Research on the Evaluation System of Light Pollution Risk Index

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Abstract. Light pollution is the general term for the sum of various harmful effects of artificial light. This report aims to establish a light pollution risk level evaluation model through light pollution risk assessment, and provide effective intervention strategies to mitigate the adverse effects of light pollution. First of all, the report follows the principle of scientific and comprehensive, and establishes a comprehensive evaluation system for the risk level of light pollution. Then, the corresponding data were collected, 19 indicators such as average night illumination, electricity consumption, glare index, artificial light intensity were selected as evaluation indicators, and the entropy weight method-TOPSIS comprehensive evaluation model was constructed to quantify the data, and the weights of each index were determined, and it was found that the proportion of glare index and community lighting weight was the largest. Then, applied to four different types of sites, the level of light pollution risk in different regions was discussed. Finally, the stability of the data is verified and it is concluded that prosperous cities have the highest light pollution levels, while protected areas have lower light pollution levels. The model passed the stability test, and a variety of visualization methods were used in the article to make the results more intuitive.

Keywords: TOPSIS, Comprehensive evaluation, Entropy-weight method, Light pollution.

1. Introduction

Light pollution refers to the negative impact of interference light or excessive light radiation on humans, ecological environment and astronomical observations. Its main forms include light intrusion, glare, optical clutter, sky light, etc [1].

With the rapid development of urban construction, various light shows have begun to become "business cards" to show the degree of urban development. Elvick once said, "A lot of people have lost the night sky, and our lights obscure the night sky." [2]. Light pollution caused by lighting mainly comes from street lights and LED advertising signs in commercial gathering areas at night [3], daytime lighting is negligible, the main way to limit light pollution is to limit the brightness of lights at night. Excessive light stimulation can cause a variety of damages. Professor Randy Nelson of The Ohio State University said at the annual neuroscience conference on Jan. 21 that excessive exposure to light at night may lead to depression [4]. Light pollution not only damages human physical and mental health, but also endangers traffic safety, interferes with astronomical observation, causes energy waste, destroys ecological balance, and affects climate. Therefore, it is necessary to widely select indicators to determine the level of light pollution risk in a specific area and implement intervention strategies to mitigate these effects.

Christopher Kyba, a physicist at the German Earth Science Research Center, takes an extremely ancient method: looking up at the stars. Expecting an accurate value for the annual increase in global light pollution, Kyba's team analyzed 51,351 observations of stars and constellations seen by volunteers around the world collected by Night Earth from 2011 to 2022, and cross-checked it with satellite-based light pollution maps over the same period. The results revealed that in Europe and North America, sky glow increased by 6.5% and 10.4% per year, respectively. Citizen science data points are currently too scarce in developing countries to draw conclusions in these regions. Based on previous satellite measurements, the team estimates that the sky glow in these places is growing at a higher rate [5].

The trend towards brighter night skies is worsening, and some international organizations or associations are paying close attention to this area. The luminous data map provided by NASA shows the correlation between the level of regional economic development and the severity of light pollution, and the higher the level of economic development, the more serious the light pollution. In the study of Falchi et al. (2016), they used satellite imagery to build an up-to-date map of global light pollution and analyzed the distribution of light pollution across countries [6].

Light pollution control is a systematic and long-term project, which requires multiple measures and diversified governance. Energy is a very intuitive indicator to respond to the risk of light pollution. With the economic development and urbanization promotion, leisure areas and commercial concentrated areas mainly to enhance urban night scenery are increasing year by year, which to some extent leads to the proliferation of artificial light at night and causes serious light pollution [7].

In 2002, Switzerland issued the "Guidelines for the Application of Outdoor Luminous Advertising", which clearly stipulates that the brightness of decorative lights and luminous advertisements used by all merchants at night shall not exceed the brightness of street lights. Switzerland has also raised the barrier to entry for urban lighting and illuminated advertising in due course. The majority of designers quickly updated the design concept, taking into account the green concept and artistic interest, greatly improved the quality of urban lighting and luminous advertising, effectively reduced light pollution at the source, and integrated the artificial beauty of the urban night scene with the natural beauty of the night, meeting the yearning of modern urban people for returning to nature and the pursuit of original beauty [8].

Based on the background of current light pollution research at home and abroad and the development status of urban light pollution models, this paper further discusses the risk level and countermeasures of light pollution with reference to a large number of historical literatures. Considering the integrity and background information of social development, this study focuses on the following issues: developing indicators to quantitatively analyze the risk level of light pollution in an area, and interpreting and analyzing the results of the indicators for four types of land. Finally, three possible intervention strategies and their potential impact on light pollution are introduced.

