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Water Environment Management and Performance Evaluation in Central China: A Research Based on Comprehensive Evaluation System

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Abstract: As a developing country with insufficient water resources, China's water environment management and performance evaluation have important research value. The three provinces (Henan, Hubei, and Hunan) in central China with typical significance in geographical location and water resources governance were selected as research objects in this paper. Based on the principal component analysis (PCA) method and the pressure-state-response (PSR) model, a comprehensive evaluation system for the water environment in those three provinces during 2011–2017 was established in this paper. The evaluation results show that: (1) The water environment management and performance evaluation of the three provinces in central China were generally poor in 2011–2012, but the overall trend was rising; (2) in 2013–2014, the situation was improved compared to the previous two years, but needed further enhancement; (3) in 2015–2017, the water environment management and performance of the three provinces showed significant improvement. Among them, the Hubei Province had the highest water environment evaluation value (1.692), and the Henan Province had the most significant progress (from 0.043 to 1.671). The contributions of this paper are: (1) The comprehensive evaluation model based on PCA and the PSR model was constructed to analyze the sustainable development of water environment in central China; (2) the performance evaluation system for water environment management, which could comprehensively evaluate the performance of water environment treatment and effectively reveal the correlation between various indicators, was established. The principal factors in water environment management can be obtained by this evaluation system. Based on the analysis of the reasons underlying the above changes, the corresponding policy recommendations for improving water environment management and performance in central China were suggested in order to provide a reference for further improvement of water environment management in developing countries.

Keywords: water environment management; water performance evaluation; principal component analysis; pressure-state-response model; central China

1. Introduction

Water is the source of life, the key to production, and the foundation of ecology [1–3]. Water is one of the most valuable and irreplaceable resources in the world, on which all the life on Earth depends for survival and development [4–6]. With the rapid development of the economy, population explosion, rapid industrial growth, and surging water consumption, the sustainable development of the water environment is receiving more and more attention from all sectors of the society. In 1972, the first United Nations Conference on Environment and Development predicted that after the oil crisis, the next crisis would be the water crisis [7]. In 2000, the World Ministerial Conference and the World Water Symposium both made "Water Safety in the 21st Century" the key topic of the conference [8,9].

China is a country with severe water shortages. It has a total freshwater resource of 2800 billion cubic meters, accounting for 6% of the global water resources, and is ranked fourth after Brazil, Russia, and Canada. However, China's per capita water resource is only 2200 cubic meters, which is only one-quarter of the world average and ranked 121st in the world, thus making China one of the 13 countries in the world with the poorest per capita water resources [10–12]. Therefore, the sustainable development of the water environment has become a research hotspot, together with other environmental safety topics [13–16].

Sustainable development means "satisfying the current needs and pursuits of the people, while not causing harm to the needs and pursuits of future generations" [17,18]. Water resources are closely linked with people's daily lives, which makes the sustainable development of the water environment one of the hottest topics today. The studies on water environment safety have mainly focused on the urban area [19,20]. There have been very few studies on the sustainability of regional water environment. In order to alleviate the constraints of water problems on China's economic and social development, the central government has implemented the strategies of "safeguarding sustainable economic and social development with the sustainable utilization of water resources" and "coordinated development of the population, resources and the environment" as China's water environment management strategies of the 21st century [21].

Geographically speaking, central China extends from the middle reaches of the Yellow River to the middle and lower reaches of the Yangtze River, covering the three provinces of Henan, Hubei and Hunan. Its location is of strategic importance—it has the Beijing-Tianjin-Hebei city cluster of the North China Plain to its north, it is neighbored by the Yangtze River Delta of Eastern China to its east, it reaches the Pearl River Delta in Southern China to its south, and it is connected to the Sichuan Basin and Guanzhong Plain to its west [22,23]. Given the fact that these neighboring regions all experience frequent water pollution incidents, with the rapid economic development of China, central China has also seen significant aggravation in water pollution accompanied by water environment quality deterioration. central China is rich in water resources, with a high population density. Due to the considerable impact of human activities, as well as poor hydrodynamic conditions in this region, pollutants cannot diffuse easily and the water pollution issue deserves sufficient attention [24]. Regarding the current situation, the central government has specifically formulated and proposed the "Rise of central China Strategy", which is expected to fundamentally enhance central China's ability to pursue sustainable development [25]. Therefore, this paper selected the performance of water environment management and sustainable development in central China as the research object, which has important implications to the water environment improvement and sustainable development of developing regions.

Although the existing literatures have made many explorations on the sustainable development of water environment (please refer to the "Literature Review"), there are few studies that combine the principal component analysis (PCA) method and the pressure-state-response (PSR) model to construct a performance evaluation system to take advantage of both methods. Therefore, two contributions may be made by this paper to enrich existing researches:

(1) A comprehensive evaluation model based on PCA and the PSR model was constructed to analyze the sustainable development of water environment in central China. The main advantage of PCA is that it can effectively reorganize discrete variables by mathematical statistical methods and reflect the data characteristics by a few variables. The main advantage of the PSR model is that it highlights the causal relationship between the environment and the stress facing the environment, as well as the mutual restriction and interaction between the three layers of stress,

state, and response. Hence, the comprehensive evaluation model in this paper can determine a few composite variables from various variables to replace the existing variables by mathematical dimension reduction methods to explore the causal relationship between human activities and environmental changes based on the evaluation of the sustainability of environmental systems.

(2) A performance evaluation system for water environment management, which could comprehensively evaluate the performance of water environment treatment and effectively reveal the correlation between various indicators, was established. The principal factors in water environment management can be obtained by this evaluation system. Therefore, the evaluation indicator system and the weights of different indicators in this system can be determined for quantitative calculation by substituting the standardized values into the indicator system. This performance evaluation system can be used to evaluate the performance of water environment management and sustainable development. After careful selection of specific indicators and use of official statistics from the three provinces in central China, the objectivity of calculation results was ensured in this paper to contribute to evaluate the performance of water environment management and sustainable development in China.

The structure of this paper is as follows: Section 2 is the literature review, Section 3 introduces the research methods used in this paper, Section 4 lists the calculation results, Section 5 analyzes the water environment management and performance evaluation of the three provinces in central China from 2011 to 2017, and Section 6 summarizes the findings in this paper and provides corresponding policy recommendations.

2. Literature Review

It is generally agreed by the academia that performance evaluation should consider various factors including efficiency, effectiveness, and satisfaction [26–28].

Among the existing studies, Lu et al. established a credibility-based optimization model for water resources management in South central China to show the confidence level of the optimal management strategies. Their results indicated that an aggressive strategy should be considered if system benefit is not the major concern of the government. They also suggested that part of system benefit could be sacrificed to protect local groundwater resources [29].

Cai et al. used the composite index method to conduct a spatiotemporal analysis of water resources vulnerability in China. They found that water resources in north and central China are more vulnerable than in the western area. Moreover, water pollution was worsening remarkably in central China, and water resource shortage has been one of the most serious challenge for sustainable development there [30].

Yao et al. investigated the 14 antibiotics in groundwater and surface water at the Jianghan Plain in central China. They demonstrated that the total concentrations of antibiotics in the spring samples were higher than those in summer and winter. By the risk quotient and mixture risk quotient methods, they evaluated the environmental risks for surface water and groundwater in central China [31].

Hu et al. analyzed 13 antibiotics in the Hanjiang River, one of the main rivers in central China. Their results showed that the hazard quotients of antibiotics were higher in the sediment than those in the water body of the Hanjiang River. Moreover, antibiotic mixtures posed higher ecological risks to water resource in central China than aquatic organisms [32].

Jia et al. constructed an index system to quantify the water environmental carrying capacity. They showed that the potential of water environmental carrying capacity is decreasing from the east China to the west. Moreover, the water resource vulnerability in the west is higher than that of central China [33].

Zhou et al. established a non-radial directional distance function to measure the performance of water use and wastewater emission. Their results indicated that eastern China performs better than central China, with the average technology gap of 51%. Since the technological heterogeneity directly affected the environmental efficiency of industrial water in China, they also assessed the technological efficiency of each province and provided corresponding improvement targets for them [34].

