Risk assessment system and prevention suggestions of night light pollution based on AHP and PLS

Tianqi Ying *, Linzhi Jiang, Xianpeng Chen, Xinzhi Liu

Hohai University, Jiangsu, China

* Corresponding Author Email: hhuam2ytq@163.com

Abstract. The appearance of light has brought great convenience to people's life and promoted the development of the social economy. However, inappropriate or overused artificial lighting creates severe light pollution, adversely affecting people, organisms, and the climate. In this paper, the analytic hierarchy process is used to evaluate the severity of the influence of light pollution. The partial least squares, regression curve, and other methods comprehensively analyze the causes of light intensity and pollution. Finally, suggestions are put forward for preventing and controlling light pollution in different areas.

Keywords: Light Pollution, AHP, State Space Regression Model, Light Response Model, Partial Least Squares.

1. Introduction

"It's true that we will never reach the goal of no brightness over cities," says Kaiba. Nevertheless, there is every reason to think that, with excellent design, the Milky Way could be seen even in cities with hundreds of thousands of inhabitants." The appearance of the electric lamp has brought great convenience to people's life, improved the efficiency of production and life, and promoted the development of a social economy. The widespread use of artificial light brings convenience to people but also brings a negative side - light pollution at night. Dark Night International defines light pollution as "inappropriate or overused artificial lighting that has serious environmental consequences for people, wildlife, and the climate." According to Science magazine, the study shows that the acceleration in light pollution is far greater than previously observed by the U.S. Defense Meteorological Satellite Program and Soma's National Polar-orbiting Partner satellites. Satellite observations show that the night sky is getting brighter by about 2% a year on average. Studies have pointed out that, for organisms, light pollution at night will affect the natural life of animals and plants and destroy the balance of ecosystem and biodiversity; In humans, it can interfere with the body clock, disrupt the endocrine balance, lead to physical and psychological problems, and even affect sleep quality; For the resource environment, excessive night lighting also consumes unnecessary electricity.

2. Index System of light Pollution Evaluation

2.1. Selection Evaluation Index

Before constructing the evaluation index system of light pollution risk, the corresponding construction principles should be determined, and the evaluation indexes should be reasonably selected according to the established principles. Generally speaking, there are four principles to be followed in constructing the index evaluation system: scientific, representative, integrity, and normative. They are combined with the primary form of light pollution, as shown in Figure 1 below.

