Analysis and evaluation of air quality in Shandong province based on AHP

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Abstract. In recent years, the rapid growth of economy and population has led to the continuous deterioration of air quality, so the evaluation of air quality is particularly important. According to the atmospheric environmental quality standard, this paper takes five evaluation factors as the criterion layer for the first time (SO$_2$, NO$_2$, CO, O$_3$ and PM$_{2.5}$), in addition, it is the first time to add the observation station as the sub criterion layer. Finally, the hierarchical structure model is constructed and the air quality of Shandong Province in the 12 months of 2016 is evaluated respectively. The results show that: in 2016, the period of better air quality in Shandong Province is mainly in summer, while in winter, the air quality is poor but the fluctuation is small; from the spatial distribution situation In a year, the region with the best air quality is the eastern coastal cities, followed by the central and western regions; in terms of the total number, the number of cities with poor air quality rating is the largest, followed by the cities with good air quality rating, and the cities with excellent air quality rating are the last, that is to say, the overall air quality of Shandong Province in 2016 is poor.

Keywords: air quality assessment, Shandong Province, AHP, pollution factor, air monitoring station.

1. Introduction

In recent years, the development of urbanization intensifies the loss of fossil energy, and the large amount of fossil fuel combustion leads to the decline of air quality. The public's vision of improving air quality is increasing day by day, so it is necessary to renovate the atmospheric environment. But before the air pollution control, an important work is to evaluate the air quality comprehensively. Only in this way can the relevant departments make targeted air pollution control decisions.

At present, there are many methods used in air quality assessment, such as air pollution index method [1], principal component analysis method [2], grey clustering method [3], comprehensive index method [4], neural network method [5] and analytic hierarchy process [6]. Among them, analytic hierarchy process (AHP) has attracted much attention because of its qualitative and quantitative analysis in the evaluation process. It is also often used in tourism resource evaluation [7], public facilities location [8], water security evaluation and environmental protection measures research. At present, many domestic scholars have done a lot of work on the air quality evaluation by using the analytic hierarchy process (AHP). He Bin [6] and others have divided the air quality into four grades by using the analytic hierarchy
process (AHP), and made a comprehensive evaluation of the air quality in four quarters of a year with SO$_2$, NO$_x$, and TSP as evaluation factors. Ma Jianhua [9] divided the air quality into three grades, and comprehensively evaluated the air quality of Urumqi in four years with SO$_2$, NO$_x$ and TSP as evaluation factors. Zhuo Qian, Zheng Jian, Yi Rui, Zhang HongRi, Zhang Qinhu and Deng Wanghua [10-16] divided the atmospheric quality into three grades in the hierarchical structure model with SO$_2$, NO$_2$ and PM$_{10}$ as the evaluation factors, and all of them showed interannual variation in time scale. Han Zhuo [17] evaluated the air quality of Xi’an City, still taking SO$_2$, NO$_2$ and PM$_{10}$ as the evaluation factors. Different from the predecessors, he divided the air quality into two grades in the hierarchical structure model.

Although domestic scholars have made a lot of evaluation on air quality by using analytic hierarchy process (AHP), most of the evaluation factors are SO$_2$, NO$_2$ and PM$_{10}$, and the evaluation model established is also limited to the three-level evaluation model, and most of them are annual changes. In addition, the evaluation area is limited to the city level. On the basis of previous studies, this paper does not take a single city as the evaluation area, but evaluates the air quality of 17 cities in Shandong Province. Five evaluation factors of SO$_2$, NO$_2$, CO, O$_3$ and PM$_{2.5}$ were selected for the first time, and a four layer evaluation model was established to analyze and evaluate the air quality of Shandong Province in 2016 in the form of spatial distribution map.

