Analysis of ecological security evaluation and zoning threshold determination of typical energy industrial area based on PSR model

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Abstract
Ecological security is the main way to measure the effects of urbanization and industrialization in developing regions on the ecological environment. As an important coal chemical industry base in China, Taiyuan is located in the Loess Plateau, resulting in great pressure on the ecological environment. Based on the pressure-state-response (PSR) model, this study selected 15 evaluation indicators to evaluate the ecological security of 10 counties (districts/city) in Taiyuan City. Using the spatial principal component analysis (SPCA) method and GIS technology to simulate and analyze the ecological security distribution of this area, for the first time, the typical method and average method were used to divide the threshold of the ecological security level to achieve a more reasonable ecological security classification method. The results showed that from 2000 to 2016, the ecological security level of Taiyuan city and its surrounding areas was relatively low, mainly concentrated in Xinghualing, Yingze and Jiaonaoping districts, while the ecological security level of Loufan county, Qingxu County, Gujiao city and Yangqu County was relatively high. Among these, energy mining and urbanization have had a relatively obvious impact on ecological security. It could provide more detailed ideas for the protection of ecological security in different areas and enrich the research on the ecological security of important coal chemical bases.

1. Introduction

The issue of ecological security is a derivative of economic and social development. In particular, the current stability of ecological security (Zhao et al 2018) is constantly being affected, and poor ecological security may even retard economic development (Chu et al 2017). For sustainable development, economy and ecology are coordinated and indispensable (Sinha et al 2013). Based on traditional production methods (Xu et al 2020), it puts forward a significant threat to the surrounding ecological environment in the process of resource extraction and transportation (Zhao et al 2019). As an important coal chemical industry base, Taiyuan needs to pay special attention to ecological security assessment in the process of seeking a new model of economic transformation and abandonment of the development model of economic priority over ecological environment. This is also the epitome of the economic development of the same type of developing countries and is worthy of further discussion.

Ecological security assessments include complex research categories, development directions and objects of evaluation. Owing to the close connection between its research content and practical applications, research in recent years has also focused on many aspects, all for making ecological security develop towards a stable state. Scientific ecological security evaluation is often based on appropriate methods; therefore, the exploration of evaluation models and methods is also a focus. Currently, the PSR model is the most widely used. The PSR model, a more developed ecological security evaluation index system, is used to assess the extent of the impact of human activities on ecological security. The benefit of this evaluation index system is that it takes into account both the factors influencing the pressure that the ecosystem itself and human activities place on the ecological environment, as well as the state that the ecosystem is in when it is under its own and external pressure. It also
takes into account human factors, such as socioeconomic and governmental decisions, which reflect the human response after the ecosystem has been destroyed. For example, Das et al (Das et al 2020) used the PSR model to assess the health of the wetland ecosystem in Mursidabad in 2013 and 2020, and used the analytic hierarchy process to calculate the wetland ecosystem health index. Sun et al (Sun et al 2019) used the PSR model, Analytic Hierarchy Process (AHP), and Fuzzy Comprehensive Evaluation (FCE) methods to assess the ecological status of Jiaozhou Bay. The results showed that Jiaozhou Bay was in a sub-healthy state. Wang et al (Wang et al 2019) used the PSR model and analyzed 24 indicators to evaluate the sustainability of Beijing’s water resources in 2012 and 2016. The results showed that the efficiency of water sustainability in Beijing is poor. Many derivative models of the PSR model can also be found in research, such as the DFSR(Drive force-State-Response) model (Zhang and Zhou 2012), DPSIR(Driver-Pressure-State-Impact-Responses) model (Jago-on et al 2009) and DPSER(Driver-Pressure-State-Effect-Responses) model (Kelble et al 2013). Researchers choose appropriate models to carry out evaluation according to the ecological characteristics of the research object, and each model has its own advantages, which greatly enriches ecological security evaluation research.

