Evaluation and Analysis Model of Light Pollution Risk Level Based on Multiple Indicators

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Abstract. A new environmental problem-light pollution has gradually attracted the attention of governments all over the world. To develop a model to evaluate the risk level of light pollution， we have set up three first-level indicators which are regional development level, population, and biological environment, and set up two-level indicators under them like: urbanization rate, lighting intensity, biology diversity.etc.We use the light pollution index obtained by satellite detection, and get the final regression equation of light pollution index by ridge regression fitting with the data of 28 provinces, and then verify it with the image observed by Luojia –1, and determine the model equation of Light Pollution Index. Then we optimize the model through both geography and climate, and correct the provinces where the light pollution index fitted by the regression equation is different from the real light pollution index, making the model accuracy further improved.

Keywords: Light pollution; Ridge regression; Comprehensive pollution light index.

1. Introduction

Excessive or inappropriate use of artificial light is called light pollution, which includes light trespass, over-illumination and light clutter. Most of these phenomena are located in cities, but they may also happen in areas which is remote from cities. Light pollution has a far-reaching impact: as for the natural environment, it has an influence on plant growth and animal migration patterns; as for human beings, it can disrupt our circadian rhythms, causing sleep disorders, and may affect our physical and mental health. Meanwhile, artificial lighting glare is also a cause of car accidents. Based on this situation, the government can announce some measures or conduct corresponding publicity to reduce the adverse effects of light pollution. However, improper measures or reducing the use of artificial light blindly may lead to the increase of criminal incident. To develop a model to evaluate the risk level of light pollution, and validate its rationality and applicability, we have studied the research results in recent years and found that the evaluation indicators are divided into two categories: comprehensive factors as the main evaluation index and physical factors as the main evaluation index;For comprehensive factors , many studies have given various evaluation indicators [1]~ [4].At the same time, the establishment of evaluation models is becoming more and more mature, such as ridge regression model [5]~[8];For physical factors, many previous studies have provided comprehensive evaluation criteria [9][10]. To solve this question，we mainly select five first-level indicators. Then, a number of secondary indicators are subdivided under the primary indicators. We collect relevant data from each province and use them to model light pollution indicators through ridge regression. Also, we use the data about LII from Luojia--1 to verify our model.

2. Evaluation and Analysis Model of Light Pollution Risk Level Based on Multiple Indicators

2.1. Problem Analysis

According to the problem, the influence of light pollution is mainly reflected in the level of development, health, biological environment and so on. Therefore, we take the above several aspects as the as the subjects of our study, establish secondary evaluation analysis indicators, and build LPIR

(Light pollution integrated index risk evaluation model) model to analyze the data systematically, and get the comprehensive pollution light index(CPLI). Meanwhile, to validate the feasibility of the model, we use the geographic data (satellite images) collected by the Luojia-1 night light remote sensing satellite to analyze and evaluate the light intensity index (LII) and verify the above model, so as to achieve the purpose of comprehensive evaluation.

2.2. Establishment of LPIR Model

2.2.1 Variable Selection

Based on the publicly available data, combined with the relevant studies, and considering the quantifiability and operability of the factors, this essay extends the above first-level evaluation indicators (development level, health level, biological environment), and establishes the following independent variables.The indicators were classified as shown in Figure 1.

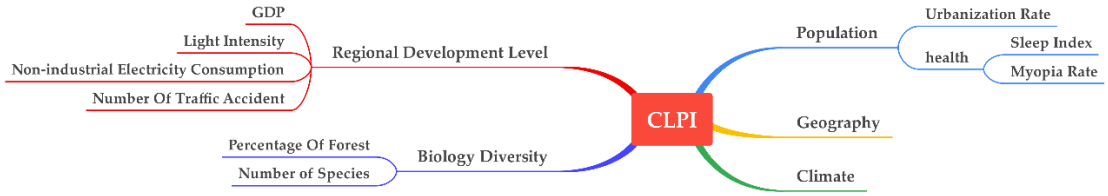


Figure 1: Indicators of CLPI

• Urbanization Rate: This variable reflects the degree of modernization, and then can indirectly reflect the level of light pollution.

• GDP (for each province): This variable reflects the Level of economic development, which has a close relation to the establishment of artificial light source.

• Light Intensity: Conducts a questionnaire survey by investigating the living lights in residential areas, and get the value of this variable after summarizing and scoring. This variable is an important index which reflects the level of light pollution.

• Non-industrial Electricity: This variable is obtained by subtracting the total electricity consumption from the electricity consumption of the primary and tertiary industries. It mainly reflects the situation of non-industrial electricity consumption, which is the main power consumption to support artificial light sources

• Percentage of Forest/Biology Diversity: Light pollution will change the circadian rhythm of plants and the living habits of animals, and then affect their growth cycle and population number, and affect the biology diversity in this area. Therefore, the two indicators can reflect the level of light pollution reflected indirectly.

• Number of Traffic Accidents: Light pollution may affect the driver's judgment, and then lead to traffic accidents.

• Sleep Index: Light pollution may affect the quality of human sleep.

• Myopia rate: Light pollution promotes the occurrence of myopia through its optical characteristics. This variable reflects the level of light pollution indirectly.

At the same time, we chose the data of DMSP, as the dependent variable of regression to train the model.

