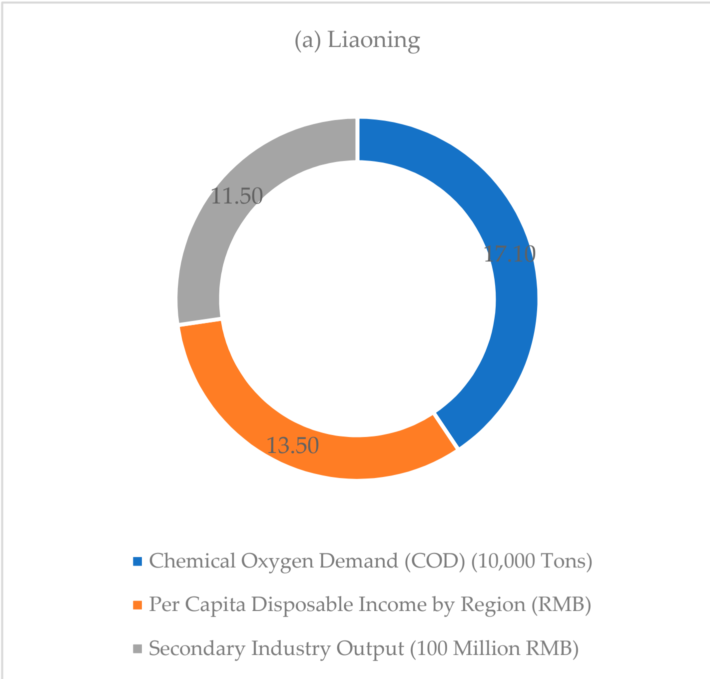
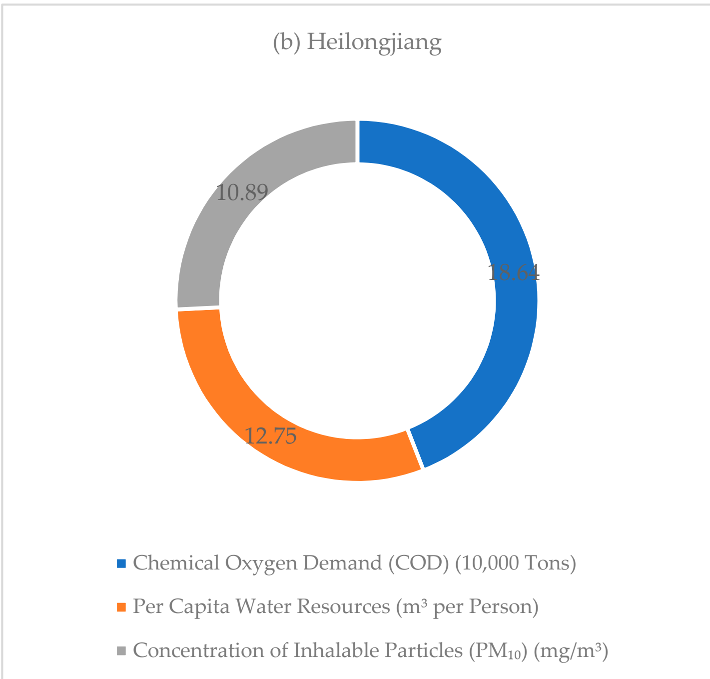


Figure 2. Scores of 11 Indicators Affecting Water Environment Safety in the Three Northeast Provinces.

As shown in Figure 2, from 2009 to 2017, the top 3 indicators that had the greatest impact on the three northeast provinces were Chemical Oxygen Demand (COD), Per Capita Water Resources, and Per Capita Disposable Income by Region. Their respective indicator scores were 16.64, 13.75, and 12.56.