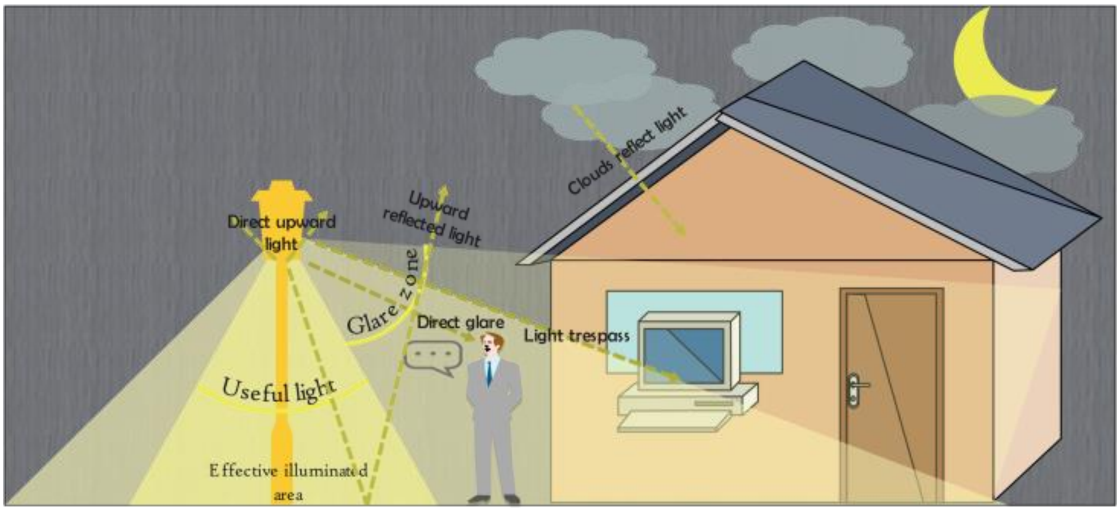

Figure 1. Form of light pollution

When a light is shone at night, it creates four parts of the light. The first is useful light, the lighting needed for everyday human life. The ground reflects part of the light to form the reflected light. The second part is the direct upward light, which will reflect through the clouds and, together with the upshot light, form the cloud reflection light, which will significantly increase the brightness of the night sky; The third part is a glare area generated by the Angle between the light source and the viewpoint. When we look directly at the light source, direct glare will be generated, making it difficult for our eyes to adapt and temporarily blind, leading to traffic accidents [1] [2]. In addition to the effective area will be irradiated, there will also be a light invasion phenomenon; that is, because the reflected light is irradiated to an area other than the effective area, the brightness of the earth's sky will become brighter, the immediate living environment will be affected, for example, resulting in the shortening of the night time of animals and plants, increase in daytime activities, will also affect the expected life of human beings, such as sleep quality, immunity decline.

Based on the above analysis of the formation and types of light pollution, we selected five evaluation indicators from resources, health, ecology, and social security. Human sleep quality, population crime rate, traffic accidents, biological growth, and energy consumption establish the index system of light pollution risk assessment.

2.2. Index Analysis

In order to judge whether the relationship between the five indicators selected by us and the risk level of light pollution is reasonable, we will briefly elaborate and prove the relationship between them to verify the rationality and adaptability of the index system.

(1). Sleep quality

Rapid urbanization and economic development inevitably lead to nighttime light pollution, and the negative impact of nighttime light pollution on human health should not be ignored. However, sleep quality reflects human health level to some extent, so we take sleep quality as the starting point to study the relationship between nighttime light pollution and our health level. Most spatial data have spatial autocorrelation, breaking the basic assumption that the observed values are independent in classical regression analysis. Therefore, we consider the spatial regression model of the spatial effect to estimate sleep quality more accurately.

By combining the luminous intensity data (LI) and sleep quality data (SQI), we built a spatial regression model of night light pollution and residents' sleep quality [3] to judge the relationship between them. We get:

$$SQI = \rho W_1 + \beta X + \mu \quad (1)$$

$$\mu = \lambda W_2 + \varepsilon \quad (2)$$

Where: SQI is sleep quality index; X is the light index in the research unit; ρ is the spatial autoregressive coefficient of X; W_1 and W_2 are the spatial weight matrices of sleep quality and residual error respectively. β is the spatial regression coefficient of light index; μ is the residual term; λ is the spatial regression coefficient of the residual term; ε is a random error.

The relationship between LI and SQI was simulated by local function to reduce the effect of spatial heterogeneity. The linear fitting equation of sleep quality and total lighting was obtained.

$$SQI = -0.256LI + 5.84 \tag{3}$$

It can be seen that the stronger the illumination, the lower the SQI, and the worse the sleep quality, which is a positive indicator.

(2). Crime rate

According to relevant public information [4], the crime rate at night is higher than in the daytime, and the night naturally provides the conditions for criminals to commit crimes. Nighttime lighting is one of the many vital factors affecting nighttime crimes. Some scholars pointed out in the study of places and facilities with a high incidence of crime that the distribution pattern of luminous light fits with the aggregation pattern of street robbery crime. We preprocessed crime data and luminous remote sensing data, analyzed the spatial distribution pattern of holes based on the preprocessed luminous remote sensing data and criminal data, and constructed the relationship curve between crime rate (CR) and nocturnal natural brightness (LI)

$$CR = \frac{CT}{LI+NBN} \tag{4}$$

Among them, NBN is natural brightness at night, and CT is criminal tendency.

We computed CT=48.35 and NBN =36.78 by MATLAB reasonable sum. The SSE = 2.364e − 05 and RMSE = 0.00162 of these curves indicate that the crime rate curve is well-fitted. In order to verify the authenticity of the fitted curve, we substituted the data from Henan Province, China. According to the data query, we found that the crime rate was 0.0058, and the actual value was 0.0053. Therefore, there is a logarithmic relationship between LI and CR; that is, the stronger the illumination, the smaller the CR, and the lower the crime rate, which is a negative indicator.

