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Illume Guard
——Light Pollution Evaluation Research

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Abstract. As the problem of light pollution is becoming more and more serious, it is urgent to establish a general comprehensive index for light pollution risk evaluation. In this paper, to measure and mitigate the impact of light pollution in each region, we collected relevant data, and established A comprehensive light pollution risk evaluation model to study the risk level of light pollution in each area. light pollution is mainly divided into nighttime light over-brightness pollution, spectral light pollution and glare pollution that can be subjectively perceived by individuals. Correspondingly, four indicators were selected, which are the OBI, AER, AP and $PLPI$. Using the entropy weighting method, the four indicators are assigned weights and summed to form the LPI. Define the value of LPI in 0-0.1 as almost no pollution; in 0.1-1 as light pollution; 1-3 as moderate pollution; 3 and above as heavy pollution.

Keywords. Light pollution risk assessment model; Entropy weighting method; Mathematical modeling

1. Introduction

With the rapid development of human society, artificial illumination has become an important demand of human beings, while the problem of light pollution has also arisen. Light pollution is any manifestation of the excessive or improper use of artificial illumination. Scientific research shows that the excessive use of artificial illumination at night is the main source of light pollution [1], over-illumination at night, light clutter and glare pollution to human beings jointly cause light pollution at night [2-4]. Light pollution leads to a significant degree of adverse effects on the biological behavior of plants and animals, including the social life and health of human beings. The effects of urban lighting will also extend to the adjacent ecological protection areas [5], leading to more severe light pollution.

It is crucial to build a model for the risk quantification of light pollution. The construction and planning of each region need to consider how to reasonably plan artificial light sources and reduce the risk of light pollution to a certain range, so as to maintain the biological diversity and make the healthy development of human society.

At present, there are many models for light pollution assessment, but most of them have index or regional limitations, and they are not a general risk assessment model. Moreover, the suggestions on light pollution restrictions are mostly theoretical, rather

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than quantified practical changes. Therefore, a risk assessment model that can comprehensively measure the multifaceted light pollution is needed and can be applied to different regions and scenarios worldwide.

2. Assumptions and Justification

- Most of the effects of pollution on the environment and organisms originate from nighttime light pollution, and daytime pollution is not considered.
- The light pollution risk evaluation model is a time-point evaluation model, not a time period evaluation model.
- The variability of topography and building layout in different areas can also affect light pollution propagation, and light scattering is not considered in this paper.
- The light sources of light pollution can be divided into two types: Static light sources and dynamic light sources, and the static light sources are dominant.
- The response degree of different organisms to light pollution is different, and this model mainly considers the response pattern of human.
- The indicator system in this paper is not affected by other external factors, such as weather and meteorology.

3. Notations

The following **Table** 1 explains the symbols in the article.

Table 1. Symbol description.

Symbols	Definition	Units
LPI	Light pollution index	
OBI	Objective brightness index	
$SLPI$	Spectral light pollution index	
$PLPI$	Perceived Light Pollution Index	
DN	Area light intensity value	cd
AER	Action efficacy of radiation	
AP	Spectrum overload	
G	Glare evaluation value	
L	Light source brightness value	$cd/_{m^2}$
λ	Wavelength	nm
h	Modified coefficient	
N	Degree of change in risk level of light pollution	

4. Light Pollution Risk Evaluation Model

The time-point evaluation of light pollution at night can be divided into three main areas: overly bright light pollution at night, colored light pollution and glare pollution that can be subjectively perceived by individuals.

4.1. Objective Brightness Index

4.1.1. Indicator Selection–OBI

An indicator named Objective Brightness Index (OBI) for nighttime lighting was constructed using nighttime remote sensing data and regional brightness values. The index will use the DMSP-OLS open-source data published by the National Geographic Data Center (NESDIS) under the National Oceanic and Atmospheric Administration (NOAA) [6], as a data source for detecting light pollution.

4.1.2. Definition of Symbols

The following **Table** 2 explains the symbols in this model.

Table 2. Symbol description.

Symbols	Definition	Units
DN	Area light intensity value	cd
n	Year	
i	The i-th gray level	
C	Number of pixels	px

4.1.3. Data Preprocessing

Step 1. Sensor Error Correction

Since the DMSP data need to solve the error problem caused by different sensors by inter-correction of data of each year in practical application. Using Elvidge's invariant area method, establish the regression correction model according to Equation (1):

$$DN_{adjusted} = a \times DN^2 + b \times DN + c \tag{1}$$

In equation (1), $DN, DN_{adjusted}$ denote the DN values of raster data before and after correction at the same coordinate point, and a, b, c denote the constant terms and correction coefficients of the regression correction model, respectively.