3. Materials and Methods

3.1. Principal Component Analysis

The PCA method was first introduced by the American statistician Pearson in the study of biological theory [35]. The main idea is to reorganize discrete variables by mathematical statistical methods and attempt to reflect the data characteristics by a few variables [36–38]. This method determines a few composite variables from various variables to replace the existing variables by mathematical dimension reduction methods, such that these composite variables contain as much amount of information as the original variables and are independent from each other. This method could remove overlapping information in quantitative analysis in order to reflect the same amount of information with a minimum number of mathematical variables [39,40].

The PCA method uses variance as a measure of information amount. It attempts to reorganize the various existing variables with certain correlation with each other into a new set of mutually independent composite variables to replace the existing variables. If the first linear combination selected, i.e., the first composite variable, is denoted as F1, and the information amount carried by each variable is measured by the variance, then the larger the $Var(\mathrm{F1})$ value, the larger the amount of information is contained. Therefore, among all the linear combinations, the F1 with the largest variance should be selected. Such F1 is also called the first principal component. If the first principal component could not sufficiently represent all the information contained in the original p variables, a second linear combination should be considered. In order to effectively reflect the information in the original variables, the information contained by F1 does not need to be covered by F2 again. By applying the same mathematical method, F2, i.e., the second principal component, could be obtained given that $\mathrm{Cov}(\mathrm{F1}, \mathrm{F2}) = 0$. By the same methods, the third, the fourth, the fifth, … and the pth principal component could be determined.

Based on this method, this paper constructed a matrix of water environment sample data of central China:

$$X = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1p} \\ x_{21} & x_{22} & \cdots & x_{2p} \\ \vdots & \vdots & \vdots & \vdots \\ x_{p1} & x_{p2} & \cdots & x_{pp} \end{pmatrix}, \tag{1}$$

where X_{ij} stands for the jth indicator of the ith data.

(1) Standardize the raw data X:

$$x_{ij}^{*} = \frac{x_{ij} - \overline{x_j}}{\sqrt{var(x_j)}} \; (i = 1, 2, 3 \cdots p; j = 1, 2, 3 \cdots p) \tag{2}$$

The x_{ij} in the above equation is the observed sample data and x_{ij}^{*} is the standardized data, where $\overline{x_j}$ is the average of the jth indicator:

$$\overline{x_j} = \frac{1}{p} \sum_{i=1}^{p} x_{ij} \tag{3}$$

$\sqrt{var(x_j)}$ is the standard deviation of the jth indicator:

$$var(x_j) = \frac{1}{p-1} \sum_{i=1}^{p} \left(x_{ij} - \overline{x_j}\right)^2, (j = 1, 2, 3 \cdots p) \tag{4}$$

(2) Construct a correlation coefficient matrix R for the standardized data x_{ij}^*:

$$R = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1p} \\ r_{21} & r_{22} & \cdots & r_{2p} \\ \vdots & \vdots & \vdots & \vdots \\ r_{p1} & r_{p2} & \cdots & r_{pp} \end{pmatrix} \quad (5)$$

R is a $p \times p$ matrix in which the element r_{ij} can be defined as:

$$r_{ij} = \frac{\sum_{k=1}^{p} (x_{ki} - \overline{x_i})\left(x_{kj} - \overline{x_j}\right)}{\sqrt{\sum_{k=1}^{p} (x_{ki} - \overline{x_i})^2 \sum_{k=1}^{p} (x_{kj} - \overline{x_j})^2}} \quad (6)$$

(3) Calculate Eigenvalues and Eigenvectors

$$|\lambda E - R| = 0 \quad (7)$$

In the above formula, $\lambda_i (i = 1, 2, 3 \cdots, p)$ is the eigenvalue and E is an identity matrix of the same order as R. By solving the above formula, the eigenvalues can be obtained. The eigenvalues were further sorted by value. The eigenvalue λ_i represents the variance of the ith principal component, reflecting the degree of influence of each principal component.

(4) Calculate the Contribution Rate of Each Component

a. The contribution rate of Principal Component A_i to the variance can be written as:

$$W_i = \frac{\lambda_i}{\sum_{i=1}^{p} \lambda_i} \ (i = 1, 2, 3 \cdots, p) \quad (8)$$

b. The cumulative contribution rate of the first n principal components to the variance can be written as:

$$G_i = \sum_{i=1}^{n} \lambda \frac{i}{\sum_{i=1}^{p} \lambda_i} \ (i = 1, 2, 3 \cdots, p) \quad (9)$$

(5) Determine the Principal Components

Based on the standardized raw data, the contribution rates of different principal components can be obtained by substituting the principal components into the expressions above.

3.2. The Comprehensive Evaluation Method Based on the PSR Model

The PSR model was developed by Rapport and Friend in Canada to assess the impact of human activities on the ecological environment [41]. This model highlights the causal relationship between the environment and the stress facing the environment, as well as the mutual restriction and interaction between the three layers of stress, state, and response [42–44]. The main purpose of the PSR model is to explore the causal relationship between human activities and environmental changes based on the evaluation of the sustainability of environmental systems [45,46]. Therefore, the PSR model can be used to study the sustainable development of the water environment in central China.

The water environment is a dynamic environment. This paper adopted the PSR model to study the changes in water environment in central China during the study period and to further analyze the sustainability of the water environment. To evaluate water environment sustainability under the

PSR framework based on the construction of distance function and discrete coefficients, the formula following formula was used:

$$CI = \frac{X_1 + X_2 + X_3}{\sqrt{X_1^2 + X_2^2 + X_3^2}} \quad (10)$$

In the above formula, CI is the coordination degree function, and X_1, X_2, and X_3 represent the scores corresponding to the pressure, state, and response layers, respectively. The closer the scores under the pressure, state, and response layers to each other, the closer the coordination coefficient is to $\sqrt{3}$, indicating a better sustainability level.

3.3. Comprehensive Evaluation of the Performance of Water Environment Management and Sustainable Development

Through calculation based on the above method, this paper constructed an evaluation indicator system and determined the weights of different indicators in this system. Next, this paper performed quantitative calculation by substituting the standardized values into the indicator system. The specific method is:

$$ICP = \sum_{i=1}^{p} P_i W_i \quad (11)$$

In the formula above, ICP is the water environment management index, P_i is the indicator value, and W_i is the weight of the indicator. This index can be used to evaluate the performance of water environment management and sustainable development. As can be seen from the above formula, the value of the index should range from [0, 1].

3.4. Indicator Selection and Data Source

In the selection of specific indicators, this paper emphasized the principle of comprehensiveness and objectivity to ensure that the indicator system could comprehensively evaluate the performance of water environment management and sustainable development. The data of the indicators were all from official statistics to ensure the objectivity of calculation results, and the study period was from 2011 to 2017 [47–51]. The finalized indicator system is shown in Table 1.

Table 1. Indicator System for Performance Evaluation of Water Environment Management based on the Pressure-State-Response (PSR) Model.