(3). Traffic accidents

With the rapid economic growth, the number of motor vehicles presents a surging trend, producing the corresponding light pollution. According to accident statistics, about half of all traffic accidents occur at night. However, the traffic volume during this period is much less than the daytime traffic volume, but the death toll is more than half of the daytime death toll, and the traffic accident caused by glare is a significant factor.

There are two main ways to evaluate glare: psychological and physiological. Psychological glare is due to the frequent exposure to high-brightness light sources in our vision, which makes the vision uncomfortable and tiring. When the beam of head-on headlights irradiates the driver’s eyes, the pupil diameter will decrease so that the retina can adapt to the road lighting condition caused by head-on headlights, and the driver’s physiological blinding will occur. Therefore, we construct the model of human psychological blinding degree (GI) and night brightness (LI) [5] [6]:

$$GI = log(LI * L^{2.5}/10^5) \tag{5}$$

Where: L is the distance between the light source and the eye. Studies have shown that 0 < G < 2, people will not produce psychological discomfort caused by glare fatigue. That is, within a specific range, the stronger the illumination, the larger the GI, and the larger the mental glare, which is a negative indicator.

(4). Biological growth energy

Light is the clean energy that all living things rely on for survival, while light pollution will disturb the biological clock of animals and the growth rhythm of plants. Ambient light can penetrate the skull of mammals with enough light to activate the photoelectric cells buried in the brain tissue and enable the growth of living things. We use the nutrients synthesized by plant photosynthesis to build a function for biological growth, and we get:

$$BG = In - Out \tag{6}$$

Where we set night light intensity (LI) to obey the normal distribution function of time t and established the function of photosynthetic capacity (IN) and night light intensity [7] as:

$$IN = Pmax * (1 - exp(-K * (LI - I_0))) \tag{7}$$

Where K_1 represents the basal metabolic rate within a unit of time, K_2 represents the photosynthesis increment within a unit of time, and finallyK1 = 0.5, K2 = 2. The more robust the light, the larger the BG, the more beneficial to plants, which is a positive indicator.

(5). Energy consumption

According to the data, about 13 percent of the country's electricity consumption is used for outdoor lighting, and about 35 percent of light waste is caused by inaccurate lighting. Excessive lighting wastes a lot of money and energy and causes severe environmental damage. In order to explore the relationship between energy consumption (EC) and light intensity (LI), we establish the following unitary linear model of light pollution, which can provide a scientific basis for controlling and managing light pollution.

$$EC = \alpha LI + \beta \tag{8}$$

Plug in the data and we get, α = 0.0125, β = 37.35. We know that the stronger the light intensity is, the bigger the EC is and the larger the resource consumption is, which is a negative indicator.

2.3. Establish the Indicator System

Through the above data analysis, each index has a positive or negative relationship. There- fore, we finally selected five indicators of light pollution risk assessment. Moreover, assign corresponding weight α_1, α_2, α_3, α_4, α_5, establish the following evaluation index system, ac- cording to which we can evaluate the light pollution risk level of a particular area. The model is shown in Figure 2 below.

