TOPSIS Comprehensive Evaluation Model for Light Pollution based on Entropy Weight Method

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Abstract. Light pollution is a serious and growing problem worldwide. How to develop a widely applicable light pollution indicator analysis model to help people monitor and mitigate light pollution is a question worthy of our consideration. This paper uses the TOPSIS integrated evaluation and decision method based on Entropy Weight Method (EWM) and Analytic Hierarchy Process (AHP) to identify indicators and establish a widely applicable LPI (Light Pollution Index) analyze Model for the global light pollution problem. Then this model is used for analyzing specific differentiated areas and develop optimal intervention strategies. In order to build an accurate model to assess global light pollution hazard levels, this paper have to take three key aspects into account: Light Trespass, Glare, Spill Light. For each aspect, six to eight sub-indicators were selected to measure different aspects of light pollution. This paper evaluated all indicators and by combining EWM and AHP, this paper obtained a Light Pollution Index Analyze Model. To verify the rationality and reliability of this model, this paper uses TOPSIS integrated evaluation and decision method based on EWM to predict and rank 20 countries worldwide in terms of light pollution risk index. The results show that comparing our data with monitoring data of Light Pollution Map, the two rankings show a high degree of agreement. Therefore, the model of this paper is reasonable and reliable. And the research of this paper can provide effective help to the research and monitoring of light pollution.

Keywords: Light Pollution, AHP, EWM, Topsis Integrated Evaluation.

1. Introduction

1.1. Background

Light pollution was first identified by astronomers in the 1930s [1]. It is used to describe the excessive or poor use of artificial light. Nowadays, it has become a widely discussed environmental issue following water pollution, air pollution, and noise pollution [2]. In 2001, 19% of the global land area suffered from light pollution, which is higher than the threshold, and about 21% of the world's population lived in an environment where light pollution existed [3].

At present, with the rapid urbanization and economic development around the world, light pollution is expanding at an unprecedented speed and to an unprecedented extent [2,4]. However, there is no widely applicable global indicator for light pollution risk levels, and it is not possible to accurately detect and analyze light pollution in each location [5]. Therefore, the development of a widely applicable evaluation system for the various influences of light pollution and the development of intervention strategies to mitigate these effects are of great importance for both humans and non-humans [6,7].

1.2. Literature Review

A number of researchers have previously contributed to the research of light pollution. Luoxi Hao et al. analyzed the multiple effects of urban night lighting problems on visual, physiological, and psychological health and the risk of disease through mechanistic and empirical literature studies [8]. Pan Jiaying qualitatively evaluated the effects of glare through a parametric model to quickly assess the light pollution situation in the area [9]. Jing Shuai established a parametric model to analyze light pollution using its working principle of continuous iteration to find the optimal solution, and simulated different categories of light spillover to quantify the degree of light pollution [10].

We also found a lot of literature on light pollution analysis and used them to identify indicators. We also developed a analytic hierarchy process model based on the similarity between the identified indicators in this literature. Then a widely applicable light pollution evaluation system was developed by TOPSIS integrated evaluation and decision method based on Entropy Weight Method, and its feasibility was verified based on literature and database.