2. Data sources
The data is from China national environmental monitoring station. There are 107 air quality monitoring points in Shandong Province. Each monitoring point carries out all-weather automatic monitoring of air pollutants and records the concentration value every hour. Based on the atmospheric environment monitoring data of Shandong Province in 2016, according to the minimum requirements for the validity of pollutant concentration data in the "atmospheric environmental quality standard" (gb3095-20122012 Revision), after eliminating the number of stations that do not meet the requirements, the original data of 80 effective air quality monitoring points can be obtained. After calculation, the statistical values of air pollution factors (SO$_2$, NO$_2$, CO, O$_3$ and PM$_{2.5}$) in Shandong Province from January to December 2016 were obtained. Taking Jinan City in January as an example (Table 1), the air quality of Shandong Province is comprehensively evaluated and analyzed.

| Name of atmospheric monitoring point | Name of elements | Scientific Research Institute | Agricultural scientific institute | Area for development | Chemical factory, Jinan | Provincial seed warehouse | Municipal monitoring station | Changqing Party School | Environmental monitoring station | Mingshui |
|------------------------------------|------------------|-------------------------------|-------------------------------|---------------------|------------------------|--------------------------|---------------------------|-------------------------|-----------------------------|---------|
| SO$_2$ (μg·m$^{-3}$)               | 59.62            | 81.76                         | 64.49                         | 92.95               | 90.70                  | 94.94                    | 71.27                     | 95.03                   | 78.60                        |
| NO$_2$ (μg·m$^{-3}$)               | 50.09            | 52.48                         | 63.97                         | 76.84               | 77.47                  | 81.53                    | 73.79                     | 53.35                   | 60.05                        |
| CO (mg·m$^{-3}$)                   | 1.67             | 2.38                          | 1.66                          | 1.93                | 2.05                   | 2.37                     | 1.80                      | 1.89                    | 1.66                         |
| O$_3$ (μg·m$^{-3}$)                | 28.87            | 17.51                         | 26.76                         | 20.99               | 20.60                  | 22.20                    | 23.99                     | 28.46                   | 25.93                        |
| PM$_{10}$ (μg·m$^{-3}$)            | 120.24           | 137.40                        | 97.44                         | 140.33              | 127.59                 | 120.22                   | 126.17                    | 114.03                  | 107.83                       |

3. Application of AHP in air quality evaluation of Shandong Province
In the establishment of AHP model, the target layer should be defined first, and then the related elements should be reasonably decomposed into different levels. Moreover, different elements at the same level in the model need to be compared between each other, and the weight of each element relative to the previous level can be obtained by comparison, and finally the comprehensive weight can be obtained. By comparing the size of the comprehensive weight, the scheme corresponding to the maximum weight is the optimal solution to the problem.

3.1. Establish hierarchical structure model
The first step of AHP is the establishment of hierarchical structure model. In this paper, based on the concentration limit of pollutants in the "air environmental quality standard" of China, according to the monitoring data of each observation point, the main air pollutants are selected as the evaluation factors,
and the hierarchical structure model is established (Figure 1). In the model, the atmospheric environmental quality is the total target layer (A), the five evaluation factors (SO$_2$, NO$_2$, CO, O$_3$ and PM$_{2.5}$) are used as the criterion layer (B), and the observation stations in Jinan City are taken as the sub criteria layer (C), and the air quality level is the final scheme layer (D).

**Figure 1.** Stratified index system of atmospheric environment quality in Jinan

### 3.2 Construct judgment matrix and find eigenvector

After the construction of AHP model, the next step is to construct judgment matrix. The criteria of constructing judgment matrix (A-B) are as follows: the station monitoring mean value of each pollution factor is the scale, and the secondary standard of atmospheric environmental quality is the benchmark.

\[
\frac{B(SO_2)_{\text{mean value}}}{B(SO_2)_{\text{standard}}} ; \frac{B(NO_2)_{\text{mean value}}}{B(NO_2)_{\text{standard}}} ; \frac{B(CO)_{\text{mean value}}}{B(CO)_{\text{standard}}} ; \frac{B(O_3)_{\text{mean value}}}{B(O_3)_{\text{standard}}} ; \frac{B(PM_{2.5})_{\text{mean value}}}{B(PM_{2.5})_{\text{standard}}}
\]

(1)

Then, the square root method [6] is used to calculate the maximum eigenvalue and eigenvector of (A-B). Due to the consideration of socio-economic characteristics and regional pollution characteristics, there should be some differences among monitoring points. Among them, the population distribution in social and economic factors and regional GDP have great influence on the location of monitoring points. Therefore, according to the statistical data of 2016 statistical yearbook of each city, the distribution of monitoring points, the total population at the end of the year, the total population of the whole city and GDP and other factors are comprehensively considered to construct the judgment matrix (B-C). If the proportion of GDP of each monitoring point in the GDP of the whole city is recorded as A, the proportion of the population of each monitoring point in the population of the whole city as B, and the concentration value of the evaluation factor of each monitoring point as C, then the scale calculation criteria are as follows:

\[
\frac{(a+b)/2 \times c}{5}
\]

(2)

The judgment matrix (B$_1$-C) is constructed and its maximum eigenvalue and eigenvector are obtained. In addition, the judgment matrix of the other four pollution factors is constructed by the same method.

