Study of Light Pollution Risk Evaluation Model

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Abstract. The invention and widespread use of artificial light are important progress in human history, but the light pollution formed by its excessive or poor use is a serious danger to biodiversity and ecosystems, etc. Behind the bright lights of the busy city, it is also a metaphor for the bright starry sky far away from us. Though using the theory and methods of risk identification and evaluation hierarchical model, and unconfirmed measurement model, the index system and the measuring method on the risk level of light pollution are established, the Light pollution risk evaluation model is formed, and they are applied to interpret their results for the four diverse types of locations. The order of the ratings is urban communities, suburban communities, rural communities, and protected land according to high to low. They meet the results from the literature, which confirms the reasonableness of the risk level measures developed. Our work provides a certain reference for the research and treatment of light pollution.

Keywords: Light Pollution; Risk Identification Theory; Unconfirmed Measurement Model.

1. Introduction

Light pollution is the excessive or poor use of artificial light. Although the invention and widespread use of artificial light is obviously one of the most important technological progress, with the industrialization and urbanization of society, light pollution has become the fifth largest pollution, is a new type of pollution after air pollution, water pollution, noise pollution, and solid waste pollution [1]. We can see the world's light pollution situation in figure 1.

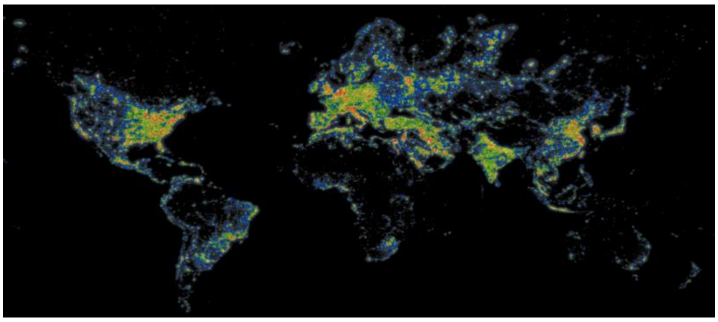

Figure 1: World map of artificial light pollution in 2020

The figure above comes from the website :Light Pollution Science and Technology Institute [2]. Red indicates high levels of light pollution. The country with the most light pollution in the world is Singapore [3].

The paper [4-5] carries out a comprehensive evaluation study of light pollution in residential areas and utilizes the conclusions therein to preliminarily describe the impact of light pollution on the indicators of residents' production and life. The paper [6] in the index compares the current status of light pollution standards at home and abroad and the evaluation requirements of urban night light pollution and analyzes the practicality of evaluation indicators. The research in the papers [7-8], respectively, carried out experiments and data corroboration from the impact of night light on the crime rate and socio-economic aspects, which helped us to establish the relationship equations to these indicators. Paper [9] proposed an evaluation method based on color CCD camera and image processing technology, through the camera imaging and luminance measurement, combined with MATLAB image processing technology, to calculate the luminance contrast and glare values in light-polluted environments. Whereas this paper [10] investigated the application of non-cognitive measurement models in environmental risk assessment, this paper refers to its model and applies it to the risk assessment of light pollution established above.

The paper [11] collected, analyzed the magnitude brightness, illuminance and spectral curve data of each area through the actual measurement of the nighttime light environment in the business districts of Dalian and Milan, which provided us with a reference for the relevant nighttime light data of the selected locations.

The above research explores the evaluation indicators of light pollution and objectively evaluates the current situation of light pollution. It also analyzes the impact of light pollution on residents' lives and urban safety. On this basis, this article evaluates and ranks four representative land-based light pollution risks by developing widely applicable evaluation standards.

2. Light pollution risk evaluation model based on Risk Identification Theory and Unconfirmed Measurement Model

2.1. Construction of light pollution risk assessment index system

As a relatively new environmental problem, light pollution has not been fully recognized, but its various forms pose serious threats to biology and the environment, including eye and skin damage, mental and nervous system effects, and possible cardiovascular and cerebrovascular diseases and traffic safety risks [1].

