Study of Light Pollution Risk Measurement Based on GIS And EWM-AHP

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Abstract. Light pollution has serious negative impacts on all aspects of human health and biological circadian rhythms. To gain insight into the determinants of light pollution risk and to establish a widely applicable metric to accurately assess the light pollution risk level of an area, an evaluation model of light pollution risk level is developed in this paper. In terms of data acquisition, this paper uses ArcGIS to obtain 12 impact evaluation factors of light pollution risk level. In terms of model building, the metrics of each influencing factor were selected during the process of exploring each influencing factor and the mathematical model of light pollution risk level, and the entropy weight method-hierarchical analysis method (EWM-AHP) combined weight calculation method was used, and finally a model based on logical relationships was established to bring in the data to get the light pollution risk level of the area.

Keywords: Risk level of light pollution; GIS; EWM-AHP Method; Comprehensive evaluation.

1. Introduction

People could always glance up at night to view the magnificent starry sky and be in awe of the magnitude of the universe less than a century ago. The use of artificial light at night has prolonged people's working hours, but it has also made most people almost lose the pleasure of enjoying the starry sky, and even need to bear a heavier price in many ways.

The International Commission on Illumination (CIE) defines light pollution as the sum total of all adverse effects of artificial light (E-ILV 17-29-177 in CIE-S017-2011 (CIE, 2020)). According to the International Dark-Sky Association (IDA) (International Dark-Sky Association (IDA), 2018), light pollution is essentially any form of environmental degradation in which excessive artificial lighting sources (luminaires such as streetlights, neon signs, and illuminated light boards, etc.) affect the environment and human health.

In order to accurately assess the level of light pollution risk in an area, this paper provides insight into the determinants of light pollution risk and establishes a widely applicable metric. In recent years, scholars have made diverse progress in quantifying the assessment of indicators from the process of light pollution generation and propagation. Liu Ming et al. proposed an evaluation index of urban light pollution and an urban light pollution evaluation procedure from the perspective of the overall planning of urban night lighting [1]; Salvador Bará et al. took the transfer of light pollution into account and emphasized the impact of total light pollution on municipal aspects [2]; Constantinos A. Bouroussis et al. quantified more comprehensively the indicators from the perspective of light pollution generation by drone technology [3]; Jiang Wei et al. used linear regression trend method and nighttime light index method to show the light pollution characteristics of China at national, regional and provincial scales, respectively [4].

This paper first qualifies the risk level of light pollution by processing and visualizing NPP-VIIRS nighttime lighting data in ArcGIS, and then proposes a light pollution risk level evaluation model from the generation, propagation, and risk caused by light pollution. It then performs a quantitative analysis of each evaluation factor, obtains data using ArcGIS, and imports it into the model. The general idea of this paper is shown in Figure 1 below.