Finally, the judgment matrix (C-D) is constructed according to the monitoring value of each pollution factor and the limit value of atmospheric pollutant grading concentration. The construction scaling criteria are as follows:

\[
\frac{1}{|B_1-B_{1\text{standard}}|} ; \frac{1}{|B_2-B_{2\text{standard}}|} ; \frac{1}{|B_3-B_{3\text{standard}}|} ; \frac{1}{|B_4-B_{4\text{standard}}|} ; \frac{1}{|B_5-B_{5\text{standard}}|}
\]

(3)
Fill in the judgment matrix \((C_1-D)\) according to the above formula, and then construct the judgment matrix of the remaining 8 stations according to the same method, and calculate the maximum eigenvalue and eigenvector.

### 3.3. Hierarchical single sort, and consistency test of judgment matrix

The process of calculating the corresponding eigenvectors from each group of judgment matrices is hierarchical single ranking, and the result of ranking is the relative importance weight of each element on the same level relative to an upper element. After that, we need to check the judgment matrix that has been filled in. If the judgment matrix fails to pass the consistency test, the judgment matrix needs to be filled in again.

In AHP, \(CR\) is used to check the judgment matrix, in which the consistency ratio \(CR = CI / RI\), where \(CI\) is the consistency index, its calculation formula is \(CI = (|\lambda_{max} - n|) / (n - 1)\). \(RI\) is the average random consistency index, which can be obtained by looking up the table (Table 2) corresponding to the matrix. If the calculated \(CR\) is less than 0.1, the judgment matrix passes the test. It can be seen from table 3 that the \(CR\) of the judgment matrix listed in the table is less than 0.1, so each judgment matrix has passed the test.

#### Table 2. Average random consistency index

| Matrix order \((N)\) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---------------------|---|---|---|---|---|---|---|---|---|----|----|
| \(RI\)              | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.46 | 1.49 | 1.52 |

#### Table 3. Hierarchical single ordering of judgment matrix and its consistency test

| \(\lambda_{max}\) | \((A-B)\) | \((B_1-C)\) | \((B_2-C)\) | \((B_3-C)\) | \((B_4-C)\) | \((B_5-C)\) | \((B_6-C)\) | \((B_7-C)\) | \((B_8-C)\) | \((B_9-C)\) |
|-------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0.067             | 0.082   | 0.088   | 0.096   | 0.131   | 0.112   |         |         |         |         |         |
| 0.135             | 0.138   | 0.113   | 0.168   | 0.098   | 0.157   |         |         |         |         |         |
| 0.080             | 0.111   | 0.140   | 0.119   | 0.152   | 0.114   |         |         |         |         |         |
| 0.049             | 0.083   | 0.088   | 0.072   | 0.062   | 0.085   |         |         |         |         |         |
| 0.668             | 0.076   | 0.083   | 0.072   | 0.057   | 0.072   |         |         |         |         |         |
|                   |         |         | 0.136   | 0.101   | 0.112   |         |         |         |         |         |
|                   |         |         | 0.061   | 0.065   | 0.070   |         |         |         |         |         |
|                   |         |         | 0.147   | 0.175   | 0.143   |         |         |         |         |         |
|                   |         |         | 0.129   | 0.159   | 0.136   |         |         |         |         |         |
| \(CI\)            | 0       | 0       | 0       | 0       | 0       |         |         |         |         |         |
| \(RI\)            | 1.12    | 1.46    | 1.46    | 1.46    | 1.46    | 1.46    |         |         |         |         |
| \(CR\)            | 0       | 0       | 0       | 0       | 0       |         |         |         |         |         |