Indicator Type	Indicator Number	Indicator Description	Unit of Measurement	Nature of Indicator
The Pressure Layer	ZP1	Total Wastewater Discharge	10 Thousand Tons	Negative Indicator (a lower value is preferred)
	ZP2	Chemical Oxygen Demand (COD)	10 Thousand Tons	Negative Indicator (a lower value is preferred)
	ZP3	NH_3-N Emissions	10 Thousand Tons	Negative Indicator (a lower value is preferred)
	ZP4	Phosphorus Emissions	10 Thousand Tons	Negative Indicator (a lower value is preferred)
	ZP5	Lead Emissions	Kilogram	Negative Indicator (a lower value is preferred)
	ZP6	Mercury Emissions	Kilogram	Negative Indicator (a lower value is preferred)
	ZP7	Cadmium Emissions	Kilogram	Negative Indicator (a lower value is preferred)
	ZP8	Chromium Emissions	Kilogram	Negative Indicator (a lower value is preferred)
	ZP9	Arsenic Emissions	Kilogram	Negative Indicator (a lower value is preferred)
	ZP10	General Industrial Solid Waste	10 Thousand Tons	Negative Indicator (a lower value is preferred)

Table 1. *Cont.*

Indicator Type	Indicator Number	Indicator Description	Unit of Measurement	Nature of Indicator
The State Layer	ZS1	Regional GDP	100 Million RMB	Positive Indicator (a higher value is preferred)
	ZS2	Regional Secondary Industry Output	100 Million RMB	Positive Indicator (a higher value is preferred)
	ZS3	Birth Rate	‰	Positive Indicator (a higher value is preferred)
	ZS4	Mortality Rate	‰	Positive Indicator (a higher value is preferred)
	ZS5	Natural Population Growth Rate	‰	Positive Indicator (a higher value is preferred)
The Response Layer	ZR1	Afforestation Area	Hectare	Positive Indicator (a higher value is preferred)
	ZR2	Constructed Wetland Area	1000 Hectares	Positive Indicator (a higher value is preferred)
	ZR3	Comprehensive Utilization of General Industrial Solid Waste	10 Thousand Tons	Positive Indicator (a higher value is preferred)
	ZR4	Investment in Industrial Wastewater Treatment	10 Thousand RMB	Positive Indicator (a higher value is preferred)
	ZR5	Investment in Industrial Waste Treatment	10 Thousand RMB	Positive Indicator (a higher value is preferred)
	ZR6	Investment in Ecosystem Construction and Protection	10 Thousand RMB	Positive Indicator (a higher value is preferred)

In the above table, the indicators of the pressure layer were measured by the discharge of major pollutants. The lower the indicator value, the lower the pressure on the water resources caused by pollutant emission during economic development. The indicators of the state layer were divided into two categories: The gross domestic product and the change in population. The higher the indicator value, the bigger achievement in water quality improvement. The indicators of the response layer represent the expenditure or investment of the government in order to take actions against water pollution. The higher the indicator value, the more emphasis the local government has put on water pollution control and the stronger the enforcement.

4. Results

Based on the model and methodology introduced in Section 3, as well as the indicators selected, this paper obtained the below calculation results from the PSR model (as shown in Table 2):

Table 2. Calculation Results of Eigenvalues and Eigenvectors from the PSR Model.

	Principal Component Variable	**Z1**	**Z2**	**Z3**	**Z4**	**Z5**
Eigenvalue	Eigenvalue	9.977	2.409	2.319	1.352	1.255
	Principal Component Contribution Rate	47.511	11.473	11.044	6.438	5.974
	Cumulative Contribution Rate	47.511	58.983	70.028	76.465	82.44
	Independent Variables	**Vector1**	**Vector2**	**Vector3**	**Vector4**	**Vector5**
Eigenvector	P3	−0.3359	−0.0455	−0.2503	0.27644	−0.18581
	S5	−0.1400	0.02874	−0.1249	0.41216	−0.0617
	P6	0.23879	0.31971	−0.0977	0.36257	−0.0647
	S2	−0.1322	−0.0566	0.13636	0.17075	0.303756
	R6	0.08740	−0.0894	0.39251	0.09988	0.227806
	Different Variables	**P3**	**S5**	**P6**	**S2**	**R6**
Correlation Coefficient between Variables	P3	1	—	—	—	—
	S5	0.464	1	—	—	—
	P6	0.814	−0.067	1	—	—
	S2	0.406	−0.005	0.667	1	—
	R6	0.723	0.106	−0.421	−0.276	1

As can be seen from the eigenvalues and variance contribution rates in Table 2, there were five indicators whose eigenvalues are greater than 1, which thus became the candidates of the principal component variables. These variables are: NH_3-N Emissions, Natural Population Growth Rate, Mercury Emissions, Regional Secondary Industry Output, and Investment in Ecosystem Construction and Protection, whose cumulative variance contribution rate reached 82.44%, indicating that the five principal component variables could explain 82.44% of the information contained in the 21 indicators. These principal component variables were then sorted by their variance contribution rates and expressed as Z1, Z2, Z3, Z4, and Z5 respectively. The factor variance contribution rates are shown in Table 3 below.

Table 3. Factor Variance Contribution Rate.

Total Variance Contribution									
Indicator	Initial Eigenvalue			Sum of Squares of Extracted Loads			Sum of Squares of Rotated Loads		
	Total	Variance	Cumulative	Total	Variance	Cumulative	Total	Variance	Cumulative
1	9.977	47.511	47.511	9.977	47.511	47.511	9.272	44.154	44.154
2	2.409	11.473	58.983	2.409	11.473	58.983	2.489	11.852	56.006
3	2.319	11.044	70.028	2.319	11.044	70.028	2.113	10.060	66.066
4	1.352	6.438	76.465	1.352	6.438	76.465	2.042	9.723	75.790
5	1.255	5.974	82.440	1.255	5.974	82.440	1.397	6.650	82.440
6	0.838	3.990	86.430	—	—	—	—	—	—
7	0.769	3.663	90.094	—	—	—	—	—	—
8	0.582	2.769	92.863	—	—	—	—	—	—
9	0.543	2.584	95.447	—	—	—	—	—	—
10	0.312	1.488	96.935	—	—	—	—	—	—
11	0.234	1.113	98.048	—	—	—	—	—	—
12	0.193	0.917	98.965	—	—	—	—	—	—
13	0.085	0.405	99.370	—	—	—	—	—	—
14	0.059	0.279	99.648	—	—	—	—	—	—
15	0.032	0.151	99.799	—	—	—	—	—	—
16	0.023	0.111	99.910	—	—	—	—	—	—
17	0.012	0.059	99.970	—	—	—	—	—	—
18	0.006	0.027	99.997	—	—	—	—	—	—
19	0.001	0.003	100.000	—	—	—	—	—	—
20	0.000	0.000	100.000	—	—	—	—	—	—
21	0.000	0.000	100.000	—	—	—	—	—	—

The rotated factor load matrix indicates the correlation between the 21 indicators and the five principal components, as shown in Table 4.

Table 4. Rotated Factor Load Matrix.

Indicator	Principal Component				
	Z1	Z2	Z3	Z4	Z5
ZP1	0.170	−0.253	−0.506	0.709	−0.045
ZP2	0.949	0.008	0.088	0.245	0.030
ZP3	0.954	0.017	0.106	0.211	0.029
ZP4	0.924	−0.002	0.055	0.315	−0.035
ZP5	0.780	0.090	0.272	0.020	0.274
ZP6	0.697	0.212	0.446	−0.028	0.216
ZP7	0.736	0.211	0.222	0.005	0.409
ZP8	0.714	0.224	0.260	−0.246	−0.220
ZP9	0.888	0.154	0.183	0.191	0.233
ZP10	0.202	−0.811	0.198	−0.299	−0.173
ZS1	0.878	0.200	0.307	−0.090	0.187
ZS2	0.358	0.115	0.101	0.814	−0.100
ZS3	0.461	0.757	−0.067	−0.213	−0.138
ZS4	0.679	0.313	0.142	0.722	−0.007
ZS5	0.375	0.774	−0.087	−0.234	−0.099

Table 4. *Cont.*

Indicator	Principal Component				
	Z1	**Z2**	**Z3**	**Z4**	**Z5**
ZR1	−0.229	0.077	−0.850	−0.070	−0.016
ZR2	0.716	0.145	−0.074	0.079	−0.270
ZR3	−0.859	0.337	0.142	0.145	−0.026
ZR4	0.133	−0.042	−0.039	−0.085	0.431
ZR5	−0.147	0.327	−0.697	0.149	0.065
ZR6	0.741	0.150	0.036	−0.545	−0.012

Extraction Method: Principal Component Analysis Method. Rotation Method: Caesar Normalization Maximum Variance Method. Note: Rotation *a* has converged after 11 iterations.

It can be seen from Table 4 that:

(1) The indicators that are strongly correlated with Principal Component Z1 include: ZP3, ZP2, and ZP4;
(2) The indicators that are strongly correlated with Principal Component Z2 include: ZS5, ZS3, and ZR3;
(3) The indicators that are strongly correlated with Principal Component Z3 include: ZP6, ZS1, and ZP5;
(4) The indicators that are strongly correlated with Principal Component Z4 include: ZS2, ZS4, and ZP1;
(5) The indicators that are strongly correlated with Principal Component Z5 include: ZR6, ZR4, and ZP7.

