Light Pollution Risk Level Evaluation model Based on AHP and TOPSIS

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Abstract. In recent years, light pollution problem was hanging over our heads. This paper established Light Pollution Risk Level Evaluation Model(RLE Model)to evaluate the light pollution risk Level of 4 different types of communities. It focused on the following 5 indicators: SQM, region type, GDP, population density and biodiversity. We not only considered the SQM value, but also incorporate other influencing factors into the model and use the Analytic Hierarchy Process(AHP) method to calculate reasonable weights (W1=0.0437, W2=0.0752, W3=0.1425, W4=0.2677 and W5=0.4710). These weights allowed our metric to identify the risk level of light pollution in a region objectively and comprehensively. This paper also use Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to evaluate the light pollution level of different location and got the light pollution level index. This paper divided the light pollution risk levels of 12 sample points into three levels. Four community risk levels are ranked from high to low as urban, suburban, protected areas, and rural areas.

Keywords: light pollution risk, AHP, RLE Model, TOPSIS.

1. Introduction

With the acceleration of urbanization, the problem of light pollution is becoming more and more serious [1]. Global light pollution is flooding the skies of many parts of the world, and the situation is getting worse every year [2]. If there are 250 visible stars in the sky when someone is born, by the time they ‘re 18 they’ll only see 100, and over that same period the sky will have increased in brightness by more than a factor of four. More than 80 % of people in the world, especially 99 % of Americans and Europeans, live in a sky polluted by light, and it is almost impossible for people to gaze at the sky [3]. Light pollution not only damages human health, but also restricts urban development and even threatens biodiversity [4].Therefore, the creation and optimization of the intervention strategies for the light pollution deserves our attention. We established a Light Pollution Risk Level Evaluation model(RLE Model) to identify the light pollution risk level of 4 different kinds of location, and comprehensively considered five indicators of diversity of species, population density, regional type, GDP and biodiversity.

2. Light Pollution Risk Level Evaluation model(RLE Model)

2.1. Calculation of Index Weight Based on AHP (Analytical Hierarchy Process)

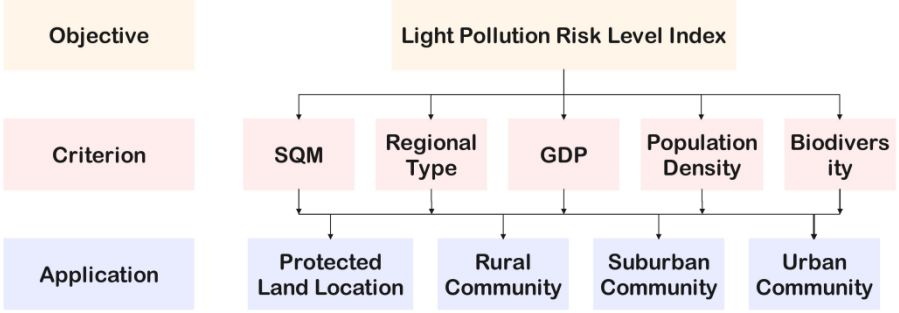


Figure 1: AHP process chart

The AHP (analytic hierarchy process) is a decision-making method that decomposes the elements related to decision-making into levels such as goals, criteria, and schemes, and conducts qualitative and quantitative analysis on this basis [5]. The analytic hierarchy process is mainly divided into four steps : First, build a ladder-level model ; the second is to construct judgment moment The third is to determine the index weight, and the weight of each influence factor is determined by the normalization method. The order of importance; the fourth is the consistency test to test the rationality of the index weight [6]. This method has the characteristics of system, flexibility and simplicity [7]. The risk level of light pollution is not only closely related to the value of light pollution, but also depends on the level of development, population, biodiversity and other factors. Among them, the sky quality meter (SQM) makes it easy to measure the zenith brightness [8], thus reflecting the degree of light pollution. Usually, its value is between 16-22 mag/arc sec^2, 16 mag/arc sec^2 represents the brightest zenith brightness and 22 mag/arc sec^2 represents the darkest, with the least light pollution. Therefore, as the figure 1 shows, we establish the following five evaluation indicators : SQM, regional type, GDP, population and biodiversity. Next, we will introduce AHP to establish an evaluation model of five indicators to obtain their weights.

