Study on optimal intervention strategy of light pollution based on DSP model

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Abstract. Light pollution is a new type of environmental pollution, which has attracted the attention of many countries in the world and become a global environmental issue.In order to measure the impact of light pollution quantitatively and solve the problem of light pollution more pertinately, we established the light pollution risk level hierarchical model (RLG) to assess the risk level of light pollution in a region widely.Based on this, in order to more effectively control light pollution in a specific location, we construct a prediction model (DSP) based on different strategies introduced impact factors ξ_i and apply it to two specific areas. The two sites are scored by combining the RLG model, and verify that the model can determine the optimal intervention strategy for a specific location and provide inspiration for local light pollution control. The results show that: (1) The risk level of light pollution is not only affected by the total amount of light pollution, but also affected by the development level, population level, ecological level, geography and climate. (2) We derived the formula that the above factors affect the classification of light pollution risk level. (3) A DSP model was established to determine the optimal light pollution intervention strategy for a specific location.

Keywords: light pollution, the RLG model, the DSP model, Optimal intervention strategy.

1. Introduction

Since the reform and opening up, China has accelerated the urbanization process and the rapid economic development, which has brought the great development of urban nighttime lighting facilities."City that never sleeps" has become a new synonym for urban civilization and economic development level.However, excessive lighting also brings inevitable urban luminous pollution, which has a certain impact on human health, life, habitat and reproduction of animals and plants.The rapid economic development has also led to the intensification of nighttime light pollution [1].

With the continuous development of lighting technology, light pollution has become a problem that cannot be ignored, especially in developed countries or regions.The United States is a strict country for the control of light pollution, more than 1/3 of the regions have the management of light pollution laws and regulations, but so far has not formed a unified legal document, in our country, has not issued a formal standard and regulation for the prevention and control of light pollution [2].To solve the problem of light pollution, scholars at home and abroad have put forward their own views.In 2010, Huang from Heilongjiang University made a bold innovation in the legal system of light pollution. He proposed the light pollution list system, the planning system, the incentive and reward system, the information construction system, the science and technology support system, and the total amount control system.The types of infringement and the way to bear responsibility are elaborated in detail, and the victims of light pollution infringement are given maximum relief [3].In 2001, astronomer Cinzano et al. from Italy published the world's first artificial atlas of night sky brightness [4], providing valuable materials for the study of night sky light environment.Jing [5], in order to

solve the problem of urban light pollution, realized the prevention and control of urban light pollution by using green energy-saving buildings.Based on the urban structure and building distribution,the corresponding building parametric model is established.Using its continuous iteration to find the working principle of the optimal solution, respectively analyze the causes and forms of light pollution.

Summarizing the views of various researchers, it is evident that there is no unified light pollution prevention legislation in China, and no uniform light pollution prevention standards applicable to all countries have been developed internationally. On the whole, there are few studies on the optimality selection of light pollution intervention strategies. In view of this, this paper proposes an optimal intervention strategy for light pollution based on the DSP model to provide guidance for the prevention and control of light pollution.

2. Model building

2.1. Establishment of light pollution risk level model

2.1.1. Calculation of total light pollution

According to the research, the brighter the city is, the more serious the light pollution will be. In the study of light pollution, the night light data is taken, as shown in Figure 1:

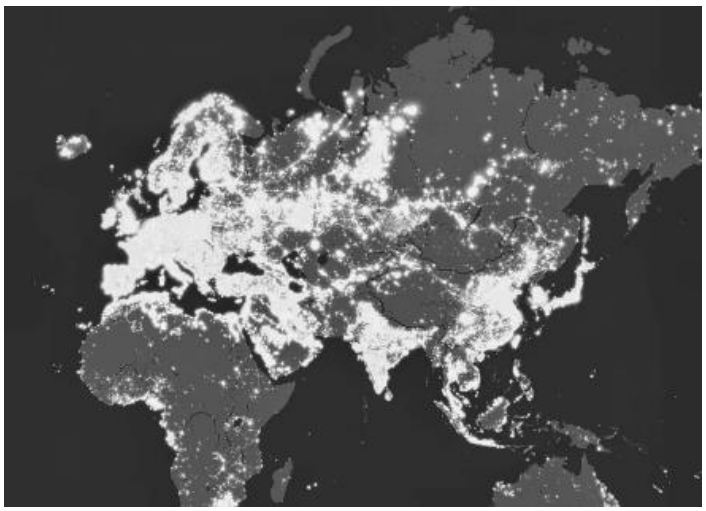


Figure 1. Night light map

By combining night light data with GIS technology and superimposing direct and indirect light pollution [6], the grade map of regional light pollution can be obtained, as shown in Figure 2 below. Through analysis, the process and trend of light pollution in propagation and development can be obtained. In the figure below, there are nine levels of light pollution according to the degree of impact, i.e., 1 to 9. The lower the level, the lower the degree of pollution. We divide the total amount of light pollution into three forms, as shown in formula (1):

$$Z_{TLP} = \sum_{j=1}^{3} W_{1j} X_1 \tag{1}$$

Where, X_1 represents the degree of local light intrusion, X_2 represents the degree of local over-illumination, and X_3 represents the degree of local light clutter.

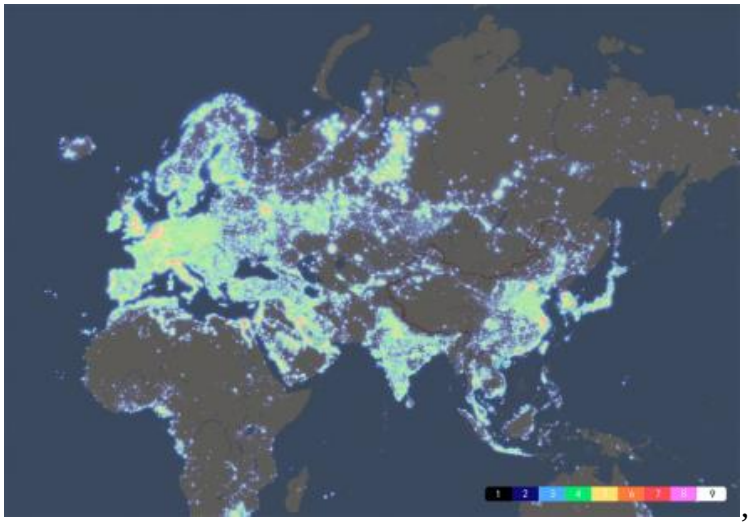


Figure 2. Map of regional light pollution levels

2.1.2. Analysis of other influencing factors

The classification of light pollution risk level mainly depends on the total amount of light pollution, but it is also affected by the development level, population, ecological level, geography, climate and other factors in a specific area.The mathematical expression for defining the influence of other factors on the risk level of light pollution is shown in Formula (2):

$$Z_{OIF}=W_{21}Y_{dev}+W_{22}Y_{pop}+W_{23}Y_{eco}+W_{24}Y_{geo}+W_{25}Y_{cli} \quad (2)$$

Where,Y_{dev}, Y_{pop}, Y_{eco}, Y_{geo} and Y_{cli} respectively represent the influence degree of development level, population level, ecological level, geography and climate on light pollution risk level.

The mathematical expression (3) of the influence of development level on light pollution risk level is:

$$Y_{dev} = -\sum_{k=1}^{4} W_{21k}X_k \quad (3)$$

Where,X_4 stands for GDP, X_5stands for CPI, X_6stands for PPI,X_7stands for employment rate, is an indicator reflecting the degree of labor employment.

The mathematical expression (4) of the influence of population level on the risk level of light pollution:

$$Y_{pop} = k_1X_8 - k_2\ln(X_8 - 1) + \xi \quad (4)$$

Where, X_8 is population density, k_1 is the importance of health index, k2 is the importance of safety index, where k1=0.9, k2=0.1, ξ is the disturbance term.