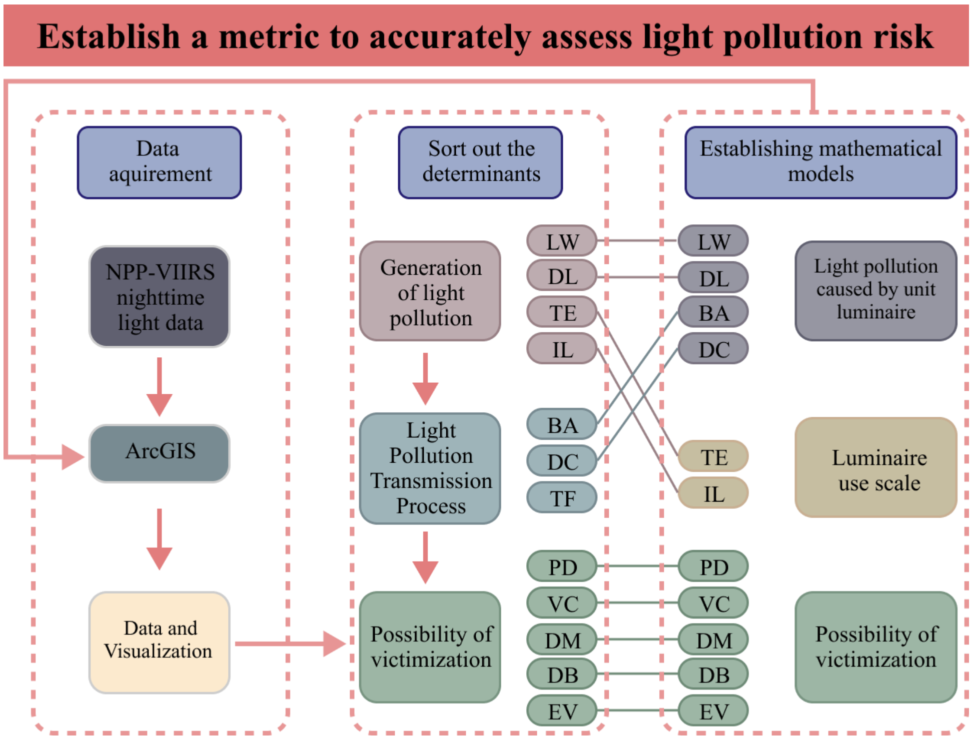

Figure 1. Model building idea

2. Data acquisition and pre-processing

In order to better understand the current situation of light pollution to build a risk level evaluation model, and to better integrate the evaluation factors, this paper uses ArcGIS to extract the data that can directly reflect the current situation of light pollution - nighttime light data, and visualize the nighttime light brightness in the Chinese region to visualize the current situation of light pollution.

The NPP-VIIRS nighttime light measurements were collected by the Suomi-NPP satellite using VIIRS between April and October 2012 at an altitude of 824 kilometers for the National Oceanic and Atmospheric Administration. The information was gathered by using a polar orbit to piece together several cloud-free photos. The NPP-VIIRS nighttime light image data has a spatial resolution of 0.5 km and no saturation effect, which can accurately reflect the nighttime lights in the urban core and has a better radiation detection capability [5]. However, compared to the DMSP/OLS data, it does not remove fires, gas flaring, volcanoes, or auroras, and the corresponding background noise is not filtered. For this investigation, the NPP-VIIRS evening lighting statistics for 2022 were chosen.

The paper selects the Asia Lambert Conformal Conic projection coordinates that are appropriate for China, transforms the NPP-VIIRS nighttime lighting data's coordinates, crops the nighttime lighting data in ArcGIS using the administrative boundary vector of all prefecture-level cities in China as a mask, and then obtains the nighttime lighting dataset and resample it to 50km*50km resolution[6]. The paper also uses the threshold approach to pre-process the NPP-VIIRS photos in order to lessen the noise in the nighttime illumination data. After that, the paper extracts the total DN value of the 2022 NPP-VIIRS image data for all prefecture-level cities. Figure 2 below displays the final results of the data visualization.

In the subsequent evaluation model building, the same method was used to obtain the original data from China National Basic Geographic Information Center and OpenStreetMap and to integrate the data in GIS.