2. Materials and methods

2.1. Data acquisition

First, a wide selection of indicators to cover many aspects of light pollution, which in turn measures the risk level of light pollution in an area. Data from different regions were collected on 19 indicators, including average night illumination, electricity consumption, glare index, and artificial light intensity. These data sources are summarized in Table 1.

Table 1. Data source collation

Database Names	Database Websites Data	Type
NOAA	**https://ngdc.noaa.gov/eog/dmsp/**	geography
Colorado School of Mines	**https://eogdata.mines.edu/**	science
China statistical yearbook	**https://www.tongjinianjian.com/**	Statistics
national bureau of statistics	**https://data.stats.gov.cn/**	Statistics
Beijing Statistical Yearbook	**https://nj.tjj.beijing.gov.cn/**	Statistics

2.2. Data feature

Capacity: Because the influencing factors of light pollution are complex and involve all areas of life, the data collected by the team is huge, involving 19 different directions and different regions.

Types: Because the description of a single type of data is too one-sided to directly reflect the causes of light pollution, we collect a variety of data.

Variability: Because the amount of data collected is too large, the direct analysis error is large, and the correlation is very low, we first scaled the data.

Authenticity: The data collection sources are all real data released by the official websites of the country and provinces and cities, and the data sources are highly reliable.

Complexity: Huge amounts of data from multiple sources.

Value: Using the powerful ability of the Internet to collect data, processing and analyzing data using familiar modeling methods, and finding the most critical factors affecting light pollution plays an important role in studying ways to improve light pollution.

2.3. Method introduction

Data preprocessing: Due to the large variety and quantity of data collected, in order to obtain more accurate results, we have standardized the data.

(1) Establish the original data matrix

After collecting the original data, this paper establishes the spatial matrix C, which is composed of n years and m indicators.

$$\mathrm{C} = \lfloor \mathrm{C_{ij}} \rfloor_{n*m}, \quad \mathrm{i} = 1,2,3,\cdots,n, \quad \mathrm{j} = 1,2,3,\cdots m \tag{1}$$

(2) Data dimensionless processing

This paper uses the range method to standardize the data, this method calculates the difference between the maximum and minimum values of each index to calculate the difference, and then subtracts each value corresponding to the index from the maximum value and divides the difference.

If the indicator is positive, the formula used when dimensionalizing the data is as follows:

$$\mathrm{X}'_{\mathrm{ij}} = \frac{C_{ij} - \min(C_{\mathrm{j}})}{\max(C_j) - \min(C_j)} \tag{2}$$

If the indicator is negative, the formula used when dimensionalizing the data is as follows:

$$\mathrm{X}'_{\mathrm{ij}} = \frac{m\mathrm{ax}(C_{\mathrm{j}}) - C_{ij}}{\max(C_j) - \min(C_j)} \tag{3}$$

In the above two formulas, each symbol has the following meanings: $\mathrm{X}'_{\mathrm{ij}}$ X_{ij} are the results of dimensionless processing of the data corresponding to the jth index of the ith year and the raw data without dimensionalization, respectively; $\max(C_j)$ and $\min(C_j)$ represent the maximum and minimum values of the data corresponding to the different indicators, respectively.

The resulting data dimensionless results are formed into a new matrix C':

$$C' = \lfloor X'_{ij} \rfloor_{n*m}, \quad i = 1,2,3,\cdots,n, \quad j = 1,2,3,\cdots,m \tag{4}$$

2.4. Model evaluation indicators

The 19 cover various fields such as regional economy, medical and health care, transportation conditions, and geographical environment (Table 2).

Table 2. 19 evaluation indicators

1	**Total social electricity consumption (10,000 KWH)**
2	Artificial light intensity
3	City road lighting lights
4	dazzle
5	The mean value of the night illumination value DN
6	Permanent resident population (ten thousand people)
7	educational appropriations
8	Number of medical and health institutions
9	Regional GDP (one billion yuan)
10	Air pollution (smoke, dust)
11	Total water supply (one hundred million tons)
12	Built-up area
13	The natural growth rate of the permanent resident population is (%)
14	The total number of traffic accidents occurred
15	jobless rate
16	Total sown area of crops (ten thousand ha)
17	Highway mileage (ten thousand kilometers)
18	Green area of the park at the end of the year (ten thousand hectares)
19	Urban vegetation coverage rate

3. The Construction of the index system

3.1. The establishment of the index system

This paper analysis to analyze the light pollution in reserves, rural communities, and suburban and urban communities, using the entropy weight method combining TOPISIS, in the whole process, with night illumination mean, electricity consumption, glare index, artificial light index 19 evaluation index, build light pollution evaluation model, and according to the construction model for quantitative calculation, based on the calculation results.

