Quantitative Light Pollution Risk Assessment System Based on TOPSIS Method and RLE Modeling

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Abstract. Light pollution is causing great harm to human physical, mental health and the ecosystem. With the development of the times, light pollution is getting more and more intense. In order to better recognize and solve these problems, this paper focuses on constructing a light pollution risk level evaluation system to quantify light pollution, measure the light pollution risk level of each region, and give some feasible measures to reduce light pollution. The light pollution risk level (LPRL) index is established to measure the light pollution risk level; the perturbed TOPSIS method combined with entropy weighting is used to construct a comprehensive evaluation model (TEW) to evaluate the LPRL values of the four cities, and cluster analysis is performed. A region's total artificial light radiation is modeled and quantitatively analyzed with the Regional Artificial Light Radiation Estimation (RLE) model, and possible measures to reduce the LPRL values are proposed. The results show that rational control of light hours for urban communities can reduce LPRL values by 34%. For suburban communities, rational use of light can reduce LPRL values by 30%. Finally, some measures are proposed to reduce light pollution.

Keywords: Light pollution risk level, TOPSIS evaluation, RLE modeling.

1. Introduction

The International Dark Night Association defines light pollution as the inappropriate or excessive use of artificial light that can have serious environmental consequences for humans, wildlife, and the climate and consists of three main categories: bright white pollution, artificial daylight, and colored pollution[1].Its impact is wide-ranging, non-cumulative, but transient. The situation of light pollution is getting increasingly severe, and the prevention and control of light pollution is urgent for the sustainable development of human beings and ecology. Studies have shown that light pollution can adversely affect human and physiological health[2],also impacting, among other things, wildlife and ecosystems. The effects of artificial light pollution on birds, flora, and fauna were studied and analyzed by SORDELLOR et al.[3].Hao Qingli et al.[4]studied and analyzed light and noise pollution to evaluate the ecological damage to birds.

Research led by the University of Exeter investigated light emissions from 1992 to 2017, and after correcting the data, global light pollution increased by 270% and as much as 400% in some areas[5]. Hao Ying et al.[6] conducted regional light environment tests for representative cities in four regions of China and comparatively analyzed the current status of light pollution. Li Jiayi et al.[7] used the luminous remote sensing image technology to monitor nighttime light pollution in Nanjing and showed that the intensity of light pollution was decreasingly radiating from the central city to the surrounding area. Liu Tianyuan[8] analyzes and researches the practice of light pollution control in foreign countries. The possible thresholds affecting light pollution were summarized by Xiong Ruiyu et al.[9]. However, the studies done in China are insufficient to propose effective and targeted interventions for the region to reduce the negative impacts of light pollution.

This paper uses the entropy weighting method combined with entropy weighting to establish a comprehensive evaluation model to evaluate different areas' light pollution risk levels, establishes a regional artificial light radiation estimation model for quantitative analysis, and proposes measures to reduce the LPRL value. This model can evaluate the risk level of light pollution in different areas and propose effective interventions to reduce the risk level of light pollution in the place.

2. Materials and methods

2.1. TOPSIS model

The entropy weighting method is an objective weighting method that determines the weights of indicators based on the information provided by multiple indicators. Information entropy is a measure of uncertainty, the more consistent the distribution of an amount of information, the greater the uncertainty of the information it provides. The greater the information entropy of an indicator, the smaller the degree of variation of the indicator, the less information it provides, the smaller the role it plays in the comprehensive evaluation, and the smaller its weight[10].

2.2. Artificial light radiation model

Artificial light radiation estimation model is based on light flux, i.e., the size of the spectral radiant power after the influence of light radiation power through the human eye's visual function of the physical indicators, to construct the light intensity of a single point light source and the intensity of the regional light radiation, the greater the intensity, the more serious the light pollution; to change the relevant parameters to implement interventions, and to evaluate the risk level of light pollution through the value of the LPRL.