Therefore, Z1 and Z3 could be defined as the principal components of the stress layer, which comprehensively reflect the overall conditions of the pressure indicators; Z2 and Z4 could be defined as the principal components of the state layer, which comprehensively reflect the overall improvement of the state indicators; and Z5 could be defined as the principal component of the response layer, which comprehensively reflects the overall conditions of the response indicators.

Based on the calculation method introduced in Section 3, this paper further obtained the expressions of Z1, Z2, Z3, Z4, and Z5 (see Equations (12)–(16) below):

$$\begin{aligned} Z1 = 0.073 \times (ZP1) \quad & +0.115 \times (ZP2) + 0.115 \times (ZP3) + 0.115 \times (ZP4) + 0.062 \times (ZP5) \\ & +0.022 \times (ZP6) + 0.046 \times (ZP7) + 0.078 \times (ZP8) + 0.075 \times (ZP9) \\ & +0.102 \times (ZP10) - 0.006 \times (ZR1) + 0.111 \times (ZR2) - 0.184 \times (ZR3) \\ & +0.071 \times (ZR4) + 0.025 \times (ZR5) + 0.125 \times (ZR6) + 0.072 \times (ZS1) \\ & -0.011 \times (ZS2) + 0.029 \times (ZS3) + 0.049 \times (ZS4) + 0.016 \times (ZS5) \end{aligned} \tag{12}$$

$$\begin{aligned} Z2 = -0.127 \times (ZP1) \quad & -0.056 \times (ZP2) - 0.053 \times (ZP3) - 0.057 \times (ZP4) \\ & -0.002 \times (ZP5) + 0.073 \times (ZP6) + 0.052 \times (ZP7) + 0.045 \times (ZP8) \\ & +0.021 \times (ZP9) - 0.392 \times (ZP10) + 0.035 \times (ZS1) + 0.085 \times (ZS2) \\ & +0.285 \times (ZS3) + 0.104 \times (ZS4) + 0.297 \times (ZS5) - 0.038 \times (ZR1) \\ & +0.001 \times (ZR2) + 0.253 \times (ZR3) - 0.024 \times (ZR4) + 0.112 \times (ZR5) \\ & -0.031 \times (ZR6) \end{aligned} \tag{13}$$

$$\begin{aligned} Z3 = -0.225 \times (ZP1) \quad & -0.036 \times (ZP2) - 0.029 \times (ZP3) - 0.041 \times (ZP4) \\ & +0.062 \times (ZP5) + 0.184 \times (ZP6) + 0.038 \times (ZP7) + 0.066 \times (ZP8) \\ & +0.024 \times (ZP9) - 0.007 \times (ZP10) + 0.07 \times (ZS1) + 0.136 \times (ZS2) \\ & -0.052 \times (ZS3) + 0.045 \times (ZS4) - 0.057 \times (ZS5) - 0.103 \times (ZR1) \\ & -0.097 \times (ZR2) + 0.243 \times (ZR3) - 0.485 \times (ZR4) - 0.357 \times (ZR5) \\ & -0.128 \times (ZR6) \end{aligned} \tag{14}$$

$$\begin{aligned} Z4 = +0.281 \times (ZP1) \quad & +0.087 \times (ZP2) + 0.071 \times (ZP3) + 0.12 \times (ZP4) + 0.008 \times (ZP5) \\ & +0.018 \times (ZP6) + 0.005 \times (ZP7) - 0.123 \times (ZP8) + 0.085 \times (ZP9) \\ & -0.2 \times (ZP10) - 0.044 \times (ZS1) + 0.429 \times (ZS2) - 0.097 \times (ZS3) \\ & +0.07 \times (ZS4) - 0.104 \times (ZS5) - 0.057 \times (ZR1) + 0 \times (ZR2) \\ & +0.167 \times (ZR3) - 0.128 \times (ZR4) + 0.02 \times (ZR5) - 0.315 \times (ZR6) \end{aligned} \tag{15}$$

$$\begin{aligned} Z5 = -0.012 \times (ZP1) \quad & -0.022 \times (ZP2) - 0.025 \times (ZP3) - 0.068 \times (ZP4) \\ & +0.156 \times (ZP5) + 0.108 \times (ZP6) + 0.262 \times (ZP7) - 0.209 \times (ZP8) \\ & +0.127 \times (ZP9) - 0.152 \times (ZP10) + 0.67 \times (ZR1) - 0.228 \times (ZR2) \\ & +0.012 \times (ZR3) + 0.043 \times (ZR4) + 0.094 \times (ZR5) - 0.044 \times (ZR6) \\ & +0.085 \times (ZS1) - 0.093 \times (ZS2) - 0.118 \times (ZS3) - 0.041 \times (ZS4) \\ & -0.084 \times (ZS5) \end{aligned} \tag{16}$$

The component score matrix of Equations (12)–(16) is also shown in Table A1. The evaluation scores of the above five principal components can be integrated into one Comprehensive Evaluation Index Z, as shown in (17) below:

$$Z = 47.511\% \times Z1 + 11.473\% \times Z2 + 11.044\% \times Z3 + 6.438\% \times Z4 + 5.974\% \times Z5 \tag{17}$$

5. Discussion

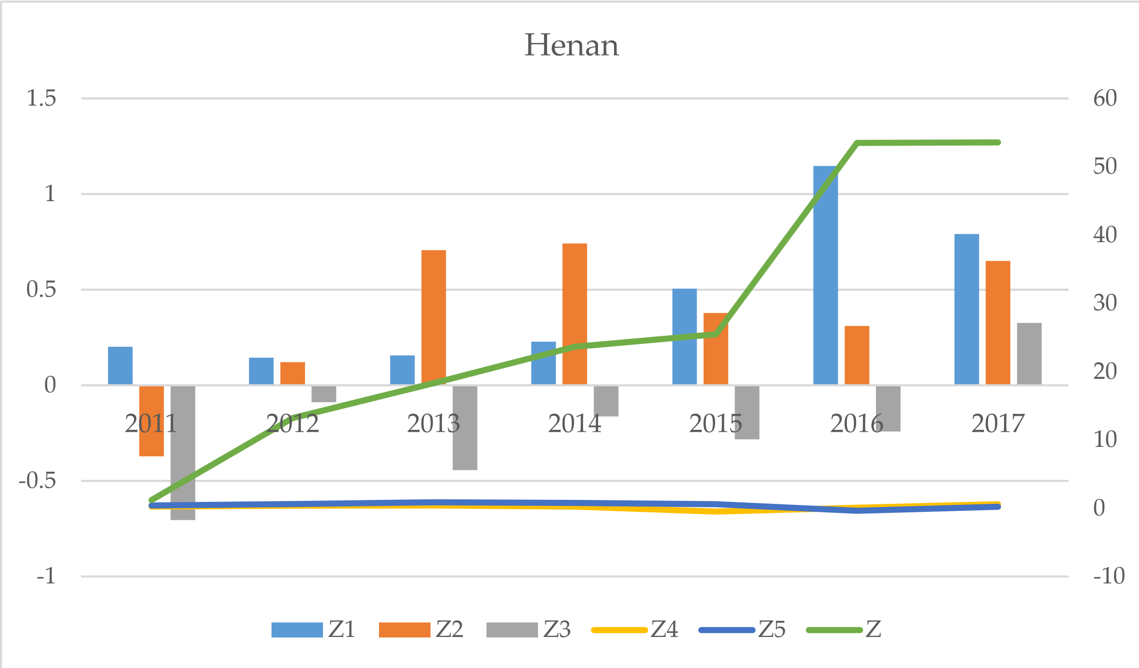
Based on the above expressions of the Pressure Index Z1, the State Improvement Index Z2, the Response Index Z3, and the Comprehensive Evaluation Index Z, this paper obtained the scores of each index in each of the central China provinces within the study period and made further comparison on the index scores by year and by province, respectively (see Figure 1 below and Table A2).