In the model construction part, a brief overview of the four steps of the original data matrix, data dimensionless, index weight and entropy weight method, and TOPSIS value calculation. The result calculation part makes the numerical calculation according to the constructed model. The main calculation results are the index weight of the data and the TOPSIS value. According to the calculation results, the weight of the light pollution is analyzed.

Model building:

(1) To build up the raw data matrix

After collecting the raw data, this paper establishes the spatial matrix C, which consists of n years and m term indicators.

$$C = \lfloor C_{ij} \rfloor_{n*m}, \quad i = 1,2,3,\cdots,n, \quad j = 1,2,3,\cdots m \tag{5}$$

(2) Data were processed dimensionless

This paper uses the extreme difference method to standardize the data dimensionless. This method calculates the difference between each index's maximum value and minimum value and then divides each value corresponding to the index from the maximum value.

If the index is positive, the formula used for classifying the data is as follows:

$$X'_{ij} = \frac{C_{ij} - \min(C_j)}{\max(C_j) - \min(C_j)} \tag{6}$$

If the index is negative, the formula used for classifying the data is as follows:

$$X'_{ij} = \frac{max(C_j) - C_{ij}}{\max(C_j) - \min(C_j)} \tag{7}$$

In the above two formulas, the meanings of each symbol are as follows: X'_{ij} X_{ij} The results of the data corresponding to the item j index of year i and the original data without dimensionless method , respectively; $\max(C_j)$ and $\min(C_j)$ each represents the maximum and minimum values of the corresponding data of the different indicators.

The resulting data dimensionless results in a new matrix C':

$$C' = \lfloor X'_{ij} \rfloor_{n*m},\quad i = 1,2,3,\cdots,n,\quad j = 1,2,3,\cdots,m \tag{8}$$

(3) Index weight determination

This paper uses the entropy weight method to determine the index weight. This method only calculates the original data by numerical value but is not affected by the subjective evaluation, so the final weight has high enough objectivity. The specific determination process is as follows:

1) The ratio Y_{ij} of the value of index j to the sum of index j in the first i year was calculated for the data after data standardization:

$$Y_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{m} X'_{ij}},\quad (0 \le Y_{ij} \le 1) \tag{9}$$

2) The entropy value e_j of the j-th-term index is calculated:

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} (Y_{ij} * \ln(Y_{ij})) \tag{10}$$

3) Because the smaller the entropy value, the greater the difference between the indicators, Therefore, the calculation result of the above formula needs to be processed to obtain the value d_j of item j index:

$$d_j = 1 - e_j \tag{11}$$

4) Calculate the corresponding comprehensive weights of each index w_j:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{12}$$

(4) Standardized weight calculation

There are common k-indicators in a toughness dimension or toughness trait. The dimension weight or feature weight is α_t, The normalized weight of item t index in this toughness dimension or toughness characteristic is β_t, β_t It is used to analyze weights and calculate dimension toughness index and characteristic toughness index. The specific calculation formula is as follows:

$$\alpha_t = \sum_{j=1}^{k} w_j,\quad \beta_t = \frac{w_t}{\alpha_t} \tag{13}$$

(5) Composite toughness index calculation

TOPSIS Method, called the approximate ideal solution sorting method, the method needs to use the n scheme of m index matrix, construct a positive and negative ideal point, the optimal and worst scheme, respectively, calculate the scheme and Euclidean distance between the positive and negative ideal point, to get close to the positive ideal point and away from the negative ideal point of relative stick progress, as the basis of evaluation [9].

According to the matrix C', this paper can find out the positive ideal solution A^+ of each index and Negative ideal solution A^-:

$$A^+ = (X_{i1}^{'+}, X_{i2}^{'+}, X_{i3}^{'+}, \cdots, X_{im}^{'+}), \quad X_{ij}^{'+} = \max(X_{ij}^{'}), \quad 1 \le i \le n, j = 1,2,3,\cdots,m \tag{14}$$

$$A^- = (X_{i1}^{'-}, X_{i2}^{'-}, X_{i3}^{'-}, \cdots, X_{im}^{'-}), \quad X_{ij}^{'-} = \min(X_{ij}^{'}), \quad 1 \le i \le n, j = 1,2,3,\cdots,m \tag{15}$$

1) The Euclidean distance D_i^+ and D_i^- between each index and the positive and negative ideal solution was calculated separately:

$$D_i^+ = \sqrt{\sum_{j=1}^{m} w_j (X_{ij}^{'+} - X_{ij}^{'})^2} \tag{16}$$

$$D_i^- = \sqrt{\sum_{j=1}^{m} w_j (X_{ij}^{'} - X_{ij}^{'-})^2} \tag{17}$$

2) Calculate the closeness between each city to the ideal solution as C_i, it is the comprehensive evaluation index.