Figure 3 shows the top 3 indicators that had the greatest impact on water environment safety for different provinces in northeast China from 2009 to 2017. Among them, the top 3 indicators for Liaoning Province were Chemical Oxygen Demand (COD) (indicator score: 17.10), Per Capita Disposable Income by Region (indicator score: 13.50), and Secondary Industry Output (indicator score: 11.50). The top 3 factors for Heilongjiang Province were Chemical Oxygen Demand (COD) (indicator score: 18.64), Per Capita Water Resources (indicator score: 12.75), and Concentration of Inhalable Particles (indicator score: 10.89). The top 3 factors for Jilin Province were slightly different: Per Capita Water Resources (indicator score: 15.75), Chemical Oxygen Demand (COD) (indicator score: 14.87), and Service Industry Output (indicator score: 11.55).





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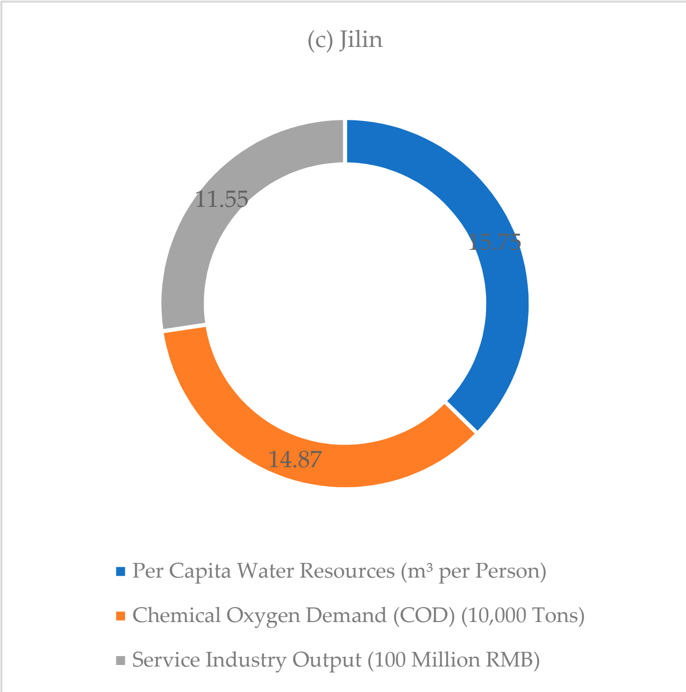

Figure 3. Top 3 Influential Indicators in the 3 Northeast Provinces of China (2009–2017): (**a**) Liaoning; (**b**) Heilongjiang; (**c**) Jilin.

4. Discussion

4.1. Advantages of Evaluation Method

This paper has obtained weights and calculated the evaluation results by using the Entropy Weight Method, the Grey Correlation Analysis Method, and the Principal Component Analysis Method. The Entropy Weight Method helps to avoid subjective influence as much as possible but this method fails to consider the interactions between different indicators [49]. The Grey Correlation Analysis Method measures the relative weight of different indicators according to the similarity (or dissimilarity) between the development trends of various indicators and could reflect the correlation between different indicators very well, but this method is susceptible to extreme values [54,55]. The Principal Component Analysis Method could simplify the data based on the concept of dimension reduction, and avoid problems such as multicollinearity. However, when the calculated weights are negative, the implications of the comprehensive evaluation result in real life would become fairly vague [56,57]. Therefore, this paper has integrated all these three methods in weight determination in order to draw on the strengths of each method, make up for the weakness of each method, and avoid the drawbacks of only depending on a single method. After that, this paper has tested the concordance of the weighting results of these three methods by using the *Kendall* coefficient of concordance and concluded that the results are consistent. Based on that, this paper has used the weighted average value of the indicators accordingly, making sure that the weights are not only statistically significant but also have practical significance. By using the improved weights in the Fuzzy Evaluation Model, this paper could achieve more accurate and comprehensive evaluation results, which truly reflect the water environment safety level of northeast China.

Based on that, this paper has adopted the improved Fuzzy Comprehensive Evaluation Method to convert the measured values of each indicator for water quality to relative level numbers that reflect differences by using the interpolation function. In this way, indicator values of different categories, units, and orders of magnitude are mapped to the same evaluation standard, and therefore become comparable and additive. This evaluation method overcomes the shortcomings of the traditional comprehensive evaluation model. It is not only simple in calculation but also fully reflects the systematic and comprehensive characteristics of the water environment.