This paper further discretized the Comprehensive Evaluation Index (Sustainability Index) Z in order to define the corresponding intervals for each sustainability level. The results are shown in Figure 2 below and Table A3:

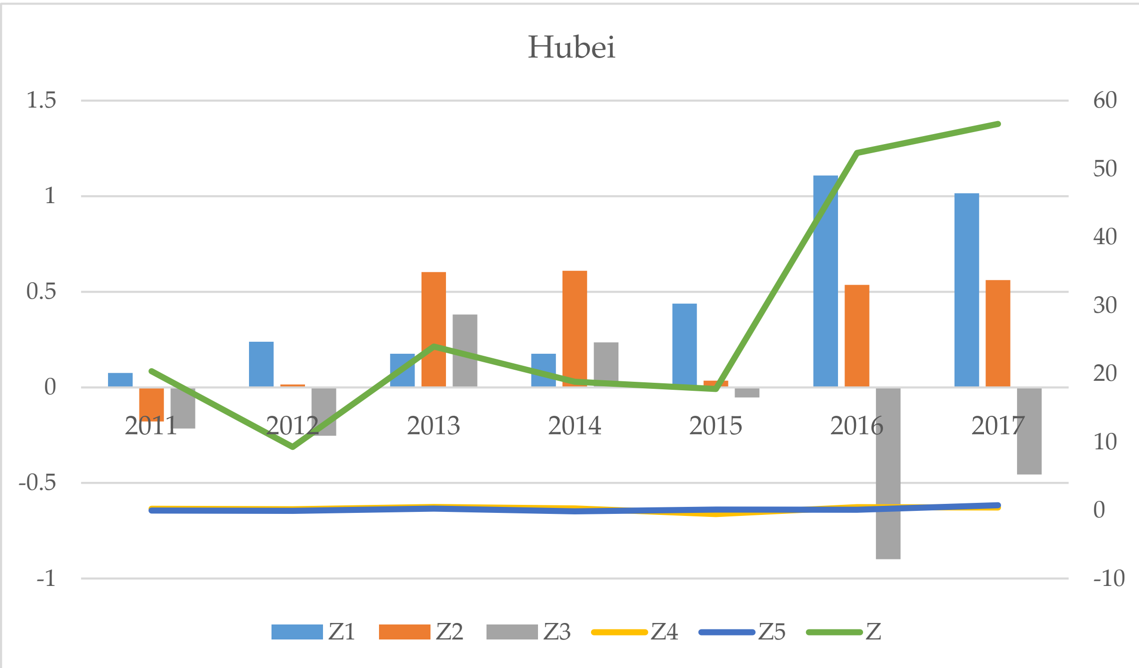
Per the common standards followed by academic researches, a discretized evaluation value between 0 and 0.3 indicates a poor level of sustainable development, a discretized evaluation value between 0.3 and 0.6 indicates a medium level of sustainability, a discretized evaluation value between 0.6 and 0.9 indicates a good level of sustainability, and a discretized evaluation value above 0.9 indicates an excellent level of sustainable development [52,53]. It can be seen from the data in Table A3 that the level of sustainable development of the three provinces in central China during 2011 and 2012 was generally poor, but it was on an improvement trend. The overall level of sustainable development was in the medium range during 2013 and 2014, which improved compared with the previous two years, but there was still room for improvement. By 2015–2016, due to the government's strong implementation of environmental protection policies, strengthened environmental protection supervision, and the introduction of a series of laws and regulations such as the Environmental Protection Law, the sense of responsibility for environmental protection became deeply rooted in the hearts of the people [54–56]. Therefore, during this period and beyond 2017, the sustainability level of the water environment in these provinces has seen huge improvements.

It can be noted by sorting the discretized comprehensive evaluation scores in 2017 that the Hubei Province had the best sustainability level in water environment, the Henan Province achieved the biggest improvement in terms of water environment sustainability, and the Hunan Province's sustainability level in water environment was medium. Overall, the sustainability level of water environment in central China has improved.

Based on Section 3.3, this paper further calculated the comprehensive evaluation scores of the water environment management and sustainable development performance in the three provinces of central China (see Figure 3 below and Table A4).

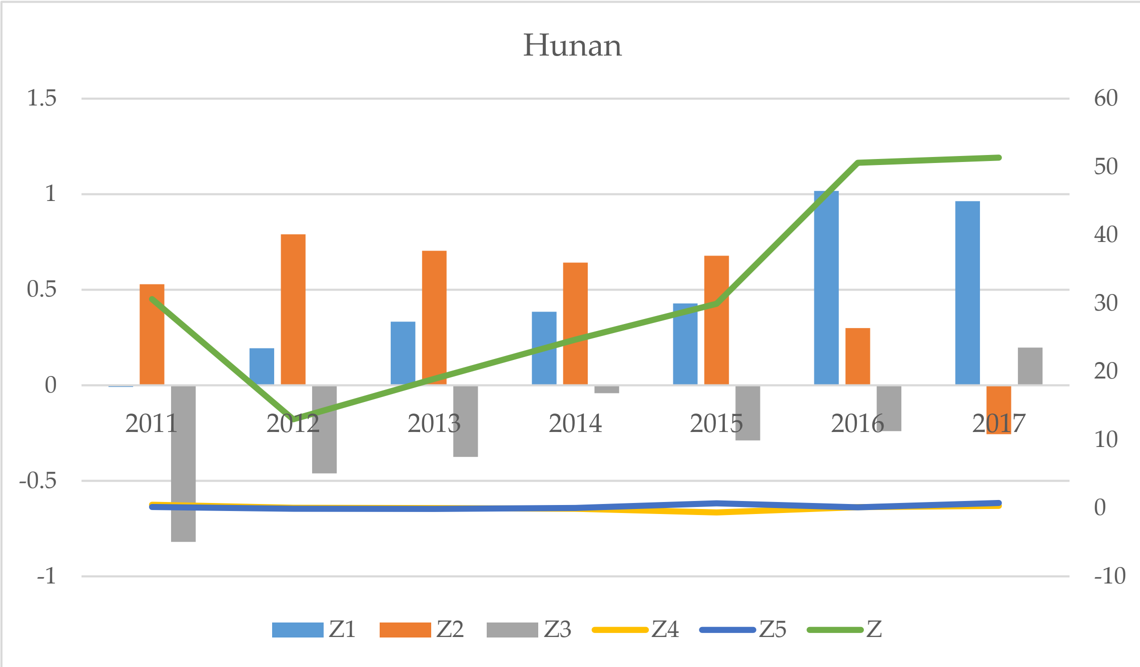


(**a**)



(**b**)

Figure 1. *Cont.*



(**c**)

Figure 1. Scores of principal component indices and sustainable development indices in central China from 2011 to 2017: (**a**) Henan Province; (**b**) Hubei Province; (**c**) Hunan Province.