Different evaluation methods may cause significant differences in the data presentation of the evaluation results. A reasonable choice of evaluation method ensures the objectivity of the evaluation process. Of course, the use of evaluation methods is also closely related to the actual ecological characteristics of the evaluation objects. At present, there are various types of methods used for ecological security assessment, and the most commonly used is the comprehensive index method, which includes the landscape ecology method, matter element evaluation method, principal component analysis method (Cano-Orellana and Delgado-Cabeza 2015), ecological footprint method (Monfreda et al 2004) and other methods. The evaluation method must fit well with the evaluation model to ensure the objectivity of the evaluation to the greatest extent. At the same time, to better measure the changes in ecological security levels, most studies use the natural discontinuity classification method, which can better characterize the level difference of the ecological security index. However, there is no unified method for determining the breakpoint of mutations. Whether to choose the average value of the ecological security index in different years or use the ecological security index value of a typical year as the discontinuity point needs to be resolved.

Based on PSR evaluation model, this study comprehensively considered the impact of economic, social, and natural indicators on ecological security in a typical industrial area. Two methods were adopted for the first time to determine the ecological security grade classification standards. Based on scientific ecological security delineation standards, the spatial principal component analysis method was used to quantitatively analyze ecological security changes in various regions. The research results could enrich scientific research on ecological security, and could also provide a scientific reference for the ecological security management of important coal chemical bases.

2. Research area and data sources

2.1. Research area
Taiyuan is located between 37°27′~38°25′(N) and 111°30′~113°09′(E), which is the capital of Shanxi Province (figure 1). It is surrounded by mountains on three sides in the west, north, and east, and valley plains in the middle and south (Zhao et al 2021). Taiyuan has a continental climate in the northern temperate zone with hot and rainy summers and cold and dry winters. The annual average temperature is 9.5 °C and the average annual precipitation is 456 mm. The land area of Taiyuan is 6909000.96 hm², of which agricultural land accounts for the largest proportion, about 84% of the total area, and the area of cultivated land only accounts for 16.9% of the total area of the city. Construction land accounts for only 9.25% of the city’s total area. Forests are mainly young forests, with a minor area, and the forest coverage rate is far from the world average. The quality of forestland is relatively poor, and the land is barren and arid.

Abundant coal resources are a well-known characteristic of Shanxi (Zhang et al 2020), and the mineral resources in Taiyuan are also relatively rich. At present, proven mineral deposits mainly include iron, manganese, copper, aluminum, lead, zinc, and other metal mines and non-metallic mines such as coal, sulfur, gypsum, vanadium, salt peter, refractory clay, quartz, limestone, and dolomite. Relying on its own resource advantages, rapid industrialization and urban construction have been achieved. At the same time, it has caused great damage to the environment and intensified the contradiction between economic development and ecological security. Therefore, better coordinate between the ecological environment and economic development is a major challenge facing Taiyuan.

2.2. Data sources
Socioeconomic and natural data were obtained from the statistical yearbooks of Taiyuan City in 2000, 2004, 2008, 2012 and 2016 and the records of relevant government departments. Topographic data such as geology
and geomorphology, latitude and longitude, geographic location, and altitude were obtained from the geospatial data cloud (http://www.gscloud.cn/).

3. Establishment of ecological security index system

This research mainly used the PSR model method (He et al 2018), while referring to the existing ecological environment assessment results and city ecological security assessment methods, and combined natural and human activity factors to analyze the ecological security of Taiyuan on a quantitative basis. The assessment system included three climate factors (Mcdonald 2018), involving average annual precipitation and average annual temperature. The other was economic and social, including the natural growth rate, self-fertilizer application, pesticide usage, total population, population density, GDP per capita, rural per capita income, effective irrigation area of farmland, per capita arable land area, actual cultivated land area and other factors. The third category was natural resources (Hongyan et al 2015), including factors such as forest area, forest coverage rate, and land area. The indicator systems are listed in table 1.