1.3. Our Work and Aim

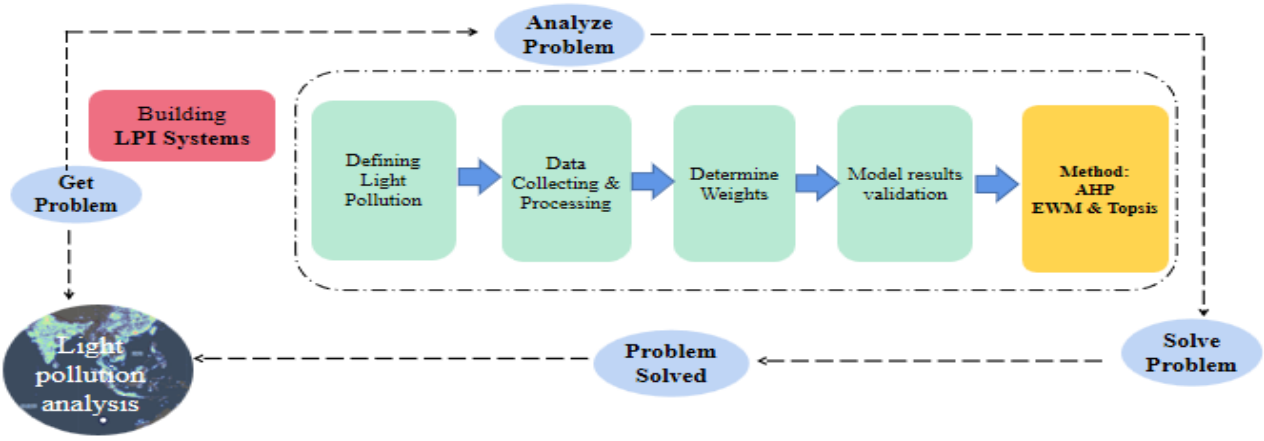


Figure 1. The diagram of our work

Figure 1 is a map to show the process of our work. In order to explore a widely applicable model of light pollution risk evaluation system and effective intervention strategies, this paper will conduct research on the factors that affect light pollution based on the background information. This paper need to determine light pollution analysis indicators and design a model to determine the light pollution risk level of an area by calculating its LPI.

2. The Basic Fundamental of EWM-based TOPSIS Integrated Analysis

2.1. The Structure of EWM-based TOPSIS Integrated Analysis

This paper takes three key aspects into account: Light Trespass, Glare, Spill Light. For each aspect, six to eight sub-indicators were selected to measure different aspects of light pollution. This paper firstly calculated the weights of all indicators in the light pollution index analysis model using EWM, and then predicted and ranked the light pollution risk indices of 20 countries around the world using the Topsis integrated evaluation and decision making method.

2.2. Model Evaluation Metrics

In terms of index analysis of the model, this paper uses the N-K model to analyze the sensitivity of the LPI model to determine the accuracy of the LPI model.

First, we conduct sensitivity analysis on the value. We can conclude that when the variation of lighting time and light intensity change from 10% to 10%, the changes in the value of LPI corresponding to light intensity are small and the overall trend is flat. Therefore, we believe that between the two indicators of lighting time and light intensity, lighting time is more sensitive and affects light pollution risk level a lot.

Next, we conduct sensitivity analysis on the material. We conclude that when the the higher the reflectivity of the material, the lower the upshot light is. But from the figure we can get that the value of LPI corresponding to upshot light are smaller and the overall trend is more flat than lighting time. Meanwhile, lighting time corresponds to a relatively large amount of changes in our model, so we think the sensitivity of the recent fire situation to be strong. This result verifies the reasonableness of our model.

