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Research on Light Pollution Risk Level Evaluation and Intervention Strategies

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Abstract: In recent years, the environmental pollution generated by light pollution has become increasingly serious, and indeed, inefficient and unnecessary artificial light sources have exerted a lot of negative effects on human activities and natural environment. Therefore, it is of great importance to detect and evaluate the light pollution risk level in a region, and to specifically deal with and improve the light pollution in the region. Based on the global entropy weight method, entropy weight TOPSIS method, BP (back propagation) neural network model, the present study takes 4 regions in China from 2013 to 2020 as the research objects to construct the light pollution risk evaluation model, and determine the sensitivity of different indexes to the risk degree of light pollution, so as to explore the strategies to reduce light pollution. It is found that the severity of light pollution in coastal regions is higher than that in inland regions, while the severity of light pollution in developed regions is higher than that in less developed regions, so the light pollution can be alleviated by limiting the use of nighttime artificial lighting, population transfer and economic transformation, lighting technology innovation, as well as the use of clean energy.

1. Research Background

With the widespread use of artificial light sources all over the world, various kinds of lamps and glass curtain walls are ubiquitous, which make the city night as bright as day and subsequently result in light pollution. Zuo [1] have pointed out that nighttime light pollution could widely affect astronomical observation, residents' health, as well as animal and plant health, cause energy waste, and restrict the high-quality development of cities.

Therefore, light pollution is a hot topic in international community. Many countries have taken a series of measures to control light pollution, and China is also further optimizing the control strategy. Based on the background, this study takes 4 regions in China from 2013 to 2020 as the research objects to construct a light pollution risk level evaluation index system by using the global entropy weight method and entropy weight TOPSIS method, then measure the levels of light pollution risk in the 4 regions, and determine the sensitivity of different indexes to the risk degree of light pollution based on the thought of BP neural network and linear planning, so as to explore the strategies to reduce light pollution. As shown in the following figure, Figure 1 is a thermal map of light pollution in China captured from the website Astrocom-Global Light Pollution Map.

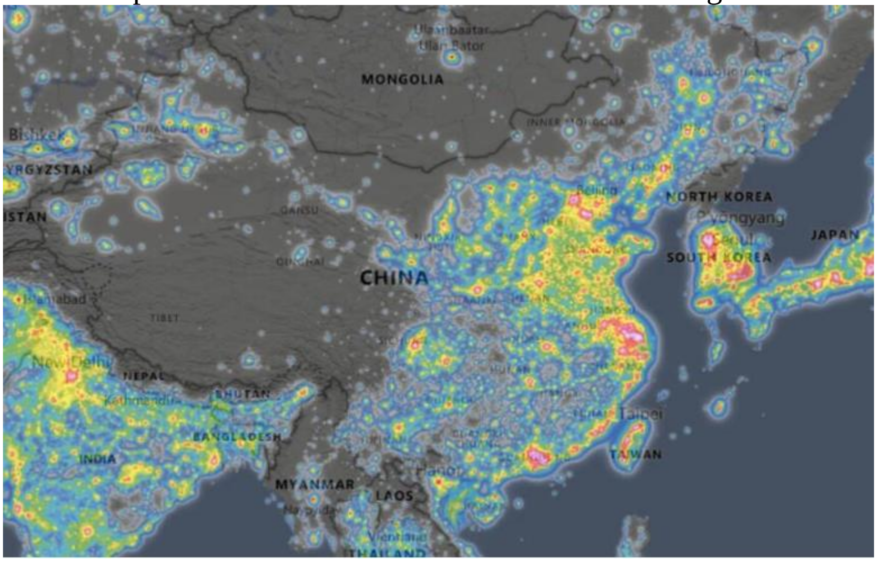

Figure 1: Thermal Map of Light Pollution in China

The conceptual logic constructed in this study is shown in Figure 2, which is also the basis for establishing the index system to evaluate light pollution risk level:

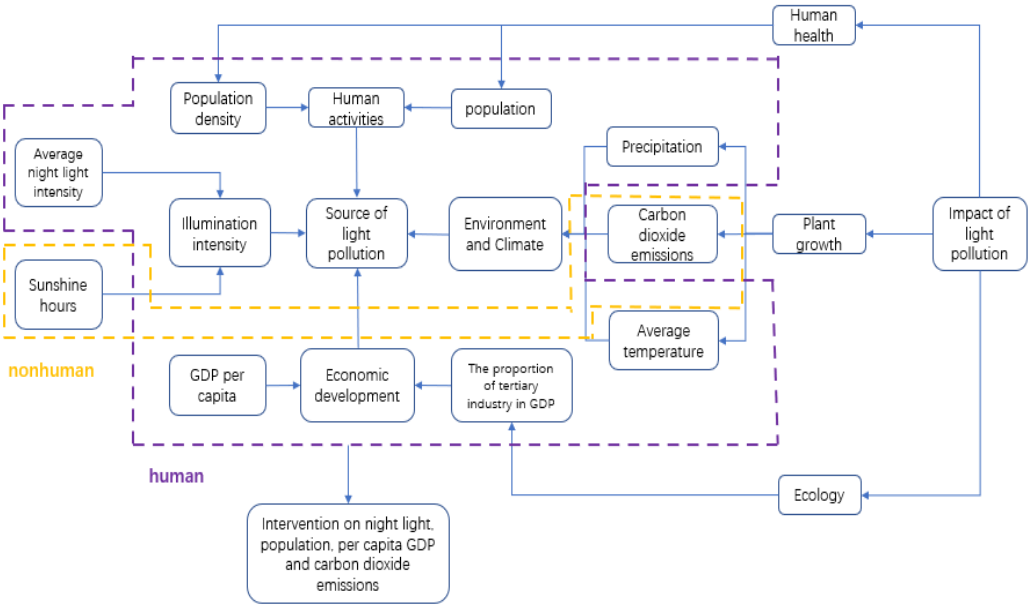

Figure 2: Conceptual logic diagram involved in present study

2. Research Hypothesis and Related Description

2.1. Research Hypothesis

All regions hold positive attitudes towards reducing light pollution and would like to adopt human interventions to reduce the light pollution risk level.

2.2. Research Description

First of all, the NPP/VIIRS nighttime light data can truly represent the overall nighttime artificial light data in each region. The data source in the study is true and reliable.

Secondly, in the model, due to the difficulty of accurate data in a specific region, the present study does not truly select data in urban, suburban and rural regions separately, and instead divides data by population density in a relative manner.

Thirdly, the symbols used in this paper are mainly listed in Table 1.

Table 1: Description of symbols

Symbol	Description
X_{ij}	Value of the j-th index in the i-th region
$x_{ij}^{'}$	Corresponding standardized data
f_{ij}	Proportion of the j-th index in its i-th region
e_j	Information entropy of each index
g_j	Variable coefficient
w_j	Information entropy of each index

3. Research Process

3.1. Index Construction and Weight Calculation

3.1.1. Collection and Processing of Nighttime Lighting Data

By use of DMSP-OLS open source data released by the National Environmental Satellite Data and Information Service (NESDIS) under the US National Oceanic and Atmospheric Administration (NOAA) and NPP-VIIRS open source data from 2013 to 2018 provided by the light pollution map website, the paper has conducted the statistics of the total amount of nighttime lights in cities in China. Based on the ArcGIS visualization software, the remote sensing image of nighttime light in China from 2013 to 2020 is processed to obtain the nighttime light change data in cities in China for 8 years. Based on the vector data of urban administrative regions in China, this paper has trimmed the light images from three dimensions, namely, national, geographical zoning and coastal cities from 2013 to 2020, and makes use of one-dimensional linear trend regression analysis to obtain the nighttime light evolution characteristics in China, and carries out the numerical quantitative research to analyze the characteristics of light change. By fitting the DN values of each raster time series, one-dimensional linear regression analysis eliminates the influence of anomalous factors on the DN values, and reflects the changing trend of the DN values of each raster image element, so as to reveal the evolution in space and time [2,3].

The method is used to calculate the position trend of each image element in the image, that is, R. The positive value R indicates that the nighttime light of the image element shows an increasing trend over 8 years, while the negative value R indicates that the nighttime light of the image element shows a continuous decreasing trend over 8 years.

$$R = \frac{n\times\sum_{i=1}^{n} i\times DN_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} DN_i}{n\times\sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{1}$$

Here, R is the slope of the regression equation of the light image element DN value, namely the DN value of year i, and n is the time span of the study, which is 8.

The rest index data in the paper are collected from China Statistical Yearbook from 2013 to 2020.