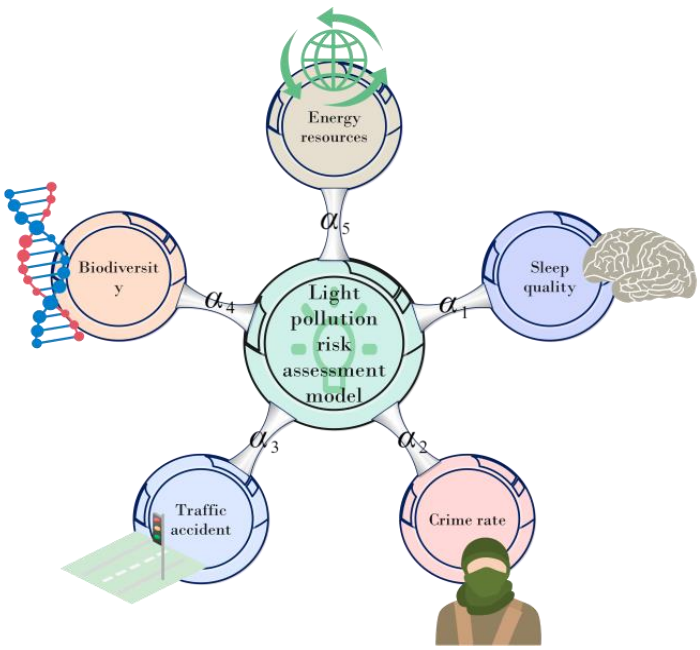

Figure 2. Index system

3. Light Pollution Risk Assessment Model

According to the light pollution risk assessment model established, we evaluate the light pollution risk level for four different types of cities in China; we use hierarchical analysis to derive the weights of each index, and use the light pollution sub-risk evaluation model to rank and classify different areas, then we select seven factors that may have an impact on light pollution, which are: population density, per capita economy, power generation, the number of tall buildings, longitude, latitude, and altitude. By linear regression and correlation analysis of the factors through partial least squares, we found the three factors that significantly influence the degree of light pollution. We established the function of light intensity and factors through which the light intensity of the area can be inferred, as shown in the figure below. As shown in the Figure 3 below.

Figure 3. Light pollution risk assessment model

3.1. Risk Assessment Based on AHP

(1). Calculation of LI of Different Land Types

By judging the degree of light pollution of different land types, we analyzed each influencing factor and the interrelationship among influencing factors. We formed different elements of the decision-making problem. At the same time, the analytic hierarchy Process (AHP) [8] is used to confirm the weight indicators of sleep quality, crime rate, traffic accident, biological growth, and energy consumption in the risk system. These indicators are characterized by layering and interlacing. The analytic hierarchy process (AHP) we use crisscross integrates the characteristics of each indicator. By analyzing and evaluating various factors highly correlated with light pollution, we establish the ownership relationship of the selected indicators and finally make a comprehensive evaluation and explanation of the risk level and pollution severity of light pollution.

Given the four types of areas the question requires, our team plans to use four similar corresponding areas in China to evaluate the degree of light pollution. The selected areas are Hulunbuir, Nanyang, Kunming, and Nanjing, corresponding to protected land and rural, suburban, and urban areas. We can obtain the DN value corresponding to a region through the above model affecting the regional light intensity, and then according to the conversion equation:

$$LI = (DN - 0.532439)/0.00242822 \quad (9)$$

And then we get the light intensity LI.

After the light intensity is obtained, five indicators affecting the severity of light pollution in these four areas are further calculated, and hierarchical analysis will be carried out on these five indicators.

(2). Construct the hierarchical structure mode

Based on the index system of light pollution risk constructed above and combined with different land types, the AHP structure model was constructed, as shown in the figure 4 below.

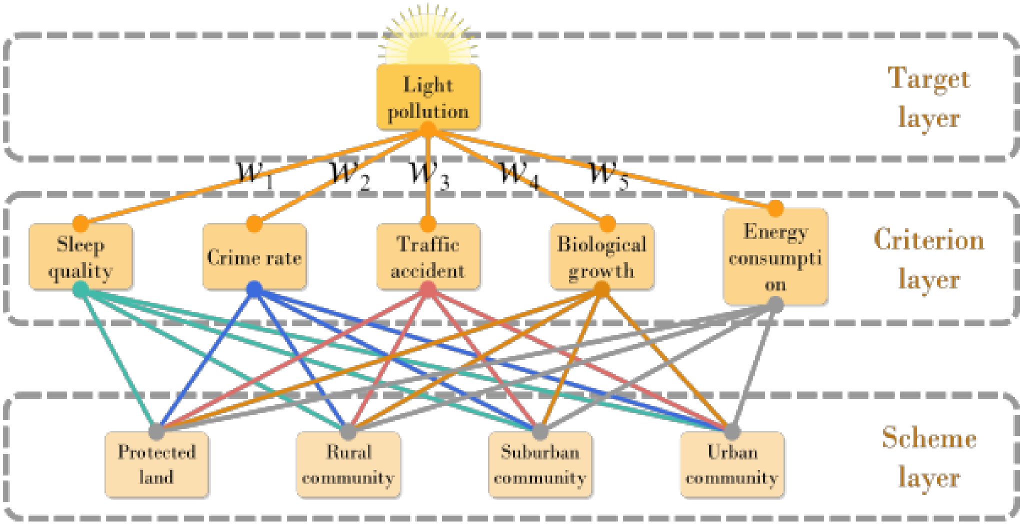

Figure 4. Example of a figure caption

(3). Construction of judgment matrix and weight calculation

To construct the judgment matrix of the upper layer, the elements of this layer should be compared in pairs, and the comparison adopts the relative scale. The 1~9 scale criterion is used to determine the quantitative value. The greater the importance, the higher the value.

