Research on Light Pollution Risk Assessment Model Based on AHP-EWM

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Abstract. In the past ten years, municipalities and private light users worldwide have installed light-emitting diodes in urban spaces and public streets to save energy. Yet an increasing body of research suggests LED create more light pollution. Light pollution is threatening us. By combining AHP and EWM, a light pollution risk assessment model is developed, considering 20 factors in 5 categories, including physical properties of lamps, natural conditions and economic development. The model divides the light pollution risk score into 5 intervals. The light pollution risk assessment model is applied to Shennongjia, China (protected land), Wanrong, Laos (rural area), Chiang Rai, Thailand (suburban area) and Tokyo, Japan (urban area). The calculated light pollution risk scores and grades are 0.11 (good), 0.23 (good), 0.45 (moderate) and 1.3 (very unhealthy). The paper also proposes some intervention strategies to suppress the adverse effects of light pollution.

Keywords: Light Pollution, AHP-EWM, Risk Assessment Model, Intervention Strategies.

1. Introduction

In recent decades, global urbanization and population growth have accelerated, and the density and scope of artificial lighting has become increasingly extensive, creating a new global lighting environment [1]. Artificial lighting at night is a double-edged sword that raises a series of human health and ecological problems while improving social development and quality of life. Globally, more than 6 million km^2 of protected areas are reported to be under enormous human pressure. Among these disturbances, severe nocturnal light pollution has widespread and far-reaching biological impacts on species and ecology [2,3], affecting bird migration, disrupting circadian rhythms, and destroying species diversity.

Therefore, action to curb the negative effects of light pollution is necessary. However, the degree of exposure to light pollution varies from region to region. Based on determining light pollution risk levels, targeted interventions based on local ecological and economic conditions are essential to address the light pollution problem.

2. Light pollution risk assessment model

Light pollution is a problem caused by the excessive use of lighting systems by humans. Light pollution is a convergence of many problems[4], and the paper introduces 20 indicators to assess the risk of light pollution in a region using the joint AHP-EWM weighting method in five dimensions. Table 1 illustrates these indicators.

Table 1. Light pollution risk assessment index

Light Pollution Risk Evaluation Index			
Physical Property of Lamps	Night Lighting Duration	Economic Development	Per Capita GDP
	Overall lighting ratio		Disposable Income
	Glare Control Level		Employment Rate
	Zenith Luminance	Energy consumption	Residential Energy Consumption
	Extinction Duration		Industrial Energy Consumption
	Light Intensity		Commercial Energy Consumption
Natural Conditions	Air Quality Index	Community Features	Population Density
	Forest Coverage Rate		Traffic Density
	Precipitation		Lighting Power Consumption
	Altitude		Community-Friendly Lighting Subsidies

2.1. Indicator weight determination

Considering the internal connection of the indicators the paper selects, the paper uses the subjective and objective weighting method to determine the indicator weight.

2.1.1 Calculate weight by AHP

Analytic Hierarchy Process (AHP) regards the complex problem to be studied as a large system affected by many factors, and then decomposes the interrelated and mutually restrictive factors into several orderly levels according to their affiliation. And according to certain objective facts, make a comparative judgment on the importance of the two indicators. Through the analysis of each level, the weight of the importance of different programs is obtained. Include the following four steps.

Establish a hierarchical structure model: target layer, criterion layer, solution layer.

Construct the judgment matrix:

$$A=(a_{ij})_{n\times m}, a_{ij}>0, a_{ji}=\frac{1}{a_{ij}}, a_{ii}=1 \tag{1}$$

For the five aspects of the criterion layer, the judgment matrix obtained through the demand map of light pollution and the scaling method is as follows:

$$\begin{pmatrix} 1 & \frac{1}{2} & 4 & 3 & 3 \\ 2 & 1 & 7 & 5 & 5 \\ 2 & \frac{1}{7} & 1 & \frac{1}{2} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{5} & 2 & 1 & 1 \\ \frac{1}{3} & \frac{1}{5} & 3 & 1 & 1 \end{pmatrix} \tag{2}$$

The consistency test of the judgment matrix is carried out using the consistency ratio CR. The calculation formula is as follows:

$$CR=\frac{CI}{RI} \tag{3}$$

$$CI=\frac{lambda_{\max}-n}{n-1} \tag{4}$$

Where RI is the average random consistency index, CI is the consistency index.