3.1.2. Selection of Indexes

In accordance with the principles of scientificity, typicality, hierarchy and operability, the index system is established. However, the lack of index data, inconsistency in index selection, and quantitative model construction by using microscopic indexes may lead to empirical results that are difficult to be convincing and deepgoing.

Therefore, the study takes into account the effects of all aspects of light pollution, the measurability of influencing factors, and the availability of influencing factor data. From the perspective of human and non-human, four main indexes, namely illumination intensity, economic development, human activities, as well as environment and climate, are selected as important factors to measure the light pollution risk level. In addition, nine specific second-level measurement indexes are selected. The index system constructed in this study is shown in Figure 3.

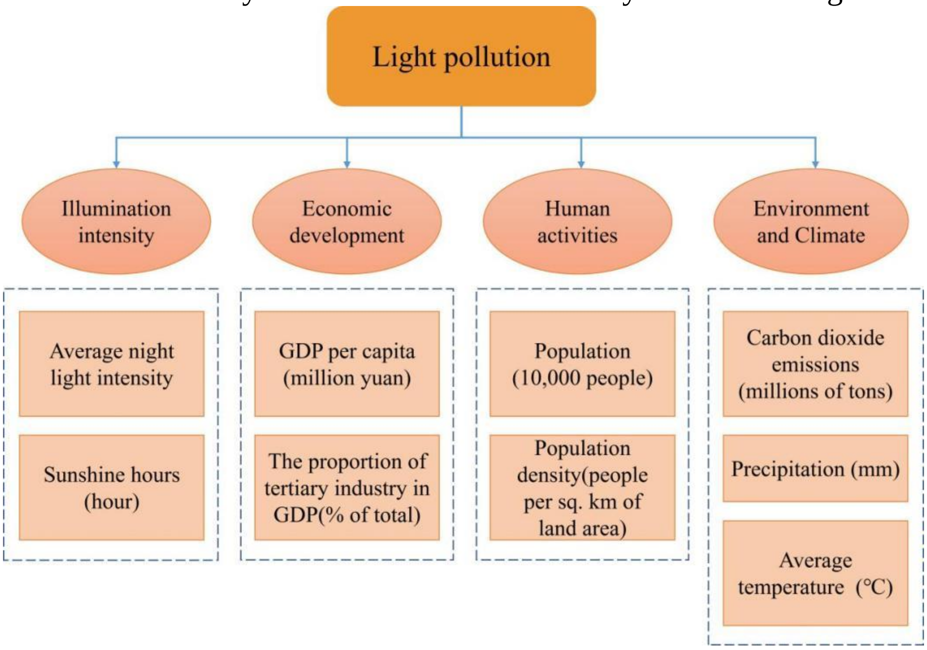

Figure 3: Light pollution risk level evaluation index system

(1) Average nighttime illumination intensity: nighttime light data can fully reflect the degree of light pollution.

(2) Hours of sunshine: it is the number of hours that the sun actually shines on the ground, which takes into account the light pollution generated by the sun during the day.

(3) GDP per capita: For developing countries, there is a direct relationship between GDP per capita and the degree of environmental pollution.

(4) Proportion of the tertiary industry in GDP: economic development would inevitably cause damage to the environment.

(5) Population: there is a correlation between the number of people and the level of light pollution, and the higher the number of people, the higher the lighting requirements.

(6) There is a positive correlation between population density and light pollution level.

(7) Carbon dioxide emission: energy consumption and industrial development have emitted large amounts of carbon dioxide.

(8) Precipitation: it varies in coastal and inland regions, taking into consideration the differences in geographical location and climate.

(9) Different regions have different latitudes and longitudes, so different regions are significantly different in temperature.

3.1.3. Model Construction Using Global Entropy Weight Method

In the study, data of nine indexes in Beijing, Shanghai, Lhasa and Shennongjia National Nature Reserve from 2013 to 2020 are selected to construct the evaluation model, while the global entropy weight method is used to construct the evaluation model. Traditional objective allocation method can only conduct two-dimensional data table analysis, but the global entropy weight method is an improvement for traditional entropy weight method, which not only keeps the advantage of entropy weight method, that is, objective allocation, but also introduces a global idea of analyzing the evaluation indexes from the vertical and horizontal perspectives [4,5].

Entropy is an index used to measure the degree of disorder in a system. The smaller the information entropy of the index, the greater the degree of variation of the index value, the more information the index provides, the greater its role in the comprehensive evaluation, and the greater the weight. According to the basic idea of global entropy weight method, the three-dimensional time series data table has been organized into a two-dimensional table, and then the calculation is carried out according to the traditional entropy weight method. Based on the weight of the index system determined by the global entropy weight method, the calculation steps are as follows.