3. Model building and solving

3.1. Light Pollution Risk Level Assessment

3.1.1 Ideal level of artificial lighting

The amount of artificial lighting in an area at night is assumed to be a desirable value, which is defined as the amount of artificial lighting required in the area that is just right for human production, life, and development, and that does not have any adverse effects on humans and non-humans. The characteristics of an area determine this value, and if the area's characteristics remain unchanged, it will be a more precise value to represent it with Q_0.

3.1.2 Actual artificial lighting levels

The actual light level is a criterion for determining the level of artificial light that exists in a community. In countless cases, the actual light level is generally more significant than the ideal light level, thereby creating light pollution in the community that negatively impacts the survival of human and non-human life, represent it with Q_a.

3.1.3 Light Pollution Risk Levels

Using LPRL values to measure the level of light pollution risk in an area.Set G to 7, as shown in Table 1.

$$\mathrm{LPRL} = \left|\frac{Q_a - Q_0}{Q_0}\right| * G \tag{1}$$

Table 1. Table of LPRL levels

LPRL	Risk Level	Risk Explanation
0-1	I	Extremely low level
1-2	II	Low level
2-3	III	Medium low level
3-4	IV	Average level
4-5	V	Medium high level
5-6	VI	High level
6-7	VII	Extremely high level

3.2. Construction and Solution of TOPSIS Evaluation Model with Entropy Weights

3.2.1 population density

The first indicator is population density, the average number of people per unit of land area over time. In most cases, population density is an essential characteristic of an area. Without considering other factors, it can be assumed that population density has a relatively strong positive correlation with the amount of artificial light in the area.

3.2.2 gross domestic product

The second indicator is GDP, which results from the productive activities of a country's (or region) resident units over a certain period. It is an essential indicator of a region's economic development level. The higher the GDP of a place, the greater the amount of artificial lighting generated by nighttime lighting installations, considering that it may contain many commercial areas, entertainment venues, and high-rise buildings.

3.2.3 Green coverage

Green cover is the degree of vegetation cover in an area. Theoretically, where there is a green cover, species diversity is high. The requirement for artificial light should be reduced to avoid harm to animals from the amount of artificial light, so the green cover is used as the third indicator.

3.2.4 quantity of light radiation

Using the raster map of light pollution in 2021 taken by VIIRS combined with the Arc GIS software to analyze each region, the light data of each region can be measured directly, which will be used as the fourth indicator.

The four indicators of population density, GDP, green coverage, and light radiation were established, and the data of the four indicators were collected to form a data matrix, which was cleaned, sieved, normalized, dimensionless, and normalized in order to obtain the required standard data matrix:

$$\mathrm{R} = \left(\mathrm{r_{ij}}\right)_{\mathrm{m*n}} \tag{2}$$

3.3. Regional artificial light radiation estimation model (RLE model) construction and solution

3.3.1 Intensity of light from a single point source

Suppose there are N artificial light sources in a region; define the position and height of each source as $(\mathrm{x_i}, \mathrm{y_i}, \mathrm{z_i})$, where i = 1, 2, ... , N.

Each light source can be regarded as a point light source, and its radiation intensity is expressed in luminous flux in lumens (l\m). Assuming that the spectral energy distribution of each point source can be approximated as a spherical distribution, they will form a spherical illumination area in space.

Use the following formula to calculate the light intensity of a point source in lux.

$$I_i = \frac{Phi_i}{4\pi d_i^2} \tag{3}$$

Where: is the distance from the point light source to the illuminated point in meters (m).

3.3.2 Artificial area light radiation

Divide the area into small m regions, and calculate the total light intensity in each j region using the following equation.

$$I = \sum_{i=1}^{N} \sum_{j=1}^{M} I_{ij} \cdot t_i \cdot v(d_i) \tag{4}$$

In the formula,I_{ij} denotes the light intensity of light source i on region j,t_i is the time that light source i illuminates region j in hours (h), $v(d_i)$ is the cooling and heating coefficient of the region j illuminated by the light source i.