Step 2. Continuity Correction of Data

Since the raster pixel values of the same coordinate points may decrease or go to zero, it needs to be corrected. The continuity correction function is given by equation (2):

$$DN_n = \begin{cases} DN_{n-1} & DN_{n-1} > DN_n \\ DN_N & DN_{n-1} \leq DN_n \end{cases} \tag{2}$$

In Equation (2), DN_n, DN_{n-1} represent the values of raster image elements at the same position in year n and year n-1, respectively.

4.1.4. Indicator Establishment

Using the Extract by Mask tool in the ArcGIS platform, the DMSP/OLS stabilized lighting data of cloud-free images with radiometric calibration in the region is cropped. The attribute table of the cropped image is then derived, which covers the grayscale values and the number of corresponding image elements.

Based on the gray value of the image elements, the OBI value of the light intensity can be calculated using equations (3) and (4) as follows:

Table 3. Formulas for calculating OBI value.

Indicator name	Expression formula	Indicator description
Total value of nighttime light pixels (OBI)	$OBI = \sum_{i=1}^{63} C_i \times DN_i$(4.3)	Total number of lights in the statistical area
Nighttime light pixel value per square kilometer (OBI/km^2)	$\overline{OBI} = \left(\sum_{i=1}^{63} C_i \times DN_i\right) \div \sum_{i=1}^{63} C_i$ (4.4)	Average level of light radiation (intensity) in the statistical area

Tip：DN_i is the i-th gray level degree, C_i is the number of pixels corresponding to the gray level degree. Due to the gray level of the satellite map is 2^6，the range of i is (1,63).

4.2. Spectral Light Pollution

4.2.1. Indicator Selection—$AER\backslash AP$

Studies have shown that the effects of the spectrum on organisms and the environment arise from two main factors: the degree of Action Efficacy of Radiation (AER) and the degree of Excessive Color Pollution (AP), which is determined by the quality of light (or color) [8].

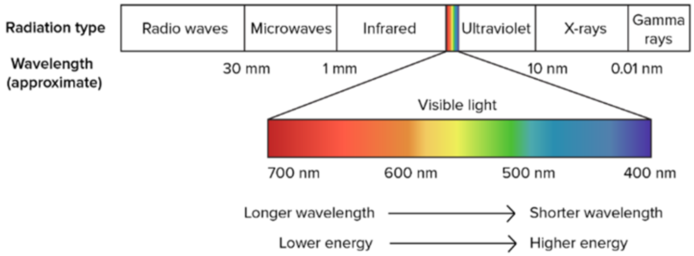

Figure 1. Spectrum (Figure Source: catalyticcolor.com).

4.2.2. Definition of Symbols

The following **Table** 4 explains the symbols in this model.

Table 4. Symbol description.

Symbols	Definition	Units
S	Action spectrum	
P	Spectral power distribution	
K_a	Spectral coefficient of action of the a-th organism	
ϕ	Radiant energy value of the light source	W

4.2.3. Indicator Establishment

(a) Action Efficacy of Radiation –AER

Action Efficacy of Radiation (AER) is a measure of the extent to which the radiance of a light source affects the behavior of organisms.

Step 1. Present the Role Spectrum

A measure is first needed to quantify the degree of effect of different spectra on organisms, called the action spectrum [9]. The figure 2 below shows the variation of the action spectrum [10]:

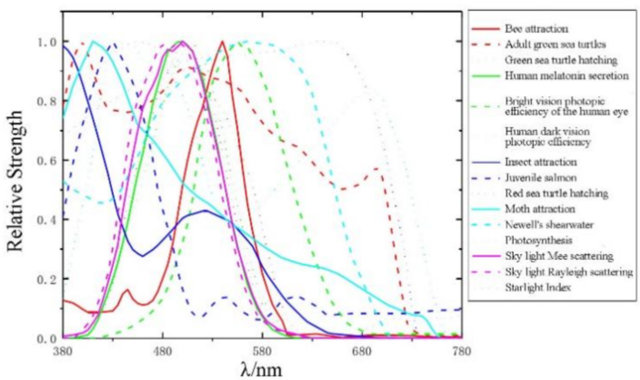

Figure 2. Degree of Spectral Response of Different Species

Step 2. The Theoretical Formula for AER.

Action Efficacy of Radiation (AER) is calculated using the formula (5)

$$AER = \frac{K_a \int P(\lambda)S(\lambda)}{\int P(\lambda)d\lambda} \tag{5}$$

In Equation (5): $P(\lambda)$ represents the spectral power distribution of the light source, $S(\lambda)$ represents the action spectrum, K is the corresponding coefficient, for different action spectra this coefficient is also different, the default is 1.0.