First of all, n variables in m regions in t years are evaluated, and for each year there is a cross-sectional data table containing eight 8×9 order matrices arranged in a chronological order, resulting in a 32×9 order global evaluation matrix.

The idea of global variables is introduced to arrange the table in a time order, forming a global evaluation matrix, denoted as:

$$X=(X^1,X^2,X^3,\ldots,X^t)_{mt\times n}=(x_{ij})_{mt\times n} \tag{2}$$

Standardized data:

$$x_{ij}=\frac{x_{ij}-\min\limits_i x_{ij}}{\max\limits_i x_{ij}-\min\limits_i x_{ij}}\times 99+1 \quad (1\le i\le mt, 1\le j\le n) \tag{3}$$

Here, i represents region i, while j represents the j-th index. xij is the original value. Max xij and min xij represent the maximum and minimum values of the j-th index in the sample, respectively. The index values are then standardized:

$$f_{ij}=\frac{x_{ij}'}{\sum_{i=1}^{11}x_{ij}'} \quad (1\le i\le mt, 1\le jn) \tag{4}$$

Represent the standardized index value, and then calculate the information entropy of the j-th index in turn:

$$k=\frac{1}{\ln mt}$$
$$e_j=-k\sum_{i=1}^{11}f_{ij}\ln f_{ij} \quad (1\le i\le mt, 1\le j\le n) \tag{5}$$

Calculate the redundancy of the information entropy of the j-th index:

$$g_j = 1 - e_j \tag{6}$$

Calculate the weight of each index:

$$\omega_j = \frac{g_i}{\sum_{j=1}^{n} g_i} \tag{7}$$

3.1.4. Solving by Global Entropy Weight Method

Through MATLAB software, the weight of each index is objectively calculated by the global entropy weight method, as shown in Table 2. As is seen from the table, the importance ranking obtained from the weight ranking is as follows from high to low: human activities, economic development, environment and climate, and illumination intensity. From the influence of second-level indexes shown in Figure 4, it can be found that population and population density have exerted the greatest influence on the light pollution risk level, which indicates that urban communities with large population and high population density have a relatively high contribution to the light pollution level.

Table 2: Weight calculation of indexes by global entropy weight method

First-level index	Second-level index	Weight	Total
illumination intensity	average nighttime illumination intensity	0.1337	0.1428
	hours of sunshine	0.0091	
economic development	GDP per capita	0.1086	0.1783
	proportion of the tertiary industry in GDP	0.0697	
human activities	population	0.2298	0.5096
	Population density	0.2798	
environment and climate	carbon dioxide emission	0.1122	0.1694
	precipitation	0.0139	
	average temperature	0.0433	

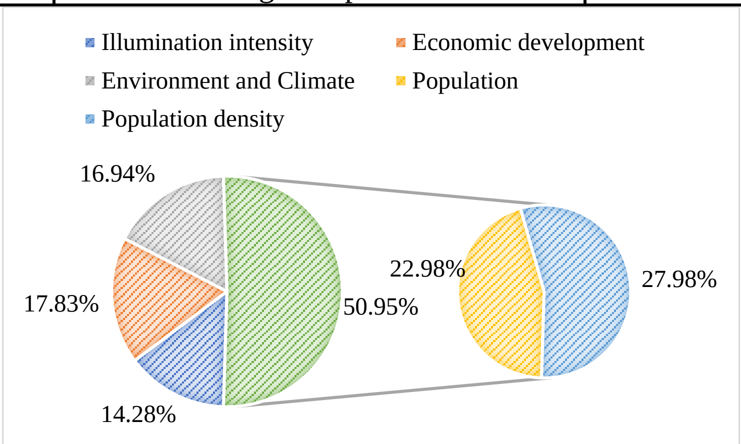

Figure 4: Pie chart of evaluation index weight

Figure 2 shows the weight of each first-level index: the weight of illumination intensity is

14.28%, that of environment and climate is 16.94%, that of population density is 27.98%, that of population is 22.98%, while that of economic development is 17.83%.

3.2. Calculation of Comprehensive Score of Urban Light Pollution Risk Level

3.2.1. Construction of a TOPSIS Model Based on Global Entropy Weight Method

To dynamically compare the light pollution risk levels in different regions, the TOPSIS method is adopted to calculate the comprehensive score based on entropy weights calculated.