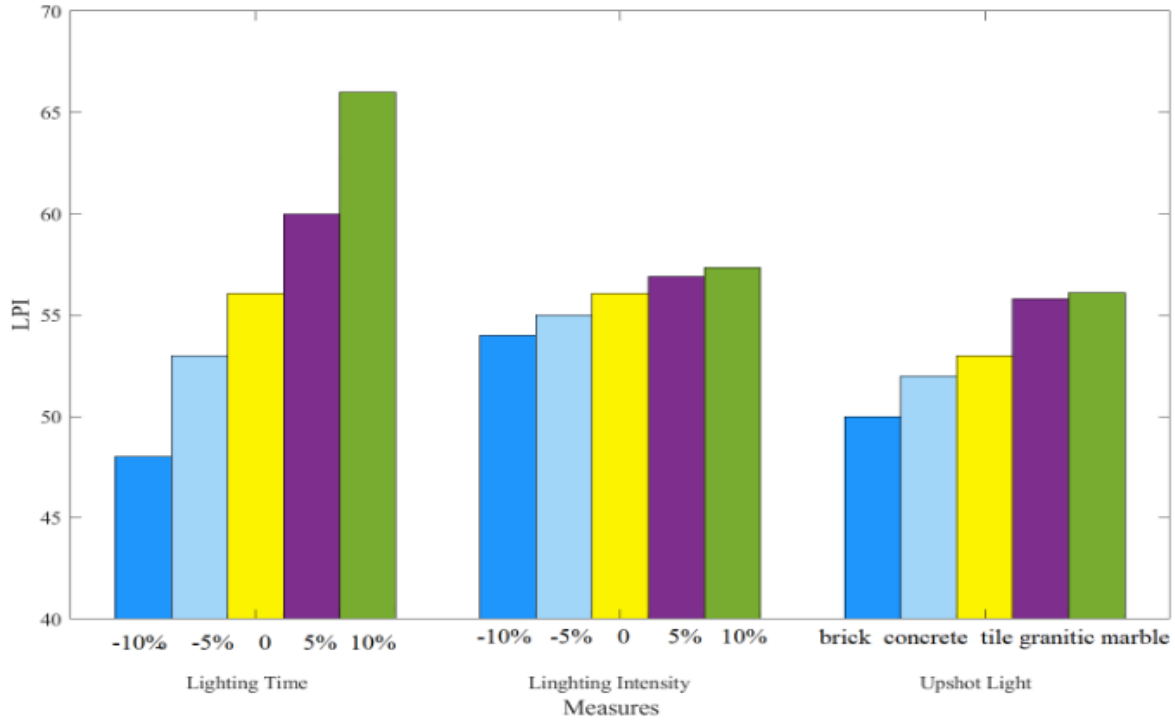


Figure 2. New York: Three Intervention Strategy

2.3. Evaluation of Model Strengths and Weaknesses

2.3.1 Strengths

1. The selection of indicators in our model is scientific and comprehensive. We counted nearly 30 data sets from 20 countries. These indicators are important factors affecting light pollution and make our study more reliable.

2. We combine subjective and objective weighting methods, so we calculate more reliable weights. We combine literature and experience by combining subjective APH with objective EWM, thus making our results more objective.

3. We use a comprehensive evaluation and decision making method based on the entropy coefficient of TOPSIS. The data are ranked and the data units are unified to finally obtain more reliable results.

4. We conduct sensitivity analysis on our model, and find that the model has good robustness in a specific fluctuation range. It also can make different strategies to improve light pollution condition according to different indicators, which is highly effective and practical.

2.3.2 Weaknesses and Further Improvements

1. Our LPI model has a high demand for original data and contains complex calculations. There will be difficulty in collecting all the data. And the indicators we choose, such as the upshot light, are also difficult to calculate as well.

2. The model does not study countries like Iceland, which are located at high latitudes, because most of these countries are above 55 degrees latitude and have high aurora activity, which may have a significant impact on the radiation values.Therefore we do not take into account the interference of sudden influences such as the aurora when considering the global light pollution situation.

3. Results

3.1. Evaluation Index

Figure 3 shows a basic diagram of our model. It is comprised of three first-level indicators and twenty second-level indicators.