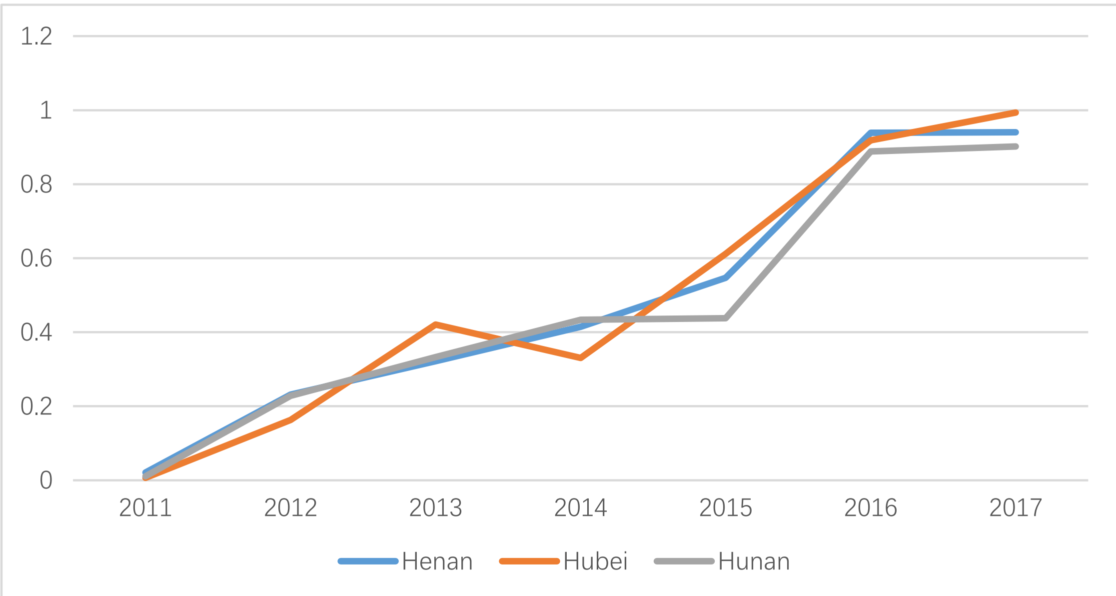
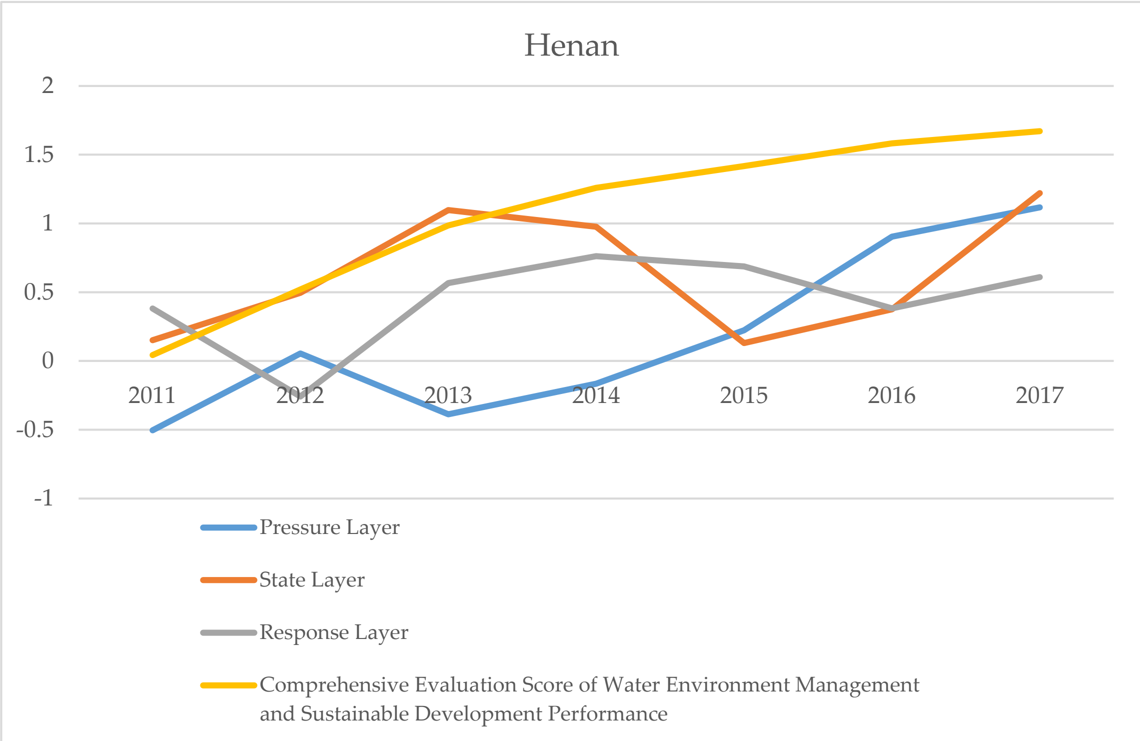
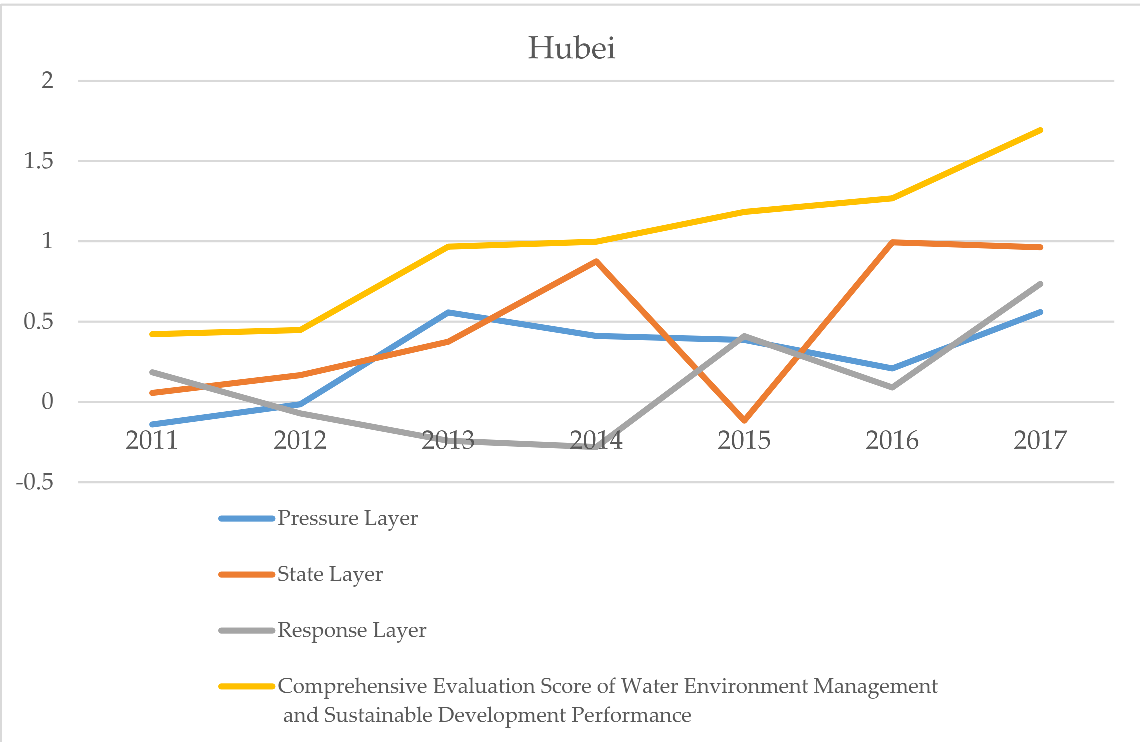


Figure 2. The comprehensive evaluation scores of the sustainability index after discretization for provinces in central China from 2011 to 2017.

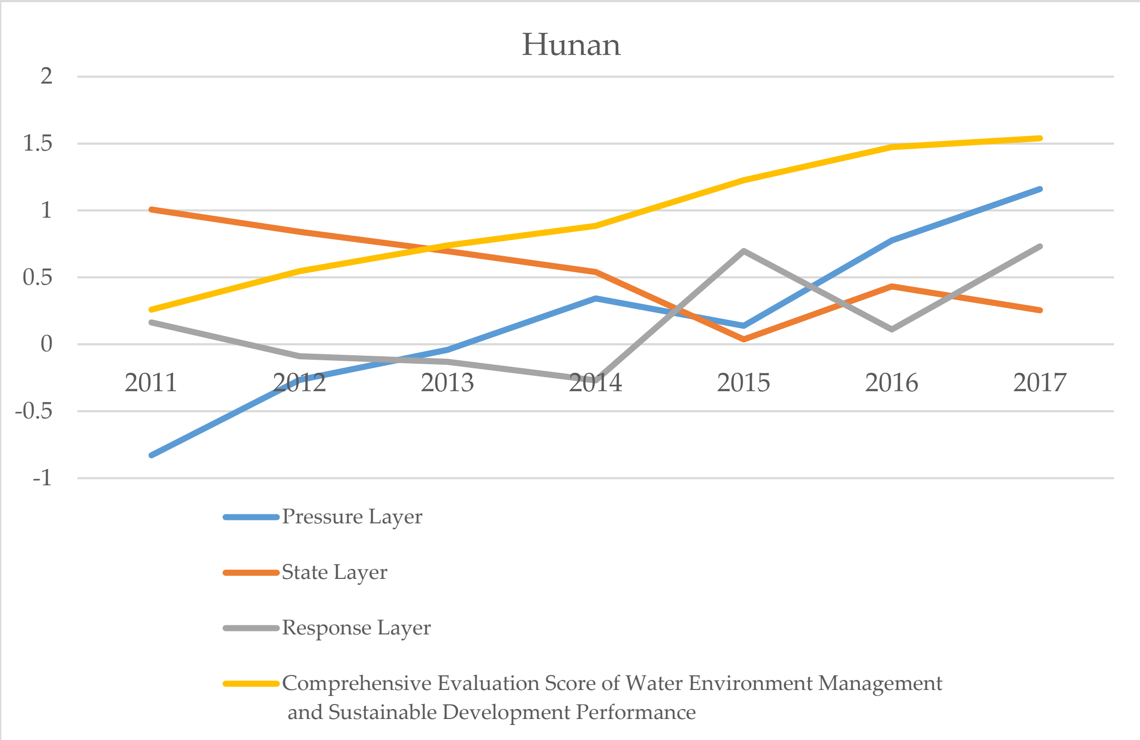


(**a**)