4.2. Analysis of Evaluation Results

According to the evaluation results, the water environment safety level of northeast China has shown an improvement trend since 2009 and has been fluctuating around a certain level since 2014. This paper's evaluation results are also consistent with the water quality condition as well as its development trends in the northeast region as reflected in the Annual Statistic Report on Environment in China [41]:

(1) Heilongjiang Province suffered serious water pollution in its rivers in 2009. By the end of 2017, the qualification rate of river water that meets the water quality standards in Heilongjiang Province had exceeded 75.2%; the percentage of water whose quality met Level I, II, and III standards had reached 67.5%; while the water whose quality fell into Level V only accounted for 3.1% of the sample. Therefore, there have been significant improvements in the river water quality and water environment safety in Heilongjiang Province.
(2) In 2009, in the section of major rivers of Liaoning Province, the percentage of water whose quality was above Level V standards was 65.8%. According to the 2017 data, the percentage of water whose quality met Level I, II, and III standards was 30.6%; the percentages of water whose quality fell under Level IV, V, and below V were 52.8%, 8.3%, and 8.3%, respectively.
(3) In 2009, in the monitored section of major rivers in Jilin Province, the percentages of water whose quality fell into Level II, III, IV, and V were 16.9%, 35.0%, 20.8%, and 10.4%, respectively. According to the 2017 Environmental Bulletin data, in the monitored river sections of Jilin Province, the percentages of water whose quality fell into Level II, III, IV, and V improved to 34.1%, 37.6%, 8.6%, and 4.7%, respectively.

Therefore, overall speaking, the water environment in the three northeast provinces has shown an improvement trend. In recent years, these provinces have issued a series of targeted policies and enhanced the comprehensive management efforts on the water environment. The local governments have focused on the several major water bodies including rivers, centralized sources of urban drinking water, reservoirs, and off-shore waters, and established a water environment management system that is in continuous improvement and covers multiple processes including access, management, and monitoring [58,59]. These measures have achieved positive results.

Among the major factors that have the greatest impact on the water environment safety of the northeast provinces:

(1) Chemical Oxygen Demand (COD): This indicator reflects the quality of water and its impact on the ecological environment. The reducing substances in water are mainly organic substances, and their main sources are the decomposition of animals and plants and the discharge of domestic sewage and industrial wastewater. When the water is contaminated by organic matters, the Chemical Oxygen Demand (COD) increases [60–62]. According to our results, this indicator had the greatest impact on the water environment safety of northeast China. The industrial development in the past years has brought considerable damages to the water environment in this region. The discharge of industrial wastewater and agricultural wastewater has caused organic pollution of the water bodies. Chemical Oxygen Demand (COD) was the most influential factor in the water environment of both Liaoning Province and Heilongjiang Province, which indicates the significance of organic pollution control in the northeast region.
(2) Per Capita Water Resources: This indicator reflects the capacity of water resources in a certain region. The fact that this indicator has a huge impact on the water environment safety of northeast China has reflected the problem of water shortage and waste of water resources in this region. The northeast provinces are endowed with an admirable natural and geographical environment, as well as famous rivers such as the Heilongjiang River, Nen River, Songhua River, and Liao River.

However, despite their abundant river systems, the northeast provinces face serious problems including waste of water resources, low water recycling rate, and extensive irrigation style in agricultural practice. Due to the dry climate in recent years, this region has experienced droughts during springtime, which has aggravated the issue of water shortage in the northeast region. Such problems are particularly prominent in Heilongjiang Province [63–65].

(3) Per Capita Disposable Income: This is an important economic indicator that reflects the impact of human economic activities on the generation of water resources and the number of water resources available. The higher the per capita disposable income, the stronger the investment capacity in water conservancy infrastructure, which could further ensure economic security and facilitate the improvement of water environment safety [66,67]. This indicator was the third most important indicator that affects the water environment safety in northeast China, indicating that the water environment management is closely related to the local economic development level. Economic development is an important source of local government's fiscal revenue, supporting the government's efforts in environmental protection policy implementation and construction of related infrastructure. Meanwhile, economic development is also the basis of technological innovation and institutional reform of enterprises, which drives the research and development as well as promotion of wastewater treatment technologies and improvement in the utilization efficiency of water resources. In addition, per capita disposable income also plays an important role in advancing the reform of agricultural production technology. Therefore, increasing per capita disposable income is an important condition and foundation for water environment safety enhancement.