#### Table 4. Hierarchical single ordering of judgment matrix \((C-D)\)

| Judgment matrix | \((C_1-D)\) | \((C_2-D)\) | \((C_3-D)\) | \((C_4-D)\) | \((C_5-D)\) | \((C_6-D)\) | \((C_7-D)\) | \((C_8-D)\) | \((C_9-D)\) |
|-----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| \(W_i\)         | 0.500       | 0.511       | 0.475       | 0.517       | 0.512       | 0.510       | 0.505       | 0.507       | 0.495       |
|                 | 0.500       | 0.489       | 0.525       | 0.483       | 0.488       | 0.490       | 0.495       | 0.493       | 0.505       |

Table 4 only gives the final results of hierarchical single ranking. Because when \((C-D)\) is a second-order matrix, \(RI\) is always zero, so the matrix \((C_1-D)\) satisfies the consistency. Similarly, the judgment matrices of the remaining eight stations are also satisfied.

### 3.4. Calculation of combined weight and consistency test of hierarchical total ranking

Hierarchical total ranking is to calculate the relative important weight of all elements in the same level for the target layer. Therefore, according to the eigenvectors obtained from \((A-B)\) and \((B-C)\), the total ranking weight table is established as follows (Table 5).
Table 5. Total ranking weight of hierarchy

| hierarchy B | B1  | B2  | B3  | B4  | B5  | Total ranking weight of hierarchy |
|-------------|-----|-----|-----|-----|-----|-----------------------------------|
| hierarchy C |     |     |     |     |     |                                   |
| C1          | 0.067 | 0.135 | 0.080 | 0.049 | 0.668 | 0.106                          |
| C2          | 0.138 | 0.113 | 0.168 | 0.098 | 0.157 | 0.148                          |
| C3          | 0.111 | 0.140 | 0.119 | 0.152 | 0.114 | 0.119                          |
| C4          | 0.083 | 0.088 | 0.072 | 0.062 | 0.085 | 0.083                          |
| C5          | 0.076 | 0.083 | 0.072 | 0.057 | 0.072 | 0.073                          |
| C6          | 0.130 | 0.143 | 0.136 | 0.101 | 0.112 | 0.119                          |
| C7          | 0.058 | 0.077 | 0.061 | 0.065 | 0.070 | 0.069                          |
| C8          | 0.176 | 0.126 | 0.147 | 0.175 | 0.143 | 0.145                          |
| C9          | 0.146 | 0.142 | 0.129 | 0.159 | 0.136 | 0.138                          |

In the AHP model, each layer needs to be checked for consistency. In addition, it is necessary to check the consistency of the total ranking, so that we can ensure that all the judgment matrices constructed above are reliable.

Suppose that the ranking structure of all factors in level A is $a_1, a_2, \ldots, a_m$. If the consistency ratio of hierarchical total ranking is $CR = CI/RI = \frac{\sum_{i=1}^{n} a_i CI}{\sum_{i=1}^{n} a_i RI} < 0.1$, the result is considered to be satisfactory. According to the test, $Cr = 0 < 0.1$, so the above results are acceptable.

3.5. Determination of air quality level

According to the results of the previous calculation, suppose that the eigenvector of judgment matrix $(A-B)$ is $W_1$, the eigenvector of judgment matrix $(B-C)$ is $W_2$, the eigenvector of judgment matrix $(C-D)$ is $W_3$, and the final air quality level is $Z$. the final air quality level can be determined by the operation of decision combination vector.

$$Z = w_2 \cdot w_3 \cdot w_1 = \begin{bmatrix} 0.503 \\ 0.497 \end{bmatrix}$$ (4)

According to the comparison of $Z$ value, the atmospheric quality corresponding to the maximum weight is the first level standard, so the atmospheric quality of Jinan in January 2016 is grade I. The air quality levels of other months can be calculated by the above methods, and the judgment matrix and the total ranking of levels meet the consistency test.