Is the mathematical expression (5) of the influence of ecological level on the risk level of light pollution:

$$X_9=0.25\times sf+0.2\times zf+0.2\times sm+0.2\times tt+0.15\times wf \quad (5)$$

Where, X_9 represents the ecological environment status index, which is used to evaluate the overall status of regional ecological environment quality. sf represents the biological abundance index, zf represents the vegetation cover index, sm represents the water network density index, tt represents the land degradation index, and wf represents the pollution load index.

Different from other biodiversity measurement standards, biodiversity index can emphasize the importance of endangered species to a certain extent, which is conducive to human protection and has certain practical significance.The quantitative characteristics of a population in an ecosystem include relative density (abundance), relative frequency, relative significance and importance value.It can be calculated with the following expressions (6)-(10):

$$M_1 = \frac{a}{\sum a_i} \times 100\% \quad (6)$$

$$M_2 = \frac{b}{\sum b_i} \times 100\% \quad (7)$$

$$M_3 = \frac{c}{\sum c_i} \times 100\% \quad (8)$$

$$M_4 = (M_1 + M_2 + M_3)/3 \quad (9)$$

$$X_{10} = \sum (P_i/M_4)^2 \quad (10)$$

Where,M_1, M_2 and M_3 respectively represent the number, frequency and chest height area of a certain species. X_{10} is the biodiversity index, N is the total important value of all species in the sample, Pi is the relative importance value of the ith species, and S is the total number of species in the sample.

Finally, the weighted summation of ecological environment status index EI and biodiversity index is used as the influence of ecological level on light pollution risk rating. The mathematical expression is shown in Formula (11):

$$Y_{eco} = W_{231}X_9 + W_{232}X_{10} \quad (11)$$

Mathematical expression of the effect of geographical level on light pollution risk level (12) :

$$Y_{geo} = k_3 \frac{X_{11}}{b_1} \quad (12)$$

Where, X_{11} represents the latitude of the region,$k_3$is the importance of the geographical index, and b1 is the global average annual sunshine duration.The mathematical expression of the influence of climate level on the risk level of light pollution (13):

$$Y_{cli} = e^{R(X_{12} - b_2)} \quad (13)$$

Where, X_{12} denotes the carbon dioxide concentration in the area, b2=400 (in the natural environment, the normal content of carbon dioxide in the air is (400 PPM)).R stands for self-regulating factor, originally a measure of ecosystem stability, which indicates an area's ability to maintain a certain degree of regulation over the effects of carbon dioxide on it.

2.1.3. Weight determination

In the construction of hierarchical model, the determination of evaluation index weight plays a crucial role, which directly affects the accuracy of model evaluation.Entropy weight method is an objective weighting method and analytic hierarchy process (AHP) is a subjective weighting method.We combine EWM and AHP to determine the weights of indicators [7].This is a comprehensive evaluation method combining subjective and objective methods and synthesizing various methods, which can effectively improve the correctness and rationality of the evaluation.The final weights determined by us are shown in Figure 3:

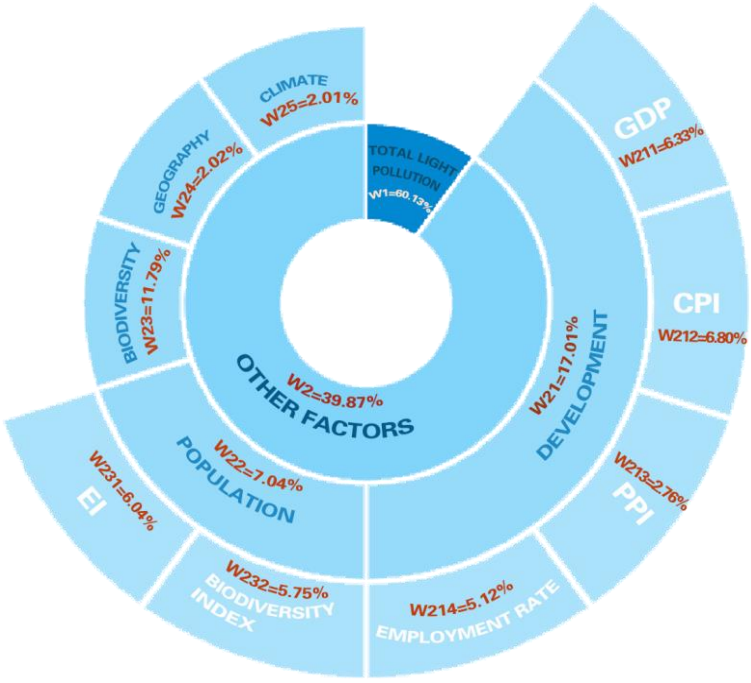


Figure 3. Three-level index weight

2.1.4. Score calculation

Based on the idea of the Topsis method [8-9], we treated the untreated initial value of the light pollution risk level as follows:S_0.

$$S_i = \frac{S_0 - S_{min}}{S_{max} - S_{min}} \tag{14}$$

$$S_{final} = \frac{S_i}{\sum_{i=1}^{n} S_i} \times 9 \tag{15}$$

Where, S_i represents the light pollution risk level classification obtained by Topsis method, S_{max} represents the theoretical maximum value, and similarly,S_{min} represents the theoretical minimum value. The final light pollution risk level classification value S_{final} can be obtained by multiplying the normalized treatment of A by the maximum level 9 of the light pollution risk level.

2.2. Establishment of influencing factor model

2.2.1. Influencing factor model

We divide the light pollution intervention strategies into three categories: intelligent light control, policy instruments and control of illegal lights. Let ξ_{im} be the maximum value of the impact factor of different light pollution intervention strategies on light pollution risk level grading evaluation index X_i.

Ifξ_{im}<1, it means that adopting the strategy can theoretically reduce the index to$\xi_{im}\xi_i X_i$;If ξ_{im}=1, it means that adopting strategies has no effect on indicators;If ξ_{im}>1, it means that adopting the strategy can theoretically increase the index to $\xi_{im}\xi_i X_i$.

In addition, since the promotion degree of the strategy effect will gradually slow down with the progress of the strategy, we set the change of the strategy effect over time to meet the Logistic model, as shown in FIG. 4.From this, we can obtain the mathematical expression of the change of strategy promotion effect over time as follows (16):

$$\xi_i(t) = \frac{\xi_{im}}{1 + (\frac{\xi_{im}}{\xi_{i0}} - 1)e^{-r(t-t_0)}} \tag{16}$$

Where r is the efficiency of policy implementation, and we assume that all strategies have the same efficiency for each indicator (Figure 4).

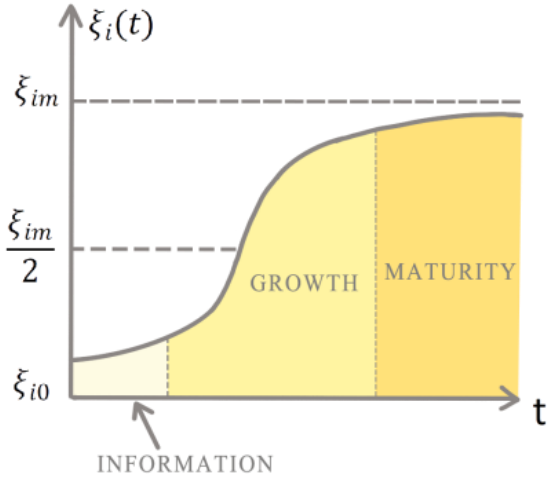


Figure 4. Curve of policy promotion effect over time

It can be seen that the influence factors $\xi_i(t)$ have the following rules:

(1) $\lim_{t\to\infty}\xi_i(t) = \xi_{im}$. That is, regardless of the initial value of the population $\xi_i(t)$, the impact factor is limited by ξ_{im}.