4. Analysis of data processing model

4.1. Spatial principal component analysis method

Spatial principal component analysis (Kang et al 2018, Wei et al 2020) is a technique to simplify datasets, which first transforms a large number of original variables into a small number of new variables through principal

![Figure 1. Geographical division map of counties (districts/cities) of Taiyuan City.](image)

| Target layer | Project layer | Index layer |
|--------------|--------------|-------------|
| Comprehensive Ecological Security Index (A<sub>1</sub>) | economic development (B<sub>1</sub>) | GDP per capita (¥)(C<sub>1</sub>) |
| | | Rural per capita income (¥)(C<sub>2</sub>) |
| ecosystem (B<sub>2</sub>) | | Average annual precipitation (mm)(C<sub>3</sub>) |
| | | Average annual temperature (°C)(C<sub>4</sub>) |
| | | Land area (km<sup>2</sup>)(C<sub>5</sub>) |
| | | Forest cover rate (%) (C<sub>6</sub>) |
| population and life (B<sub>3</sub>) | | Forest area (hectare)(C<sub>7</sub>) |
| | | Natural growth rate (%)(C<sub>8</sub>) |
| | | Self-fertilizer application (tons)(C<sub>9</sub>) |
| | | Pesticide usage (tons)(C<sub>10</sub>) |
| | | Total population (C<sub>11</sub>) |
| | | Population density (person/km<sup>2</sup>)(C<sub>12</sub>) |
| | | Actual cultivated land area (C<sub>13</sub>) |
| | | Per capita arable land area (C<sub>14</sub>) |
| | | Effective irrigation area of farmland (hectare)(C<sub>15</sub>) |

Source: Above related references.
component analysis to achieve dimension reduction analysis of data. Combined with spatial analysis technology, the data is presented in the spatial dimension, which strengthens the comprehensiveness and accuracy of the data.

4.2. Assessment steps

(1) Standardization of raw data

The standardization of the original data involves the elimination of different dimensions under various indicators, which reduces the influence of different dimensions on subsequent assessments. This method is shown in formula (1).

\[ X'_i = \frac{X_i - \bar{X}_i}{S_i} \quad (1) \]

where \( X'_i \) is the standardized variable, \( X_i \) is the original variable, and \( S_i \) is the standard deviation of the \( i \)th variable.

(2) Solve the correlation matrix (Al-Wabel et al 2017)

The correlation coefficient between any two original variables is solved, and the correlation coefficient matrix of the original variables is constructed. The calculation method for the correlation coefficient between variables is shown in formula (2).

\[ r_{ij} = \frac{\sum X_i X_j - \frac{\sum X_i \sum X_j}{n}}{\sqrt{\sum X_i^2 - \frac{\sum X_i^2}{n}} \sqrt{\sum X_j^2 - \frac{\sum X_j^2}{n}}} \quad (2) \]

where \( r_{ij} \) is the correlation coefficient between variables \( X_i \) and \( X_j \), and \( X_i \) is the value of the \( i \)th variable after the standard.

(3) Calculate the eigenvalue of the correlation matrix

The eigenvalue of the above matrix is calculated using a mathematical method, and after the eigenvalue is known, the load matrix is calculated using the principal axis method.

(4) Calculate the contribution rate

The size of the eigenvalue of a certain principal component, to some extent, represents the magnitude of the influence of the principal component on all indicators. We usually choose principal components with eigenvalue greater than 1. The percentage of the eigenvalue of each principal component to the total eigenvalue is the contribution rate of the principal component from which the cumulative variance contribution rate can be obtained. The calculation methods are shown in formula (3) and formula (4).

\[ p_j = \frac{\lambda_j}{m} \quad (3) \]

\[ \sum p = \sum \frac{\lambda_j}{m} \quad (4) \]

where \( p_j \) is the contribution rate of the \( j \)th principal component, \( \lambda_j \) is the eigenvalue corresponding to the \( j \)th principal component, \( m \) is the sum of the eigenvalues corresponding to the principal component, and \( \sum p \) is the cumulative contribution rate of the principal component.