3.3.3 Intervention

By adjusting the amount of artificial light in the area by adjusting the relevant parameters in the RLE model and updating the LPRL values by combining them with the LPRL model, it is easy to find the changes in the LPRL values before and after the intervention. Finally, the interventions are evaluated and analyzed.

In this paper, three interventions were implemented, namely: rational use of light (reducing the loss of propagation time), use of warm light (reducing the amount of light radiation), and classified into four categories according to the GDP and control of light length (reducing the length of light), and 40 different areas were selected, and the interventions were classified accordingly.

4. Results and analysis

4.1. Analysis of TOPSIS model results

The results show that as an area's indicators change, so does its LPRL value. The more developed an area is (e.g., central city), the higher its LPRL value is. Conversely, protected areas (e.g., national nature reserves) have lower LPRL values. While suburban and rural areas have LPRL values in between. For areas with high population densities, overuse of artificial lighting or underuse of artificial light has the most significant impact on people and therefore has the highest LPRL values. For suburban and rural areas with low population density and GDP, the LPL value is lower. However, it will always be higher than the LPRL value for protected areas, which is consistent with reality.The assessment scores are shown in Figure 1.

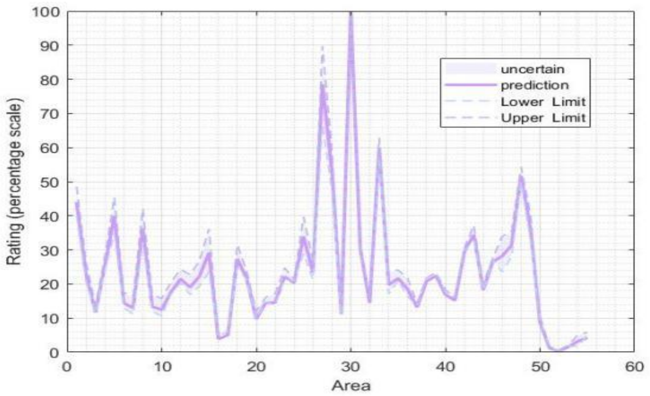

Fig 1. Graph of evaluation scores of different regions

4.2. Analysis of RLE model results

Plotting the LPRL metrics before and after the three interventions of reducing the loss of propagation time, reducing the amount of light radiation, and reducing the length of light for the four regions of urban, suburban, rural, and protected areas, can be seen that the interventions can reduce the LPRL values of the different regions to varying degrees.As shown in Figures 2 to 4.