1	1/2	1/3	2	1
2	1	1/2	4	2
3	2	1	5	7
1/2	1/2	1/3	1	1/2
1	1/2	1/4	2	1

Figure 5. Judgment matrix

After establishing two basic sub-models, we have to correct them in consideration of evaporation heat transfer. Then we define two evaluation criteria to compare the two sub-models in order to determine the optimal bath strategy.

Combining with expert opinions, we made pairwise comparison, thus obtaining the evaluation matrix A of the criterion layer to the target layer, as shown in Figure 5. A positive reciprocal matrix A is said to be consistent if it satisfies $a_{ij} \cdot a_{jk} = a_{ik}$, i, j, k = 1, 2, · · ·, n. Due to the property of uniform matrix, it can be known that the normalized eigenvector of A can be used as the weight vector. For A pairwise comparison matrix A that is inconsistent, but within the allowable range, it is suggested to use the eigenvector corresponding to the largest eigen root as the weight vector, have the following relationship.

$$Aw = \lambda w \tag{10}$$

A in the above equation is the judgment matrix, *lamada* is the eigenvector of A, and w is the weight vector.

Finally, the weight of the light pollution criterion layer index is calculated as follows:

w = [0.12460.21390.46160.08650.1132]

(4). Consistency Check

The consistency test is to determine the allowable range of inconsistencies for A. Since the A we get does not precisely conform to the agreement matrix, we need to increase the allowable range of A. Assuming that A is a positive reciprocal matrix of order n, the consistency index is defined as:

Firstly, we define two evaluation criteria. Then we contrast the two sub-models via these two criteria. Thus, we can derive the best strategy for the person in the bathtub to adopt.

$$CI = \frac{\lambda - n}{n-1} \tag{11}$$

CI is a consistency index, and the larger the CI, the more serious the inconsistency.

In order to measure the size of CI, the random consistency index RI was introduced – a_{ij} was obtained through random simulation by Saaty, the founder, and A was formed. RI was obtained by calculating CI.

Define the consistency ratio CR = CI/RI, when CR < 0.1, pass the consistency test.

In this case, we conducted A consistency test on matrix A and obtained CR = CI/RI = 0.0871 < 0.1, which passed the consistency test.

(5). Comprehensive weight calculation of each scheme

For the index weights w that pass the consistency test, we can continue to use the analytic hierarchy process (AHP) to get the evaluation matrix of the scheme layer to the criterion layer. Also, after passing the consistency test, we can get the weight of the scheme layer *fw* to the criterion layer to get the weight of the final scheme layer $Total_w$ to the target layer to judge the severity of light pollution in these four areas.

$Total_w = w * fw = [0.18760.18900.29380.3293]$

The results show that the damage of light pollution in Nanjing is the most serious, which means that the damage of light pollution in urban areas is the most serious.

As for the evaluation of indicators, our team summarized the calculated values of each indicator in the four different regions and carried out the positive normalization and nor- malization of these values using MATLAB. The normalization results of five evaluation indicators in the four regions are shown in Figure 1. Finally, the light pollution severity scores of four different types of areas were obtained by linear weighting calculation:

score = [0.46990.47840.49340.5133]

The results also show that the damage of light pollution in Nanjing is the most serious, which means that the damage of light pollution in urban areas is the most serious.

