A Comprehensive Light Pollution Rating Method for Developing Individualized Treatment Measures

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Abstract. With the advancement of the economy and technology, the issue of man-made light pollution is progressively worsening, exerting a significant impact on the overall environment. To enhance public awareness regarding light pollution and mitigate its effects in different regions, this study focuses on regional analysis encompassing internal and external factors. The internal light pollution risk score incorporates environmental factors, urbanization factors based on Analytic Hierarchy Process, education factors based on Monte Carlo simulation, technological factors and economic factors, which is calculated by TOPSIS with Entropy Weight Method. Additionally, the external light pollution risk score is calculated by considering neighboring areas that may contribute to light pollution. Based on regional characteristics, tailored governance measures are derived. At the same time, it is also of great significance in environmental protection, urban planning, technological innovation and sustainable development.

Keywords: Light Pollution；Entropy Weight Method；Monte Carlo Simulation Method

1 Introduction

In order to simultaneously promote economic development and meet the needs of night lighting [1], China launched the "Night Economy and Culture" to respond. Due to the lack of systematic utilization of light sources, the ecological light environment has been compromised, among which the light pollution phenomenon is the most serious. Light pollution, arising from the alteration of natural nocturnal lighting levels due to artificial light sources, is primarily categorized into skylight pollution, glare pollution, and light intrusion. Its profound impact on the overall ecological environment underscores the urgent need for resolution of this issue [2]. In this regard, the CIE issued the "Urban Lighting Master Planning Guide" in 2019, which stipulates the standards and guidance recommendations for lighting systems. In 2017, China also issued the Outdoor Lighting Interference Light Limit Specification (GB/T 35626-2017), which specifies the zoning of lighting brightness and the restriction requirements for lighting equipment. The research on the prevention and control measures of light pollution has been very in-depth [3~5]. With the development of SQM and GIS, global light pollution maps have also been drawn with increasing clarity and resolution, among which NASA's light pollution map is the most representative. In order to reflect the different degree of regional light pollution more directly, the evaluation methods of light pollution have also been studied. The precision of satellite measurement is very high, but it can’t get the information of light source. The ground survey method can obtain the light source information, but the precision is low and the workload is large. Aerial measurements are harder to quantify. The main mathematical method is TOPSIS,

PMIS 2024, March 15-17, Changsha, People's Republic of China

DOI 10.4108/eai.15-3-2024.2346520

but the research on how to determine the priority and cost performance of these measures is insufficient. Methods for strengthening public awareness of light pollution are also immature.

Therefore, this paper studies a light pollution risk rating method that is easy for the public to publicize and understand. On this basis, it assists relevant managers to formulate individualized governance measures for the region.

2 The light pollution rating method

2.1 The internal light pollution rating method

(1) The environmental factor

Light pollution does great harm to the whole ecological environment. For the animals and plants in the ecological environment, biodiversity was used as a factor of environmental score. For people, air quality is a factor [6]. After the two factors are normalized and de-dimensional, the following model is established, called equation (1).

$$EN_T = \frac{EN_2}{EN_1} \quad (1)$$

In which, EN_T, EN_1 and EN_2 represent the region's environmental score, biodiversity, and air quality, respectively.

(2) The urbanization factor

The level of urbanization also has a strong influence on the level of light pollution in the region. The urbanization level of a region is mainly closely related to the number of buildings, traffic conditions and population density [7]. After normalization of the three factors, the following model is established, called equation (2).

$$UR_T = UR_1 \cdot \omega_1 + UR_2 \cdot \omega_2 + UR_3 \cdot \omega_3 \quad (2)$$

In formula, UR_T, UR_1, UR_2 and UR_3 represent the urbanization score, the number of commercial building clusters, the average night traffic flow, and the local population density respectively. ω_1, ω_2 and ω_3 are the weights corresponding to the three variables. The results obtained are shown in Table 1.