(**b**)

Figure 3. *Cont.*



(c)

Figure 3. Evaluation values of sustainable development in provinces of central China from 2011 to 2017: (**a**) Henan Province; (**b**) Hubei Province; (**c**) Hunan Province.

The period chosen by this paper, 2011–2017, is an important development stage ranging from the beginning of China's "Twelfth Five-Year Plan (2011–2015)" to the mid-term of "Thirteen Five-Year Plan (2016–2020)". During this period, the threat to China's water environment intensified. The three provinces of central China also took corresponding measures to govern their own water environment, which led to continuous improvement in the sustainable development of their water environment. It can be seen that the sustainability level of the water environment in central China showed a gradual improvement trend during the study period, with the largest improvement seen during 2011–2014. Among them, the Henan Province experienced a particularly significant improvement in water environment sustainability during the study period. Analysis of the principal component values of the Henan Province showed that in recent years, the Henan Province experienced huge improvements in the values of principal components Z1, Z2, and Z3, and the corresponding indicators with the largest correlation degree with these three are, respectively, NH_3-N (Ammonia Nitrogen Emission), Natural Population Growth Rate, and the Investment Amount in Ecosystem Construction and Protection.

(1) Ammonia nitrogen refers to the nitrogen in water in the form of free ammonia and ammonium ions. Human activities have caused nitrogenous substance to enter the water environment mainly through untreated urban household wastewater and industrial wastewater, as well as various kinds of leachates. The main reason why ammonia nitrogen exceeds the acceptable standard is that the designed size of the sewage treatment facility is too small and the treatment equipment is underloaded, so the free ammonia in the sewage cannot fully complete the nitrification reaction. In addition, excessive sewage discharge has also resulted in a sharp increase in ammonia nitrogen, which has seriously hammered the sustainable development of the water environment. During the study period, the Henan Province strictly regulated sewage discharge, achieved an overall balance of water resources by reducing ammonia nitrogen emissions, strengthened the promotion

of water resource protection, and made great efforts to enhance the sense of responsibility of all sectors of society for water resource protection [57]. At the same time, the Henan Province actively introduced highly efficient energy-saving technologies to timely process the sewage, regularly investigated and monitored the sources of water pollution, and conducted statistical analysis on sewage treatment results to derive the performance of water pollution control during defined periods of time, which helped the Henan Province achieve satisfactory water environment management results [58].

(2) As one of the key indicators defining the sustainability of water environment, the Natural Population Growth Rate reflects the relationship between human and the nature, as well as the social aspect of environmental protection, industrialization, and urbanization. As a populous province, the Henan Province strictly implemented the family planning policy in order to control the natural population growth rate and actively utilized market-based approaches to adjust the natural population growth rate in the context of the Chinese government gradually liberalizing the birth control policies in China [59,60], thus contributing to the sustainable development of the water environment.

(3) As a response layer indicator for sustainable development, the Investment Amount in Ecosystem Construction and Protection reflects the sense of responsibility and commitment of the local enterprises and government regarding ecological environment construction. During the study period, the average annual investment in ecosystem construction and protection in the Henan Province was around 7 billion RMB [61], which exceeded the investment amount by other provinces. This also explains the significant improvement in water environment protection and sustainable development achieved by the Henan Province in the past five years.

The Hubei Province, which showed the best overall sustainability level during the study period, did not only take a series of measures in the above key areas that contribute to the sustainable development of water environment as the Henan Province [62], it also paid more attention to scientific and technological innovation, such as adopting the new clean wastewater treatment technology in the treatment and control of pollutants including mercury [63,64]. Therefore, the Hubei Province achieved outstanding pollution control results in terms of the pressure layer indicators such as ZP6.

Basing on the actual conditions of water environment management in the three provinces of central China and the availability of data, we mainly selected Afforestation Area, Constructed Wetland Area, Comprehensive Utilization of General Industrial Solid Waste, Investment in Industrial Wastewater Treatment, Investment in Industrial Waste Treatment, and Investment in Ecosystem. Construction and Protection were the indicators of results. In future research, we will further supplement the indicators as references to the real effects of the pressures and the corrections of the externalities caused by human activities. These indicators include, but are not limited to, the conditions and impact of the discharges of treated wastewater on the natural environment, the increase in corporate profits brought about by the recycling of wastewater, the costs saved by the recycling of wastewater (such as management fees and sewage charges), fines for compensation for water environmental treatment, etc.

6. Conclusions

This paper selected the performance of water environment management and sustainable development in the three provinces of central China as the research object and constructed a comprehensive evaluation system for water environment management and sustainable development by integrating the PCA method and the PSR model in order to comprehensively analyze the performance of water environment management and sustainability of development. The constructed evaluation system could comprehensively analyze the result of water environment treatment in a certain region and is able to effectively reveal the correlation between different indicators, thus determining the principal factors in water environment management. With the help of this system, this paper evaluated the performance of water environment management in the three provinces of central China from 2011 to 2017.

The results show that the sustainability level of the water environment in central China has shown an improvement trend during the study period, with the largest improvement seen during 2011–2014. The evaluation results vary among different provinces. The Henan Province has experienced the most significant improvement during the study period. Its comprehensive evaluation score of water environment management and sustainable development reached 1.671 in 2017, ranking second in central China. Overall, Hubei Province maintained the best water environment management and sustainable development level during the study period, with a comprehensive evaluation score of 1.692 in 2017.

The contributions of this paper are:

(1) A comprehensive evaluation model based on PCA and the PSR model was constructed to analyze the sustainable development of water environment in central China. The main advantage of PCA is that it can effectively reorganize discrete variables by mathematical statistical methods and reflect the data characteristics by a few variables. The main advantage of the PSR model is that it highlights the causal relationship between the environment and the stress facing the environment, as well as the mutual restriction and interaction between the three layers of stress, state, and response. Hence, the comprehensive evaluation model in this paper can determine a few composite variables from various variables to replace the existing variables by mathematical dimension reduction methods, to explore the causal relationship between human activities and environmental changes based on the evaluation of the sustainability of environmental systems.
(2) A performance evaluation system for water environment management, which could comprehensively evaluate the performance of water environment treatment and effectively reveal the correlation between various indicators, was established. The principal factors in water environment management can be obtained by this evaluation system. Therefore, the evaluation indicator system and the weights of different indicators in this system can be determined for quantitative calculation by substituting the standardized values into the indicator system. This performance evaluation system can be used to evaluate the performance of water environment management and sustainable development. After careful selection of specific indicators and use of official statistics from the three provinces in central China, the objectivity of calculation results was ensured in this paper to contribute to evaluate the performance of water environment management and sustainable development in China.

