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Evaluation of Light Pollution Level Based on Combined AHP and EWM Assignment

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Abstract. In this study, a combination of Analytic Hierarchy Process (AHP) subjective weighting and Entropy Weight Method (EWM) objective weighting is used. Using simple and easy index data, a light pollution level evaluation model that can be widely used in various places is established. The light pollution is divided into four grades: high pollution, moderate pollution, low pollution, and extremely low pollution according to the score from high to low. Then the evaluation model is applied to four regions with significantly different natural and human environments, namely Tibet Qiangtang National Nature Reserve, Malyang Township, suburbs of Guangzhou City and urban areas of Guangzhou. The light pollution scores of the four regions obtained by the model are 8.83,36.67,64.58 and 83.03, respectively. The model results are consistent with the actual situation.

Keywords. Light pollution, AHP, EWM, combined AHP and EWM

1. Introduction

In recent years, with the continuous advancement of China's urbanization process, bright lights can be seen everywhere in the city, but the attendant light pollution problems continue to highlight. While artificial light brings us convenience, its hazards are also widely spread around the world [1]. Light pollution not only damages people's physical and mental health [2], but also adversely affects traffic safety and ecological balance [3]. In addition, light pollution can also have an impact on flora and fauna [4]. Studies have shown that light pollution is likely to become another major "environmental killer" that directly affects human health in the 21st century [5].

This study establishes an assessment model that can be widely used to assess the level of light pollution in an area by calculating some readily available data and using it as an indicator. The Economy-Regional-Ecology (ERE) model covers three dimensions of economic development, regional construction, and ecological environment, and comprehensively evaluates the light pollution level of a region. The AHP is a subjective method, which is based on a hierarchical structure system, compares the indicators with each other [6]. The EWM is an objective method that uses data sets to determine the weight of indicators [7]. This study combines AHP and EWM for combined weighting.

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2. Light Pollution Level Evaluation Indicator System

The CIE (Commission Internationale de I´Eclairage) divides the Earth's light environment brightness areas into four categories, which are dark areas, including nature reserves; low-brightness areas, including rural areas; medium-brightness areas, including suburbs; and high-brightness areas, including cities [8]. Based on the above brightness divisions, the level of light pollution risk is positively correlated with the level of regional economic development and is affected by the level of regional GDP and economic development. Based on the nighttime lighting data [9], we construct the regional lighting index CNLI (Compounded Night Light Index), as shown in equation (1).

$$CNLI_i = I_i \times S_i \tag{1}$$

I_i represents the average relative light intensity of a place; S_i indicates the ratio of light area of a place to the total area of the region.

Reflected light is one of the important sources of light pollution [10]. Defining the reflection coefficient of building materials as ρ_j, the regional surface reflection properties (RSRP) formula is as follows:

$$RC_i = \frac{\left(\sum_{j=1}^{n} BRSA_{ij} \times \rho_{ij}\right)}{G_i} \tag{2}$$

$BRSA_{ij}$ is the area building reflective surface area; G_i is the total area of the area.

The average density of buildings in the region is defined as σ, then we can obtain the equation (3):

$$\boldsymbol{\sigma = x} \tag{3}$$

x is the horizontal distance between the light intrusion and the light source.

We consider the range of lighting height h between the lighting patch height h_1 of the first-floor store and the height h_2 of the highest building in the area. Inappropriate lighting (IL) intensity is shown in equation (4):

$$\boldsymbol{ILI_i = \int_{h_1}^{h_2} \frac{I_i \times \cos\theta}{r^2}} \tag{4}$$

We make the following definitions for the light intrusion and the light source: r is the distance from the light intrusion to the light source; x is the horizontal distance between the two places; h is the vertical distance between the two places. Since the illuminated building surfaces are all vertical, it follows equations (5) and (6):

$$\boldsymbol{\cos\theta = \frac{x}{r}} \tag{5}$$

$$\boldsymbol{x = \sqrt{r^2 - h^2}} \tag{6}$$

Substituting equations (3), (5), and (6) into equation (4), the quantification of the regional improper lighting situation is obtained, as shown in equations (7).

$$\boldsymbol{ILI_i = \int_{h_1}^{h_2} \frac{I_i \times \sigma_i}{\sigma^2 + h^2}} \tag{7}$$

The leaf light absorption coefficient Abs is a calculation of the ratio of light intensity irradiated to the plant leaves that is absorbed and utilized by the plant under photosynthesis. Vegetation greening in the area can mitigate the light pollution level to some extent, as shown in equation (8).

$$\mathbf{AB_i} = \frac{\mathbf{Abs \times VSA_i}}{\mathbf{G_i \times I_i}} \tag{8}$$

AB_i is the vegetation uptake; VSA_i is the area of regional greenery.

