Light Pollution Impact Risk Measure Model Based on Ahp-Critic Method

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Abstract. With the intensification of light pollution, the assessment of light pollution risk level has become a focus topic. This paper proposes the LPIRM light pollution risk classification model to solve the problem of difficult accurate assessment of community light pollution risk degree. LPIRM model is divided into DRS and ELPI systems. Considering human and non-human factors, this paper selects 12 indicators to construct the District risk status system (DRS). The External light pollution impact index (ELPI) was constructed considering three main light pollution phenomena. In this paper, AHP-CRITIC method is used to calculate the total value of DRS, and GE matrix is used to calculate the combined value of DRS and ELPI, so as to establish a Light pollution impact risk measure model (LPIRM) that comprehensively considers the internal stability of a community and the influence of external light. Finally, K-means algorithm was used to cluster the calculated results, and risk I-V light pollution risk classification was proposed. According to the classification results, the paper concluded that the risk classification based on LPIRM model has guiding significance for the proposal of subsequent light pollution solution strategies.

Keywords: Light Pollution, Risk Level, AHP-CRITIC, LPIRM, K-means.

1. Introduction

Light pollution is a common problem worldwide, with multiple impacts on humans and ecosystems[1]. Moreover, the lighting“improvements”of the night vision in urban areas often happen to harm the natural rhythm the starry sky disappears, the 24-hour circadian rhythm is disturbed[2]. Several studies have been conducted in these years confirming that the light pollution has negative impact on our lives. This paper does some literature reviews about the light pollution research that has been done by scientists.

Light is a necessity due to man's naturally poor night vision and instinctive fear of the dark. Outdoor lighting promotes social and economic development. However, artificial light also has a series of direct and indirect effects on organisms and the environment[3]. Another study by Spoelstra et al. (2018) examined the impacts of artificial light at night on wildlife behaviors taking Parus major as a study subject. The study demonstrated that the light pollution can change the timing of clock controlled activity,leading to influence behaviour and physiology of species[4]. A third study by Lamphar et al. (2022) reviewed the health effects of of light pollution on human breast and prostate cancer. The study found that Long-term exposure to light pollution can be a risk factor for breast cancer[5]. All of the studies show the practical impacts on different species, but there is lack of the evaluation the risk level of the light pollution, which they determined by their subjective cognition. The purpose of this paper is to design an evaluation model that considers internal and external factors to determine light pollution levels in different locations, to provide better evaluation methods for policymakers to implement reasonable light pollution control strategies.

2. Materials and Methodologies

2.1. Data Acquisition and Pre-processing

Table.1. Data official website source table

Database Functionality	Database website
Collect usual global data such as crime index, and extreme weather.	https://data.worldbank.org.cn
Collect data from united nation such as population, industrial level.	https://data.un.org/
Collect some specific radiance data	https://www.lightpollutionmap.info/
Globe at Night-Sky Brightness Monitoring Network	https://www.globeatnight.org/maps.php
Get some specific data from satellite	https://data.noaa.gov/dataset

When selecting appropriate indicators to construct the light pollution impact risk measure model, it is necessary to ensure that the sources of indicator data are valid and accurate, and this paper shows the sources of different types of data in Table 1, whose Website are international official websites.

In this paper, the collected data were checked and found to have some deficiencies. The availability and completeness of data is a fundamental issue, and if the assessment modeling is based on unreliable and untrue data, it cannot provide an effective solution regardless of its value. Therefore, to ensure the validity and accuracy of the model calculation, this paper fills in the missing data.

Observing the data used, the missing values do not exceed 3%, so three methods are chosen for data filling in this paper, which are.

- If the indicators are smooth, previous data can be adapted to replace them.
- If the data before and after can be obtained, the average value can be taken for the missing value.
- The regression interpolation method and some methods for handling outliers were applied for processing the data to make it more convincing.