2.2. Judgment Matrix & Consistency Test

Table 1: The Judgment Matrix of Five Indicators

	Diversity of species	**Population density**	**GDP**	**Regional type**	**SQM**
Diversity of species	1	1/2	1/4	1/6	1/8
Population density	2	1	1/2	1/4	1/6
Regional type	4	2	1	1/2	1/4
GDP	6	4	2	1	1/2
SQM	8	6	4	2	1

As the table 1 shows, we use the consistency test to determine whether our judgment matrix can be used normally. The consistency ratio column CR calculation formula is as follows, in which CI represents coincidence indicator:

$$CR = \frac{CI}{RI} \tag{1}$$

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{2}$$

Table 2: Mean Random Consistency Index

n	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RI	**0**	**0.52**	**0.69**	**1.12**	**1.26**	**1.36**	**1.41**	**1.46**

Table 2 shows the mean random consistency index. If CR < 0.1, then we believe that the consistency of the judgment matrix is within the acceptable range, otherwise, we need to modify the judgment matrix. It is calculated that CR = 0.0104, so the consistency of this matrix is within the acceptable range.

2.3. Weight Calculation by Arithmetic Average Method

Firstly, we normalize the judgment matrix. Secondly, we add the normalized column data together. Finally, we get the weight vector by dividing the added data by n.

$$w_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \quad (i = 1, 2, \cdots, n) \tag{3}$$

Our result is as follows in table 3:

Table 3: Indicators and weights

Indicators	Weights
Diversity of species	W_1=0.0442
Population density	W_2=0.0759
Regional type	W_3=0.1435
GDP	W_4=0.2680
SQM	W_5=0.4684

2.4. Weight Calculation by Geometric Average Method

Step 1: A new column vector is obtained by multiplying the elements in the judgment matrix by rows.

Step 2: Each component of the new vector is squared by n.

Step 3: Normalize the obtained column vector to obtain the weight vector.

$$Judgment\ Matrix = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{4}$$

$$w_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{\substack{k=1 \\ (i=1,2,\cdots n)}}^{n}\left(\prod_{j=1}^{n} a_{kj}\right)^{\frac{1}{n}}} \tag{5}$$

Our result is as follows in table 4:

Table 4: Indicators and weights

Indicators	Weights
Diversity of species	W_1=0.0434
Population density	W_2=0.0756
Regional type	W_3=0.1427
GDP	W_4=0.2694
SQM	W_5=0.4690

2.5. Weight Calculation by Eigenvalue Method

We calculated the maximum eigenvalue of the judgment matrix and its corresponding eigenvectors. At the same time, we normalized the obtained feature vector and obtained the weight vector.

Our result is as follows in table 5:

Table 5: Indicators and weights

Indicators	Weights
Diversity of species	W_1=0.0437
Population density	W_2=0.0752
Regional type	W_3=0.1425
GDP	W_4=0.2677
SQM	W_5=0.4710

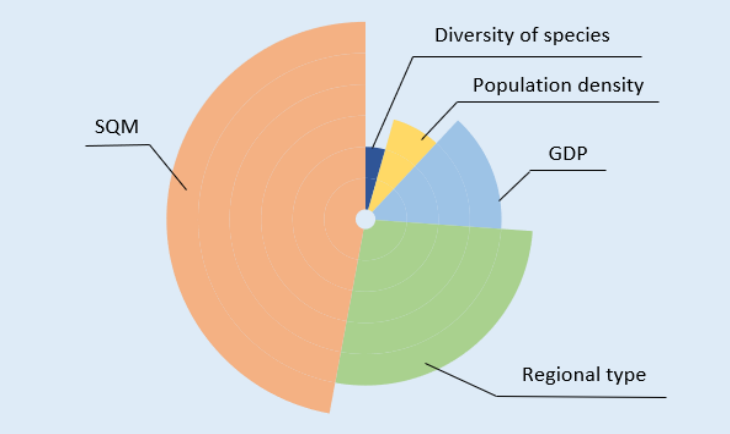


Figure 2: The ratio of five indicators

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is a common decision-making technique for multi-objective decision analysis [9]. It sorts the evaluation objects by means of the positive ideal solution and negative ideal solution of the evaluation problem. The so-called positive ideal solution is a virtual optimal object, each index value is the best value of the index in all evaluation objects; the ideal solution is another virtual worst object, and each index value is the worst negative value of the index in all evaluation objects. The difference between each evaluation object and positive ideal solution and negative ideal solution is calculated, and the advantages and disadvantages of each evaluation object are ranked.