Biodiversity plays an important role in the integrity of ecosystems. We define here the biotic index (BIO_i), as shown in equation (9).

$$\mathbf{BIO_i} = \frac{\mathbf{BT_i}}{\mathbf{G_i}} \tag{9}$$

BT_i is the total number of organisms in the region.

The above GDP, CNLI, RSRP, IL, Vegetation Absorption (VA) and Biological Indirect Effects (BIE) are used as secondary indicators. They are grouped into three dimensions: Economy Development, Regional Construction and Ecology Environment. The indicator system is shown in Table 1.

Table 1. Light pollution level evaluation indicator system.

	First Level Indicator	Second Level Indicator
Light Pollution Risk level	Economy Development	GDP
		CNLI
	Regional Construction	RSRP
		IL
	Ecology Environment	VA
		BIE

3. Weight Determination of Indicators

The secondary indicators are weighted using the EWM, and the weights of the indicators are determined according to the amount and quality of data information. We assume that there are n evaluation indicators and a total of m sets of data. The entropy value is calculated based on the original data of the indicator. The information entropy of indicator i is calculated by equations (10) and (11).

$$\boldsymbol{e_i = -(\ln m)^{-1} \sum_{q=1}^{m} P_{iq} \ln P_{iq}} \tag{10}$$

$$\boldsymbol{P_{iq} = \frac{x_{iq}}{\sum_{q=1}^{m} x_{iq}}} \tag{11}$$

where x_{iq} $(i = 1,2,\ldots,n; q = 1,2,\ldots,m)$ is the normalized value of the evaluation indicator measurement; P_{iq} is the normalized value; e_i is the information entropy of the indicator.

The first level indicators weight is determined by AHP. We construct a two-by-two comparison judgment matrix. We get the relative importance of each level of indicators and use 1 to 9 to establish the judgment matrix $\boldsymbol{A} = (a_{ij})_{m \times n}$, where a_{ij} denotes i Factor comparison j factor Mean value.

Consistency indicator (CI) is calculated by equation (12).

$$\boldsymbol{CI} = \frac{\lambda_{m\times n} - n}{n-1} \tag{12}$$

If the consistency ratio $CR < 0.1$, then the consistency of the judgment moments is considered acceptable. Otherwise, the judgment matrix needs to be corrected. The calculation method of CR is as shown in equation (13).

$$\boldsymbol{CR} = \frac{CI}{RI} \tag{13}$$

The eigenvector and eigenvalue are calculated by summation method. Sum up the data in each column, as shown in equation (14).

$$\boldsymbol{b_j} = \sum_{i=1}^{n} \boldsymbol{a_{ij}} \tag{14}$$

Get the sum vector $b_j = [b_1, b_2, \dots b_n]$. Then calculate the normalized vector $\boldsymbol{C} = (c_{ij})_{m\times n}$.

Finally, we calculate the subjective weight vector ω_i. The calculation formula is as follows:

$$\boldsymbol{\omega_i} = \frac{\sum_{j=1}^{n} c_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}} \tag{15}$$

The combination weights are calculated by equation (16).

$$\boldsymbol{W_i} = \frac{\sqrt{e_i \omega_i}}{\sum_{i=1}^{n}\sqrt{e_i \omega_i}} \tag{16}$$

4. Combination Weighting Based on AHP and EWM

According to the above light pollution level evaluation indicator system, we construct a judgment matrix for the three dimensions of Economy Development, Regional Construction and Ecology Environment, as shown in equation (17).

$$\boldsymbol{A} = \begin{bmatrix} 1 & 2/5 & 8/3 \\ 5/2 & 1 & 7/2 \\ 3/8 & 2/7 & 1 \end{bmatrix} \tag{17}$$

Substituting matrix A into equations (12) and (13), calculate the consistency ratio CR of the matrix. CR=0.045<0.1 indicating that the matrix passes the consistency test. The weights of Economy Development, Regional Construction and Ecology Environment are 0.2891, 0.5756, and 0.1353, respectively. Then the indicators under each dimension are scored separately. The weights of the three first level indicators are integrated, and the final AHP-based indicator weights are shown in Table 2.