2.2. LPIRM Model Indicator Construction

The light pollution impact risk measure model (LPIRM) consists of two parts. They are the District risk status system (DRS) and External light pollution impact index (ELPI) respectively. In this section, appropriate indicators are selected to construct DRS and ELPI.

2.2.1 District risk status system（DRS）

The risk degree of community light pollution is often measured by many factors, which should not only consider the intensity of various light pollution phenomena, but also consider the stable state of the community. If a community itself is in an unstable state and exposed to a certain level of light pollution, its light pollution risk is undoubtedly increased.

Therefore, this section constructs the DRS part of the LPIRM model from human and non-human perspectives, aiming at selecting appropriate indicators to measure the internal stability state of a community.

For the selection of DRS indicators, this paper chooses Biological environment and Climate change, two non-human indicators. Two human indicators, Regional development level and Resident living quality, are taken as second-level indicators of DRS. A total of 12 third-level indicators are selected according to the data provided by the official website. The specific selection of DRS indicators is shown in Table 2:

Table.2. DRS indicator selection

Type	Indicators	Explain	Unit
CC	Extreme weather	Number of extreme weather events per year	day
	Carbon emission	The emission of the carbon	tons
	The standard deviation of temperature	An indicator to evaluate the change in temperature	-
RDL	Per capita income	The average income for one person	dollar
	Urbanization rate	The square area of city	percentage
	Industrialization degree	The production ability of industry	percentage
BE	Biological species	The number of different species	category
	Vegetation coverage	The area used for growing plants	percentage
	Agricultural production index	The crops and livestock products	-
RLQ	Crime index	The index to evaluate the level of crime	-
	Prevalence rate	The probability to get risk in a period	percentage
	Population density	Population per unit area	per km

2.2.2 External light pollution impact index（ELPI）

In this section, this paper constructs the influence index ELPI of external light pollution in the community. ELPI is another important factor to measure the degree of community light pollution risk. It reveals the overall pressure disturbance caused by light pollution in an area and is an external risk factor to assess the impact of regional light pollution. In this paper, ELPI is constructed with three main phenomena of light pollution (**light trespass, light over-illumination, and light clutter**) [6] :

$$ELPI = \delta_1 * LT + \delta_2 * OL + \delta_3 * LC \quad (1)$$

$ELPI$: ELPI refers to the external light pollution Impact Index of a community.

LT : LT stands for light intrusion, which occurs when artificial light penetrates the boundary of adjacent property, causing problems for people living and working in nearby buildings.

OL : OL refers to light over-illumination, and over-illumination refers to illumination above a specific intensity. This paper uses luminance to represent over-illumination, the intensity of light reflected per unit area.

LC : LC refers to optical clutter, which is a phenomenon that occurs when too much light is present in a given area. It can cause glare, reduced visibility and impaired driving. Light clutter is difficult to be directly quantified by a formula, so the road traffic accident rate is used here.

δ_{1-3} : The sum of parameter δ_{1-3} is 1, indicating the weight of the three kinds of light pollution effects, which will change with different community characteristics.

2.3. DRS weight calculation method

2.3.1 The Analytic Hierarchy Process

AHP as a multi-criteria decision-making method has been widely used in many fields of economics, politics, and engineering[7]. It was proposed by Thomas L. S to find a simple way to do priority setting and making decision-making[8]. There are many advantages of AHP, such as usability, breaking down the problem into smaller steps, etc.[9]. The process of AHP is shown in Figure 1.