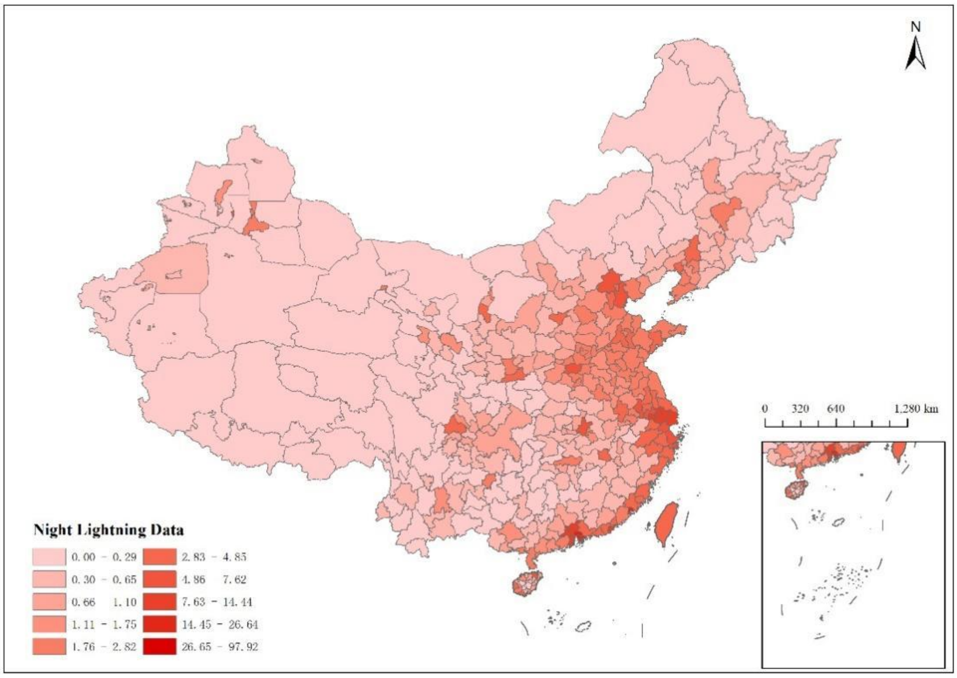

Figure 2. Night Lighting Data Map

3. Evaluation of light pollution risk level

3.1. Key factors for the three sessions

This paper sorts out the influencing factors of light pollution risk by links. The three links are, in order, the generation of light pollution, its propagation, and finally the harm caused to humans and other organisms.

The generation phase of light pollution is the source of the light pollution problem, i.e., the study of light sources. The key factors included are light wavelength (LW), light duration (LP), luminaire arrangement level (DL), and light intensity (IL).

- **Light wavelength (LW):**

Most of the white LED lights on the market now use blue LEDs to excite yellow phosphors to produce white light, while blue light is very harmful to people and other living things. Blue light on the human eye stimulation, long-term exposure to blue light will cause greater harm to the human retina, but also inhibit the secretion of melatonin in the body, increasing the risk of cancer[7]. Blue light can also affect the normal physiological activities of animals, for example, blue light will affect the migration of birds for the direction of judgment.

- **Light occupancy rate (LP):**

Light pollution is defined as excess lighting that is turned on before the sky brightness drops to a certain value, whereas LP is defined as the percentage of time that excess lighting is turned on throughout the day. In the equation below, TE represents the total lighting time in the area.

$$LP = \frac{max\{0，TE-16\}}{D} \tag{1}$$

- **Luminaire layout skeme (DL):**

The arrangement level of the luminaire directly determines the light dispersion ability and dispersion angle. Dispersion capacity and dispersion angle. Dispersion capacity depends on the shading of the luminaire, while in terms of dispersion angle, if the elevation angle exceeds 120°, the contribution to light pollution will increase significantly [8]. In the formula below, *NLA* is the number of fully shaded luminaires, *LA* is the total number of luminaires, and *NLE* is the number of lights with elevation angles over 120°.

$$DL = min\left\{1, \frac{NLA*e^{\frac{1}{NLE}-\frac{1}{LA}}}{LA}\right\} \tag{2}$$

- **Illuminance (IL):**

The data of light intensity comes from GIS processing, and to some extent it can be considered that the light intensity can represent the density of the luminaire.

Figure 3 below illustrates the primary measurable influences that contribute to the production of light pollution.

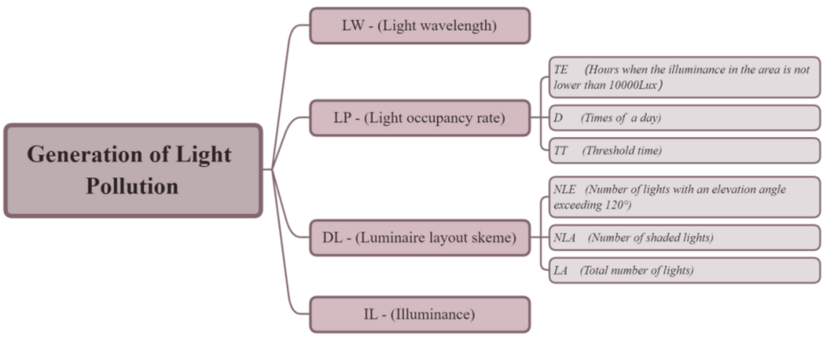

Figure 3. Generation of Light Pollution

The key factors involved in light pollution propagation are the atmospheric effect index (BA), distribution of curtain wall (DC).