The unconfirmed measurement evaluation model is more widely used in the field of environmental protection and has strong applicability; it has been used in a large number of risk evaluations in various fields of engineering construction, which can better deal with uncertain information. Light pollution contains a large amount of uncertain information, and the influence factors of light pollution risk on biotic and abiotic measures cannot be simply considered a linear correlation, so this paper uses the unconfirmed measure model to evaluate the risk of light pollution.

According to the theory and method of risk assessment and hierarchical structure model, the community light pollution risk assessment index system can be composed of a three-level index structure model and monitoring index. Considering the differences between different regions (such as urban and rural areas), their evaluation indicators are not necessarily the same. Moreover, the greater the population density, the more power consumption, the more light sources required, and the more serious light pollution. Therefore, population density is used to divide the location, and four different regions are taken as the first-level indicators, which are divided into urban community, suburban community, rural community, and protected land. The secondary index below is the factors affecting light pollution -- biodiversity, population, urban development level, geography, and climate. The following is an analysis of the damage or loss caused by light pollution to its influencing factors to sort out the three-level indicators of light pollution risk assessment and its monitoring technical indicators.

2.2. Quantification method of light pollution risk level based on unconfirmed measure

Light pollution as a by-product of community night lighting, etc. is contrary to the concept of sustainable development, and its sources are complex, so it is important for us to measure and evaluate the risk level of light pollution.

2.2.1 Quantification method of light pollution monitoring technical indicators

Due to the large number of monitoring technical indicators, it is impossible to show the quantification methods one by one. The following four monitoring technical indicators of illuminance, glare control level, light spillover, and light intrusion an examples of quantitative formulas and method descriptions.

(1) Illumination

Light on the illuminated object "adverse consequences" of the severity of illumination is a very important factor, that is, the greater the luminous flux per unit area, the more serious the light pollution. Illuminance can be tested with an illuminance meter and quantified in lux (lx) units. The quantified index gets the control range: urban is a high luminance zone (0-14.6); suburban is a medium luminance zone (0-7.6); rural is a low luminance zone (0-6.5); protected land is a dark zone (0-3).

(2) Glare control level.

The uncomfortable glare hazard caused by light pollution is mainly reflected in residential road glare, therefore, we discuss the residential road integrated brightness glare as a quantitative measure of glare caused by light pollution. Since light intensity has a great influence on glare, the equation in the literature [4] is improved to finally obtain the regression equation of road-integrated luminance glare regarding road ground illuminance and light source lamp height and light intensity as:

$$G = 57.004 + 2.882E - 8.011H + 3.121Z \tag{1}$$

where G is a comprehensive brightness glare control level for residential roads; E is the average illumination on the ground, unit lx; H is the height of the light pole, unit m; and Z is the intensity of light.

Its quantitative indicators standardized control range: 0-5 level (≤ 0.56) for urban areas; 0-4 level (≤ 0.10) for suburban areas; 0-3 level (≤ -0.37) for rural areas; 0-2 level (≤ -0.83) for protected land.

(3) Light spillover

By reviewing the literature, we understand that the study of light spill in residential areas using the spatial model of light spill is able to avoid the study of the shimmer of the light source, and only its relationship to the projection angle needs to be discussed, while the relationship between light spill and the projection angle of the luminaire is a cubic curve function, which is used as a quantitative criterion for the control level of light spill, and its functional equation [4] is:

$$S = 1.381 - 0.03a + 0.009a^2 - 3.5E\ 0.05a^3 \tag{2}$$

The control range of its quantitative indicators: urban (level 0-5): ≤ 0.80; suburban (level 0-4): ≤ 0.75; rural (level 0-3): ≤ 0.55 ; protected land (level 0-1): ≤ 0.25 .

