Study on the risk assessment of light pollution based on entropy weight method-TOPSIS model

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Abstract. In the process of rapid human development, artificial light has gradually increased. People use artificial light more consider light to bring us benefits, but light pollution and the use of light at the same time harm human beings, even to the point of endangering human health and affecting the ecological environment. The problems caused by light pollution are waiting to be solved by us and all human beings together. In this paper, regional vulnerability (e.g., regional development level, population, biodiversity, etc.) is considered. Together with the intensity of pollution sources (e.g. road glare level, light hours, light violation level, etc.), the risk level of light pollution is determined. The risk level model of light pollution was established by calculating the weights of each index using TOPSIS entropy weighting method and hierarchical analysis method. The natural interruption point method was used to classify the risk level of light pollution into level I, level II, level III, level IV, and level v. The risk level model of light pollution was applied to four regions. We derived the risk level as level IV for urban communities, level II for protected land and suburban communities, and level II for rural communities.

Keywords: TOPSIS; Entropy weight method; Light pollution; Analytic hierarchy process.

1. Introduction

With the development of the times and the improvement of human living standards, artificial light has had a positive impact on human beings. However, the excessive use of artificial light at night has flooded cities with lights. Excessive use of artificial light has had varying degrees of environmental and biological impacts on the human body, the urban environment, human mental health and physical health, and even in more remote areas. These effects include excessive light exposure caused by biorhythmic disorders, affected animal migration patterns, and may also lead to accidents caused by glare. Light pollution continues to receive widespread global attention [2]. In recent years, the study and control of light pollution has become an academic issue of particular interest to the international academic community involving the global environment. It is also a specific responsibility and obligation of human and global ecology.

We use regional sensitivity indicators and pollution source intensity indicators to measure the risk level of light pollution; regional sensitivity indicators are influenced by regional development level, population and biodiversity, while human development index and GDP indicators measure regional development level. Population measures traffic accident rate and population density, and biodiversity measures species diversity and forest cover; the intensity index of pollution sources is influenced by the level of road glare, idle time and light damage. The model is finally quantified by analyzing the weights of each indicator.

2. Light pollution risk level evaluation model

2.1 Light pollution risk level assessment

We construct an evaluation model of regional vulnerability and pollution source intensity based on the region's characteristics and the characteristics of pollution sources and take the local development level, population and biodiversity as the leading indicators of regional vulnerability.

The light intensity, glare level, spare time and light infringement level are the leading indicators to measure the intensity of pollution sources. The two are superimposed to form the result - the risk of light pollution and make a risk grading chart.We use the matrix method to overlay the Regional Vulnerability Index (RVI) and the Source Intensity Index (PSII). The natural break point grading method was used to divide the superposition results into grade I., grade II., grade III., grade IV., and grade V. Among them, grades I to V are from low-risk to high-risk levels. The risk level classification is shown in Figure 1.

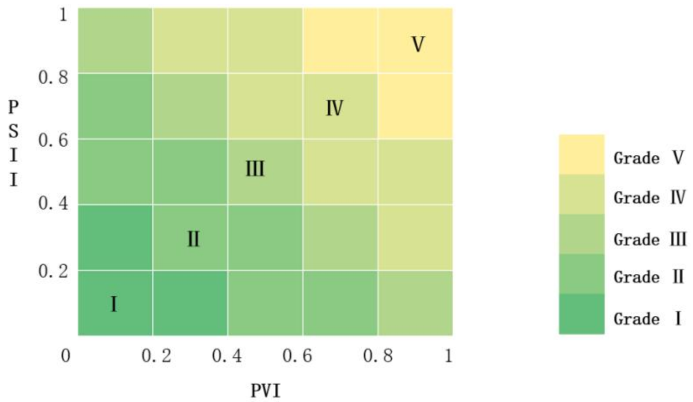


Fig. 1 Light pollution risk level color scale chart

2.2 A model for assessing regional vulnerability

2.2.1 Indicator selection

Inspired by the information in the question, we build a model with a standard two-level indicator system, the output of which is the Regional Vulnerability Index (RVI), which takes values between 0 and 1. The closer this indicator is to 1, the higher the risk level; the closer it is to 0, the lower the risk level. We chose three level 1 indicators to measure the RVI: local development level, population, and biodiversity.

(1) Level of Regional Development

Development needs economic support, so the indicator of the local level of development, local GDP, needs to be selected as the secondary indicator of the local level of development, in addition to the human development index (HDI) is also an indicator of the level of development. Therefore, the secondary indicators under the primary indicator of local development level are GDP and HDI.

Among them, the HDI is calculated by the following formula：

$$HDI = \sqrt[3]{LEI \times EI \times II} \quad (1)$$

The HDI comprises the geometric mean of three fundamental indicators: the life expectancy index, the education index and the income index.