- **Atmosphere effect index (BA):**

The more pollutants in the atmosphere, the stronger the diffuse reflection of light in the atmosphere, and the atmospheric action index is also related to the selected location's altitude [9]. In the following equation, β and θ are constants, h is the regional average altitude, and k is the pollutant concentration in the atmosphere.

$$BA = \frac{1}{\beta h - \ln k + \theta} \tag{3}$$

- **Distribution of curtain wall (DC):**

A curtain wall is a façade that reflects light from the exterior surface of a building. The density of curtain wall can express the probability of light being reflected by the façade of the external surface of the building or even reflected several times [10]. The density of curtain wall is related to the following four quantities: CP, AP, AC, AH. CP is the density of regional high-rise buildings, AP*AC is the sum of façade area of high-rise buildings, AH is the constant of reflectable area in façade, AS is the area of regional area. Curtain wall density is defined as:

$$DC = \frac{CP*AP*AC*AH}{AS} \tag{4}$$

Figure 4 below displays the primary measurable factors on the spread of light pollution.

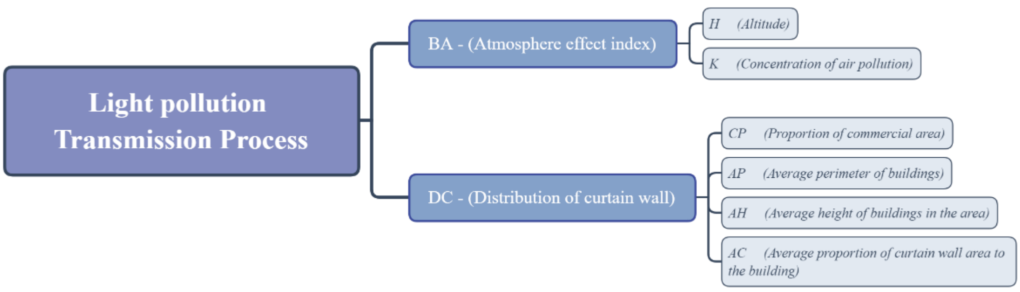

Figure 4. Light Pollution Transmission Process

The severity of the damage caused by light pollution to the organisms in the area is determined by the ecosystem's fragility and the density of the organisms. (Analogy: the number of casualties caused by an earthquake depends not only on the intensity of the earthquake, but also on population density and building resistance in the area.) We define this as the likelihood of damage, considering both humans and non-humans.

- **Population density (PD):**

the probability of victimization depends on the population density (PD), defined as:

$$PD = \frac{PN}{AS} \tag{5}$$

- **Distribution of marine life (DM):**

Number of marine organisms: There are many plankton and amphibians near the coastline, such as sea turtles, etc. We consider the density of organisms distributed along the coastline as a constant value, then the number of marine organisms affected by light pollution depends on the length of the coastline.

- **Vegetation coverage (VC):**

Plants provide food and living space for animals, so we can measure the density of plants and terrestrial animals by plant cover.

$$VC = \frac{AC}{AS} \tag{6}$$

- **Vegetation coverage (DB):**

Define the number of birdlife affected by light pollution in the area as the number of birdlife in the area in a year.

$$DB = \frac{NBA}{AS} \tag{7}$$

In addition: for some extremely fragile ecosystems we attach great importance and will use the fragility of the ecosystem to measure the wind level of light pollution in that particular area.
Figure 5 below depicts the primary factors that can affect the hazards that could result from light pollution