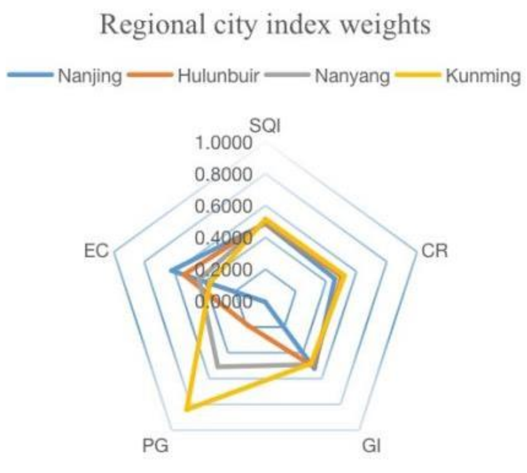

Figure 6. Normalized results

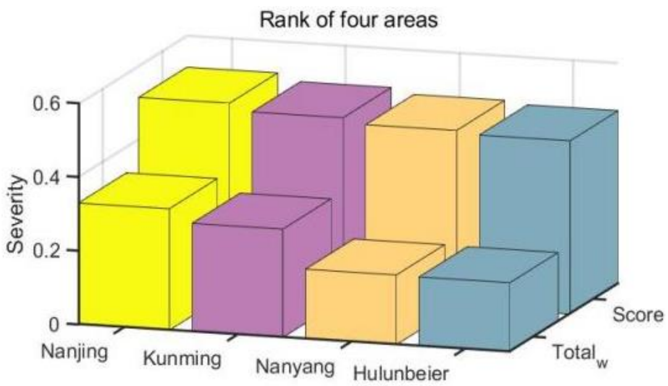

Figure 7. Different land scores

3.2. Establish Light Intensity Curve

Partial least squares regression is a modeling problem considering p dependent variables y_1, y_2, · · ·, y_p and m independent variables x_1, x_2, · · ·, x_m. The basic method first proposes the first component t1 in the independent variable set (t1 is a linear combination and extracts as much variation information as possible from the original independent variable set). At the same time, the first component u_1 is extracted from the dependent variable set, and the correlation between t_1 and u_1 is required to reach the maximum. Then, the regression of dependent variables y_1, y_2, · · ·, y_p and t1 is established. If the regression equation has reached satisfactory accuracy, the algorithm is aborted. Otherwise, continue to extract the second pair of components until satisfactory accuracy can be achieved. Suppose r components t_1, t_2, · · ·, t_r are extracted from the independent variable set. In that case, partial least squares regression will be obtained by establishing the regression formulas of y_1, y_2, · · ·, y_p and t_1, t_2, · · ·, t_r, Then, it is expressed as the regression equation of y_1, y_2, · · ·, y_p and the original independent variable, namely partial least squares regression equation [9].

In general, the partial least squares method does not need to select the existing r components t_1, t_2, · · ·, t_r to establish a regression formula, but like principal component analysis, only select the first 1 components (1 < r) to obtain a regression model with good predictive ability. The number of components l needed to be extracted for modeling can be determined by a cross-validity test.

The steps of partial least squares regression analysis of light pollution are as follows

(1). We need to request matrix $E_0^T F_0 F_0^T E_0 w1$ eigen vectors corresponding to the largest eigen value, obtained composition score vector t1 = E0w1, and the residual error matrix $E_1 = E_0 - t_1$, $t_1 = E_0\ w_1$. E_0 and F_0 are the n-times standardized observation data matrix for the independent variable group and the dependent variable group, respectively.

(2). Repeat the above steps for the RTH time, The eigen vector x corresponding to the maximum eigen value of the matrix $E_{r-1}^T F_0 F_0^T E_{r-1}$ is obtained, and the component score vector is obtained $\hat{t}_r = E_{r-1} w_r$.

(3). If a satisfactory prediction model can be obtained by extracting r components t_1, t_2, · · ·, t_r according to cross validity, the ordinary least squares regression equation of F_0 on $\hat{t}_r$ is the $t_k = w_{k1}^* x_1 + \cdots + w_{km}^* x_m (k = 1,2,\ldots,r), in\ Y = \ t1\ cdotsbet\ a1 + t_r beta_r$. The partial least squares regression equation of p dependent variable is obtained

$$y_j = a_{j1} x_1 + \ldots + a_{jm} x_m\ , \quad (j = 1,2,\ldots,p) \tag{12}$$

Here, $W_h^* = (W_{h1}^*,\ldots,W_{hm}^*)^T$satisfies $\hat{t}_h = E_0 W_h^*$, $W_h^* = \prod_{j=1}^{h-1}(1 - w_j \alpha_j^T) w_h$.