$CR\leqslant 0.1$, it passed the consistency check.

Use the eigenvalue method to obtain the index weight.

2.1.2 Calculate weight by EWH

The entropy weight method (EWM) is an objective weighting method, which determines the objective weight according to the variability of the index. The greater the degree of dispersion of the index, the greater the weight it occupies in the comprehensive evaluation.

$$\omega_j^{EWM} = \frac{1-e_j}{\sum_{j=1}^{m} 1-e_j} \tag{5}$$

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} p_{ij} \ln(p_{ij}) \ln(p_{ij}), i = 1, 2, \cdots n \tag{6}$$

$$p_{ij} = \frac{z_{ij}^{EWM}}{\sum_{i=1}^{n} z_{ij}^{EWM}} \tag{7}$$

Where e_j represents the Information entropy of j^{th} indicator, ω_j^{EWM} represents the weight of the j^{th} indicator calculated by EWM.

2.1.3 Weight average

The paper wants to reduce the subjectivity of AHP, which can be supplemented by EWM. The paper gets the weights of indicators, combining AHP and EWM.

The paper defines the equation as follows.

$$\omega_j = \alpha \omega_j^{AHP} + \beta \omega_j^{EWM} \tag{8}$$

Where w_j^{AHP} and ω_j^{EWM} represent respectively the weight of the j^{th} indicator calculated by AHP and EWM. Here the paper supposes $\alpha = 0.3, \beta = 0.7$.

Finally the paper gets the weights of all indicators. The indicator weights are shown in Table 2.

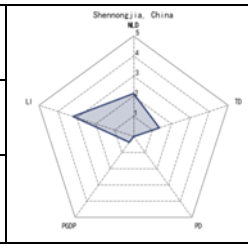
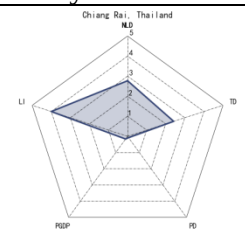
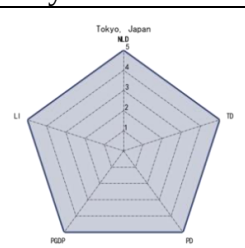
Table 2. Light Pollution Risk Indicator Weights

Physical property of lamps		Natural conditions		Economic development		Energy consumption		Community features	
Night lighting duration	0.025	Air quality index	0.036	Per capita GDP	0.057	Residential energy consumption	0.024	Population density	0.081
Overall lighting ratio	0.062								
Glare control level	0.018	Forest coverage rate	0.071	Disposable income	0.070	Industrial energy consumption	0.067	Traffic density	0.057
Zenith luminance	0.058								
Extinction duration	0.043	Precipitation	0.069	Employment rate	0.007	Commercial energy consumption	0.016	Lighting power consumption	0.073
Light intensity	0.075	Altitude	0.065					Community-friendly lighting subsidies	0.025

2.2. Application of light pollution risk assessment model

The paper applies the light pollution risk assessment model to Shennongjia in China(protected land), Wanrong in Laos(rural community), Chiang Rai in Thailand(suburban community), and Tokyo in Japan(urban community). The results of the assessment for the four communities are shown in Table 3.