(2) Population

The Population can be measured by many indicators, not only by population growth or population size but also by how safe a city is in one way or another. Therefore, we chose two secondary indicators, population density and traffic accident rate, to measure Population as a primary indicator.

(3) Biodiversity

Biodiversity is the sum of the ecological complex formed by organisms and the environment and its various ecological processes. Therefore, we need to describe biodiversity at the environmental and biological levels, and we choose two tertiary indicators, species diversity and forest cover area, to measure the secondary indicator of biodiversity.

The species diversity is calculated as follows:

$$H = \frac{1}{N}\left(log_2 N! - \sum_{i=1}^{S} log_2 N_i ! \right) \quad (2)$$

In the formula for species diversity, N is the total number of animals and N_i is the number of species; S is the species richness.

2.2.2 Regional Vulnerability Evaluation Model

We want to evaluate the regional vulnerability by building a model so that the value of regional vulnerability can be derived from the data of Regional Vulnerability Index (RVI) [1].

Where the regional vulnerability index (RVI) is given by the following formula:

$$RVI = \sum_{i=1}^{n} First\ Level\ Metric\ Weights \times Secondary\ Indicators\ Account\ for\ the\ Proportion\ of\ Level\ 1\ Indicatora \times Normalized\ Quantity \quad (3)$$

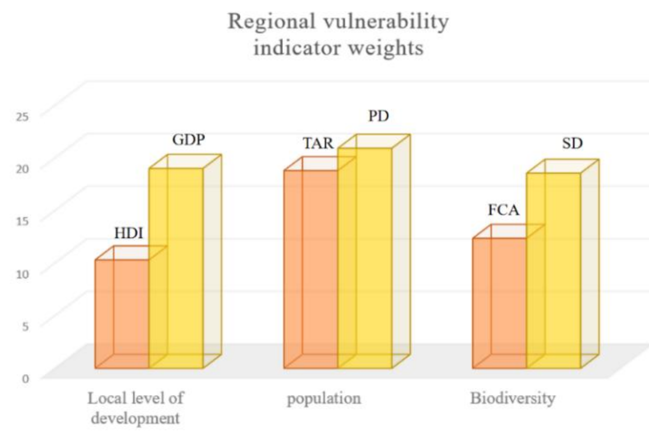
In calculating the weights of the second-level indicators, we use TOPSIS, the distance between superior and inferior solutions method, to evaluate the second-level indicators. Compared with the hierarchical analysis method, which requires subjective matrix building, too many secondary indicators, if too subjective, may build a more one-sided model. TOPSIS method avoids the subjectivity of the data, can well portray the comprehensive impact strength of multiple impact indicators, is not easy to confuse the variables, is suitable for large systems with multiple evaluation units and multiple indicators, and is more flexible and convenient [4].

We need to get the weights of the secondary indicators, combine the two tools of the entropy weight method and TOPSIS, and use the entropy weight TOPSIS method [1].

The utility values of the information and the weighting factors are shown in Table 1.

Table 1. The result of the metric weight calculation

Item	Weight(%)
Traffic Accident Rate	18.806
GDP	19.016
Species Diversity	18.563
Population Density	20.932
Forest Cover Area	12.367
HDI	10.317



Then, according to TOPSIS, the maximum and minimum values in the sample are found, and the four sample areas are evaluated by combining the distances. The evaluation calculation results are obtained in Table 2.

Table 2. TOPSIS evaluation results

Location	Composite Score Index	Sort
Urban Community	0.62640695	1
Suburban Community	0.27273573	3
Protected Land	0.40091349	2
Rural Community	0.19668214	4

To calculate the weights of first-level indicators, we used hierarchical analysis to divide the problem study into three levels: target level, criterion level, and program level, and the constructed hierarchical model is shown in Figure 4. the target level is the regional vulnerability evaluation, the criterion level is the three indicators of regional development level, population, and biodiversity, and the program level is the weights of each evaluation indicator.

Hierarchical analysis (AHP) is a system analysis method proposed by Professor T. L. Seaty, an American operations researcher, in the 1970s. This method is particularly suitable for system evaluation and decision problems with complex hierarchical structures and many qualitative and quantitative indicators [3].

The matrix is constructed according to the importance of each indicator, the evaluation indicators are compared two by two, given specific determined values listed in the matrix, and the proportion of the weight of each indicator is derived from the eigenvectors, as shown in Table 3.