(5) Calculate the evaluation value of the principal component

The principle of the principal component model is dimensionality reduction, which converts \( n \) original variables into \( m \) new variables in a linear combination. The new variables formed by the linear combination are the corresponding principal components, and the comprehensive assessment value is the linear superposition of the principal components, as shown in formula (5).

\[ F_i = u_{i1}X_1 + u_{i2}X_2 + \cdots + u_{in}X_n \]

\[ F_j = \lambda_1 F_1 + \lambda_2 F_2 + \cdots + \lambda_m F_m \quad (5) \]

where \( m \) is the number of original variables, \( n \) is the number of principal components, \( u_{ij} \) is the weight of the \( i \)th variable in the \( j \)th principal component, \( X_i \) is the standard value of the \( i \)th variable, and \( F_i \) is the \( i \)th principal component assessment value, and \( F \) is a comprehensive assessment value.

4.3. Ecological security assessment model

Based on the PSR evaluation model, this study selected natural, social, economic and other factors to build the ecological security evaluation system of Taiyuan. The data was processed using the SPCA model, and the
standardized index value was multiplied by the index weight value to obtain the sum of the index. The ecological security index calculated using the following formula and the ecological security index of Taiyuan City from 2000 to 2016 are used.

\[
ESI = F_1 \cdot \alpha_1 + F_2 \cdot \alpha_2 + \cdots + F_n \cdot \alpha_n
\]  

(6)

where ESI is the comprehensive ecological security index, \(F_n\) is the component, and \(\alpha_n\) is the weighting.

4.4. Delineation of ecological security zoning threshold

Threshold determination (Fu et al. 2019) is a critical and complex issue in several studies. At present, research on ecological security thresholds at home and abroad is difficult, and there is no effective and universal assessment. To implement scientific management of the ecosystem, quantitative research on ecological thresholds should be strengthened.

Based on the classification method of natural discontinuities in ArcGIS software, this study used two methods to divide the ecological security levels of Taiyuan regions into five levels: excellent, good, medium, poor, and inferior.

(1) Typical method

The typical method was to select the classification of the year when the ecological security index distribution map of the study area showed a trend closer to the normal distribution as the standard (Li et al. 2006, Hou et al. 2015). Based on the uniformity of the data distribution, this research used the 2012 ecological security index classification of Taiyuan as the standard (figure 2), and established the classification of Taiyuan ecological security indicators to assess ecological security.

(2) Average value method

The average value method was to calculate the average value by adding up the ecological security index of the same interval at the same interval for many years, and used as the standard for the final classification of ecological security in Taiyuan.

According to relevant literature and information, in 2009, the Taiyuan Municipal Party Committee and Municipal Government made a strategic plan to create a provincial garden city. In accordance with the overall goal of 'building a first-class livable city', the Gujiao City Landscape Bureau vigorously promoted the construction of landscaping, continued to improve the ecological environment, and continuously improved the level of urban afforestation management, and the construction of landscaping has achieved remarkable results. In December 2012, the People’s Government of Shanxi Province awarded the honorary title of 'Garden City in Shanxi Province'. It showed that the ecological environment of Gujiao City in 2012 was relatively good, and the ecological security index was relatively high. In the typical method of ecological security index classification map (figure 3), the ecological security level of Gujiao City was medium, while the ecological security level shown in the average method (figure 4) was poor. It’s clear that the results obtained using these two methods are significantly different. Obviously, the ecological security classification obtained by the method of selecting typical standards was more consistent with the actual situation, which also showed that the average method could not really reflect the research area of the whole situation, therefore, the threshold of this research assumes that the typical method should be used.
5. Results and discussions

5.1. Research on ecological security index

5.1.1. Solving the ESI formula

The principal component analysis process is completed using SPSS18.0, and the number of principal components is determined to be 5 according to the cumulative contribution rate or characteristic value of the principal components. The corresponding principal component analysis results are listed in table 2.