(2) When $0<\xi_i<\xi_{im}$, it indicates that $\xi_i(t)$ is monotonically increasing.When $\xi_i<\frac{\xi_{im}}{2}, \frac{d^2\xi_i}{dt^2} > 0$, $\xi_i=\xi_i(t)$ is a concave function;When $\xi_i > \frac{\xi_{im}}{2}, \frac{d^2\xi_i}{dt^2} < 0$, $\xi_i=\xi_i(t)$ is a convex function.

(3) When the change rate of the influence factor $\frac{d\xi_i}{dt}$ reaches the maximum value at $\xi_i=\frac{\xi_{im}}{2}$, that is, it is the accelerated growth period before the influence factor reaches half of the limit value. After this point, the growth rate will gradually decrease and finally reach 0.

2.2.2. Simulation of evaluation model

The implementation of the strategy will have an impact on the light pollution risk grading level indicator X_i. The degree of impact is represented by the impact factor $\xi_i(t)$. In addition, this impact will change with time, therefore, we define the variable S(t), which represents the light pollution risk grading level after t months of strategy implementation, with the following mathematical expression (17).

$$S(t)= \sum_{i=1}^{12} w_i x_i(t)\xi_i(t) \tag{17}$$

Where: w_i denotes the weight of indicator x_i, that is. the degree of influence on the graded level of light pollution; $x_i(t)$ denotes the value of indicator x_i after t days of policy implementation; $\xi_i(t)$ denotes the influence factor on the graded evaluation indicator F of the risk level of light pollution after t days of strategy implementation.

We selected Busan Panda Reserve in South Korea and Wolong Panda Reserve in China for simulation analysis, and took T=6 months to obtain the light pollution risk level classification after the implementation of the three intervention strategies for 6 months, and compared the optimal strategies applicable to the two places respectively.

REGION / STRATEGY	RISK LEVEL		GRADE CHANGE
BUSAN, KOREA	INITIAL TIME	AFTER 6 MONTHS	
INTELLIGENT LIGHT CONTROL	8	6.98	↓
POLICY ADVOCACY	8	7.24	↓
CONTROL OF NON-COMPLIANT LIGHTS	8	6.98	↓

Figure 5. Simulation results in Busan, South Korea

Busan, South Korea: Busan, South Korea is an urban community with a light pollution risk level of 8 before assuming that no intervention strategies were implemented. After implementing three different strategies, we found that the strategy of controlling illegal lighting was the most effective, and its light risk level changed to 6.98.The reason for the significant difference in the effects of the three strategies is that Busan has a high level of economic development, and the proportion of illegal light sources such as light clutter and excessive lighting is large. Control of these illegal lights is the optimal strategy among intervention strategies.The penetration rate of intelligent lighting in the city is high, so the strategy of intelligent lighting control is also more effective;It should be noted that we found that the strategy of only promoting policies in cities often fails to achieve the expected good results (Figure 5).

REGION / STRATEGY	RISK LEVEL		GRADE CHANGE
WOLONG PANDA RESERVE, CHINA	INITIAL TIME	AFTER 6 MONTHS	
INTELLIGENT LIGHT CONTROL	5	4.21	↓
POLICY ADVOCACY	5	4.58	↓
CONTROL OF NON-COMPLIANT LIGHTS	5	4.66	↓

Figure 6. Simulation results of Wolong Panda Reserve in China

China Wolong Panda Reserve: China Wolong Panda Reserve is an urban community. Before assuming that no intervention strategy is implemented, the light pollution risk level level is 5. After implementing three different strategies, we found that the strategy of intelligent light control is the most effective, and its light risk level level changes to 4.21.The reason for the significant difference in the effects of the three strategies is that there are very few illegal lights in China Wolong Panda Reserve, and the effect of controlling illegal lights is not big.It is located in a protected area, so the publicity of the policy can play a better effect;In fact, most of the light sources in the protected areas can be replaced by intelligent lamp control, so the effect of intelligent lamp control is the best (Figure 6).