(4). Cross validity test: Cross coefficient is obtained, that is, r principal components are tested to test the effect of the model.

Because in order to determine the level of light pollution risk in an area, we know how this light pollution is produced, what forms it takes, and what effect it has. For example, areas with more population, a more developed economy, and more housing tend to have greater demand for electricity, resulting in relatively greater light pollution. In order to judge the light intensity of a region, seven dependent variables, population (PLT), economy (ECM), annual power generation (APG), number of tall buildings (NHB), altitude (ALT), longitude (LGT) and latitude (LTT), were obtained according to our daily life experience and physical knowledge.

The partial least square method is used to consider the modeling problem with light intensity (LI). The data we collected about the above 7 indicators in different regions were taken as independent variables x_1, x_2, · · ·, x_m. The pixel DN of the satellite light source in this area is used as the dependent variable (the pixel DN here can be obtained by the light intensity conversion formula of the corresponding satellite to obtain the light intensity LI). The above algorithm obtains the weights corresponding to these seven indicators, as shown in Figure 8 and the influential independent variable is x_1, x_2, x_5, x_6. The partial least squares regression equation of theta is obtained.

$$Y = 3.11 + 0.03x_1 + 0.04x_2 + 0.03x_5 - 0.09x_6 \quad (13)$$

In the formula, pixel DN of y satellite light source is APG, NHB, LGT and ALT. The prediction effect Figure 10 of this equation is obtained.

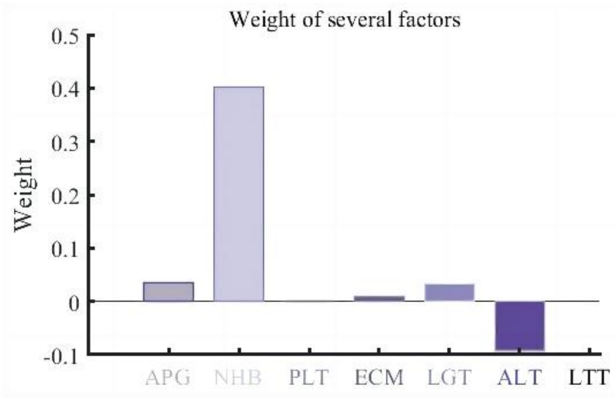

Figure 8. Weight chart

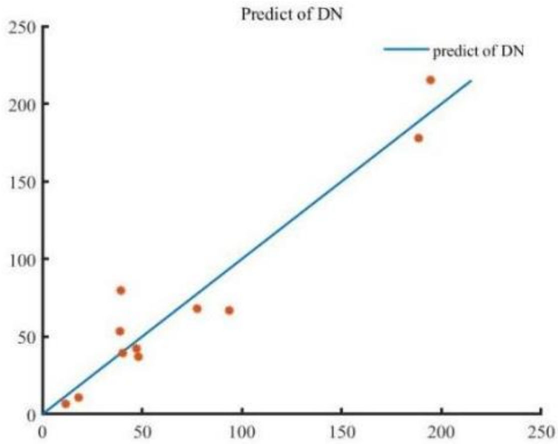

Figure 9. Regression equation prediction graph

3.3. Result Interpretation

According to the above results, Nanjing has the most serious light pollution and Hulunbuir has the lowest light pollution, which is consistent with the actual situation. According to the weight assignment method of hierarchical analysis, the greater the weight of the corresponding indicator, the higher the importance and the greater the influence in the risk of light pollution.

The weight coefficients of the first level evaluation indexes are analyzed: firstly, the weight coefficient of "traffic accidents" is the largest, which indicates that light pollution has a greater impact on traffic accidents; secondly, the weight coefficient of "crime rate" is larger, which indicates that the intensity of light at night has a certain impact on the population crime. The increase of light pollution has reduced the occurrence of crime to a certain extent. In summary, when we evaluate the risk level of light pollution in an area, the traffic accident and crime rates largely affect our judgment of the light pollution level in the area.