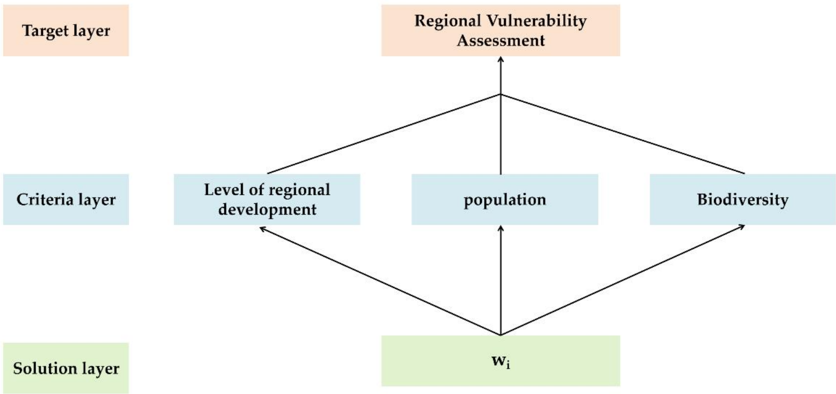


Fig. 2 AHP hierarchy diagram

Table 3. AHP analysis results of regional vulnerability

Item	Feature Vector	Weight(%)
Level of Regional Development	0.825	26.448
Population	0.824	26.416
Biodiversity	1.471	47.135

The primary indicator weights and secondary indicator weights have all been obtained, and the secondary indicator weights of the same primary indicator will be calculated to obtain the weight of the second indicator in the primary indicator, and the calculation formula is as follows.

$$w_{ij}' = \frac{w_{ij}}{\sum_{j=1}^{m} w_{ij}} \tag{4}$$

The regional vulnerability index (RVI) can be obtained with the following formula using the weights given in the previous section and the normalised data.

$$RVI = \sum_{i=1}^{n} \left[w_i \times \sum_{j=1}^{m} \left(w_{ij}' \times Normalized\ Quantity \right) \right] \tag{5}$$

2.3 Pollution source intensity evaluation model

2.3.1 Indicator selection

In the pollution source intensity evaluation model, three indicators are selected: the road glare degree [5], spare time and light infringement degree to establish the evaluation model. The output of this model is the pollution source intensity index (PSII). The value of the pollution source intensity index is taken between 0 and 1. The closer this index is to 1, the higher the risk level; the closer it is to 0, the lower the risk level.

(1) Degree of road glare

Glare can be calculated to get the specific glare value, but the specific value can not accurately represent the degree of glare. We use the statistical hierarchical clustering method, use the squared Euclidean distance to calculate the distance, evaluate the dissimilarity according to the distance, calculate the average distance to classify the degree of glare, and finally classify the degree of glare into seven levels.

(2) Illumination time

Illumination time also determines light pollution. In the case of constant light intensity, the longer the light time, the more serious the cumulative effect of light pollution is produced, so you can control light pollution by controlling the light time.

(3) Light damage degree

The degree of light infringement is the same as that of road glare is related to the degree of indicators. These indicators should also be divided into levels for quantification. The operation method is the same as the degree of road glare using the specific data of light infringement for the hierarchical clustering method. Finally, the degree of light infringement is divided into seven levels.

2.3.2 Establishing a pollution source intensity evaluation model

The evaluation of the pollution source intensity is measured using three indicators, and the value of the pollution source intensity is calculated by building a model to evaluate the pollution source intensity through the data of the pollution source intensity index (SRII)

Where the formula for the pollution source intensity index (SRII) is as follows:

$$SRII = \sum_{i=1}^{n} Index\ weight \times Normalized\ Quantity \tag{6}$$

In calculating the indicator weights, we used hierarchical analysis (AHP) to divide the problem study into three levels: target level, criterion level, and scheme level, and the constructed hierarchical model is shown in Figure 3. the target level is the pollution source intensity evaluation, the criterion level is the three indicators of regional road glare degree, spare time, and light infringement degree, and the scheme level is the weight of each evaluation indicator.

The matrix is constructed according to the importance of each indicator, the evaluation indicators are compared two by two, given specific determined values listed in the matrix, and the proportion of the weight of each indicator is derived from the eigenvectors, as shown in Table 4.

Table 4. Pollution source intensity AHP analysis results

Item	Feature Vector	Weight(%)
Degree of Road Glare	1.247	40.825
Illumination Time	0.785	25.701
Degree of Light Damage	1.022	33.475

The source intensity index (SRII) can be calculated by weighting and normalizing the processed data with the following formula:

$$SRII = \sum_{i=1}^{n} w_{ij} \times Normalized\ Quantity \tag{7}$$

3. Model Applications

The normalized data of different regions were processed through the calculation formula to calculate the regional vulnerability index (RVI) and the pollution source intensity index (SRII), and the risk level of each region was derived according to the superposition model for the evaluation of light pollution risk level. The calculated index results are shown in Table 5.