Table 1. The result of three methods

	ω_1	ω_2	ω_3	CI	CR
Arithmetic Averaging	0.3399	0.4795	0.1807		
Geometric Averaging	0.3398	0.4797	0.1805	0.0018	0.0036
Eigenvalue Method	0.3398	0.4797	0.1805		

(3) The education factor

According to the light pollution awareness survey report in Chongqing, China, although more than 85% of the participants had heard of light pollution, only 5% really understood the content or harm of light pollution [1]. It is difficult to obtain specific statistical data due to the high mobility of the population. Hence Monte Carlo simulation method is adopted to infer the level of light pollution awareness by calculating large sample data. The flow chart for the Monte Carlo simulation is as follows, called Figure 1.

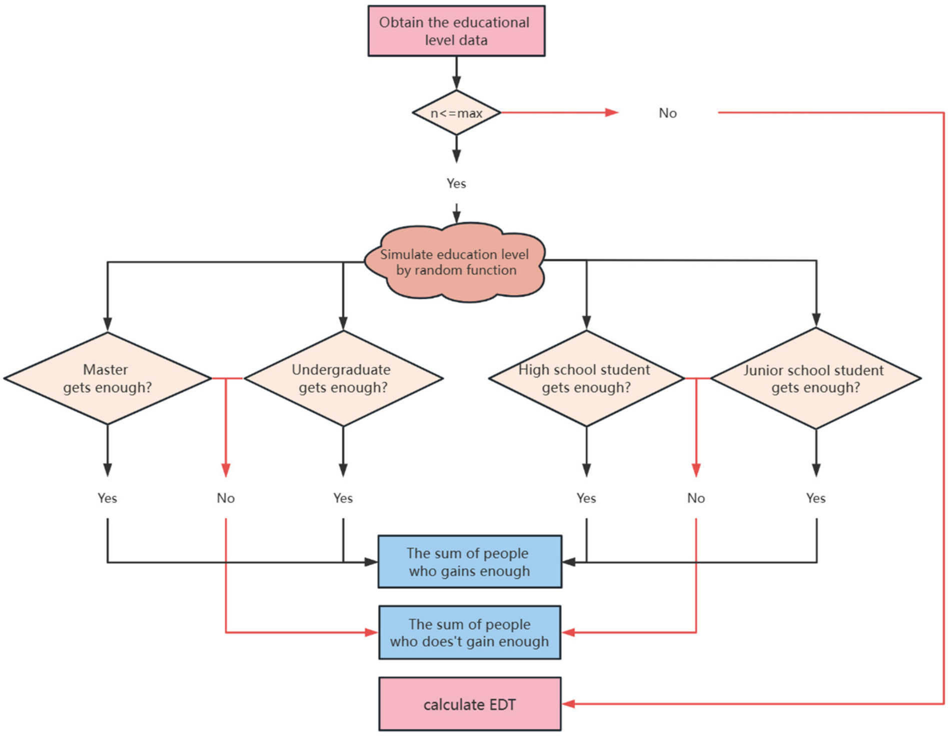

Fig. 1. Monte Carlo simulation logic schematic

Through the calculation of the above flow chart, an indicator within the range of [0,1] can be obtained, which is defined as ED_T . The specific meaning of this indicator is that the proportion of people who have sufficient understanding of light pollution in the total population of the area under test is closer to 1, the higher the awareness level of light pollution in the area under test is, and vice versa.

(4) The technological factor

Scientific and technological progress is not only a single aggravation of light pollution phenomenon. Through the brightness of the street light, energy consumption and cost comprehensive analysis and fitting forecast, the technical factor score can be estimated and is called TE_T [8].

(5) The economic factor

The influence of economy on the risk level of light pollution is more obvious. This paper mainly analyzes the local economic situation from the micro point of view, taking the regional per capita annual income as the evaluation index. By normalizing the annual per capita income, which is defined as EC_T, it is applied to subsequent calculations of the light pollution risk level model.