We use TOPSIS comprehensive evaluation method to score the light pollution level of different location and get the light pollution level index. Figure 2 shows the ratio of five indicators

There are four types of our indicators: Very small indicators, intermediate indicators, interval indicators and very large indicators. For very small indicators, the smaller the data, the better the indicators. For intermediate indicators, the optimal value of the data is a certain value in the data, but this value is not the largest or the smallest. For interval indicators, the optimal situation of data is a range rather than a value. In this range, we all think it is the optimal situation. For very large indicators, the bigger the data, the better the indicators. We need to convert the indicators into very large indicators when using the TOPSIS method. The transformation process is as follows. From top to bottom, it is the transformation process of extremely small, intermediate and interval indicators.

$$M = \max\{|x_i - x_{best}|\} \quad \tilde{x}_i = 1 - \frac{|x_i - x_{best}|}{M} \tag{6}$$

$$M = \max\{a - \min\{x_i\}, \max\{x_i\} - b\} \tag{7}$$

$$\tilde{x}_i = \begin{cases} 1 - \frac{a - x}{M}, x < a \\ 1, a \leqslant x \leqslant b \\ 1 - \frac{x - b}{M}, x > b \end{cases} \tag{8}$$

To begin with, we turned the index data into a very large index. In our RLE evaluation model, SQM is a very small indicator, and the remaining indicators are very large indicators. Therefore, we need to forward the index data of SQM, and the transformation formula is as follows :

$$x'_j = x_{j\max} - x_j \tag{9}$$

In order to eliminate the influence of different dimensions of each index, we standardize the matrix.

Assume that we have n objects to be evaluated and m evaluation indexes. The matrix we construct has n rows and m columns.

$$x = \begin{bmatrix} x_{11} & x_{12} & x_{13} & \cdots & x_{1m} \\ x_{21} & x_{22} & x_{23} & \cdots & x_{2m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & x_{n3} & \cdots & x_{nm} \end{bmatrix} \tag{10}$$

Find the distance between each evaluation object and the optimal solution Di +, and the distance from the worst solution Di-, the formula is as follows, in which S_i is the unnormalized score of our i-th object.:

$$D_i^+ = \sqrt{\sum_{j=1}^{m} w_j^2 (z_j^+ - z_{ij})^2} \tag{11}$$

$$D_i^- = \sqrt{\sum_{j=1}^{m} w_j^2 (z_j^- - z_{ij})^2} \tag{12}$$

Through calculating results we have obtained, we got the light pollution level index, and the transformation formula is as follows:

$$s_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{13}$$

3. Results

3.1. The light pollution risk level analysis about 12 sample plots

For four different types of regions, we selected three sample points for each type. A total of 12 sample plots. Through our model, the light pollution risk index is evaluated and ranked from low to high. We got the following table 6.

Table 6: The light pollution risk level analysis about 12 sample plots

	Diversity of species (species number)	Population density (people/km^2)	GDP (100 million yuan)	Regional type	SQM (mag./arc sec^2)	Light pollution risk index	Light pollution risk level
Xinfeng Town	900	123	2.15	3	21.29	0.0447	I
Liushui Town	1005	101	2.05	3	21.01	0.0526	I
Longmen Town	1105	139	2.17	3	20.99	0.0533	I
Yellowstone National Park	1300	8	1.5	5	21.99	0.0583	I
Jiuzhaigou Nature Reserve	1396	13	1.2	5	21.98	0.0585	I
Changbai Mountain Nature Reserve	4225	31	0.8	5	21.98	0.0609	II
Baoding Suburb	764	597	3725	2	20.45	0.0647	II
Liupanshui Suburb	181	306	1503.6	2	20.42	0.0651	II
Yan'an Suburb	565	440	2231.9	2	20.4	0.0661	II
Washington D.C.	387	3954	36118	1	17.35	0.1528	III
Tokyo	284	6158	64100	1	17.44	0.1598	III
New York	204	11000	75784	1	17.46	0.1632	III

Finally, we divided the light pollution risk levels into three levels, namely I, II, and III. The higher the level, the higher the light pollution risk level in the region.