![Ecological Security Grades in 2012](image1)

**Figure 3.** The Ecological Security Index of Taiyuan City in 2012 (T).

![Ecological Security Grades in 2012](image2)

**Figure 4.** The Ecological Security Index of Taiyuan City in 2012 (A).
After determining the weight of each principal component, the 5 relatively independent principal components were finally transformed from the 15 basic natural, economic, and social factors. Their cumulative contribution rate was approximately 85%, which represented the information of the sample and satisfied the assessment. Then, according to the formula, the linear equation of the regional security assessment in 2000, 2004, 2008, 2012, and 2016 in Taiyuan area can be obtained as follows:

\[
\begin{align*}
    ESI_{2000} & = 0.447F_1 + 0.753F_2 + 0.856F_3 + 0.931F_4 + 0.960F_5 \\
    ESI_{2004} & = 0.447F_1 + 0.753F_2 + 0.833F_3 + 0.891F_4 + 0.931F_5 \\
    ESI_{2008} & = 0.491F_1 + 0.752F_2 + 0.854F_3 + 0.904F_4 + 0.942F_5 \\
    ESI_{2012} & = 0.493F_1 + 0.740F_2 + 0.844F_3 + 0.895F_4 + 0.936F_5 \\
    ESI_{2016} & = 0.470F_1 + 0.740F_2 + 0.831F_3 + 0.892F_4 + 0.945F_5
\end{align*}
\]

where \( F_n (n = 1, 2, 3, 4) \) is the value after the principal component standardization of the study area from 2000 to 2016.

The ecological security index of the 10 districts and counties in Taiyuan City can be obtained from formula (7). It can be seen that from 2000 to 2016, the ecological security index of the urban area was higher than that of the surrounding counties, which had a lot to do with economic differences between regions. The level of urban development was fast, and the speed of the expansion wound soon affected the ecological security index. At the same time, the ecological security index of each county was also high. This phenomenon had a lot to do with the rapid economic development.

5.1.2. ESI index transformation

As shown in figure 5 in 2000, Qingxu County had the highest degree of ecological security, with an ecological security index of 0.52. Gujiao City followed by an ecological security index of 0.18. Yangqu County had an ecological security index of 0.13. The area with the lowest degree of ecological security was Xinghualing District, with an ecological security index of \(-0.38\). Yingze District followed an ecological security index of \(-0.36\). Jiancaoping District has an ecological security index of \(-0.10\). The ecological security degree of Jinyuan District, Loufan County, Wanbailin District and Xiaodian District was in the middle. And we can also see clearly Jiancaoping District, Yingze District, Xinghualing District, Wanbailin District and Xiaodian District’s degree of ecological security all below zero, the rest of these districts are above 0.

As shown in figure 5 the area with the highest degree of ecological security in Taiyuan in 2004 was Qingxu County, with an ecological security index of 0.51. Yangqu County followed with an ecological security index of 0.31. Loufan County, the ecological security index was 0.14. The region with the lowest ecological security degree was Yingze District, and the ecological security index was \(-0.35\). Next was Xinghualing District, its ecological security index was \(-0.34\). The ecological security index of Wanbailin District was \(-0.14\). Gujiao City, Jinyuan District, Jiancaoping District and Xiaodian District were in the middle of ecological security.

It is evident from figure 5 that the area with the highest degree of ecological security in Taiyuan in 2008 was Qingxu County, with an ecological security index of 0.57. Yangqu County followed, with an ecological security index of 0.26. Next was Loufan County with an ecological security index of 0.14. The region with the lowest ecological security degree was Yingze District, and the ecological security index was \(-0.31\). The ecological security index of Xinghualing District was \(-0.30\). Followed by Wanbailin District with an ecological security index of \(-0.20\). Gujiao City, Jinyuan District, Xiaodian District and Jiancaoping District were in the middle of ecological security.

