Study on Light Pollution Based on A Broadly Applicable Metric

Yijia Wei *

Department of Mathematics and Applied Mathematics, Shandong Agricultural University, Taian, China

* Corresponding Author Email: 3359641316@qq.com

Abstract. Nowadays, with the development of the economy, light pollution is becoming more and more serious, affecting our health, safety and environment. This paper mainly studies the problem of light pollution. First, a light pollution index measurement model is established, and a widely applicable indicator is developed to determine the risk level of light pollution in an area. Secondly, we selected several nature reserves as specific application sites, and used the model to solve the specific index values of light pollution, and the calculation showed that the calculation results of the model were basically consistent with the actual situation. Finally, based on the classification of light pollution, three intervention strategies are given, and specific implementation measures are given.

Keywords: The Garstang Cinzano Light Propagation Model, Entropy Weight Method, Intervention Strategy, Optimization Model.

1. Introduction

Light pollution is increasing and expanding in the world [1]. It is estimated that global light pollution is growing rapidly at a rate of 6% per year, with increases ranging from areas that have not been mitigated before in developing countries to areas that have been mitigated in developed countries [2]; The problem of light pollution is receiving more and more attention. Measuring and reducing light pollution is an unshirkable responsibility and obligation of human beings to care about their own and environmental safety [3]. Figure 1 provides an overview of the effect of light emitted by outdoor luminaires on the surrounding environment [4].

Terrel Gallaway studied the impact of light pollution on wildlife, human body, astronomy and energy waste, and calculated the annual loss caused by light pollution as high as 7 billion US dollars [5],by taking the United States as an example; Chun Shing Jason Pun et al. Measured the impact of artificial light sources on the night sky brightness of Hong Kong through a night sky brightness detection network [6] ; Wu Yi proposed to control light pollution from the aspects of law, planning and construction qualification certification [7] ; Wang Dong and others put forward suggestions to protect the light environment through the investigation of Shenzhen City [8] ; Liu Ming studied the measurement and evaluation methods of light pollution in urban lighting [9] ; In 1980, the International Astronomical Union (IAU) and the International Commission on Illumination (CIE) jointly issued the initiative of "reducing the sky light near the observatory city", and launched research on the prevention and control of light pollution in the field of astronomy. At present, nearly 1/3 of the United States has passed laws and regulations on light pollution control; The United States has also established the International Dark-sky Association, which specializes in light pollution control, energy waste reduction and night sky protection [10] . In fact, there are few light pollution monitoring and light pollution control strategies, so the research on light pollution is a very important work.

2. Light Pollution Indicator Measurement Model

The artificial radiation indicators we selected are: zenith radiance, average hemispheric radiation, average radiance of 60 degrees, average radiance of zenith distance greater than 80 degrees and horizontal irradiance. To perform the exponential calculation, we use the light propagation model of the atmosphere developed by Gaston and Sinzano, that is, the Gastein-Senzanno light propagation model, which takes into account the following six points: the height of the observation point, the height of the source, the transparency of the atmosphere, the angular radiative intensity of the source, extinction and double scattering correction, and shielding caused by the curvature of the Earth.

2.1. Atmospheric model

we use the clarity parameter K' defined at sea level, To obtain the clarity parameter at other altitudes, for a given ground level H , we get the K as originally defined by Garstang:

$$K = K'e^{(c-a)H} \tag{1}$$

where c = 0.104km−1 is the inverse scale height and a is its inverse scale height.

The relation between a and K is a = 0.657 + 0.059K. We performed the computations for K'=1. Values of three different K'(0.5, 1, and 2) and the corresponding other atmospheric parameters are shown in Table 1.

Table 1. K' value and other atmospheric parameters

Clarity parameter K'	Inverse scale height a (km^{-1})	Optical thickness t	Horizontal visibility (km)	Astronomical extinction at zenith in V band (magnitudes)
1	0.716	0.306	26.1	0.332

We performed the computations using a three parameters upward emission function (UEF), following :

$$I_{up}(\varphi) = \frac{a_1 \cdot 2\cos\varphi + a_2 \cdot 0.5543\varphi^4 + a_3 \cdot q1.778\cos(3\varphi - \frac{\pi}{3})}{2\pi} \tag{2}$$

Where I_{up} is the intensity of the source (W/sr), assumed azimuthally symmetric, φ is the zenith angle measured in the source reference frame, and a_1,a_2,and a_3 are three coefficients that allows to obtain a wide variety of upward emission functions. With a_1=0.757, a_2=0.212 and a_3=0.031 we have the upward function used in the new World Atlas of Artificial Night Sky Brightness, with the parameters found with the best fit with the sky brightness measurements .