Table 3. Basic Information about the Community

Protected Land			Suburban Community		
Location	Shennongjia, China		Location	Chiang Rai, Thailand	
Coordinates	31°21’N, 110°33’E		Coordinates	19°54’N , 99°49′E	
Risk Score Risk Level	0.11 Good		Risk Score Risk Level	0.45 Moderate	
Rural Community			**Urban Community**		
Location	Wanrong, Laos		Location	Tokyo, Japan	
Coordinates	18°55’N, 102°26’E		Coordinates	35°69’N, 139°69’E	
Risk Score Risk Level	0.23 Good		Risk Score Risk Level	1.3 Very unhealthy	

The light pollution risk scores of the four areas calculated by applying the light pollution assessment model are 0.11, 0.23, 0.45, and 1.3, respectively belonging to good, good, moderate and very unhealthy levels.

Shennongjia Nature Reserve is located in Hubei Province, China. It is a protected area of international significance, rich in natural resources, complete ecosystem, and well-preserved photobiotic communities. The population and traffic density are small, and it belongs to the natural dark area at night, with less light pollution and a better environment.

Wanrong is located in the northern part of Vientiane Province, Laos. It is famous for its karst land forms and outdoor activities by mountain lakes. It belongs to the countryside. The population and traffic densities are small, and the economic development is relatively backward. Residents mainly use natural light, with little lighting at night and light pollution. The geographical locations of the four communities are shown in Fig 1.



Fig 1. Community Location Map

Chiang Rai is located at the northernmost tip of Thailand, 180 kilometers away from Chiang Mai, the second largest city in Thailand. The prefecture's economy is dominated by agriculture and animal husbandry. The land in the dam area is fertile and rich in rice, known as the "Northern Granary". The mountainous area is rich in wood, and animal husbandry is very developed. With the development of regional economy, the risk of light pollution will gradually increase. The problem of light pollution is a problem that local governments and people need to pay attention to.

Tokyo is an important world-class city in Asia. It has the largest metropolitan area in the world. It is found through the night light map that its nighttime brightness is much higher than that of domestic and foreign cities. The extremely high economic development and urbanization level have resulted in extremely serious light pollution in downtown Tokyo.

3. Light pollution impact and intervention strategies

3.1. Light pollution impact system

Light pollution has a complex impact on human society and natural ecology[5]. Light pollution makes communities as bright as day at night, providing a safe and bright working environment. Many studies have shown the harmful effects of light pollution on plant and animal migration, survival and human health. Light pollution and air pollutants work together to disrupt the migration of migrating birds[6]. Light pollution not only increases the risk of obesity and mental disorders in humans, but also disrupts melatonin balance in the body and increases the number of cases of breast and prostate cancer[7]. In order to show the impact of light pollution as comprehensively as possible, this paper constructs a comprehensive light pollution impact system, using nine indicators to depict the scope and extent of light pollution impact from three aspects: ecological, social and economic. Table 4 shows our proposed light pollution impact system.

Table 4. Light Pollution Risk Evaluation Indicators

Light Pollution Impact System		
Ecology Quality Index	Species Diversity Index	The number of species of a species, the variability between species, and the closeness of relationships between species
	Air Quality Index	Average content of pollutants in the air
	Precipitation	The total amount of precipitation in a given area at a given time
	UV Index	UV intensity in outdoor radiated sunlight
Social Quality Index	Cancer Proportion	The proportion of people suffering from various types of cancer to the total population in a certain region in a certain period of time
	Sleep Disorder Rate	The proportion of people with sleep disorders in a certain area to the total population in a certain period of time
	Crime Rate	Percentage of crime cases per 100,000 population
Growth Potential Index	Per Capita GDP	Gross domestic production per unit of population in a country or region
	Lighting Power Consumption	Power consumed for lighting activities over a period of time

3.2. Light Pollution Intervention Strategies

Light pollution is a global problem that affects social development and human health, involving all aspects of environmental ecology, low-carbon energy conservation, social well-being, and power supply and lighting[8,9]. In order to reduce the harm of light pollution, the society has been trying to find solutions to improve the current situation of light pollution. This paper proposes three corresponding light pollution intervention strategies: Controlling the extent and duration of artificial light exposure. Retrofitting community street lights and electronic billboards. Implementing a subsidy policy for community-friendly lamps.