Table 2. Light pollution level evaluation indicator system.

Indicator	**GDP**	**CNLI**	**RSRP**	**IL**	**VA**	**BIE**
Weight	0.6	0.4	0.625	0.375	0.5556	0.4444
AHP Weight	0.1735	0.1156	0.3598	0.2159	0.0752	0.0601

The data of six second level indicators are obtained by calculating each data collected from 2012 to 2021 in Beijing. After standardizing and normalizing the data, the weights of each indicator are calculated, as shown in Table 3.

Table 3. Indicator weights based on EWM.

Indicator	GDP	CNLI	RSRP	IL	VA	BIE
Weight	0.1567	0.1504	0.1836	0.2610	0.1362	0.1122

The combined assignment of each indicator is calculated according to equation (15), as shown in Table 4.

Table 4. AHP and EWM combined weighting.

Indicator	GDP	CNLI	RSRP	IL	VA	BIE
Weight	0.1692	0.1354	0.2637	0.2436	0.1038	0.0843

In Figure 1, we compare the weights obtained by AHP, EWM, and combined assignment method.

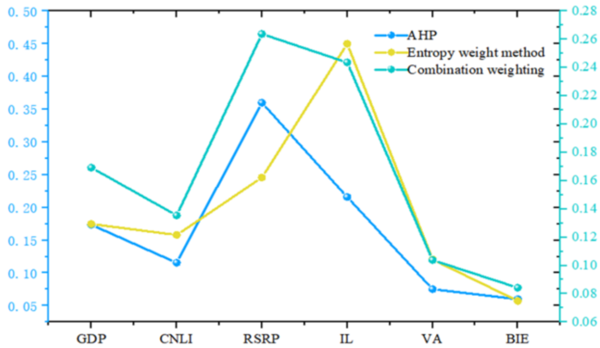

Figure 1. Comparison of the three types of empowerments.

5. Score Calculation and Grade Classification

By substituting the standardized data of each indicator of the region into equation (18), we can get the light pollution level score of the place. The higher the score, the more serious the light pollution.

$$score = (0.1692score_{GDP} + 0.1354score_{CNLI} + 0.2637score_{RSRP} \\ +0.2436score_{IL} + 0.1038score_{VA} + 0.0842score_{BIE}) \times 100 \quad (18)$$

The maximum value of each indicator was substituted into equation (18), resulting in a full score of 100 for the model, which was averaged into four levels, as shown in Table 5.

Table 5. Light pollution level.

Score	Level
$0 < \text{score} \leq 25$	Extremely Low Pollution
$25 < \text{score} \leq 50$	Low Pollution
$50 < \text{score} \leq 75$	Moderate Pollution
$75 < \text{score} \leq 100$	High Pollution

The data of each indicator are collected from four locations, namely, Tibet Qiangtang National Nature Reserve, Malyang Township, suburbs of Guangzhou City and urban areas of Guangzhou. The data are normalized into equation (18) to obtain the light pollution level scores of the four locations, which are 8.83, 36.67, 64.58 and 83.03. According to Table 5, the light pollution levels of the above four locations are in the order of Extremely Low Pollution, Low Pollution, Moderate Pollution and High Pollution.

6. Conclusion

The level of light pollution is affected by the three dimensions of economic development, regional construction, and ecological environment. The ERE model developed in this study can evaluate the light pollution level of sites in multiple dimensions, and the data of the six indicators are very easy to obtain and can be widely used in various sites. The index weight is determined by the combination of AHP and EWM, and the combination of subjective and objective assignment makes the model more convincing. The six indicators are RSRP, IL, GDP, CNIL, VA and BIE in descending order of weight. To alleviate light pollution, it is necessary to reduce the reflection characteristics of the regional surface and reduce inappropriate light. The use of glass curtain walls in restricted areas, or the use of lighting, are very effective solutions. VA and BIE are the ecological environment dimensions and have the smallest weight in the mild pollution level evaluation model. However, its role cannot be ignored, and the ecological environment should still be vigorously maintained.

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