In order to make these five factors more objectively linked together as the regional internal light pollution risk score, TOPSIS method based on Entropy Weight Method was adopted for analysis. After preprocessing the data of the five factors, the following model was established, called equation (3).

$$ILP = \alpha_1 \cdot EC_T + \alpha_2 \cdot UR_T + \alpha_3 \cdot ED_T + \alpha_4 \cdot TE_T + \alpha_5 \cdot EN_T \quad (3)$$

In the formula, α_1, α_2, α_3, α_4, α_5 are the weight values of the five factors respectively. The Entropy Weight Method is used to calculate: α_1 =0.2962, α_2 =0.3920, α_3 =0.1357, α_4 =0.0314, α_5 =0.1447. ILP represents the internal light pollution value.

2.2 The external light pollution rating method

Considering the influence of light pollution in the region itself, the influence of light pollution generated in the surrounding area on the region should not be ignored. At the same time, due to the expansion and construction of the city, the original relatively clear urban boundaries are gradually blurred, resulting in the surrounding cities will also be affected. Finally, the control policies of different regions will also be different. In order to determine which areas will cause this effect, the following constraints are established [1].

$$\begin{cases} UR_1 \geqslant UR_N \\ UR_3 \geqslant UR_P \\ 0 \leqslant R \leqslant R_0 \end{cases} \quad (4)$$

In which, UR_N and UR_P represent the threshold of the number of commercial building clusters and the local population density respectively, and R_0 is also required to limit the scope of the surrounding area.

Using the data of the National Bureau of Statistics, We get UR_N =4.6263, UR_P =2.7526, R_0 =1.5627. Therefore, when a region meets the above conditions at the same time, it is considered that the region will produce light pollution effects on the surrounding area. Taking Huangpu District of Shanghai as an example, according to the world light pollution map, like **Figure 2**, and the above constraints, we screened eligible cities. Then, we determined that Shanghai would eventually be affected by light pollution in Nantong and Suzhou.