3.2.1 Controlling the use of artificial light

More than 80% of the world's population is exposed to artificial light at night, a behavior that suppresses melatonin secretion and affects sleep quality and normal organ functioning[10]. Cutting off exposure channels to excessive artificial light and controlling the duration, distance and intensity of people's exposure to artificial light can reduce the adverse effects of light pollution.

Distance limit from enterprises with serious light pollution to residential communities.

$$C_1^1 = FCR \times \frac{ER}{LO} + TD^2 \times \frac{LI}{IEC} \tag{9}$$

where C_1^1 represents the 1st measure of the 1st strategy. FCR represents the forest cover. ER represents the employment rate. LO represents the hours of lights out. TD represents traffic density. LI represents light intensity. IEC represents industrial energy consumption.

Lighting intensity and duration control of community lamps.

Manufacturing enterprises inevitably use high-brightness lamps and lanterns in the production process to meet the brightness requirements of the production process. In order to reduce light pollution from enterprises, enterprises closer to residential communities should move out and re-plan their sites. This measure requires enterprises to pay the relocation costs, leasing costs and renovation costs, the government needs to give enterprises compensation and fund the appropriate infrastructure.

Lighting intensity and duration control of community lamps.

$$C_1^2 = \frac{PD + TD \times LPC}{LO + LI/CEC + IEC} \tag{10}$$

Where, PD represents the population density. LPC represents lighting electricity consumption. CEC represents commercial energy consumption.

In the short term, the community can not replace all the high light pollution lamps and lanterns, in the policy transition period need to mandate the use of community lamps and lanterns hours and quantities, and develop some necessary penalties, which may cause dissatisfaction from the residential, commercial and industrial areas of the population, while causing some economic losses. When implementing the restriction measures, the government should be financially compensated according to the control hours and brightness.

3.2.2 Retrofitting community streetlights and building walls

There are three types of light pollution: bright white pollution, artificial daylight, and colored light pollution. A large portion of the first two comes from streetlights and electronic billboards lining community streets, while the latter mainly comes from the glossy facades of buildings. Our community street renovation strategy curbs light pollution by replacing streetlights, building glossy facades, and removing electronic billboards.

Replacing traditional high-pressure streetlights with LED lights.

$$C_2^1 = 1000k_1 \times PD \tag{11}$$

Street lighting usually uses high-pressure sodium lamps, poor color rendering performance, and four-sided light, with obvious strobe, such lamps light pollution is more serious. The new LED lamp working temperature is low, high light utilization, no obvious strobe, and it does not make easy to cause light pollution. Therefore, the traditional street high-pressure sodium lamp replaced by LED lights can significantly improve energy utilization and reduce light pollution.

Replacing the smooth exterior of the building with a rough material façade.

$$C_2^2 = 27Area \tag{12}$$

Where, Area indicates the area of exterior wall replacement.

Common glass curtain walls, glazed brick walls, polished marble, and other architectural walls with high reflectivity, both long and short wavelengths of light, can be easily reflected by such walls. Reflected light is white, bright, and dazzling, interfering with the vision of drivers and pedestrians and quickly causing traffic accidents. Replacing smooth facades with rough facades can reduce light reflectivity, thus reducing the damage caused by light pollution.

Removing large electronic billboards.

The United Nations Environment Program survey shows that the average brightness of electronic billboards is five times that of traditional light boxes. The excessively bright lights make the surrounding environment feel like daytime, seriously affecting the residents' night rest and disturbing their lives. Removing large electronic advertising screens will save unnecessary electricity waste and improve nearby residents' quality of life.

$$C_2^3 = 3500k_2 \times DI \tag{13}$$

Where, DI represents disposable income per capita.

3.2.3 Community-friendly luminaire subsidy policy incentives

Luminaires of all types are essential contributors to artificial light. More community-friendly luminaires should be used to weaken the harmful effects of light pollution. It refers to luminaires with high energy efficiency, long service life, and low ecological and human health hazards. Implementing different subsidies for community-friendly luminaires for different actors can increase people's awareness to reduce artificial light exposure actively.