Table 5. Pollution source intensity AHP analysis results

Location	RVI	SRII	Risk level
Urban community	0.622	0.486	Grade Ⅳ
Suburban community	0.215	0.276	Grade Ⅱ
Protected land	0.471	0.071	Grade Ⅱ
Rural community	0.189	0.166	Grade Ⅰ

Through the index results, we can get a reasonable interpretation of the region, urban areas have more population and the development level of the region is higher, which can indicate that this region will be more affected by light pollution, so the regional vulnerability index is higher, representing a higher risk of regional vulnerability; urban areas will have higher light intensity and light hours because of the greater demand for artificial light, so light pollution will also be stronger. The pollution source intensity index will also be higher, and the pollution source intensity risk is medium. By superimposing the regional vulnerability index and the pollution source intensity index, we can get the risk level of urban areas as level IV.

The biodiversity of the protected area is high. The weight of biodiversity is more significant among all indicators, so the regional vulnerability index of the protected area is high, indicating a medium risk of regional vulnerability; however, the light pollution of the protected area is low, and the spare time and light intensity are low compared with other areas, so the pollution source intensity index is low. With the superposition of the regional vulnerability index and pollution source intensity index, we can get the risk level of the protected land as grade II.

The population and regional development levels in suburban and rural areas are lower than those in urban areas, and the biodiversity is lower than in protected areas. The demand for light in suburban and rural areas is lower than that in urban areas but higher than that in protected areas, and the demand for light in suburban areas is higher than in rural areas. The data show that the pollution source intensity index is higher in suburban areas than rural areas. By superimposing the regional vulnerability index and the pollution source intensity index, we can get the risk level of suburban areas as level II and rural areas as level I.

For the analysis of each data, the results are plotted in Figure 3. The comparison of indicators calculated for each region in different systems is shown in Figure 3 (left), and the comparison of light pollution risk levels is shown in Figure 3 (right).

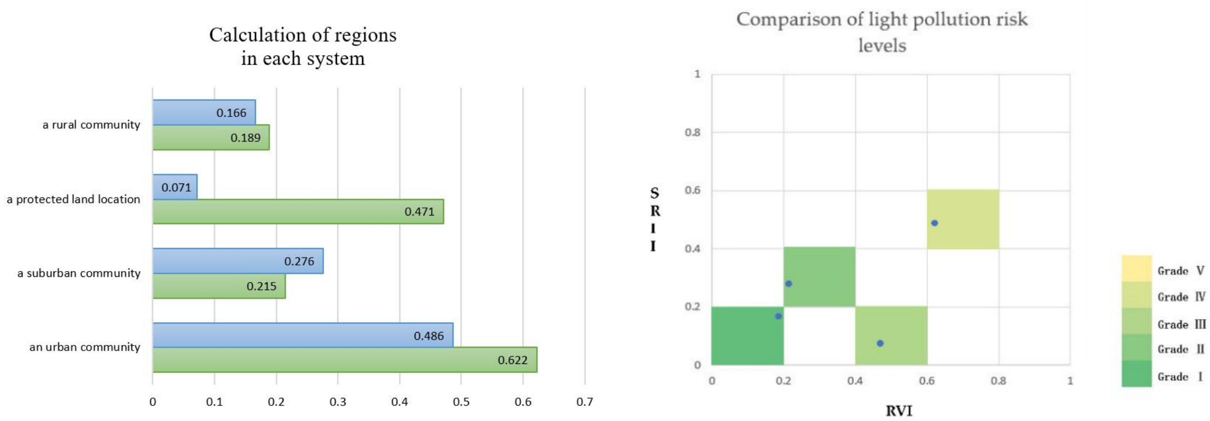


Fig. 3 Index bar chart (a) and scatter chart (b) of regions in the system

4. Summary

In this paper, the risk level of light pollution is determined by determining the regional vulnerability level and the pollution source load level, and sensitivity analysis is performed on the regional vulnerability model and the pollution source load model. When the weights of the remaining indicators are kept constant, the impact of a change in the weight of one indicator on the results is analyzed. The changes of PD, SD and FCA in the regional vulnerability model are small, and the changes of three indicators in the pollution source intensity model are large, which leads to the conclusion that the light pollution risk level evaluation model established in this paper has a high sensitivity to the pollution source intensity. Finally, the model was applied in four different types of areas, and the risk level was obtained as level 2 for protected areas and suburban areas, level 1 for rural areas, and level 4 for urban areas.

Our model can be used to analyze specific problems and obtain targeted solutions when solving practical problems. When building the risk index evaluation model, the characteristics of the area itself and the degree of light pollution that may be affected make the model more scientific and effective.

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