Based on the evaluation results, the authors proposed the following policy recommendations for the improvement of water environment management and sustainable development in central China:

(1) Strengthen the promotion and education about the importance of sustainable development of the water environment, accelerate the accumulation of human capital in the provinces of central China, and raise people's awareness of water conservation. The provinces of central China should further increase the investment in the education of water resource protection knowledge and technologies to the citizens, cultivate their awareness of ecological protection related to the water environment, help the citizens form a habit of reducing water resource input in production as well as reducing water pollution emissions in daily life, and enhance the public's understanding of the ecological and social benefits of sustainable development of the water environment. At the same time, governments at all levels below the provincial level should place great emphasis on the sustainable development of the water environment, include it in the government's key agenda, and effectively strengthen the protection of the water environment based on the actual local conditions.
(2) Establish a long-term incentive mechanism for the sustainable development of the water environment. The distribution of precipitation, the layout of industrial and agricultural production, and the level of economic development vary greatly among the provinces of central China. It is important to comprehensively consider the regional differences and the economic feasibility for the local residents when establishing a long-term mechanism to motivate the sustainable

development of the water environment. For example, special funds could be appropriated to support the technology upgrade of water pipelines and surface water delivery [65], as well as water recycling technologies that have higher costs such as the micro-irrigation technology [66]. At the same time, the local governments should reduce the administrative interventions during the promotion of water environment improvement technologies in order not to burden the residents and enterprises while promoting the sustainable development of water environment.

(3) Further increase investment in fixed assets for water pollution control. Compared with general fixed asset investment, the investment in environmental pollution control has its own positive environmental externalities and environmental spillover effects apart from the benefits of increasing household consumption and stimulating demand for related industries [67]. Therefore, investment in pollution control has more social and environmental implications than general fixed asset investment. It should be noticed that although the growth rate of fixed assets investment in water pollution control in these three provinces of central China has been higher than that of the overall environmental investment in recent years, there is still a gap in the proportion of pollution control investment in national income when compared with the average level of developed countries [47]. Thus, the investment in water pollution control should be further increased in the future.

Therefore, the public participation and long-term incentive mechanism for the sustainable development of the water environment will be included in future research. Meanwhile, the indicators, which reflect the real effects of the pressures and the corrections of the externalities caused by human activities to make our research more perfect, will also be supplemented.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Component Score Matrix and Comprehensive Evaluation Results

Table A1. Component Score Matrix.

Indicator	Principal Component				
	Z1	**Z2**	**Z3**	**Z4**	**Z5**
ZP1	0.073	−0.127	−0.255	0.281	−0.012
ZP2	0.115	−0.056	−0.036	0.087	−0.022
ZP3	0.115	−0.053	−0.029	0.071	−0.025
ZP4	0.115	−0.057	−0.041	0.120	−0.068
ZP5	0.062	−0.002	0.062	0.008	0.156
ZP6	0.022	0.073	0.184	0.018	0.108
ZP7	0.046	0.052	0.038	0.005	0.262
ZP8	0.078	0.045	0.066	−0.123	−0.209
ZP9	0.075	0.021	0.024	0.085	0.127
ZP10	0.102	−0.392	−0.007	−0.200	−0.152
ZS1	0.072	0.035	0.070	−0.044	0.085
ZS2	−0.011	0.085	0.136	0.429	−0.093
ZS3	0.029	0.285	−0.052	−0.097	−0.118
ZS4	0.049	0.104	0.045	0.07	−0.041
ZS5	0.016	0.297	−0.057	−0.104	−0.084
ZR1	−0.006	−0.038	−0.103	−0.057	0.670
ZR2	0.111	0.001	−0.097	0.000	−0.228

Table A1. *Cont.*

Indicator	Principal Component				
	Z1	Z2	Z3	Z4	Z5
ZR3	−0.184	0.253	0.244	0.167	0.012
ZR4	0.071	−0.024	−0.485	−0.128	0.043
ZR5	0.025	0.112	−0.357	0.020	0.094
ZR6	0.125	−0.031	−0.128	−0.315	−0.044

Extraction Method: Principal Component Analysis Method. Rotation Method: Caesar Normalization Maximum Variance Method.

Table A2. Comparison of Scores of Principal Component Indices and Sustainable Development Indices in Central China from 2011 to 2017.

Year	Province	Z1	Z2	Z3	Z4	Z5	Z
2011	Henan	0.201	−0.372	−0.705	0.221	0.381	1.182
2012	Henan	0.144	0.121	−0.089	0.375	0.593	13.193
2013	Henan	0.156	0.706	−0.444	0.391	0.866	18.309
2014	Henan	0.228	0.741	−0.163	0.235	0.762	23.621
2015	Henan	0.505	0.378	−0.283	−0.509	0.588	25.463
2016	Henan	1.147	0.310	−0.242	0.066	−0.383	53.493
2017	Henan	0.791	0.650	0.326	0.570	0.209	53.558
2011	Hubei	0.075	−0.178	−0.215	0.234	−0.045	20.368
2012	Hubei	0.239	0.015	−0.253	0.151	−0.071	9.275
2013	Hubei	0.176	0.603	0.381	0.473	0.242	23.973
2014	Hubei	0.176	0.610	0.235	0.265	−0.141	18.821
2015	Hubei	0.438	0.035	−0.053	−0.550	0.110	17.756
2016	Hubei	1.108	0.536	−0.899	0.458	0.090	52.328
2017	Hubei	1.015	0.561	−0.456	0.402	0.735	56.589
2011	Hunan	−0.009	0.529	−0.820	0.478	0.163	30.614
2012	Hunan	0.194	0.790	−0.461	0.051	−0.089	13.000
2013	Hunan	0.333	0.704	−0.375	−0.008	−0.131	18.949
2014	Hunan	0.385	0.642	−0.042	−0.103	0.027	24.689
2015	Hunan	0.428	0.678	−0.289	−0.641	0.697	29.943
2016	Hunan	1.017	0.299	−0.240	0.134	0.111	50.603
2017	Hunan	0.963	−0.256	0.197	0.311	0.732	51.362

Table A3. The Comprehensive Evaluation Scores of the Sustainability Index after Discretization for Provinces in Central China from 2011 to 2017.

Number	Year	Province	Discretized Comprehensive Evaluation Value Z″
1	2011	Henan	0.0208
2	2012	Henan	0.2316
3	2013	Henan	0.3215
4	2014	Henan	0.4147
5	2015	Henan	0.5471
6	2016	Henan	0.9392
7	2017	Henan	0.9403
8	2011	Hubei	0.0065
9	2012	Hubei	0.1628
10	2013	Hubei	0.4209
11	2014	Hubei	0.3304
12	2015	Hubei	0.6117
13	2016	Hubei	0.9187
14	2017	Hubei	0.9935
15	2011	Hunan	0.0108
16	2012	Hunan	0.2282
17	2013	Hunan	0.3327
18	2014	Hunan	0.4335
19	2015	Hunan	0.4379
20	2016	Hunan	0.8884
21	2017	Hunan	0.9018

Table A4. Evaluation Values of Different Components in Provinces of Central China from 2011 to 2017.

Year	Province	Pressure Layer	State Layer	Response Layer	Comprehensive Evaluation Score of Water Environment Management and Sustainable Development Performance
2011	Henan	−0.504	0.151	0.381	0.043
2012	Henan	0.054	0.496	−0.259	0.520
2013	Henan	−0.388	1.097	0.566	0.985
2014	Henan	−0.165	0.976	0.762	1.259
2015	Henan	0.223	0.130	0.688	1.417
2016	Henan	0.904	0.376	0.383	1.582
2017	Henan	1.117	1.220	0.609	1.671
2011	Hubei	−0.140	0.056	0.185	0.422
2012	Hubei	−0.015	0.167	−0.071	0.448
2013	Hubei	0.557	0.375	−0.242	0.967
2014	Hubei	0.411	0.875	−0.281	0.998
2015	Hubei	0.386	−0.116	0.410	1.183
2016	Hubei	0.209	0.994	0.090	1.268
2017	Hubei	0.559	0.963	0.735	1.692
2011	Hunan	−0.830	1.007	0.163	0.259
2012	Hunan	−0.266	0.841	−0.089	0.547
2013	Hunan	−0.041	0.696	−0.131	0.739
2014	Hunan	0.343	0.540	−0.269	0.885
2015	Hunan	0.138	0.037	0.697	1.226
2016	Hunan	0.776	0.433	0.111	1.474
2017	Hunan	1.160	0.255	0.732	1.539

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