Issuance of community-friendly lamps and lanterns technology innovation subsidies

$$C_3^1 = \frac{(AQI \times PGDP^2 + LR/GCL)}{IEC} + PD^2 + \ln LPC \tag{14}$$

Where AQI Indicates the air quality index. $PGDP$ denotes the GDP per capita. LR denotes the lighting ratio. denotes the glare control level. GCL denotes the level of glare control.

Issuance of subsidies for the consumption of community-friendly lamps

$$C_3^2 = 500k_3 \times PD \times CFS \tag{15}$$

where CFS represents community-friendly luminaire subsidy.

For individuals and groups who wholesale and purchase community-friendly luminaires, consumption subsidies can reduce consumption costs, increase consumer surplus, and gain more benefits. Therefore, by granting purchase subsidies, people will be more inclined to choose community-friendly lamps and consciously commit themselves to resisting light pollution.

4. Correlation analysis

The possible impact of the same action on the impact of light pollution in different areas is different, which is related to the local natural ecological environment and economic conditions. The possible impact of actions on the impact of light pollution is discussed using the Chinese region as an example. Considering that the paper has quantified the cost of measures with the indicators in the light pollution risk assessment model, the Spearman coefficient is used to determine the correlation between the indicators of the light pollution risk assessment model and the indicators in the comprehensive impact system of light pollution.in order to discuss the possible impact of specific measures on light pollution . Bringing in the average data of China, the Spearman correlation coefficient is as follows Fig 2.

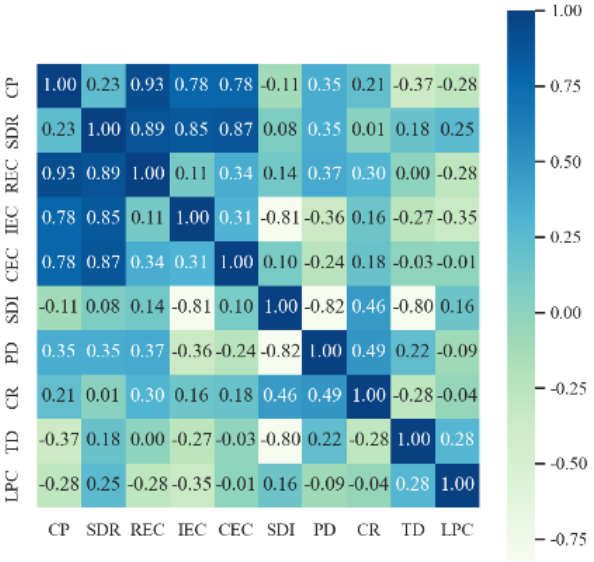


Fig 2. Spearman Correlation Coefficient Graph

5. Conclusions

(1) Cancer rate and sleep disorder rate are both significantly and positively correlated with residential energy consumption, industrial energy consumption, and commercial energy consumption.

(2) Species diversity index is significantly and negatively correlated with population density, industrial energy consumption, and traffic density.

(3) Lighting electricity consumption is significantly and positively correlated with employment rate.

Based on the Spearman correlation analysis, in China, our measures may have the following effects on the impact of light pollution:

Limiting the light hours of the lamps in the industrial area will reduce the per capita disposable income and employment rate of the local residents, improve the local species diversity index, and increase the ecological value.

Dismantling large LED electronic screens will reduce the proportion of local cancer patients and the proportion of people with sleep disorders.

Encouraging the purchase and sale of environmentally friendly lamps in stores, and reduce the sale of high-pollution lamps will increase the diversity of species in the region.

According to Spearman's correlation analysis results, limiting the light hours of lamps in industrial areas and removing large LED billboards could reduce local energy consumption and lighting electricity use to some extent. It reduces the cancer and sleep disorders rate and improves the species diversity.

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