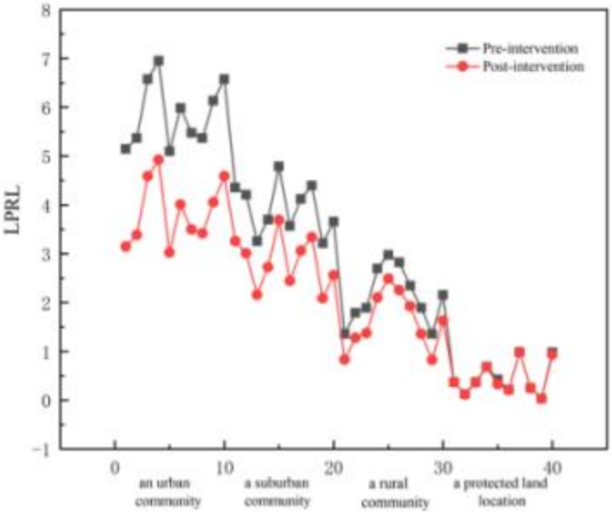

Fig. 2 The rational use of light

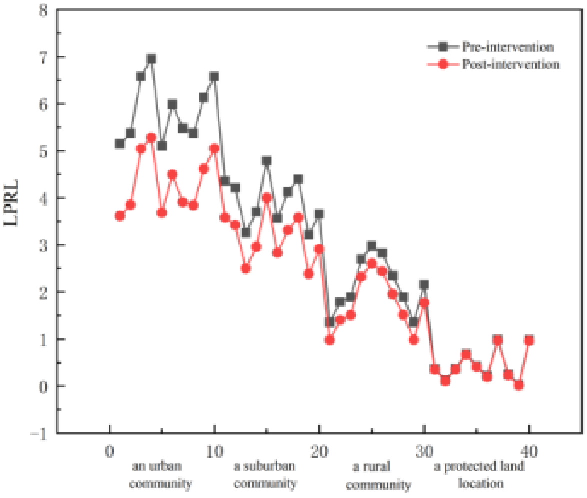

Fig. 3 The use of warm light

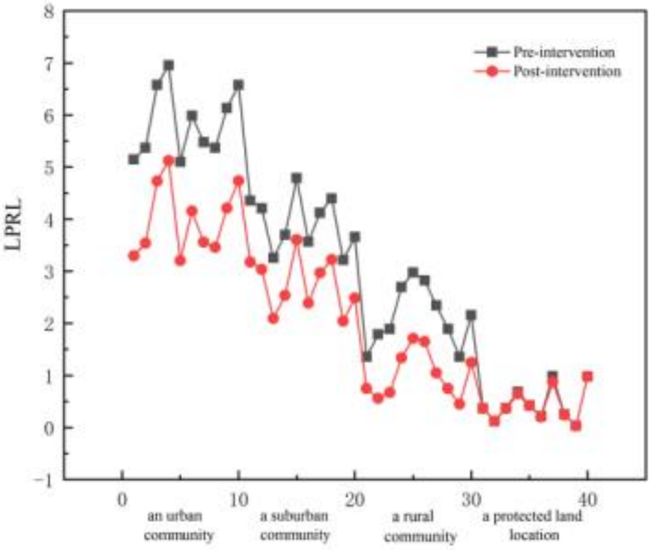

Fig. 4 Control of the length of light

Of the three measures taken, the reduction in LPRL values was significant in urban communities, while the impact on LPRL values in protected areas was negligible. For suburban areas, the best measure is the rational use of lighting, which is more dispersed and contains more greenery and high green coverage than other areas and can be used to maintain normal life activities while reducing LPRL values. For urban communities with higher population density and lower green coverage, scientific control of light hours is the best measure to reduce LPRL values. For rural communities and protected areas, the measures selected in this paper have a similar impact effect due to the characteristics of these areas themselves in order to reduce the interference of external factors. They can maintain the LPRL value at a relatively low level.The rate of reduction of LPRL values in different regions is tabulated in Table 2.

Table 2. Table of the reduction rate of LPRL values in different areas by measures

Place Influencing Factors	Rational use of light	Control of the length of light	Use of warm light
An urban community	**32%**	**34%**	**26%**
A suburban community	**30%**	**28%**	**20%**
A rural community	**26%**	**25%**	**18%**
A protected land location	**4.7%**	**4.3%**	**4.0%**

5. Conclusion and Discussion

5.1. Advantages of the model

This paper adopts the TOPSIS method combined with entropy weighting to construct a comprehensive evaluation model, determining the weights of the indicators according to the variability of the values of the indicators, which is a kind of objective weighting method, and the calculation results are more accurate, and the influence of human factors can be avoided; this method does not have the risk of expert scoring or exclusion of specific indicators, and the calculation results are more objective and reliable; this paper chooses the indicators of population density, gross domestic product, green coverage, light radiation, and other four indicators and supported by data from forty different regions, the results are relatively reliable; LPRL is a widely applicable indicator with a wide range of application, which can measure the risk level of light pollution in different regions.

5.2. Model deficiencies and improvements

Although the LPRL indicator can measure the risk level of light pollution in different areas, the inability to accurately measure the exact intensity of light radiation makes the results of the RLE model in error with the actual value; secondly, it is difficult for the entropy weighting method to take into account the horizontal influence between indicators, resulting in some limitations of this model. How to address the shortcomings of this model? More advanced instruments can be used to measure the light radiation in different regions for calculation; when building the entropy weighting method model, the model should be standardized to eliminate the quantitative differences between the indicators, or it is suggested to introduce the hierarchical analysis method to consider the correlation between the indicators.

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