5. Conclusions and Measures

This paper has proposed an improved Fuzzy Comprehensive Evaluation Method: first, based on the Entropy Weight Method, the Grey Correlation Analysis Method, and the Principal Component Analysis Method, this paper has constructed an integrated weighting model by taking the arithmetic mean of the weights obtained through these three methods, as well as established a water environment safety evaluation system with 17 indicators from the economic, environmental, and ecological aspects. After that, this paper has screened the initially selected indicators by the Principal Component Analysis Method, and eventually determined 11 indicators as the evaluation indicators. With the indicator system after screening, this paper has adopted the improved Fuzzy Comprehensive Evaluation Method to evaluate the water environment safety of the three northeast provinces and obtained the change in water environment safety of different provinces from 2009 to 2017. We find that the overall water environment safety of the region has improved first but worsened afterward. Moreover, Chemical Oxygen Demand (COD), Per Capita Water Resources, and Per Capita Disposable Income are the three major factors that had the greatest impacts on the water environment safety during the study period.

In order to effectively control water pollution and alleviate the problem of water shortage, based on the evaluation results, this paper has concluded that the treatment of reducing substances in the water, especially the organic substances is essential for the improvement of water environment safety in the northeast region. Based on that, this paper has proposed below policy recommendations:

(1) Improve wastewater treatment methods, especially for pollutants containing industrial organic matters. First, it is crucial to improve the treatment method for industrial wastewater with organic matters and improve the treatment efficiency, selecting appropriate technology according to the nature of different pollutants in the wastewater. For wastewater that contains low-boiling organic matters, the steam stripping method can be used; for wastewater that contains surface-active materials, the foam separation method can be used; for wastewater that contains macromolecular hydrophobic materials, method such as coagulating sedimentation can be used. Meanwhile, technical improvement should be performed on existing equipment, such as installing additional processes including coagulating sedimentation, filtration, and activated carbon adsorption to the

end of biological treatment process. For water pollution containing agricultural organic matter, biological means can be adopted in pollution prevention and control [68,69].

(2) Improve the utilization efficiency of water resources. According to the research results of the paper, Per Capita Water Resources has a great impact on the water environment safety of the northeast region. The water resources in China are not evenly distributed. This is especially true for the northeast region. These northeast provinces should formulate scientific water policies according to the natural environment, socioeconomic conditions, and regional development needs, as well as improve the allocation efficiency of water resources and utilize water wisely. Local governments should keep in mind the importance of effective allocation of water resources, guiding the utilization of water resources with a recycling and comprehensive perspective, as well as enhance scientific water resource utilization planning to achieve efficient resource allocation, and improve the utilization efficiency by effective and strict supervision measures. It is necessary to strengthen the recycling of water resources and save water by improving the treatment and recovery of sewage and wastewater and encouraging the recycling of water resources [70–72].

(3) Promote economic development. According to the research results of this paper, increasing per capita disposable income is an important way to improve the water environment safety in northeast China. Deepening reform and promoting the revitalization of the old industrial base in northeast China are both critical ways to advance the economic development in this region [73]. Meanwhile, improving the income distribution system and social equity is also an important measure in increasing per capita disposable income and thus improving the environment. The local governments should narrow the income gap by adjusting the income distribution policy, and increase per capita disposable income in order to provide economic support to the sustainable development of the northeast region [74]. The local governments should adhere to the people-oriented principle, pay more attention to social equity, and make use of economic adjustment mechanisms including fiscal and monetary policies, and adjust the redistribution policy in order to cultivate a fair competitive environment, protect legitimate income, and establish appropriate mechanisms for worker wage increase and guarantee for wage payments.

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