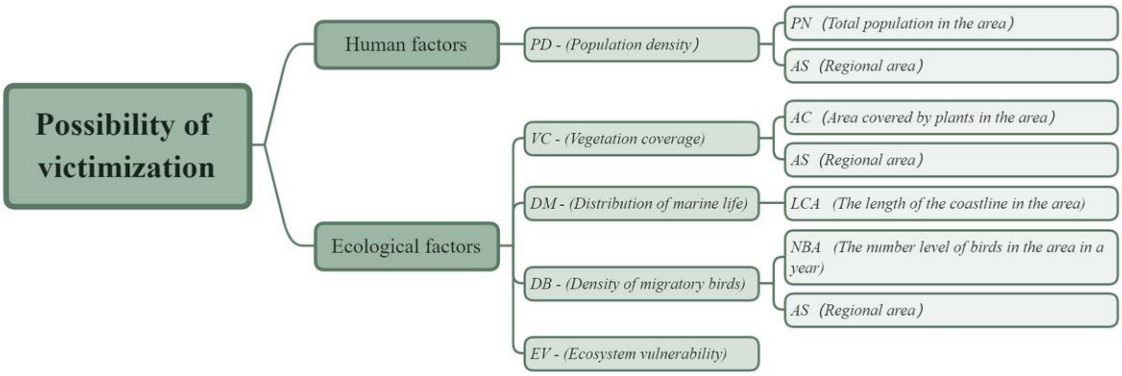

Figure 5. Possibility of victimization

3.2. Light pollution risk assessment

To clarify the relationship between each indicator and the risk of light pollution, this paper divides some of the key indicators into three categories: this paper uses the entropy weight - hierarchical analysis to determine the indicator weights, and uses light pollution caused by unit lamps, the scale of lamp use, human and non-human organisms, respectively, as sub-indicators to quantitatively describe the level of light pollution risk. The paper uses entropy-hierarchy analysis to determine the weight of the indexes, and the score can be determined by bringing in regional data and then evaluating the risk level of light pollution.

First, the paper defines the sub-indicators as light pollution caused by unit lamps, lamp usage scale, and human and biological situation. The sub-indicators that correspond to the secondary indicators are as Figure 6 below.

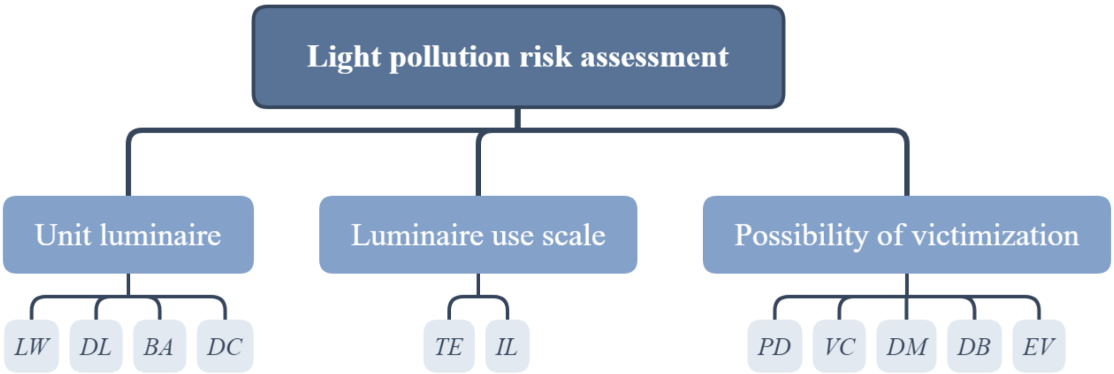

Figure 6. Light pollution risk assessment map

The factor set is U={U1,U2,U3},U1,U2,U3 respectively as stated above, and in addition the factor set is denoted as

$$U1 = (u11, u12, u13, u14) \tag{8}$$

$$U2 = (u21, u22) \tag{9}$$

$$U3 = (u31, u32, u33, u34, u35) \tag{10}$$

3.3. Weight of EWM

Entropy Weight method (EWM) is an objective weighting method to determine the weight based on the amount of information contained in each index, and its core concept is information entropy, which is used to reflect the degree of variation of the index. Let there be m evaluation objects and n evaluation indicators, and the calculation steps of EWM method are as follows[11].

(1) Among the indicators evaluated, there are positive and negative indicators, and these indicators need to be normalized.