4. Air quality assessment of Shandong Province Based on AHP model

4.1. Atmospheric quality level of 17 cities

We use the AHP model to obtain the atmospheric quality levels and corresponding weight values of all cities in Shandong Province. According to the calculated atmospheric quality weight values, we give the air quality change line chart of 17 cities in Shandong Province. Because the hierarchical structure model constructed in this paper is based on the air quality level in the latest "atmospheric environmental quality standard", and the final atmospheric quality grade is divided into two levels, so the change of the second level weight value of atmospheric quality is just opposite to that of the first level weight value. Here only shows the change of the second level weight value of each city in one year (As shown in Figure. 2). Moreover, it is not difficult to understand that the larger the secondary weight value of atmospheric quality is, the worse the air quality of the month is. Therefore, it can be seen from Figure 2 that the months with poor air quality in the whole year are mainly September, November, February, March and April.
Figure 2. Change chart of weight value of secondary atmospheric quality

4.2. Spatial distribution of air quality changes
The following group of pictures shows the spatial distribution of atmospheric quality changes in Shandong Province in December 2016. The light color indicates that the air quality is grade II, that is, the area with poor air quality. On the contrary, the dark color area is the area with first-class atmospheric quality, that is, the area with better air quality.

Figure 3. Spatial distribution of air quality in Shandong Province
From the above group of maps, we can see that the first-class atmospheric quality areas in January are mainly inland cities in the western part of Shandong Province, while in the eastern coastal areas, the atmospheric quality is mostly of grade II. From February to April, the first grade air quality areas are mainly concentrated in the eastern coastal cities, such as Weihai, Qingdao and Yantai, and the air quality of other cities is grade II; after May, the air quality of Shandong Province began to improve, except Binzhou City, Zibo City, Weifang City and Liaocheng City, the air quality of other cities was grade I. As time goes into June, July and August, the air quality of the whole province becomes the best in the year; however, the atmospheric quality in September becomes the lowest point in the whole year, and the atmospheric quality in all regions of the province is grade II standard except Qingdao. The air quality in the last three months is better than that in September, but the air quality in different regions fluctuates greatly. The air quality of Eastern, southern and southwest areas with air quality of grade I in October becomes class II standard in December. During this period, only Weihai City keeps the better first level standard unchanged.

4.3. Comprehensive evaluation of air quality in Shandong Province

In this paper, the number method is used to analyze and evaluate the atmospheric quality of Shandong Province. This method is to make statistics on the atmospheric quality classification of each city in a year, and divide the atmospheric quality into three new grades. If a city has more than six months of atmospheric quality status as grade II, its atmospheric quality is defined as poor. Secondly, if a city has 5-6 months of atmospheric quality grade II in a year, it is rated as good. Finally, when the number of air quality grade II in a year does not exceed 4 months, the evaluation result of the city is excellent. The three grades are represented by different colors. The lighter the color is, the better the air quality in the area is.

As shown in Figure 4: it is not difficult to see that the areas with excellent air quality are concentrated in the eastern coastal cities of Shandong Province, which are Qingdao, Yantai and Weihai respectively, while the areas with good air quality are mainly distributed in the southwest and northwest of Shandong Province. Finally, the areas with poor air quality are mainly distributed in the central and northern cities of Shandong Province.

Figure 4. Spatial distribution of air quality in Shandong Province Based on the number method

5. Conclusion

(1) Throughout the whole year, the air quality of the whole province is generally good in May, June, July and August. From February to April and from September to November, the air quality of the whole province is generally poor. In summary, the period of better air quality mainly concentrated in summer, while the atmospheric quality in autumn fluctuated greatly. On the other hand, the air quality in winter was poor but the fluctuation was small, and the air quality condition in spring was gradually improved with the change of time.
(2) According to the spatial distribution of the whole province, the regions with the best air quality in a year are the cities along the eastern coast, followed by the central and western regions; secondly, the atmospheric quality in the eastern region fluctuates less in the year, while the atmospheric quality in the central and western regions changes greatly, especially in autumn and winter.

(3) Finally, from the comprehensive evaluation of the air quality of the whole province, the areas with excellent air quality are concentrated in the eastern coastal cities of Shandong Province, while the areas with good air quality are mainly distributed in the southwest and northwest of Shandong Province, and the areas with poor air quality are mainly distributed in the central and northern cities of Shandong Province. In terms of the total number, the number of cities with poor air quality is the largest, followed by the cities with good air quality, and the cities with excellent air quality are at the bottom. That is to say, in the comprehensive evaluation of air quality of Shandong Province in 2016, the overall atmospheric quality of Shandong Province is relatively poor.

In conclusion, Shandong Province should give reasonable and effective improvement measures to the current atmospheric environment, especially in autumn and winter, several cities in the central and Northern Shandong Province should focus on governance, so as to meet the people's vision of a good environment

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