Take the maximum value of each column to form the optimal solution vector (Z is the rating matrix after orthogonalization processing and standardization processing)

$$Z^{+} = (Z_1^{+}, Z_2^{+}, \cdots Z_m^{+}) = (max\{Z_{11}, Z_{21}, \cdots, Z_{n1}\}, max\{Z_{12}, Z_{22}, \cdots, Z_{n2}\} \cdots max\{Z_{1m}, Z_{2m}, \cdots, Z_{nm}\}) \tag{8}$$

The worst solution vector:

$$Z^{-} = (Z_1^{-}, Z_2^{-}, \cdots Z_m^{-}) = (min\{Z_{11}, Z_{21}, \cdots, Z_{n1}\}, min\{Z_{12}, Z_{22}, \cdots, Z_{n2}\} \cdots min\{Z_{1m}, Z_{2m}, \cdots, Z_{nm}\}) \tag{9}$$

Calculate the distance from the optimal solution:

$$D_i^{+} = \sqrt{\sum_{j=1}^{m} (Z_j^{+} - Z_{ij})^2} \tag{10}$$

The distance from the worst solution:

$$D_i^{-} = \sqrt{\sum_{j=1}^{m} (Z_j^{-} - Z_{ij})^2} \tag{11}$$

Normalized score:

$$S_i = \frac{D_i^{-}}{D_i^{+} + D_i^{-}} \tag{12}$$

Score after normalization:

$$S_i^{'} = \frac{S_i}{\sqrt{\sum_{i=1}^{n} S_i}} \tag{13}$$

3.2.2. Solution Obtained from the TOPSIS Model Based on Global Entropy Weight Method

Table 3: Dynamic scores of light pollution risk levels in four regions

Year	Shanghai	Beijing	Lhasa	Shennongjia National Nature Reserve
2013	0.0281	0.0185	0.0075	0.0044
2014	0.0285	0.0189	0.0074	0.0041
2015	0.0288	0.0190	0.0075	0.0044
2016	0.0291	0.0193	0.0077	0.0045
2017	0.0295	0.0197	0.0079	0.0044
2018	0.0296	0.0200	0.0081	0.0044
2019	0.0299	0.0106	0.0086	0.0044
2020	0.0297	0.0207	0.0081	0.0044

Shanghai, Beijing, Lhasa and Shennongjia National Nature Reserve are scored by use of Matlab software, and the scores are shown in Table 3. It can be obviously seen that urban communities have the highest light pollution risk over the years, followed by suburban communities, rural communities and reserves.

Based on Table 3, the broken line graph reflecting the changing scores of light pollution risk level evaluation in the four regions with year is shown in Figure 5.

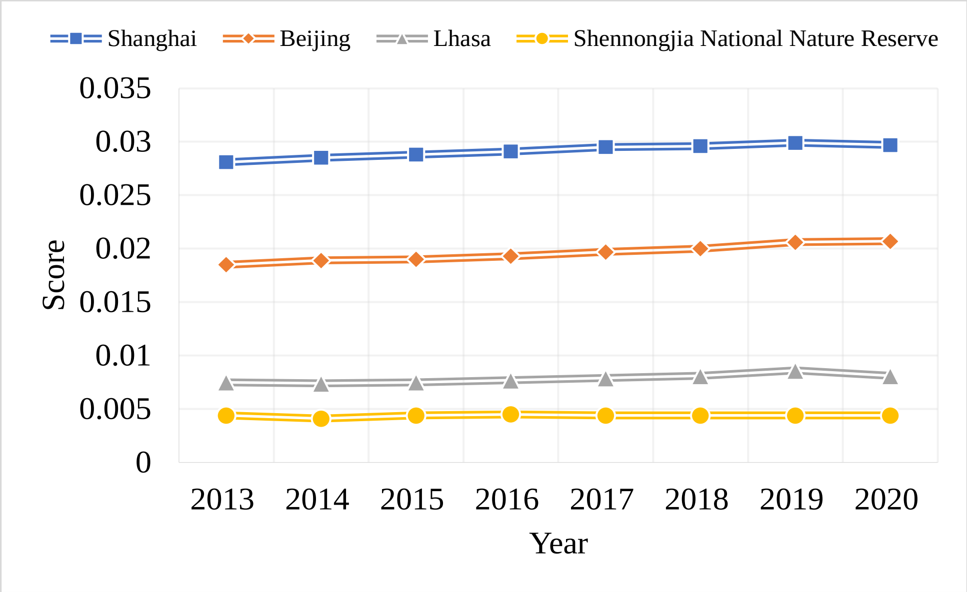

Figure 5: Light pollution risk level scores in four regions

It can concluded that from 2013 to 2020, urban communities have the highest light pollution risk level, followed by suburban communities, while rural communities and reserves have relatively lower level, and the light pollution level in urban and suburban areas increases faster than that in rural areas.