From the final results obtained from the analysis of the two methods, the final weights and the synthetic weights obtained from both are the same, indicating that the closer to the city, the more serious the light pollution is.

4. Conclusion

The above analysis shows that a region's electricity consumption is positively correlated with light intensity. Therefore, reducing electricity use and saving electricity will reduce the intensity of nighttime light to some extent. There are many factors directly related to electricity consumption and night lightings, such as reducing the lighting time of unnecessary decorative lights such as night billboards and electronic screens, and reasonably optimizing the lighting time, which saves energy and reduces light pollution [10]. The night street lights in some areas are kept on all night, so the use time of these lights should be optimized to extinguish or reduce the distance between adjacent street lights during the period with minor human activities to reduce the total number of street lights. The lighting Angle and lighting range of streetlights can also be adjusted to slow down the light intensity and reduce the influence of light pollution. Companies could also be encouraged to develop and manufacture lamps with softer lighting, which would directly reduce the impact of light pollution on people. The local government can adjust the electricity consumption time, reduce the lighting time of non-civil night lights, and encourage enterprises to produce in the daytime [11] [12].

For Chinese cities, most fast-growing urban areas are at low altitudes. The development of a city is usually affected by natural and social environmental factors. The influence of natural environmental factors (including geographical location) on the city is rigid and cannot be adjusted. It will cause lasting or even difficulty in changing the influence of urban development. Therefore, suitable natural factors require a lower elevation, accelerating the area's development. When an area develops faster and has higher levels of light, its light intensity also increases, affecting light pollution.

References

[1] Luo Zhenqing, Su Hang, Wang Zhuoli, Yang Biao. Urban lighting planning and classification of dynamic light pollution in night light environment [J]. Journal of Lighting Engineering, 2022, 33 (04): 193 - 202.

[2] Liu T Y. Light pollution treatment: a two-way study of domestic practice and foreign experience [J]. Journal of Northwest University for Nationalities (Philosophy and Social Sciences Edition), 2022 (01): 109 - 116.

[3] Yang Leyi, Chen Jieying, Zhang Luziyu, Zheng Yingying, Yu Yangfan, Fu Yingchun. Effect of light pollution on sleep based on NPP-VIIRS noctilucent data: A case study of Guangzhou City [J]. Tropical Geomorphology, 201, 42 (01): 47 - 53.

[4] Chang An. Spatial Econometric analysis of socioeconomic factors and provincial crime rate in China [D]. Tutor: Yang Fenglu. Shandong University, 2018.

[5] Tang Zuogan, Sun Yeyao, Guo Ying, et al. Street Traffic Accident Casualty Modeling based on multi-source Data fusion [C]// China Intelligent Transportation Association. Proceedings of the 15th annual meeting of intelligent transportation of China science and technology (1) ministry of China publishing group, 2020: 11.

[6] SONG Hongfei. Research on Road Traffic Blinding Law and Its Control Technology [D]. Southwest Jiaotong University, 2010.

[7] Gao Hongnai, Fu Lijiang, Xia Qian, Guo Ya. Application of observability measure in photosynthesis model performance evaluation [J]. Journal of System Simulation, 202, 34 (06): 1330 - 1342.

[8] Qi Ji, Li Yan, Li Defeng. Application of fuzzy optimization model based on improved AHP legal rights in groundwater quality evaluation [J]. Journal of North China Institute of Water Resources and Electric Power, 2002 (02): 4 - 7.

[9] Qin Hao, Lin Zhijuan, Chen Jingwu. Partial least squares regression principle, analysis procedure and procedure [J]. Journal of Mathematical Medicine and Pharmacology, 2007 (04): 450 - 451.

[10] Fu Sha, Wei Xinyu. Environmental Protection, 2021, (22): 71 - 75.

[11] Shi Zhuoyong, Song Yafei. Empirical Research on Electricity Saving of Street Lighting [J]. Shihezi Science and Technology, 2020, (04): 38 - 39.

[12] Huang Ruixue, Guo Yizao, Zhang Dingling, Zhang Hongchuan, Qin Qiying. Current situation and suggestions of light pollution at night in residential areas of Chongqing [J]. Light Sources and Lighting, 2022, (11): 5 - 7.