Step 3. The Specific Formula for AER

In the specific calculation, it is necessary to take values for $P(\lambda)$ and $S(\lambda)$. Taking the wavelength interval as 5 nm and the wavelength range as 380-780 mm, the specific Equation (6) can be obtained as follows:

$$AER = \frac{K_a(p_1 s_1 + p_2 s_2 + \cdots + p_x s_x)}{p_1 + p_2 + \cdots + p_x} \tag{6}$$

The spectral action curve of human melatonin secretion is discussed in the AER index calculation to reasonably simplify the analysis and data. For human melatonin secretion, a smaller AER value represents a lower level of contamination. It can also be obtained that this result is consistent for most organisms based on the characteristics of the action spectra.

(b) Excessive Color Pollution (AP)

Step 1. Propose the Average Spectrum of Natural Light Sources

The method of difference comparison for the degree of color excess using the spectra of standard light sources is described in Ref. [11]. For the degree of color excess infringement, the indicator AP is used to measure the average spectral difference between the performance and the natural light source.

Step 2. The Formula for AP

$$AP = \frac{\sum_{\lambda=n_1}^{n_2} \left| \frac{\phi_{ref} - \phi}{\phi_{ref}} \right|_{\lambda}}{n_2 - n_1 + 1} \tag{7}$$

In Equation (7): $n_1 = 380$ nm, $n_2 = 780$ nm.

Since the long-term effects of this unnatural light radiation on humans are unknown, it will remain unknown until the results of long-term studies are conducted [11]. So it is considered that natural light is safe, that is, the smaller the value of the AP indicator, indicating that the more similar to the spectrum of natural light sources, the smaller the degree of aggression of light clutter; conversely the degree of aggression of light clutter.

4.2.4. SLPI Influenced by Spectrum

The above two indicators together constitute the spectral light pollution index:

$$SLPI = \alpha_1 AER + \alpha_2 SQ \tag{8}$$

In equation (8): α_1 and α_2 are the weights, which are subsequently discussed specifically in the model application.

4.3. Perceived Light Pollution Index

4.3.1. Index Selection—PLPI

In this paper, Perceived Light Pollution Index ($PLPI$) is proposed to measure the impact of light pollution on individuals. It is known that the subjective perception of individuals mainly comes from the glare caused by light pollution. The combination of glare evaluation and subjective perception is used to quantify the risk of light pollution [12].

4.3.2. Definition of Symbols

The following **Table** 5 explains the symbols in this model.

Table 5. Symbol definition.

Variables	Definition	Units	Variables	Definition	Units
ω_i	Stereo angle of the i-th light source	°	F	Luminous flux of the light source	lm
θ_i	The angle of glare prod uced by the i-th light so urce	°	I	Luminous intensity of the light so urce	cd
L_i	Brightness of the i-th li ght source	cd/㎡	S	The projection surface of the light source in the direction of the line of sight	㎡
L_b	The background lumina nce of the glare environ ment	cd/㎡	θ	The angle between the normal of the light source and the line of sig ht of the human eye	°
n	Number of glare source s	individ ual	A	The area of the sphere formed by the light source in the direction of the line of sight	㎡
Ω	Stereo angle of light so urce	°	F_i	The luminous flux of the i-th light source	lm
r	Distance from the light source to the human ey e	m			

4.3.3. Indicator Establishment

Step 1. Calculate the Original Glare Level

The nighttime lighting environment includes both dynamic and static aspects. Dynamic lighting mainly includes road vehicle moving lights, etc., while static lighting includes street lights and other light sources. The original glare level is calculated using the glare level G formula proposed in the literature [13].

The calculation Equation (9) is as follows:

$$G = \frac{67.1}{L_b^{0.5}} \sum_n \left(\frac{L_i^{1.67} \times \omega_i}{8.8 \times 10^{-3} \times \theta_i^2 + 1.35} \right) \tag{9}$$

It should be noted that in equation (8) we control the following variables in accordance with the “Urban Road Lighting Design Standard CJJ45-2015” [14] which was released on November 9, 2015:

Table 6. *PLPI* controlled quantification.