4. Strategies to Reduce Light Pollution

4.1. Sensitivity Analysis

To determine the sensitivity of the different indexes to the light pollution risk level, BP neural network model is used in the four regions for training and prediction according to the above conclusions and differences in regional population density.

The present study uses the built-in neural network toolbox in Matlab to train data. Since precipitation, hours of sunshine and average temperature are not subject to human intervention, therefore, under the condition that the above indexes remain unchanged, the study respectively reduces the data of six indexes, namely average nighttime light intensity, GDP per capita, proportion of the tertiary industry in GDP, population, population density and carbon dioxide emission, by 10%, categorizes them for prediction, and compares them with the original classified data.

Taking Shanghai and Lhasa as examples, it can be found from Figure 6 that the sensitivity of indexes in the two regions is different when other index parameters remain unchanged. Therefore, it is necessary to develop site-specific interventions.

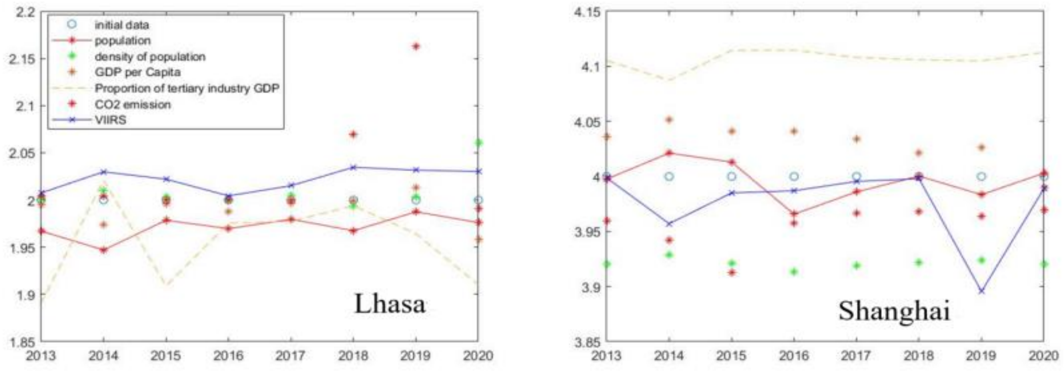

Figure 6: Broken line graphs of index sensitivity for Lhasa and Shanghai

4.2. Strategy 1: Developing Regulatory Standards to Monitor and Manage the Use of Artificial Light at Night

First of all, the regulatory and management systems shall be promulgated for light pollution prevention and control to clarify the objects, powers and responsibilities. Referring to the relevant regulations and standards of the Commission Internationale de l'Eclairage (CIE) and developed countries, light pollution environmental standards such as quantitative standards and regional division standards shall be introduced to improve supporting management systems such as environmental impact evaluation system and lighting equipment market access system. Moreover, it is necessary to promote the work enthusiasm of departments involved and to improve the social efficiency of light pollution prevention [6].

Secondly, according to urban development and public demands, normative standards for the number, density, brightness, size, lighting mode, location and angle of outdoor light boxes, signs, light projection signs, neon lights and LED displays shall be formulated for a better control and management on outdoor light source [7,8]. All kinds of buildings in cities shall moderately reduce their brightness and reduce the use. This is in line with the requirements of lighting engineering and fully takes into account the rights and interests of the public, while it can make the light satisfy the normal comfort of human body and minimize the interference to human health. In addition, it is useful to reduce the use of nighttime lights, actively prevent white light pollution, and govern light pollution.

Thirdly, according to different reflected light receptors, different glass curtain wall installation standards shall be carried out, such as limiting the area of glass curtain wall in the main roads and areas with large traffic flow, and adding outdoor signs to remind pedestrians and vehicles to pay attention to glare. If possible, the LOW-E glass that can reflect radiant heat and balance the indoor temperature as well as the intelligent breathing glass curtain wall shall be adopted [9].