The area with the highest degree of ecological security in Taiyuan in 2012 was Qingxu County, with an ecological security index of 0.54. Yangqu County followed, with an ecological security index of 0.35. Then

| Main ingredient | 2000a | 2004a | 2008a | 2012a | 2016a |
|-----------------|-------|-------|-------|-------|-------|
| Contribution rate (%) |       |       |       |       |       |
| I               | 44.655 | 47.717 | 49.130 | 49.251 | 47.039 |
| II              | 30.641 | 27.618 | 26.040 | 24.762 | 26.962 |
| III             | 10.345 | 7.972  | 10.187 | 10.389 | 9.124  |
| IV              | 7.455  | 5.833  | 5.010  | 5.135  | 6.115  |
| V               | 2.936  | 3.928  | 3.876  | 4.028  | 5.300  |
| Cumulative contribution rate (%) |       |       |       |       |       |
| I               | 44.655 | 47.717 | 49.130 | 49.251 | 47.039 |
| II              | 75.296 | 75.335 | 75.169 | 74.013 | 74.001 |
| III             | 85.642 | 83.307 | 85.356 | 84.402 | 83.125 |
| IV              | 93.097 | 89.140 | 90.366 | 89.537 | 89.240 |
| V               | 96.033 | 93.068 | 94.242 | 93.565 | 94.540 |

Source: Data analysis by SPSS18.0.
Jinyuan District, with an ecological security index of 0.12 (see figure 5). The region with the lowest ecological security degree was Yingze District, and the ecological security index was −0.30. The second lowest was Xinghualing District, with an ecological security index of −0.29. Then was Wanbailin District with an ecological security index of −0.20. Gujiao City, Loufan County, Jiancaoping District and Xiaodian District were in the middle of ecological security.

The data illustrates distinctly that the area with the highest ecological security index in Taiyuan in 2016 was Qingxu County, with an ecological security index of 0.43. Yangqu County followed, and the ecological security index was 0.26. Then was Loufan County with an ecological security index of 0.25 (see figure 5). The region with the lowest degree of ecological security was Jiancaoping District, and the ecological security index was −0.35. Followed by Yingze District, the ecological security index was −0.33. Next was Xinghualing District, with an ecological security index of −0.28. Gujiao City, Jinyuan District, Xiaodian District, and Wanbailin District had a moderate degree of ecological security.

From the analysis of the figure (figure 5), it can be concluded that the ecological security level of Qingxu County from 2000 to 2016 was relatively high, and the figure is roughly between 0.5 and 0.6. The ecological security of the district and Xinghualing District was relatively low, and the date is usually between −0.4 to −0.3. The ecological security index of Gujiao City, Jinyuan District, Loufan County, Yangqu County and other areas was in the upper-middle. There was little difference in the degree of ecological security in various regions of Taiyuan in 2004 and 2008, but the ecological security index of Xiaodian rose above zero in 2016. The ecological security index of Jiancaoping District and Wanbailin District showed a gradual downward trend.

5.2. Research on the determination of the ecological security zone threshold and the time-space difference

5.2.1. Determination of the threshold of ecological security zone
The higher the ecological security index, the higher the level of ecological security. Two different methods were used to classify the ecological security index of Taiyuan City. After comparing and analyzing the results obtained by the two methods with the actual situation, the ecological security level classified by the typical method was more accurate and objective. The specific classifications are listed in table 3.

5.2.2. Research on the space-time difference of ecological security zone
From the ecological security index map of Taiyuan in 2000 (figure 6 (left), figure 9), it can be seen that the ecological security of Qingxu County, Gujiao City, Yangqu County, and Jinyuan District was relatively high, indicating the slow economic development of these regions, the low degree of industrialization, coupled with the superiority of the geographical location, were the main reasons for the relatively good degree of ecological security in these areas. Xinghualing District, Jiancaoping District, Yingze District, Wanbailin District, and
Xiaodian District had the worst degrees of ecological security. These areas were relatively close to the urban area, and the distances between the various areas were relatively close, and industry was relatively developed. The industry was relatively concentrated, mainly dominated by companies with more serious pollution, such as the coal, metallurgy, and chemical industries. The industrial layout was unreasonable, population density was high, and the governance was more difficult. This was the main reason for the poor ecological security of these areas.