When Xij is a positive indicator

$$Y_{ij} = \frac{X_{ij} - min(X_j)}{max(X_j) - min(X_j)} \tag{11}$$

When X_{ij} is a negative indicator

$$Y_{ij} = \frac{max(X_j) - X_{ij}}{max(X_j) - min(X_j)} \tag{12}$$

Where X_{ij} is the value of the jth evaluation index of the ith evaluation object; Y_{ij} is the index value after standardization of X_{ij}.

(2) Indicator weight calculation. The formula is as follows

$$P_{ij} = \frac{Y_{ij}}{\sum_{i=1}^{n} Y_{ij}} \tag{13}$$

where P_{ij} is the weight of the indicator value of the jth indicator of the ith evaluation object.

(3) The determination of the information entropy of the index. The formula is as follows

$$E_j = -\frac{\sum_{i=1}^{n} P_{ij} \ln(P_{ij})}{\ln n} \tag{14}$$

where E_j is the information entropy; n is the number of evaluation indicators.

(4) Calculation of weights based on entropy values.

$$W_j = \frac{(1-E_j)}{\sum_{j=1}^{m}(1-E_j)} \tag{15}$$

where W_j is the weight of indicator j.

The weights calculated by EWM are as follows.

W_{E1} = (0.227905799, 0.253228665, 0.303874399, 0.214991137)

W_{E2} = (0.142919111, 0.857080889)

W_{E3} = (0.452054397, 0.228984835, 0.144982167, 0.173978601)

3.4. Weight of AHP

The 1-9 scaling method was used to compare the indicators two by two, and the judgment matrix of each layer was derived, and the AHP weights were calculated, and finally the results were tested for consistency.

The weights calculated by AHP are as follows

W_{A1} = (0.426453, 0.230764, 0.214437, 0.128346)

W_{A2} = (0.23811, 0.76189)

W_{A3} = (0.476027, 0.249392, 0.146741, 0.127839)

3.5. EWM-AHP combination weights

The hierarchical analysis method and the entropy method belong to the subjective and objective weighting methods respectively, and both methods have their own short- comings. The hierarchical analysis method is heavily interfered by human factors, but the weights obtained by the entropy method also mainly reflect the direct degree of variation of each indicator but not the importance of the indicator, so the entropy method- hierarchical analysis method (EWM-AHP) combined weighting calculation method can be used. Combining the subjective and objective methods can reflect both the judgment of decision makers on the importance of indicators and the variation differences of actual data objectively.

By linear weighting of the two weight variables, this paper obtained the most valuable combination weights W_k

$$\mathrm{Wk} = \alpha \mathrm{WAk} + (1-\alpha)\mathrm{WEk} \tag{16}$$

The coefficients represent the degree of importance of the objective and subjective weights, and we choose $\alpha = 0.4$ to calculate the final portfolio weights.

3.6. Calculation of risk assessment levels

For the three levels of indicators, there is the problem of inconsistent magnitudes, we forward and standardize the data, forward the negative indicators, and min-max standardize each data. In order to make the model more universal, and to ensure that the indicator values are all in the [0, 1] interval, we obtained the upper and lower bounds of each indicator to obtain the standardized data.

Positive indicators.

$$Y_{ij} = \frac{X_{ij} - \mu_{j,min}}{\mu_{j,max} - \mu_{j,min}} \tag{17}$$

Negative indicators.

$$Y_{ij} = \frac{\mu_{j,max} - X_{ij}}{\mu_{j,max} - \mu_{j,min}} \tag{18}$$

where $\mu_{j,max}$ $\mu_{j,min}$ are the upper and lower bounds of each indicator

We use the additive model to calculate the corresponding risk assessment score for each level separately

$$\mathrm{Rk} = \mathrm{YkWT} \tag{19}$$

The additive model is applicable to the indicators with weak correlation between each other, for the three levels of composite indicators, there is a correlation between them, so we perform multiplicative model for the indicators of the three levels.