4.3. Strategy 2: Focusing on the Impact of Population Growth and Economic Development on Light While Considering Population Mobility and Economic Transformation

Human beings would inevitably use light in their activities, which causes light pollution. In order to reduce the negative impact of light pollution, it is necessary to control population growth and mitigate the trend of mass population migration from less developed to more developed areas due to economic imbalances between regions, so as to reduce serious light pollution in developed areas, and also to reduce the difficulty of light pollution prevention and control in developed areas.

On the one hand, there is a need to strengthen regional infrastructure connectivity to promote mutual complementarity and integrated development in different regions. In the case of unbalanced human resources structure, it is an important measure for a balanced development of regional society to promote the diversified population flow. Measures shall be taken to alleviate the serious light pollution in specific areas.

Secondly, it is necessary to promote industrial upgrading and focus on technological innovation. While pursuing high-quality economic growth, it is of great importance to consider environmental protection, follow the concept of sustainable development, and push economic transformation, so as to strive to achieve the unity of economic and social benefits, and it is inadvisable to develop economy at the expense of environment.

4.4. Strategy 3: Optimizing the Lighting Technology and Management Method While Encouraging the Public to Use Light Scientifically

First of all, it can effectively save energy, reduce consumption, and alleviate light pollution to improve the lighting technology level and optimize the lighting control system. For example, continuously innovating energy-saving sensor lights and other low energy consumption lamps, adopting microcomputer intelligent controller to control the lighting time and brightness according to the season, weather and other parameters, and making use of road lighting group control system to improve the lighting quality of urban street lamps and reduce energy consumption [10].

Secondly, high-quality outdoor lighting can save 60% to 70% energy. Outdoor lighting shall be equipped with sun-visors to keep the light perfectly aligned with the ground. Installing sun-visors can save more energy while creating the same lighting effect on the ground.

Thirdly, for the time being, people generally do not realize the harm generated from light pollution, lack the correct lighting concept, and excessively pursue cities without nights and with bright night views. Light pollution popularization of science shall be propagated to the public through various media, and at the same time, the public shall be given guidance for establishing correct and reasonable lighting concepts to take the initiative to pay attention to and protect the light environment, such as forming the habit of timely turning off unnecessary indoor lighting.

5. Conclusions and Reflection

The present paper aims to explore the influence of possible influencing factors of light pollution on the light pollution risk level by data analysis and model establishment, so as to evaluate the urban light pollution risk level according to cities' historical data and then put forward targeted suggestions. In the index system construction, the study has taken into account all the human and non-human influencing factors as comprehensively as possible. Regarding the entropy weight calculation, according to the data characteristics, the paper does not adopt the traditional entropy weight method and instead uses the global entropy weight method to analyze the historical data of light pollution levels in different regions in different years, which not only keeps the advantage of the entropy weight method, that is, objectively weighting, but also introduces a global idea of analyzing the evaluation indexes from the vertical and horizontal perspectives. By combining the global entropy weight method and TOPSIS method to comprehensively evaluate the urban light pollution level, in this study, the comprehensive influence of multiple indexes on the risk level could be well described without objective function construction or examination. Due to data standardization and normalization, there are no strict restrictions on data distribution, data meaning, sample size and number of indexes, making the study more flexible and extensible. In the end, the paper puts forward three possible intervention strategies. In the face of light pollution in specific areas, the study's ideas can be taken into consideration to construct an evaluation index system for analyzing the sensitivity of light pollution level to different indexes. Then, according to the sensitivity analysis results, one or several of the three intervention strategies shall be given priority to carry out light pollution prevention and control. For example, in the above conclusion, population density, carbon dioxide emission and average nighttime light intensity exert a greater impact on Shanghai, so strategy 1 and strategy 2 can be given priority in light pollution prevention and control in Shanghai.

In the study, the determination of influencing factors on the light pollution risk level is based on previous studies, personal experience and intuition, which is subjective and has its limitations. On the basis of previous studies, the paper further studies the three cities and one nature reserve with differences, so as to draw a reference conclusion of light pollution research in the real situation. Due to limited resources, the study cannot be accurate to a certain community in a city. In fact, cities are different in size, while various regions in the same city are also different in population density and degree of development. However, this study only adopts the average value as the evaluation basis, so the accuracy needs to be improved.

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