3. Sensitivity analysis

Our objective was to select the most effective light pollution intervention strategy. We took Wolong Panda Reserve in China as an example to adjust the parameters. With the change of the implementation time of intervention strategy, the grading scores of light pollution risk level of different intervention strategies also changed. The simulation results of the algorithm are shown in Figure 7:

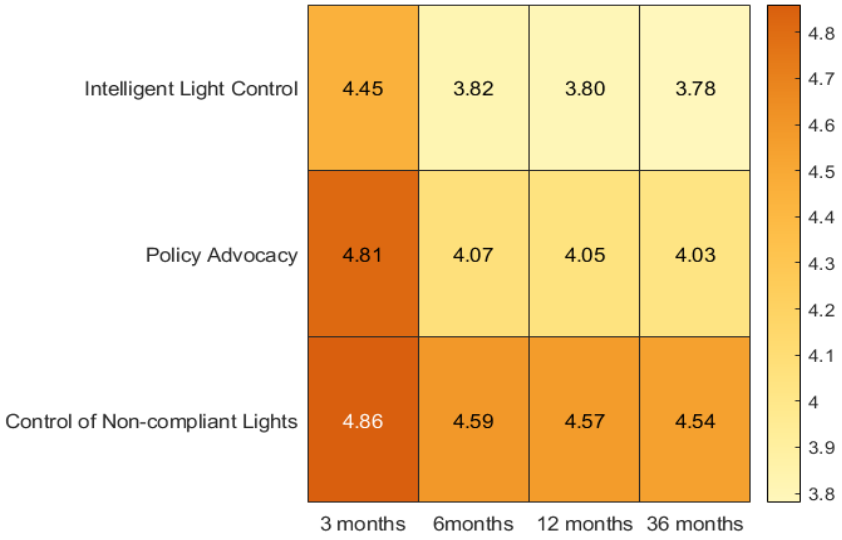


Figure 7. Sensitivity analysis

By observing the above figure, the effect growth rate of intervention strategies gradually decreases with the change of time, and the effect of intervention tends to be stable after reaching a certain value. Finally, we can find that the effect of the three strategies basically no longer changes after 180 days. At this time, the time keeps increasing, and the graded change of risk level basically no longer changes in the future. The changes of light pollution risk level grading values show robustness. Meanwhile, for this protected area, its optimal strategy intelligent light control is still the optimal strategy with the change of time.In other words, with the change of the time parameter, our model is stable when the time reaches a certain value, no matter in terms of the change range of the risk level and the evaluation of the optimal strategy.

4. Conclusion

Through searching and analyzing the data, the index to judge the risk level of light pollution is established as the total amount of light pollution and other influencing factors, among which the other influencing factors include the level of development, the level of population, the level of ecology, geography and climate. By deducing the formula that the above factors affect the classification of the risk level of light pollution.

Through topsis analysis and using EWM and AHP method to determine the weight of the index, we establish a widely applicable RLG model. The results show that the light pollution level in some areas is different from its risk level, which is caused by the influence of the above other factors on the light pollution risk level.

The light pollution intervention strategies are divided into three categories: intelligent light control, policy publicity and control of illegal light.Considering the relationship between policy effect and time, a DSP model was constructed using impact factors and applied to Busan, South Korea and Wolong Panda Reserve in China. Combined with RLG model, it was concluded that the most effective intervention strategy for the former was to control illegal lights, while the most effective intervention strategy for the latter was to control intelligent lights.Finally, it is verified that DSP model can determine the optimal light pollution intervention strategy for a specific location, so as to benefit the local light pollution control.

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