The calculation of various indicators is as follows. The average radiance of the whole night hemisphere,(L) , is the simple sum of all the computed values divided by the number of values:

$$(L) = \frac{1}{N}\sum_i B_i \tag{3}$$

Analogously, to have the average radiance in the first 10 degrees above the horizon, we just need to select and average the brightness at the points with zenith distance greater than 80 degrees. For the average radiance at 30° , we made the average of the radiances for points between 29° and 31° above the horizon. To get the horizontal irradiance E, we compute:

$$E = \frac{2\pi}{N}\sum_i \cos\theta_i B_i \tag{4}$$

Where B_i is the artificial radiance of the i-th point, θ_i is its zenith distance, and 2π/N is the solid angle element (sr) in the upper hemisphere, being N the total number of points computed in the sky using a uniform ZEA lattice.

2.2. Entropy weight method

First, standardize the data obtained. We get five indicators, set as x1, x2,..., x5. Assuming that the normalized values of each indicator data are y1, y2,..., y5, there are:

$$Y_{ij} = \frac{X_{ij} - \min(X^i)}{\max(X_i) - \min(X_i)} \tag{5}$$

Then, calculate the information entropy of each index. According to the definition of information entropy, the information entropy of data is:

$$E_j = -\frac{1}{\ln N}\sum_{i=1}^{n} P_{ij} \tag{6}$$

$$E_j = -\frac{1}{\ln N}\sum_{i=1}^{n} P_{ij} \tag{7}$$

Finally, the weight of each indicator can be determined. According to the calculation formula of information entropy, the information entropy of each index is calculated as E1, E2, E3,..., E5, calculate the weight of each index through information entropy:

$$W_i = \frac{1-E_i}{k-\sum E_i}(i = 1,2,\ldots,5) \tag{8}$$

According to the above formula, we calculate the weight as follows: the maximum weight of horizontal irradiance is 28.57%; The average radiance with zenith distance greater than 80。 is 29.82%; The average radiance at 60。 zenith distance is 19.43%; Average hemispherical radiance 16.18%; The zenith radiance is 6.01%.

The index value is obtained through the weight obtained. Standardize the index value from 0-100, and finally divide the light pollution risk level into 1 to 9 according to the light hazard level table, as shown in Table 2.As you can see, the higher the index, the higher the grade, the more serious the light pollution.

Table 2. Light pollution level table

Index	Grade
(0,20]	First level
(20,30]	Second level
(30,40]	Third level
(40,50]	Fourth level
(50,60]	Fifth level
(60,70]	Sixth level
(70,80]	Seventh level
(80,90]	Eighth level
(90,100]	Ninth level

3. Applications

The metrics were applied and interpreted separately for urban communities, suburban areas, rural areas, and protected areas, For this purpose, we selected Seattle, Tongzhou District, Shangshe New Village, and Changbai Mountain Nature Reserve as specific application sites, respectively, and we give a relevant explanation to the final grade.

Assumptions were made for Seattle, Tongzhou District, Shangshe New Village and Changbaishan Nature Reserve, respectively:

A. Vertical stratification, unchanged atmosphere, cleanliness parameter K’=1 (assessed at sea level);

B. The average altitudes of Seattle, Tongzhou District, Shangshe Xincun and Changbaishan Nature Reserve are 56m, 20m, 1820m and 2749m, respectively;

C. The constant heights of the light source in Seattle, Tongzhou District, Shangshe New Village and Changbai Mountain Nature Reserve are 68m, 32m, 1642m and 2530m (the average height of the light source height, weighted by its VIIRS-DNB radiation);

D. The azimuth symmetrically emitting function associated with the zenith is symmetrically upward. Applying computational models Equation (3) and Equation (4), Each indicator is calculated separately, and finally the results of the five indicators of zenith radiance, average 30° radiance, average all sky radiance, average radiance lower than 10° , and horizontal radiance are obtained respectively, as shown in Table 3, and the data is preprocessed.

Table 3. Calculation results of four indicators

region	Zenith radiance(Wm-2sr-1)	Average 30。 Radiance（Wm-2sr-1）	Average all sky radiance(Wm-2sr-1)	Average radiance below 10。(Wm-2sr-1)	Horizontal irradiance(Wm-2)
Seattle	3.718×10-7	4.418×10-7	3.802×10-7	2.066×10-7	1.264×10-6
Tongzhou	3.623×10-7	4.312×10-7	3.603×10-7	1.963×10-7	1.263×10-4
Shangshe New Village	3.432×10-7	4.131×10-7	3.598×10-7	1.952×10-7	1.153×10-6
Changbai Mountain Natural Reserve	3.243×10-7	3.942×10-7	3.304×10-7	1.723×10-7	1.023×10-6

The index values of Seattle, Tongzhou District, Shangshe New Village and Changbai Mountain Nature Reserve were 92.0000, 86.3505, 65.0063 and 33.0000, respectively, and the corresponding light pollution levels were 9, 8, 6 and 3, respectively.