2.2.2 Quantification Evaluation method steps of light pollution risk level

The uncertainty measurement model [5] is widely used in the field of environmental protection and has strong applicability; and it has been applied to risk evaluation in various fields of engineering construction, which can better handle uncertain information. Light pollution contains a large amount of uncertain information, and the influence factors of light pollution risk on biotic and abiotic measures cannot be simply considered a linear correlation, so this paper uses the unconfirmed measure model to evaluate the risk of light pollution. Its calculation steps are as follows:

(1) Classification of light pollution risk comprehensive evaluation level

Combined with the analysis of the problem, the comprehensive evaluation level of light pollution risk in different areas is divided into five levels as shown in Table 1 below. The corresponding risk ranking is:

Table 1: Risk Level

Risk Level	**V**	**IV**	**III**	**II**	**I**
Score Criteria	0-20	20-40	40-60	60-80	80-100

(2) Single-factor measure determination

Let the measured value ϕ_{ij} of the secondary indicators such as biodiversity and residential life under the risk level of light pollution be at the k-th evaluation level $\delta_{ijk} = \delta(\phi_{ij} \in \eta_k)$, then δ_{ijk} is a measure of light pollution water products, as a measure it must meet:

$$0 \le \delta(\phi_j \in \eta_k) \le 1$$
$$\delta(\phi_j \in \eta_k) = 1, \quad i = 1,2,3,4 \ \ \text{j=1,2,3,4,5} \tag{3}$$

where δ_{ijk} is an unconfirmed measure, referred to as a measure.

(3) Determination of indicator weights

Light pollution risk level 1 indicator x_i about the observed value ϕ_{ij} of level 2 indicator φ_i .The vector of unconfirmed measures $\delta_{ij} = (\delta_{ij1}, \delta_{ij2} \cdots, \delta_{ijp})$ that place it at each evaluation level $\eta_1, \eta_2, \cdots, \eta_P$, and in order to know the information entropy of different light pollution indicators, let the information entropy determined by the measures be:

$$e_j = -k\sum_{i=1}^{n} \delta_{ijp} \ln\delta_{ijp}, \ k = \frac{1}{\ln n} \tag{4}$$

At this point, the information entropy needs to be used to determine the third layer of light pollution indicator weights, calculated as shown in equations (6)-(7).

$$v_{ij} = 1 - e_i = 1 + \frac{1}{\ln n}\sum_{i=1}^{n} \delta_{ijp} \ln \delta_{ijp} \tag{5}$$

$$w_{ij} = \frac{v_{ij}}{\sum_{j=1}^{m} v_{ij}} \tag{6}$$

where w_{ij} denotes the j-th index of the i-th evaluation object for the light pollution level, $0 \le w_{ij} \le 1$ and $\sum_{i=1}^{m} w_{ij} = 1$.

(4) Multi-indicator integrated measurement and evaluation matrix construction

Let $\delta_{ij} = \delta(\phi_{ij} \in \eta_p)$ be the multi-indicator composite measure evaluation matrix indicating the degree to which the first level indicator ϕ_i measure belongs to the p-th evaluation level c_p.

$$\delta_{ip} = \sum_{j=1}^{m} w_{ij} \delta_{ijp} \tag{7}$$

(5) Determination of confidence identification criteria

Choose the confidence level as the identification criterion. A pre-determined confidence level λ (1 ≥ λ ≥ 0.5, in this case we choose 0.85) is taken if $\eta_1, \eta_2, \cdots, \eta_P$,then:

$$k_0 = \min\{k : \sum_{i=1}^{n} \delta_{ij} \ge \lambda, (k = 1, 2, \cdots p)\} \tag{8}$$

At this point, determine pollution level measurement sample ϕ_{ij} belongs to the class k_0 .

(6) Determine the results of light pollution risk evaluation

In summary, we get the measurement vector, we specify the scoring of the indicators for the five indicators of the score according to 5, 4, 3, 2, 1 weighted to get the risk level score, the higher the score the less risk.