The weights between the three levels are calculated by the AHP method pair ω = (1⁄3, 1⁄3, 1⁄3)

According to the multiplicative model, the final risk area score is

$$R = \prod_{k=1}^{3} R_k^{\omega_k} \tag{20}$$

This paper evaluated the risk level of light pollution in more than 200 areas and obtained the following frequency histograms, then analyzed the distribution of data according to the level of classification. The distribution of sample scores in Figure 8 clearly demonstrates the ranking process.

(1) Low risk level: [0-2]: the level of light pollution is low, the risk is low, and the light pollution to humans has little impact on the environment.

(2) Medium risk level: [2-5]: the level of light pollution is moderate, with a certain level of risk that can affect people's daily lives.

(3) Medium-high risk level: [2-5]: the level of light pollution is medium , light pollution will have a greater impact on people's daily lives and the environment.

(4) High risk level: [>10]: light pollution level is high, affecting people’s physical and mental health and ecological balance and stability.

In Figure 7 below, the risk level scores of the selected samples are visualized by interval and the risk level levels are classified according to the frequency.

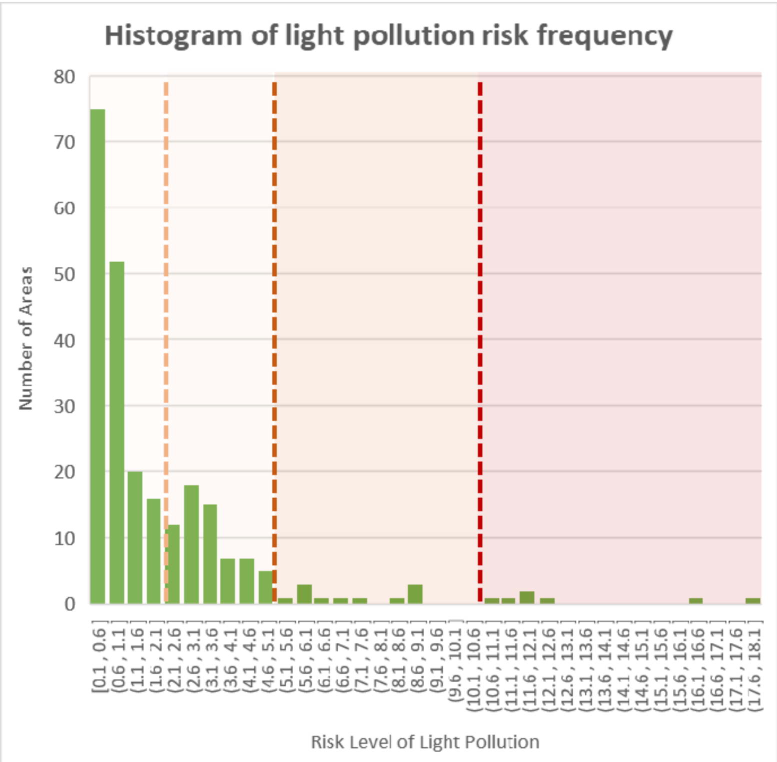

Figure 7. Histogram of light pollution risk frequency

4. Conclusions

Excessive and inappropriate use of outdoor light sources has resulted in serious light pollution. Light pollution has serious negative effects in several ways: light pollution prevents most people from enjoying the starry sky, affects human health and safety, circadian rhythms of living things, etc. The glare caused by artificial light may also cause some motor vehicle accidents. Therefore, this paper develops an evaluation model to determine the light pollution risk level and propose possible intervention strategies to mitigate its effects.

This paper first comprehensively sorted out the influencing factors in terms of light pollution generation, propagation, and causing harm, and provided methods to quantify them. In the process of exploring each influencing factor and the mathematical model of light pollution risk level, this pater classified the influencing factors into the following three aspects: light pollution caused by unit lamps, the scale of lamp use, and human and non-human organisms, respectively, as quantitative descriptions of light pollution The risk level of the sub-indicators, then each influence factor is a secondary indicator, this paper used the entropy weight method - hierarchical analysis method (EWM-AHP) combination weight calculation method, the combination of subjective and objective methods to determine the indicator weights. At the end, this paper established a mathematical model based on logical relationships, collected data, quantified, and obtained the light pollution risk level in the area.

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