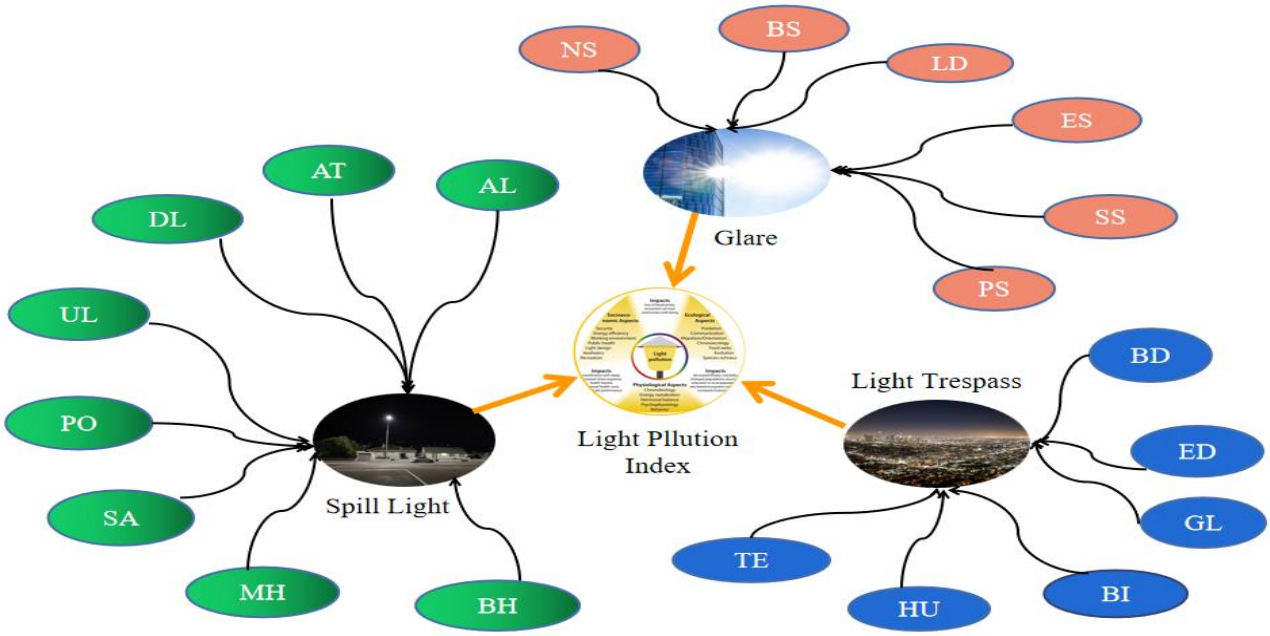


Figure 3. Diagram of Evaluation Index

3.1.1 Spill Light Index Analysis

Spill light refers to the light source that illuminates the area higher than the height of the building, the part of the light shining to the sky belongs to the spill light. In order to determine the level of pollution caused by spill light, we collected some factors affecting spill light as indicators to evaluate the level of spill light pollution. Indicators are as follows.

(1) Artificial luminous (AL)

The sources of light that are constructed artificially and are capable of emitting light of their own are typically known as artificial luminous.

(2) Population (PO) and Development Level (DL)

Population indirectly affects spill light by influencing the number of artificial light sources.

(3) Atmospheric Transparency (AT)

Atmospheric transparency affects spill light by influencing the properties of light wave transmission.

(4) Upshot Light (UL)

Upshot light refers to the part of the light that shines above the horizontal plane in the lighting.

(5) The Spectrum of Artificial Light (SA)

Any wavelength of light can produce light pollution through radiation.

(6) Mounting Height (MH) and Building Height (BH)

When the light area is higher than the building height, it will produce spill light pollution, and the location of the light source can affect the scope of the light area and affect the spill light pollution.

3.1.2 Glare Index Analysis

Glare is a visual condition that causes visual discomfort and reduces the visibility of objects due to inappropriate luminance distribution in the visual field, or the presence of extreme luminance contrast in space or time. We explore the light pollution index of glare through the number of light sources, light source brightness, eye sensitivity and adaptability, the shape of the light source, location of the light source and optical density, and other factors that affect glare.

(1) Number of the Sources (NS) and Brightness of the Sources (BS)

The number of light sources and brightness of the sources affects the intensity of light, the contrast of brightness in different spaces, and the glare.

(2) Eye Sensitivity and Adaptation (ES)

Eye sensitivity and accommodation are important influences on glare.

(3) Size of the Sources (SS)

The size of the light source affects the contrast of light in different spaces, thus affecting the light pollution of glare.