3. The light pollution risk evaluation model metric & interpret results

The findings in the literature [7] to [11] give the impact of nighttime lighting on productive life in terms of water navigation, crime rate, overall economic indicators, urban business districts, and nighttime light, respectively. In this paper, we refer to these reliable conclusions to construct the community The light pollution risk evaluation model metric.

3.1. Results and analysis of the evaluation of the risk level of light pollution

The above obtained the indicators we need, but considering the differences of different areas (e.g. urban, rural), not every indicator is applicable, and the higher the population density, the more electricity consumption, thin the community more light sources needed, and the more serious light pollution, so the population density should also be included in the indicator system. Based on this, four different types of areas are used as first-level indicators based on population density, divided into an urban community, suburban community, rural community, and protected land. Collating all the above indicators and their monitoring technical indicators, taking urban community as an example, a light pollution risk indicator system is established as shown in table 2.

Establish a light pollution risk indicator system, the rest of the type of location indicator system are the same as the city, but for each indicator is given different weights, so the degree of importance is different.

Table 2: Light pollution risk evaluation index system for urban community

First-order index	Secondary index	Three-level index	Monitoring technical indicators
Urban Communities	Biodiversity	Light intensity	Illumination
		Dynamic Light Type	Dynamic light speed
		Vegetation	Coverage rate
	Resident Life	Affects the quality of sleep of residents	Light infringement level
		Residential electricity consumption	Illumination time
		Brightness balance	Effective light distance
		Light color control	Black, white, color color comparison
	Development level	Light frequency	Light source flicker degree
		Light contrast, color contrast	Glare control level
		Zenith brightness	Up lighting ratio, light spillover
	Geography	Light spacing control	Effective light distance
		Building Type	Building material reflectance
	Climate	Nighttime color temperature	Blu-ray ratio
		Temperature rise	Ozone, carbon dioxide

Based on the evaluation method of light pollution risk level, the risk level is evaluated for each evaluation object using MATLAB 2022 software. The following suburban area is used as an example to show the calculation process and results, and only the final results are given for the other three areas.

(1) The standardized data from all locations in the current area are used as the scores of the three levels of monitoring technical indicators.

(2) Calculation of single metric measurement matrix for secondary metrics, Using y_1 as an example for demonstration:

$$y_1 = \begin{bmatrix} 0 & 0.568781 & 0.431219 & 0 & 0 \\ 0 & 0 & 0.570634 & 0.429366 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

(3) Calculate weights of Primary & Tertiary indicators based on equations (6)-(7) as shown in table 3.

Table 3: weights of primary & tertiary indicators

Secondary index	Monitoring technical indicators	Tertiary indicators
Biodiversity	Illumination	0.383918
	Dynamic light speed	0.297442
	Coverage rate	0.318641
Resident Life	Light infringement level	0.240673
	Illumination time	0.287906
	Effective light distance	0.228811
	Black, white, color color comparison	0.242610
Development level	Light source flicker degree	0.464004
	Glare control level	0.174888
	Up lighting ratio, light spillover	0.361108
Geography	Effective light distance	0.502209
	Building material reflectance	0.497791
Climate	Blu-ray ratio	0.534526
	Ozone, carbon dioxide	0.465474

(4) The weights of the secondary indicators for the current evaluation object were obtained using the entropy weighting method as:

$$W = \begin{bmatrix} 0.167472 & 0.224555 & 0.243884 & 0.154485 & 0.209604 \end{bmatrix} \tag{10}$$

(5) The tertiary weight vector is matrix multiplied with the single-indicator measure matrix of the corresponding secondary indicators to obtain the composite indicator measure matrix:

$$\delta = \begin{bmatrix} 0 & 0.218365 & 0.335283 & 0.127711 & 0.318641 \\ 0.24261 & 0.008039 & 0.287122 & 0.305592 & 0.156636 \\ 0.361108 & 0 & 0.485158 & 0.153734 & 0 \\ 0 & 0.130073 & 0.434041 & 0.435886 & 0 \\ 0 & 0.081026 & 0.737553 & 0.18142 & 0 \end{bmatrix} \tag{11}$$