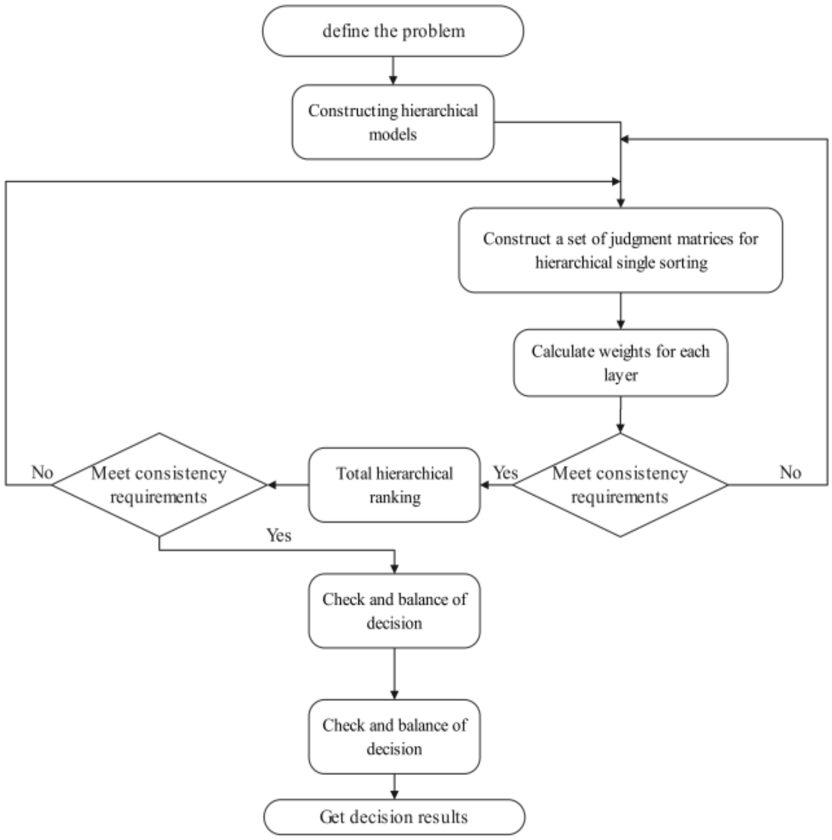

Figure 1: AHP flow chart

(1) This paper needs to standardize the index data to eliminate the deviation caused by different units of the index. Since the collected indicators fall into two categories: extremely large and extremely small, this paper transforms them as follows:

$$\text{Positive indicator: } x^{*}_{ij}=\frac{x_j-\min\{x_j\}}{\max\{x_j\}-\min\{x_j\}} \tag{2}$$

$$\text{Negative indicator: } x^{*}_{ij}=\frac{\max\{x_j\}-x_{ij}}{\max\{x_j\}-\min\{x_j\}} \tag{3}$$

(2) To ensure the robustness and accuracy of the results, we use the arithmetic average method, geometric average method and eigenvalue method to calculate and normalize the weights of the judgment matrix respectively and take their average values as the final calculated weights. The weights of CC, RDL, BE and RLQ obtained are $(0.15, 0.14, 0.29, 0.42)$.

(3) The consistency ratio of DRS is CR=0.0709 <0.10, so the consistency of this judgment matrix is acceptable, and this weight vector can be used as the weight of our index.

2.3.2 The CRITIC Method

CRITIC is a common method of objectively calculating weights.Decision makers use objective methods without initial information or subjective judgment[10].The CRITIC method is based on the objective properties of the indicators themselves, i.e., they are assigned weights based on the conflicting nature of the indicators. The calculation process of CRITIC is as follows:

(1) Indicator contrast is expressed by the standard deviation of the data in each column.

$$\sigma_j=\sqrt{\frac{\sum_{i=1}^{m}\left(x^{*}_{ij}-\bar{x}^{*}_{j}\right)}{m-1}} \tag{4}$$

σ_{ij} is the contrast of the j indicator.

(2) Indicator conflict degree indicates the degree of contradiction between indicators.

$$f_j = \sum_{m}^{i=1}\left(1 - r_{ij}\right) \tag{5}$$

f_j is the magnitude of the contradiction between the indicators. r_{ij} denotes the correlation coefficient between indicator i and indicator j.

(3) Define the information carrying capacity. The greater the amount of information, the greater the weight of the indicator.

$$C_j = \sigma_j f_j \tag{6}$$

C_j is the information carrying capacity of index j.