From the 2004 Taiyuan ecological security index map (figure 6(right), figure 9), it can be seen that Qingxu County, Yangqu County, and Loufan County had relatively high levels of ecological security, indicating that these regions had slow economic development, low industrialization, and geographic location. The superiority of these areas was the main reason for their higher degree of ecological security. The ecological security of Gujiao City was in the middle, and industrial enterprises were gradually developing, but the pollution control policy was not strict enough, and the ecological environment had been damaged to a certain extent. Xinghualing District, Jiancaoping District, Yingze District, Wanbailin District and Xiaodian District had the worst ecological security.

Industrial development in these areas was mostly dominated by coal, metallurgy and chemical industries. The previous industrial layout had not been well planned, and the centralized development of the industry had formed a certain scale of pollution.

The ecological security index map (figure 7(left), figure 9) of 2008 shows that the ecological security of Qingxu County and Loufan County was relatively high, indicating that the economic development of these regions was slow and the degree of industrialization was not high. The superiority of the geographical location was the main reason for the better degree of ecological security in these areas. In the construction in 2008, more than 400 million yuan were invested to build 17 key county environmental comprehensive improvement projects in Yangqu County, involving road construction, function enhancement, ecological greening, and urban management. The improvement of the county environment and human settlements requires new ways of scientific and harmonious development. Increasing the construction of forest belts around cities, towns, and villages, building green corridors, and developing eco-tourism had significantly improved people’s livelihood environment. This was also the reason why Yangqu County’s ecological security had always been high. The degree of ecological security in Jinyuan District was relatively poor. Industrial enterprises were gradually developing, but the pollution control policy was not sufficiently rigorous, and the ecological environment had been damaged to a certain extent. Xinghualing District, Jiancaoping District, Yingze District, Wanbailin District and Xiaodian District had the worst degree of ecological security. The industrial layout and population density in...
these areas were highly concentrated, and the production of polluting chemical companies and human social activities had caused considerable pressure on the local ecological environment.

As shown in the regional ecological security index map (figure 7(right), figure 9), Qingxu County, Yangqu County and Jinyuan County had a high degree of ecological security, indicating that the slow economic development and low degree of industrialization in these regions, coupled with the advantages of geographical location, were the main reasons for the relatively high degree of ecological security in these regions. Gujiao City and Loufan County were in the middle of the ecological security level, and industrial enterprises gradually developed. However, pollution control policies were not sufficiently rigorous, and the ecological environment was damaged to a certain extent. However, since 2013, the first landfill area of Gujiao’s harmless domestic waste treatment plant had been put into operation, and the preliminary work of the second sewage treatment plant and the beautification of the water storage of Fenhe River had been basically completed. The region has comprehensively strengthened the management of urban greening, covering an area of 80,000 mu, fulfilling the target of Taiyuan City of more than 15 percent. The forest coverage rate has increased from 17.9 percent in previous years to 20.1 percent, and the urban green coverage rate has increased from 39.3 percent to 39.8 percent. Xinghualing, pointed out that the lawn area, Yingze District, Wanbailin region and the degree of ecological security of knick-knacks worst, the coordination between the development of industrialization and ecological environment protection in these areas was still a matter worthy of attention.

Qingxu, YangQu County, Loufan County, and Gujiao City had a high level of ecological security, and the investment in ecological construction kept growing (figures 8, 9). The ecological security of Jinyuan District and Xiaodian District was relatively poor. Industrial enterprises were developing rapidly, and heavy industries such as coal mines and metallurgy were increasing day by day. The layout of light and heavy industries was unreasonable, pollution control policies were not comprehensive enough, and the ecological environment was damaged to a certain extent. The ecological security levels of Xinghualing District, Jiancaoping District and Yingze District had always been low, and the lowest level of ecological security was Wanbailin District. Combining the ecological security status of the region for several years, we found that the industrial development in these regions has brought greater pressure on the ecological environment, and regional transformation and development were facing challenges and opportunities.