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{18}$$

3.2. Evaluation of the risk level of light pollution in different location types

Based on the above model, this paper determined the weight of each index by using the entropy weight method. The specific results are as follows (Figure 1).

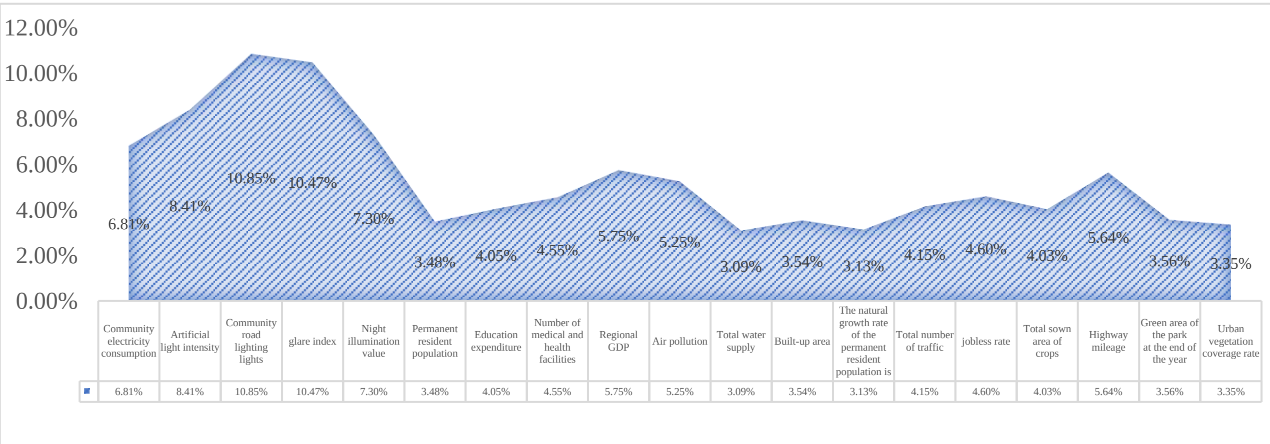

Figure 1. Indicator weight calculation

(1) Chart description:

The above table shows the weight calculation results of the entropy weight method, and the weight of each index is analyzed according to the results.

The weight calculation results of the entropy weight method show that the weights of important influence indicators are: the weight of artificial light intensity is 8.409%, the weight of urban road lighting is 10.85%, the weight of glare is 10.47%, Among them, the maximum index weight is the urban road lighting (10.85%), and the minimum value is the total water supply (3.087%).

Further use TOPSIS comprehensive evaluation to obtain the ranking of light pollution risk levels in urban, suburban, rural and nature reserves (Table 3).

Table 3. TOPSIS Comprehensive score and index ranking

Index value	Positive ideal solution distance (D+)	Negative ideal solution distance (D-)	Comprehensive score index	sort
city	0.23986483	0.83093968	0.77599569	1
suburbs	0.61956249	0.40216697	0.39361395	2
rural area	0.7704513	0.31489058	0.29013031	3
Natural protection area	0.80634752	0.22046808	0.21471049	4

The D + and D-values, these two values respectively represent the distance between the evaluation object and the optimal or worst solution (i.e. A + or A-). The practical significance of these two values is that the distance between the evaluation object and the optimal or worst solution, the greater the value, the farther the distance, the larger the object D + value, the farther the distance from the optimal solution; the greater the D-value, the farther the distance from the worst solution. The most understood subject is that the smaller the D + value and the larger the D-value.

Comprehensive score C value, C = (D-) / (D + + D-), the calculation formula, the numerator is D-value and the denominator is the sum of D + and D-; the larger the D-value, the farther the distance from the worst solution, the better the study object; the greater the C value, the better the study object [10].

(2) Interpretation of result:

Through the weight of figure 1, this paper intuitively sees the community road lighting, night illumination value, glare index and artificial light intensity and regional power consumption of light pollution risk level, in addition to a region of air pollution, GDP and highway mileage on the region of light pollution risk level has certain influence.

4. Conclusion

This report establishes a light pollution risk level evaluation model and provides effective intervention strategies to mitigate the adverse effects of light pollution. We chose 19 indicators in the relevant literature and a comprehensive evaluation model of entropy weight-TOPSIS was constructed to quantify the data, determine the weights of each index, and find that the proportion of glare index and community lighting weight accounted for the largest. Then, applied to four different types of sites, the level of light pollution risk in different regions was discussed. Finally, the stability of the data is verified and it is concluded that prosperous cities have the highest light pollution levels, while protected areas have lower light pollution levels. We also conduct an error analysis, discuss the advantages and disadvantages of the model, further generalize the model, and the model passed the stability test. It is hoped that this conclusion will be helpful in the study of reducing light pollution.

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