	Static lighting (Street light for example)	Dynamic lighting (Headlights for example)
Light intensity in vertical situation (I)	1000 cd (Maximum Allowed)	18000 cd (High beam standard)
Angle of glare generation (θ_i)	30°	
Light source to human eye distance (r)	$\frac{\sqrt{3}}{2}\mathrm{h} \approx 13$ m ($Height\ of\ street\ light\ is\ about$ 15 m)	$\sqrt{2} \times [0.5H(Average\ road\ width) - 1.8]$

Step 2. Processing the G Level

For the G-value we process as follows:

$$I = \frac{F}{4\pi} \tag{10}$$

$$L = \frac{I}{S\cos\theta} \tag{11}$$

$$\Omega = \frac{A}{r^2} \tag{12}$$

4.3.4. Subjective Perceived Light Pollution Index -- PLPI

Based on the above processing, the value of $PLPI$ is calculated by the following equation (13):

$$\frac{1}{PLPI} = \frac{67.1}{L_b^{0.5}} \sum_n \left(\frac{F_i^{1.67} \times 0.037}{\cos\theta_i^{1.67}\, r^2 (8.8 \times 10^{-3} \times \theta_i^2 + 1.35)} \right) \tag{13}$$

Tip: Inverse processing can make the results have a positive relationship with the degree of light pollution, which better reflects the degree of light pollution.

The smaller the $PLPI$ value, the smaller the degree of light pollution reflected by subjective perception, and conversely, the larger.

4.4. Light Pollution Index – ***LPI***

For the three most important nighttime light pollution evaluation indicators, which are OBI, $SLPI$ and $PLPI$, a comprehensive evaluation index--LPI, is obtained by using the entropy weighting method for objective weighting.

Step 1. Dimensionless Normalization

To prevent the influence of dimensions on the sample data in numerical analysis, it is necessary to normalize the indicators before calculating the comprehensive index. The normalized value is shown in the following Equation (14):

$$y_{ij} = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})} \tag{14}$$

In Equation (14): x_{ij} represents the j-th data under the $i-th$ indicator and y_{ij} represents the normalized value of the data under each indicator after normalization.

Step 2. Calculate the Entropy Value and Entropy Weight of the Index

The entropy value of the i-th indicator has the following eq. (15):

$$E_i = -k \sum_{j=1}^{n} P_{ij} \ln(P_{ij}) \tag{15}$$

In Equation (15), constant $k = {}^{1}/_{\ln(n)} > 0$,from which it is ensured $0 \leq E_i \leq 1$.

From the above equation, it can be seen that the entropy value tends to 1 when each data under a certain indicator tends to be consistent; the larger the entropy value reflects the greater similarity of each data under that indicator, the smaller the role of that indicator in decision-making, i.e., the smaller the weight.

The degree of consistency of the contribution under the i-th indicator has the following Equation (16):

$$D_i = 1 - E_i \tag{16}$$

The weight of the i-th indicator based on the degree of consistency of the contribution of the i-th indicator has the following Eq. (16):

$$W_i = \frac{D_i}{\sum_{i=1}^{m} D_i} \tag{17}$$

The magnitudes of entropy value and entropy weight are not the determining importance factors in the evaluation process. They represent the quantitative differences of the useful information provided by each evaluation index in the evaluation process and are an objective evaluation method based on actual sample data.

Step 3. Light Pollution Risk Evaluation Index—LPI

In rating the regional light pollution risk, four index types from the three light pollution factors described above are assigned weights to derive the final index for evaluating light pollution risk:

$$LPI = \alpha X_1 + \beta X_2 + \delta X_3 + \rho X_4 \tag{18}$$

In Equation (18), α, β, δ and ρ correspond to w_1, w_2, w_3 and w_4; X_1 represents OBI, X_2 represents AER, X_3 represents AP, X_4 represents $PLPI$. It should be noted that the weights of each indicator are different in different regions.

Step 4. Light Pollution Risk Evaluation Level

After analyzing a certain number of areas to derive the risk score, the level of light pollution risk can be classified, and the results are shown in the following **Table 7**:

Table 7. Light Pollution Risk Rating Table

Light pollution risk score *LPI*	**Light pollution risk rating**	**Specific manifestations of light pollution**
0-0.1	Almost no pollution	There is very little artificial light in the area, and the impact on the environment and organisms is minimal, and people in the area subjectively perceive darkness at night.

0.1-1	Light pollution	There is less artificial light in the area, but there is a certain degree of impact on the environment and living things, and people in the area at night subjectively think it is darker.
1-3	Moderate pollution	There is more artificial light in the area, which has a greater impact on the environment and organisms, and people in the area subjectively perceive it as brighter at night.
3 and higher	Heavy pollution	Excessive artificial light in the area has seriously damaged the behavior and health of the environment and living things, and people in the area at night subjectively perceive brighter.

5. Conclusion

With the constant development of human material life and culture, light pollution has gradually become a problem that deserves human attention. How to evaluate the risk brought by light pollution is then an important part of the study of light pollution. Accordingly, this paper establishes A Light Pollution Risk Evaluation Model to evaluate the risk level of light pollution in each place. We hope to help people understand the hazards of light pollution by rating the level of light pollution risk.

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