From the hierarchical visualization map (figures 6–9), we can see that the urban area and neighboring counties had a poor degree of ecological security. Within the spatial scope, most of the study area showed an ecological security level. The trend of the city gradually improved in the surrounding area, and the security of the ecological environment was gradually improved from the city to the surrounding area. From the perspective of spatial distribution, the degree of ecological security in Taiyuan showed great differences in different regions. Areas with high ecological security were mainly distributed in Loufan County, Qingxu County, the southwestern part of Gujiao City, and the western and southwestern margins of Yangqu County.

Several districts and counties adjacent to Taiyuan City had the worst ecological security and the layout of functional areas and industries in the urban area was not appropriate. The living area, industrial area, and commercial area of the urban area were mixed in the built-up area, and the division of functional areas was relatively unclear. However, light and heavy industries were mainly concentrated in urban areas, including power plants, material plants, chemical plants, food processing plants, printing plants, mechanical lathe plants, plastics, and rubber light and textile industries as the main areas. Among them, electric power, building materials, metallurgy, coal, chemical and other industries were the leading industries that cause environmental pollution in industrial plant areas, residential areas, and commercial areas. On the one hand, it affected the normal quality of life of residents, and on the other hand, it was not convenient for centralized pollution control.
The unreasonable layout of some heavily polluting enterprises was also the main reason for the poor ecological environment.

6. Conclusions

Based on the understanding of ecological security and urban ecological security, this research used the PSR model, took Taiyuan City as the research object, and established an indicator system for evaluating urban ecological security by collecting indicator data. Therefore, this study selected 15 indicators, divided into ecological environment, social economy, and population life. After spatial principal component analysis, the indicators were assembled and classified. Two different methods were used to classify ecological security index of Taiyuan City. Finally, the typical method was determined based on the literature and related materials to be more objective and accurate to determine the ecological security threshold.

According to the results of the ecological security analysis of the sub-regions, the ecological security index of Qingxu County was excellent in most of the years studied, but declined considerably in 2016, which might be related to the vigorous economic development of the county. The ecological security level of Yangqu County was medium in 2000, and it has been good since 2004, and the ecological security status is relatively stable. The ecological security index of Loufan County was generally on the rise, but the ecological security index of Gujiao
City showed a downward trend from 2000 to 2012 and increased significantly in 2016, which was closely related to the ecological construction in environmental governance. The ecological security of Jinyuan District was unstable, the overall ecological security index was low, the planning of factories and enterprises was unreasonable, and there were many polluting enterprises, which were important factors affecting the ecological security of Jinyuan District.

According to the results of this research, the low level of sustainable development in Taiyuan City was mainly caused by the simple pursuit of economy at the cost of the environment for many years. If people want to change the present situation, they must make great efforts to adjust the industrial structure, improve the utilization rate of resources, reform the mode of economic development, and coordinate the ecological environment with economic development to ensure the sustainable development.

Although the index system of this research was constructed based on the existing research results of a large number of scholars, owing to data constraints, the establishment of the ecological security index system of Taiyuan City was not perfect. In future research, we should explore more scientific and applicable evaluation methods and climate indicators, while selecting important indicators to establish an evaluation system that will be gradually improve the reliability and accuracy of the evaluation results.

Due to the limitation of data sources, the time span of this study is relatively short and the indicators are not comprehensive enough. In future research, a longer time span can be studied and more comprehensive indicators can be selected as much as possible.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Declaration

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Conflicts of interest

The authors declare no conflicts of interest.

Availability of data and material

All data generated or analyzed during this study are included in the manuscript.

Code availability

Not applicable.
Author contributions

Conceptualization, W G; methodology, Y Z; software, Y Z; validation, I Z; formal analysis, Y Z and K Y; investigation, L Z; writing—original draft preparation, Y Z; writing—review and editing, Y Z; visualization, Y Z. All authors have read and agreed to the published version of the manuscript.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

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Data access statement

All of the data is already provided in the article.

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