2.3.3 AHP-CRITIC calculates the DRS value

With the above steps, we obtain the AHP-CRITIC combination weights, and the calculation formula is as follows.

$$W_{total} = \beta W_{AHP} + (1-\beta)W_{CRITIC} \tag{7}$$

From above, β =0.4, which means we use a subjective weight of 0.4 and an objective weight of 0.6. Then, the AHP-CRITIC combination weights as shown in the following figure 2:

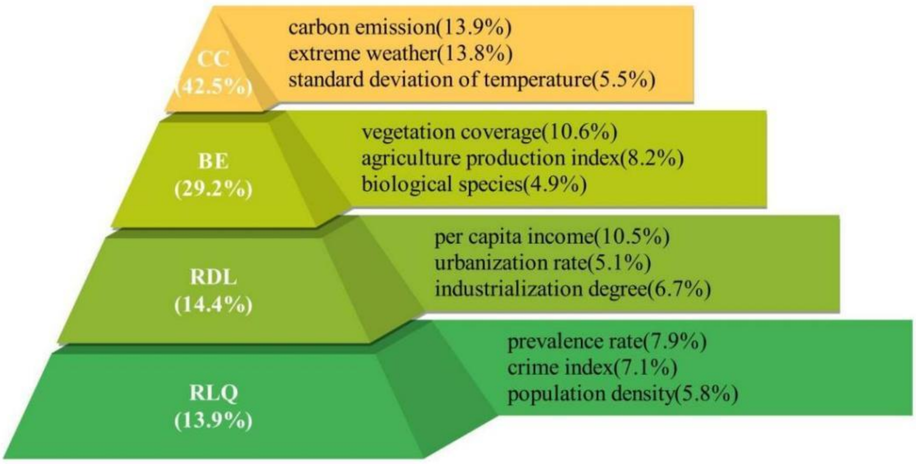

Figure 2: DRS weight result graph

With the above AHP-CRITIC combination weights, we can then bring in the value of the indicator data, and calculate risk status values within the community:

$$DRS = \sum_{j=1}^{n} w_{total} * x_j \tag{8}$$

2.4. The GE matrix evaluates the LPIRM

2.4.1 GE matrix

GE matrix is a common commercial evaluation management model, which can combine and analyze the internal and external factors of the system, to carry out the objective evaluation. In this paper, the GE matrix is applied to the evaluation of community light pollution risk. The external light pollution impact index (ELPI) in the LPIRM model is taken as the horizontal coordinate of the GE matrix, and the regional internal risk status (DRS) in the model is taken as the vertical coordinate of the GE matrix, to evaluate the light pollution risk.

2.4.2 Calculation of LPIRM value

Taking DRS and ELPI as the horizontal and vertical coordinates of GE matrix, this paper set the vector of community light pollution risk assessment model LPIRM as follows:

$$\overrightarrow{LPIRM} = \overrightarrow{DRS} + \overrightarrow{ELPI} \tag{9}$$

Therefore, the value of the LPIRM model can be defined as follows:

$$LPIRM = \sqrt{DRS^2 + ELPI^2} \tag{10}$$

From Formula 10, the final LPIRM model of this paper synthesizes the internal risk state of communities and external light pollution factors, and fully considers the different characteristics of different communities, to develop a set of widely applicable community light pollution risk measurement models.

2.4.3 K-means to divide the LPIRM risk level

In this paper, the k-means algorithm is used to cluster the results of the LPIRM model and divide them into 5 intervals. To identify the specific values of the five grades, the following operations are carried out in this paper, as shown in Table 3.