(4) Position of the Sources (PS)

The location of the light source affects the light pollution of glare by influencing the contrast of light in different areas.

(5) Light Density (LD)

Light density affects light pollution from glare by influencing the intensity of light.

3.1.3 Light Trespass Index Analysis

Light trespass is the phenomenon of light entering the interior of a building from the external environment. We collected Building Density, Exposure Duration, Geographic Location, Biodiversity, Humidity, and Temperature to determine the light pollution index of light intrusion.

(1) Building Density (BD)

Building density affects the reflection and refraction of light between buildings, affecting light intrusion.

(2) Biodiversity (BI)

Biodiversity can change the path of light transmission.

(3) Exposure Duration (ED)

The longer the exposure time, the more light the room receives and the higher the degree of light intrusion.

(4) Geographic Location (GL)

Different geographical locations, different topography and climate, and different levels of light invasion.

(5) Humidity (HU) and Temperature (TE)

Temperature and humidity are important manifestations of the indoor environment, and light invasion can regulate indoor temperature and humidity to a certain extent.

3.2. Determining the Weights of First-level Indicators

The AHP is used to calculate the data. First, formulating a matrix of pair-comparison based on relevant literature and theories. Then calculate the initial weight coefficient w_i' according to the formula:

$$w_i' = \sqrt[n]{a_{i1}a_{i2}a_{i3}\cdots a_{in}} \tag{1}$$

Next, normalized weighted as:

$$\mathrm{w_i} = \frac{\mathrm{w_i'}}{\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{w_i'}} \tag{2}$$

Finally, conducting the consistency test. The result shows CR = 0.0149 < 0.1. That means this approach is acceptable.

3.3. Determining the Weights of Second-level Indicators

The relative data is computed by EWM. First, computing the proportion of the i^{th} under the j^{th} index and regarding the proportion as the probability used in the relative entropy calculation. Denote data of the j^{th} index and the i^{th} sample point as z_{ij} .We can derive probability p_{ij} by:

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^{n} z_{ij}} \quad \text{i = 1,2,3…,n , j =1,2,3…,m} \tag{3}$$

where n is the number of years studied, and m is the number of indicators.

Secondly, calculating the information entropy of each indicator, and obtaining the information utility value. Then normalizing it to obtain the entropy weight of each indicator. For the j^{th} index, the formula is:

$$e_j = -\frac{1}{ln\, n}\sum_{i=1}^{n} p_{ij}\, ln(p_{ij}), \quad \text{j =1,2,3…,m} \tag{4}$$

Information utility is computed as:

$$d_j = 1 - e_j \ , \text{j =1,2,3…,m} \tag{5}$$

Normalizing the information utility and calculate the weight as:

$$\omega_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \ , \text{j =1,2,3…,m} \tag{6}$$

The final weights calculated by the two methods are shown in the following table 1:

Table 1. Final Weights of Two Levels

	Indicators(1)	Weights	Indicators(II)	Weights
Light Pollution Index(LPI)	Light Trespass	0.4306	BD	0.2091
			ED	0.2398
			BI	0.0527
			GL	0.3735
	Glare	0.3152	HU	0.0625
			TE	0.0624
			NS	0.1171
			SS	0.0413
			BS	0.2059
			PS	0.0697
			ES	0.3602
	Spill Light	0.2542	LD	0.2058
			AL	0.3205
			PO	0.1945
			AT	0.0252
			SA	0.0693
			DL	0.1946
			MH	0.0407
			UL	0.1146
			BH	0.0406

3.4. Establishing Light Pollution Index Model

The model for light pollution index is implemented in TOPSIS integrated evaluation and decision method based on entropy coefficient. The value and rank of LPI in countries are calculated by this approach.