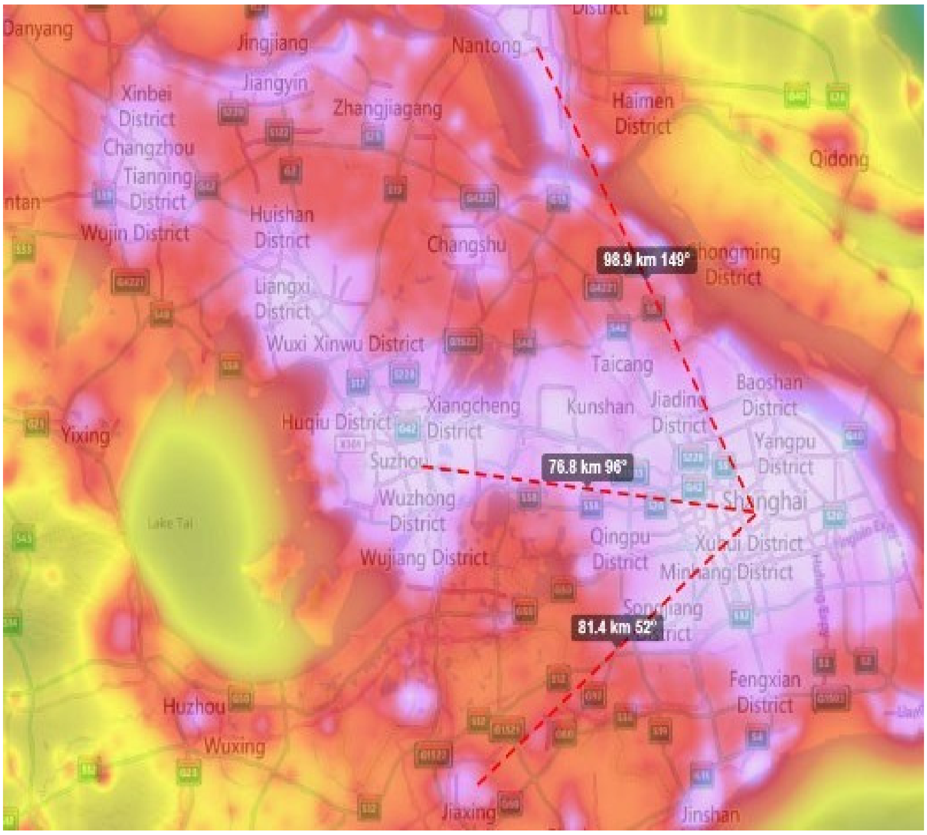

Fig. 2. Map of light pollution in Huangpu district, Shanghai

After selecting regions, their influence should be inversely correlated with the square distance between the two places, and positively correlated with their own internal light pollution risk. Therefore, the following model is established, called equation (5).

$$SU_T = \sum_{i=1}^{n} \frac{ILP_i}{R_i^2} \tag{5}$$

The formula calculates the sum of the light pollution effects of the i selected areas on the object area.

2.3 The Comprehensive Light Pollution Rating Method

The effect of internal light pollution and external light pollution is superimposed. That is the total value of the light pollution risk score of the target area, which is defined as LP. The following model is established, called equation (6).

$$LP = ILP + SU_T \tag{6}$$

LP is a value between 0 and 0.5, so it is divided into ten equal points to establish 0 to 10 light pollution risk levels. The higher the risk level, the greater the impact of light pollution in the region.

3 Experimental results

In order to ensure that the model is as general as possible, the model was applied to typical areas around the world. The risk level values with high agreement were obtained. The following four typical areas are shown as the results: Dja Animal Reserve in southern Cameroon, Africa; Ajana in Central Australia; Vicksburg, Mississippi, United States; and Shanghai Huangpu District, China, called **Table 2**.

Table 2. Presentation of four regional results.

	EC_T	UR_T	ED_T	TE_T	EN_T	SU_T	LP	Rate
Dja Faunal	0.0184	0	0	0.2683	0.4411	0	0.1012	3
Ajana	0.0125	0.048	0.609	0.3578	0	0	0.1308	3
Vicksburg	0.1568	0.1568	0.5558	0.7155	0.5403	0.0149	0.3235	7
Huangpu	0.9865	0.9865	0.5659	0.5367	0.7166	0.0128	0.4722	10

The light pollution risk level of the region is clear, so immediate action should be taken to resist the phenomenon of light pollution. However, this model can help regional managers determine the priority and cost performance of treatment measures based on regional characteristics. The following is the example of Huangpu districts.

Huangpu District is the most economically developed area in Shanghai, with tall buildings and heavy traffic, so the risk level is calculated as the highest level 10. Taking into account the above regional characteristics, it is found that LP can be reduced by about 6.87% by improving the commercial building cluster in the urbanization level factor, such as improving the lighting of high-rise buildings.

If the average traffic flow in the urbanization level factor is improved, LP can be found to decrease significantly, about 10.48%, due to the huge population base and traffic flow in Huangpu District. If the education level is improved, LP is only reduced by 2.90% due to the good education level in Huangpu District.

Therefore, in view of the current situation of Huangpu District, reducing the average traffic flow is the most suitable means of inhibition, which can be achieved through cross-peak travel and other methods. At the same time, reducing vehicle emissions can also improve air quality, thereby improving environmental factors [9].

4 Conclusions

In order to alleviate the severity of light pollution, it is urgent to conduct multi-factor evaluation of regional light pollution risk level and adopt corresponding intervention strategies. This paper considers multiple internal and external factors, has strong universality, and transforms complex data into simple ranking indicators, with good readability. This method is helpful to assess the risk level of light pollution in most areas, and has important reference and publicity significance for the prevention and control of light environment. At the same time, the model and strategy can be adapted to various analysis methods. However, the deterioration rate of light pollution is extremely fast, and the limit value is difficult to define, so the maximum value of the secondary index selected by the model is often difficult to accurately estimate. In the follow-up study, the rating range should be corrected in time to improve the accuracy and practicability of the model.

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