Table.3. K-means grading process

Algorithm 1: K-means to divide the LPIRM risk level

Input: LPIRM model values based on data from different communities
Output: Risk level Specific value partition
Repeat
  for i=1,…, n **do** // Cluster assignments update
    Set $b^{(i)} = \arg\min \| x(i) - u_j \|^2$;
  end
  for j=1,…, k **do** // Cluster centroids update
    Set $u_j = \frac{\sum_{i=1}^{n} 1\{b^{(i)} = j\} x^{(i)}}{\sum_{i=1}^{n} 1\{c^{(i)} = j\}}$
  end
  until convergency
Return risk grading value

3. LPIRM grading results

According to the method introduced in Section 2, this paper constructs the DRS system of community internal stability and ELPI system of external light pollution factors, and constructs light pollution impact assessment model LPIRM through GE matrix. Finally, this paper uses the K-means clustering method to grade light pollution risks, and the results are shown as follows.

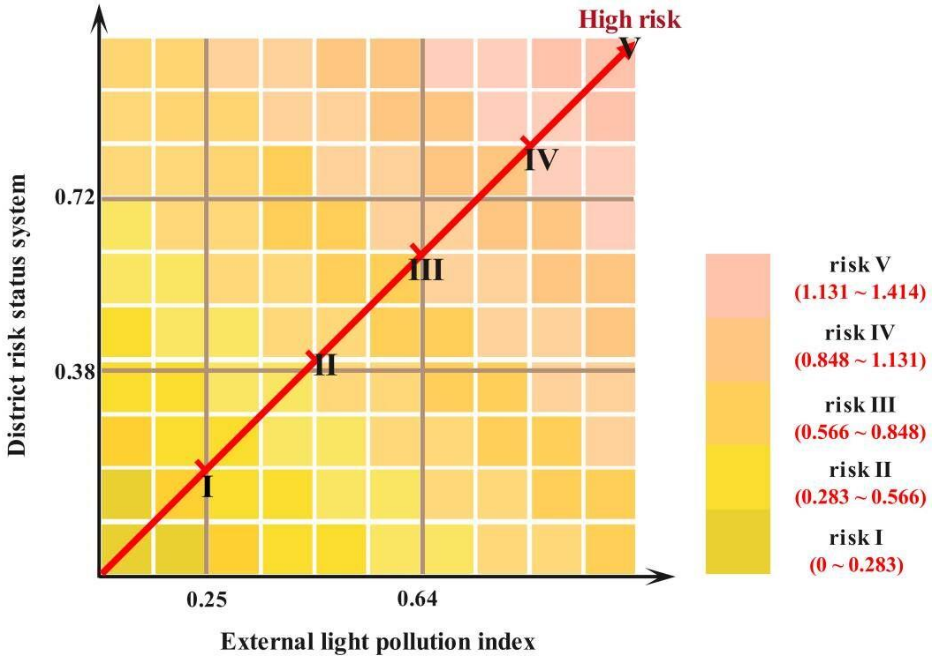

Figure 3: Light pollution impact risk classification

Figure 3 shows the classification of the impact risk of light pollution in this paper. Based on the community data of more than 30 countries, this paper carries out K-means clustering partitioning on the results of the LPIRM model, and divides the impact risk level of community light pollution into five levels (**I-V level**). The specific level values are shown in Table 4.

Table.4. Risk level numerical table

RiskI	RiskII	RiskIII	RiskIV	RiskV
0~0.283	0.283~0.566	0.566~0.848	0.848~1.131	1.131~1.141

4. Conclusions

To solve the problem of community light pollution risk measurement, so as to better assist the government to propose governance policies. In this paper, based on the internal risk state DRS and external light pollution impact ELPI , a light pollution impact risk measurement model LPIRM was constructed by the GE matrix. For the DRS system, combining subjective and objective factors, this paper uses the AHP-CRITIC method to construct. For the ELPI system, this paper combines three kinds of light pollution phenomena to construct. Finally, this paper divides light pollution into I-V risk levels through the k-means clustering of LPIRM results. By classifying the risk levels based on the LPIRM model, researchers can assess the light pollution risk levels of a community more comprehensively and accurately, so as to formulate different governance strategies according to different levels. Therefore, the LPIRM risk classification model proposed in this paper has guiding significance for the governance of light pollution.

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