4. Light pollution intervention strategies

In order to reduce or even eliminate the adverse effects of light pollution, three possible intervention strategies are proposed, and the specific actions to implement each strategy are discussed, as well as the potential impact of these intervention strategies on the overall impact of light pollution.

A. Strictly control the construction standards of the building. First of all, it is necessary to strictly control the use area of the glass curtain wall. For special geographical locations, such as intersections of multiple roads, glass curtain walls must not be used. For exterior wall paint materials, people gradually replace dazzling white paint with light yellow and beige to reduce the high brightness of reflected light.

B. Specify clear lighting standards. Reasonable lighting standards are very important to control light pollution. When formulating lighting standards, the following principles should be considered: First, emphasize the requirements of resource conservation and environmental protection. Light pollution is closely related to the light wave characteristics of light, and low-pressure sodium lamps are preferred for environmental protection lamps, followed by high-pressure sodium lamps. Lamps with strong blue light scattering are the lamps with the strongest light pollution, such as metal halide lamps, white LED lamps[11], reducing use and strictly limiting light intensity; Second, fully consider the requirements of long-term economic and social development, set up regional lighting, refer to the international advanced standards of the same period, and avoid innovation. The third is to encourage scientific and technological innovation, in the invention and design of lamps, and the use of new technologies to reduce the harm of light pollution.

C. Formulate relevant legal measures. In order to better control light pollution, national legislation is an effective measure to prevent and control light pollution. First, light pollution is defined according to regional characteristics, and light pollution standards are clearly defined, as well as definition standards and punishment standards for different pollution behaviors. The second is to improve the procedures for resolving disputes over light pollution in environmental protection and the regulations on investigating administrative, civil, and criminal liabilities for light pollution.

5. Optimization model in intervention strategy

Our intervention strategies are to strictly control the building construction standards, specify clear lighting standards, and formulate relevant legal measures. The three intervention strategies are used as constraints and are represented by B, S and V. Take the change of the two site indicators as the objective function, ΔI, and establish the optimization model. Set the target function as:

$$\Delta I = \Delta I_1 + \Delta I_2 + \Delta I_3 + \Delta I_4 + \Delta I_5 \tag{9}$$

Among them, ΔI1 to ΔI5 represent the variation of the five indicators (factors): zenith radiance, average 30° radiance, average all sky radiance, average radiance below 10° , and horizontal irradiance. Three intervention strategies are applied to the objective function, and they all meet the following constraints:

$$\begin{gathered} k_1 B + k_2 S + k_3 V > 0 \\ k_1 + k_2 + k_3 = 1 \\ k_1, k_2, k_3 = 0 \ or\ 1 \end{gathered} \tag{10}$$

Solve the optimization model and observe the impact of three intervention strategies on the indicators widely applicable to the objective function. The results are shown in Table 4.

Table 4. The change of indicator values in the selected two regions

	Index value after intervention	
	Seattle index (initial index value is 92.0000)	Shangshe New Village Index (initial index value is 65.0063)
Intervention 1	70.5952	61.5877
Intervention 2	71.6043	55.7504
Intervention 3	83.4872	63.7481

Then, they correspond to changes in the level of light pollution (i.e. the level of light pollution has decreased by several levels) and the most effective intervention strategies are obtained, respectively: the results are shown in Table 5.

Table 5. The change of indicator values in the selected two regions

	Index value after intervention	
	Seattle level change (initial level is 8)	Shangshe New Village level change (initial level is 6)
Intervention 1	-2 level	0 level
Intervention 2	-2 level	-1 level
Intervention 3	-1 level	0 level

Finally, from Table 5, it can be seen that Seattle's effective intervention strategies are intervention strategy 1 and intervention strategy 2; The effective intervention strategy of Shangshe New Village is intervention strategy 2.

6. Advantages & Disadvantages

6.1. Advantages and applicability of the model

1) What the model establishes is a widely applicable index, which is a comprehensive index that integrates various index factors, and the reference value of the broad index is great.

2) There is a strict model for the calculation of each index factor. The point spread function and Fourier transform are used as the solution methods, which are both rigorous and innovative.

3) Light pollution is a global problem at present, and the establishment of the model provides an evaluation index for light pollution on the one hand, and also facilitates the formulation of solutions on the other hand, which plays a positive role.

6.2. Disadvantages and extensibility of the model

1) The calculation data of each index may not be easy to obtain and prone to errors. We can seek more easily available factors to build models.

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