3.2. Analysis of results

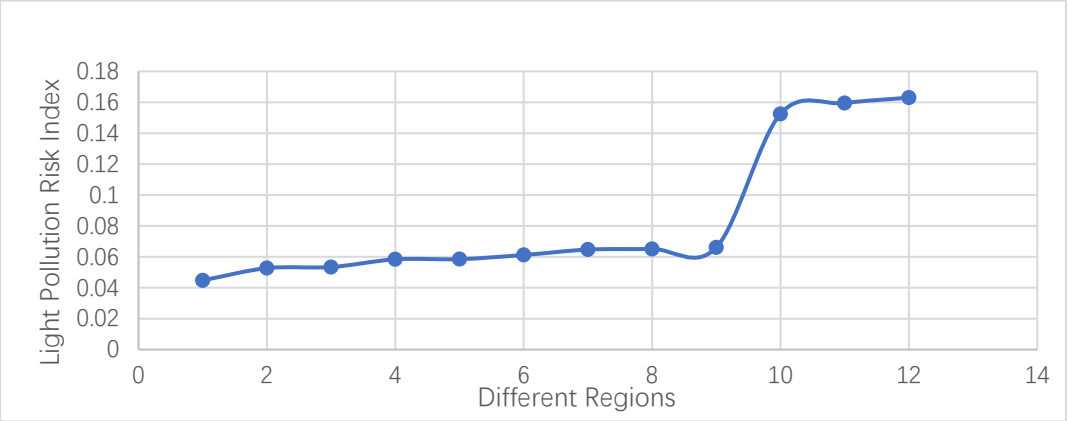


Figure 3: The datas about Light Pollution Risk Index for different region**s**

As shown in the figure3, the black ,red, orange, blue point represent the urban community, the suburban community, the protected land location and the rural community. Through images and charts, we can find that although the SQM value of protected land location is bigger than that of rural communities, that is, the light pollution degree of protected land location is smaller than that of rural communities while the light pollution risk index of nature reserves is higher than that of rural communities. This shows us that the risk level of light pollution in nature reserves is higher, that is, its ecological environment is more likely to be affected by light pollution. The reason for this result is that we set different Regional type values for different regions. We set the regional type values of urban, suburban, rural, and protected land location to 1, 2, 3, and 5, respectively, indicating that the tolerance of these areas to light pollution is different. The higher the value, the lower the tolerance of the region to light pollution. Due to the rich species diversity of the nature reserve, the regional type value is also the highest, even reaching 5. This shows us that our light pollution risk assessment model is objectively and comprehensively evaluated the light pollution risk level of a region, not only based on the index of light pollution value.

4. Conclusions

Our light pollution risk level evaluation model with multiple considerations and intuitive results. Evaluating the light pollution risk level from five aspects of SQM, regional types, location's level of development, population and biodiversity is a more suitable scheme for every location, and an intuitive rating scale is given. The analytic hierarchy process has the advantage of combining qualitative and quantitative analysis[10].Our model works well on a protected land location, a rural community, a suburban community, and an urban community, which means that our model is adaptable. We selected multiple sample points from four different types of communities, making our model more rigorous and objective in evaluating the risk level of light pollution in different regions. When calculating the effectiveness of intervention strategies, we used the predictive light pollution risk index. This avoided the problem that the light pollution risk index after intervention is too different from the actual light pollution risk index caused by insufficient fitting accuracy.

References

[1] Gao Zhengwen, Lu Yuntao, Chen Yuanxiang. Urban light pollution and its countermeasures [J]. Environmental protection, 2019, 47 (13): 44-46.

[2] Xinyu. Light pollution overwhelms the sky speed beyond imagination [N]. Chinese Journal of Science, 2023-01-31 (002).

[3] Fabio Falchi, P. C. (2016). The new world atlas of artificial night sky brightness. Science Advances, 2(6), 1-26.

[4] Liu Tianyuan. Light pollution control: a two-way investigation of domestic practice and foreign experience [J]. Journal of Northwest Minzu University (Philosophy and Social Sciences Edition), 2022 (01): 109-116.

[5] Deng Xue, Li Jiaming, Zeng Haojian, etc. Analytic hierarchy process weight calculation method analysis and its application research [J]. Mathematics practice and understanding, 2012, 42 (07): 93-100.

[6] Lin Yuqing. Research on the effectiveness of green economy development based on AHP analytic hierarchy process [J]. Industrial innovation research, 2023 (05): 1-4.

[7] Wang Yingluo. System engineering [M]. Second edition. Background : Mechanical Industry Press, 2003, 130 - 140.

[8] Li-Wei Hung, Identifying distinct metrics for assessing night sky brightness, *Monthly Notices of the Royal Astronomical Society*, Volume 511, Issue 4, April 2022, Pages 5683–5688

[9] Xia Shaowei and so on. An Introduction to Systems Engineering [M]. Beijing: Tsinghua University Press, 1995.

[10] Guo Jinyu, Zhang Zhongbin, Sun Qingyun. Research and Application of Analytic Hierarchy Process [J]. Chinese Journal of Safety Science, 2008 (05): 148-153.