First, standardizing the matrix consisting of i countries and j evaluation indicators as:

$$a_{ij} = \frac{y_{ij}}{\sum_{i=1}^{n} y_{ij}^2} \ , \quad \text{i = 1,2,3…,n , j =1,2,3…,n} \tag{7}$$

Then a weighting matrix X can be conducted by

$$x_{ij} = \gamma_{jz}\omega_{ij} \ \ \text{(i = 1,2,3…,n j =1,2,3…,n)} \tag{8}$$

Third, setting a positive ideal solution and a negative ideal solution and then calculate the distance between X_i. The negative ideal solution and the positive ideal solution by the following formula:

$$S_i^+ = \sum_{j=1}^{m}(x_{ij} - x_j^+)^2, \quad \text{i} = 1,2,3\ldots,\text{n} \tag{9}$$

$$S_i^- = \sum_{j=1}^{m}(x_{ij} - x_j^-)^2, \quad \text{i} = 1,2,3\ldots,\text{n} \tag{10}$$

Where S_i^+ is the distance between X_i and the positive ideal solution. X_j^+ stands for the j^{th} component of ideal solution. The meaning of S_i^- and X_j^- are opposite.

And then, the relative closeness of the solution X_i to the ideal solution is computed by:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{11}$$

Using the obtained comprehensive weights and the value of relative closeness, the comprehensive score of each country can be calculated. The formula is:

$$LPI_i = 100(\omega_i + C_i), \quad \text{i} = 1,2,3\ldots,\text{n} \tag{12}$$

4. Analysis of Results

The final rankings and values of LPI in 20 countries which are got by the models are shown in the following Table 2 (The lower the LPI, the higher the ranking):

Table 2. Rankings and values of LPI in 20 countries computed by LPI model

Ranking	Countries	LPI	Ranking	Countries	LPI
1	Australia	8.01098	11	Mexico	48.71095
2	Angola	10.02460	12	Saudi Arabia	81.38409
3	Peru	11.27468	13	United States	82.01485
4	Russia	12.38507	14	Turky	82.11367
5	Chile	12.88720	15	Germany	82.27417
6	Canada	22.53187	16	France	82.60381
7	Brazil	23.01179	17	Japan	83.38882
8	Argentina	24.12293	18	United Kingdom	84.32259
9	South Africa	24.75485	19	Italy	93.29280
10	China	36.62486	20	South Korea	93.98835

Light pollution map displays light pollution related content over Microsoft Bing base layers by NASA's VIIRS/NPP Lunar BRDF-Adjusted Nighttime Lights Yearly. Table 2 shows the light pollution risk levels for the same countries based on light pollution map.

Table 3. Rankings and values of LPI in 20 countries according to Light Pollution Map

Ranking	Countries	LPI	Ranking	Countries	LPI
1	Australia	0.037	11	Mexico	0.487
2	Angola	0.046	12	Saudi Arabia	0.889
3	Peru	0.106	13	United States	0.891
4	Russia	0.123	14	Turky	1.025
5	Chile	0.191	15	Germany	1.122
6	Canada	0.225	16	France	1.361
7	Brazil	0.227	17	Japan	1.399
8	Argentina	0.253	18	United Kingdom	1.663
9	South Africa	0.286	19	Italy	3.178
10	China	0.391	20	South Korea	3.883

The result of the two ranks shows a high degree of consistency. Africa, Oceania, and Latin America have the lowest levels of light pollution. Europe and North America have the highest levels of light pollution. Light pollution in Asia is higher than in Europe and lower than in Africa. From the comparison between prediction data and actual data, the Light Pollution Index model has better prediction performance, which can meet the demand completely, and has fast prediction speed and convenient operation.

5. Conclusions

The light pollution map provides the basis for the establishment of light pollution index model. Traditional light pollution detection methods require daily observation and consume a lot of time and resources. In this paper, TOPSIS integrated evaluation and decision method based on EWM is used to establish a light pollution index model to evaluate the risk level of light pollution, which saves resources to a certain extent. The experimental results show that the light pollution index model has high accuracy and practical application value.

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