(6) Obtain the measurement vector M and determine the confidence and risk level by the measurement vector:

$$M = \begin{bmatrix} 0.142548 & 0.075453 & 0.460595 & 0.232868 & 0.088537 \end{bmatrix} \tag{12}$$

3.2. Metric results and interpretation of the risk level of light pollution in the community

3.2.1 Metric results of the risk level of light pollution in the community

According to the application of the model, the first three values in the measurement vector add up to more than 0.85, we have more than 85% certainty that the risk level of this evaluation object (suburban community) is IV, and the weighted risk score is 2.950607.

From the same steps as above, the final light pollution risk level scores and risk level classes of the four areas are obtained in Table 4.

Table 4: Risk levels and risk scores for the four locations

	Monitoring technical indicators	**Tertiary indicators**	**Risk level**
Protected land	0.85	4.84866	**I**
Rural community	0.9	3.88174	**III**
Suburban community	0.9	2.95061	**IV**
Urban community	0.95	1.17386	**V**

As can be seen from Table 4, the level of light pollution risk is least in protected lands, followed by rural areas, then suburban areas, and the greatest risk is in urban community. This conclusion is in line with reality and verifies the accuracy of our conclusion sideways.

3.2.2 Intervention strategies and specific actions

Based on the four community ranked top three significant influencing factors, different intervention strategies and different specific implementation actions are proposed for different influencing factors by combining the topics, the queried literature and the control intervals of each monitoring technical index.

Reduce the overall lighting power by 20%, so that the illumination of the light to the personnel in a reasonable range of 2 to 10 lx.

Reduce the day and night light exposure time by 20%, so that Control the per capita lighting exposure time of urban residents between 8~12h.

Limit the use time and frequency of uplighting, reduce the use time by 70%, the proportion of uplighting in the city safety road should be in 0% ~ 13%.

Suburban communities: 10% overall reduction in lighting power, 5% increase in vegetation planting in suburban areas, 15% reduction in light source flicker.

Rural communities: the effective light distance should be controlled at 9m or more, the light power of rural communities should be reduced by 5%, and the day and night light exposure time should be reduced by 10%.

Protected land: 30% reduction in reflectivity of building materials, 10% overall reduction in light power, 5% increase in vegetation planting.

4. Conclusions

A evaluation index system of light pollution risk level is established using a hierarchical structure model. The monitoring technical indicators corresponding to the three-level indicators are determined by literature research method. The light pollution risk evaluation model is constructed based on the unconfirmed measurement model to determine the measurement criteria of light pollution risk level. The light pollution risk level measure developed based on the unconfirmed measurement model is applied to four different types of locations to assess their risk levels, and obtain their corresponding risk level score and ratings. The order of the ratings is urban communities, suburban communities, rural communities, and protected land according to high to low. They meet the results from the literature, which confirms the reasonableness of the risk level measures developed.

With the deepening of research and analysis, we can use multiple Logistic regression model to measure the relationship between 14 monitoring technical indicators and light pollution risk level in 4 different types of locations in the future, and select important monitoring technical indicators according to the regression coefficient. The control range of each monitoring technical index is determined by the relevant literature. Adjust the selected monitoring technical indicators to the corresponding control range, and put forward further intervention strategies and specific actions. The adjusted monitoring technical index value is substituted into the unconfirmed measurement model, the risk level after the implementation of the corresponding strategy is calculated, and then the potential impact measure of light pollution effect is obtained. At the same time, taking the urban community and suburban community with high risk level of light pollution as an example, taking the light pollution hazard system as the research location, a multi-objective 0-1 mixed integer optimization model based on light pollution hazard system will be established. The improved implicit enumeration method designed by hierarchical sequence method and implicit enumeration method can be used to solve the problem, and the optimal light pollution hazard system is obtained in order to obtain effective intervention strategies and their accurate impact on the risk level.

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