2.2.2 Model Introduction

In the standard linear regression, we train the model by minimizing the square error between the real value and the predicted value, assuming that:

$$RSS = \sum_{i=1}^{n}(y_i - y_i')^2 \tag{1}$$

The least square method is to minimize the sum of squares of residuals, which is

$$J_\beta(\beta) = \underset{\beta}{argmin} \sum_{i=1}^{p}(y_i - x_i\beta_i - \beta_0)^2 \tag{2}$$

Converted into a matrix is:

$$\boldsymbol{J}_{\beta}(\beta) = \underset{\beta}{argmin}(y - X\beta)^{T}(y - X\beta) \tag{3}$$

$$\beta = (X^{T}X)X^{T}y \tag{4}$$

And ridge regression is an improved least square estimation method. By giving up the unbiased of the least square method, the regression coefficient is obtained at the cost of losing some information and reducing accuracy. It is a more practical and reliable regression method, and the fitting of data with outliers is stronger than that of the least square method.

In ridge regression, the cost function adds the penalty to the coefficient value on the basis of RSS and becomes:

$$\boldsymbol{J}_{\beta}(\beta) = \underset{\beta}{argmin}(y - X\beta)^{T}(y - X\beta)\boldsymbol{J}_{\beta}(\beta) = \text{RSS}+\lambda\sum_{j=0}^{n}\beta_{j}^{2} \tag{5}$$

Matrix form becomes:

$$\boldsymbol{J}_{\beta}(\beta) = \sum_{i=1}^{p}(y_{i} - X_{i}\beta)^{2} + \lambda\sum_{j=0}^{n}\beta_{j}^{2} \tag{6}$$

The above formula are (1)—(6).

Next, we use spsspro software to analyze this model, and the following is the analysis process: Firstly, the original data is standardized, and the corresponding variables after processing are set as follows $Y_{st}, Z_1, Z_2, Z_3, Z_4, Z_5, Z_6, Z_7, Z_8, Z_9, Z_{10}$ Standardized regression model is set to

$$\begin{aligned} Y_{st} &= B_1 \times Z_1 + B_2 \times Z_2 + B_3 \times Z_3 + B_4 \times Z_4 + B_5 \times Z_5 \\ &+ B_6 \times Z6 + B7 \times Z_7 + B_8 \times Z_8 + B_9 \times Z_9 + B_1 0 \times Z_{10} + \varepsilon \end{aligned} \tag{7}$$

The formula is as (7).

Figures 2 and 3 show the ridge trajectory plots:

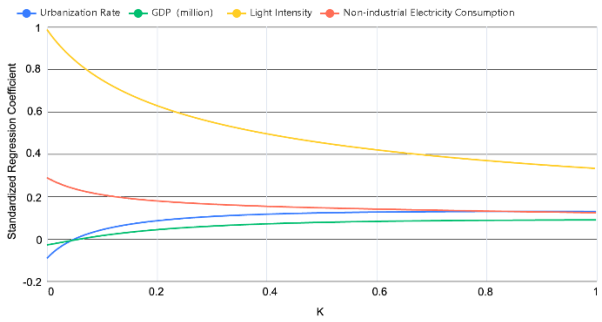


Figure 2: Ridge trace map1

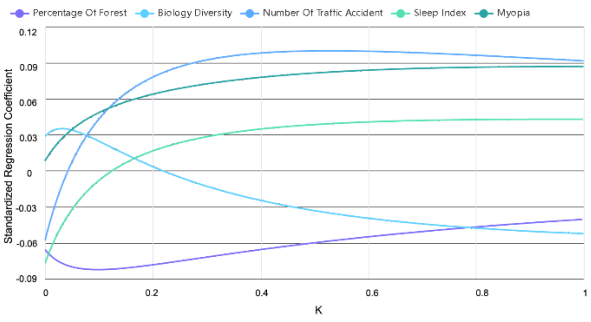


Figure 3: Ridge trace map2

P.S: The figures above show the situation when the standardized coefficients of each independent variable of this model tend to be stable in visual formalization.

Next, by spsspro, we get the summary of the calculation results as Table 1.

Table 1: Results summary

K=0.15	Unstandardized Coefficients		Standardized Coefficients	t	P	R^2	Adjusted R^2	F
	B	Standard Error	Beta					
ε	-0.039	0.0451	-	-0.878	0.391	0.919	0.878	22.68(0.000***)
Urbanization Rate	0.049	0.052	0.0687	0.937	0.361			
GDP(million)	0.0187	0.041	0.03	0.437	0.6687			
Light Internsity	0.543	0.058	0.681	9.408	0.000***			
Non-industrial Electricity Consumption	0.106	0.038	0.19	2.814	0.011**			
Percentage Of Forest	-0.036	0.029	-0.08	-1.245	0.229			
Biology Diversity	0.017	0.089	0.014	0.191	0.850			
Number Of Traffic Accident	0.032	0.033	0.065	0.972	0.344			
Sleep Index	0.003	0.031	0.007	0.108	0.915			
Myopia Rate	0.03	0.036	0.058	0.842	0.411			
Dependent variable: Composite Score								

The results of ridge regression show that the P value of significance based on F test is less than 0.05, which is significant at the horizontal level, rejecting the original hypothesis, indicating that there is a regression relationship between independent variables and dependent variables. At the same time, the goodness of fit R2 of the model is 0.919, and the model is excellent.

At the same time, we get its non-standardized coefficient as follows:

B1=-0.039,B2=0.049,B3=0.018,B4=0.543,B5=0.106,B6=-0.036,B7=0.017,B8=0.032,

B9 =0.003,B10=0.03.

Taking its absolute value and observing it, we can see that the relative importance of these 10 indicators to the evaluation of light pollution is in descending order: light intensity and non-industrial electricity, urbanization rate, percentage of forest, traffic accident rate, myopia rate, GDP, biology diversity and sleep index.

Finally, we get the formula of comprehensive evaluation model.

$$Y_{st} = B_1 \times Z_1 + B_2 \times Z_2 + B_3 \times Z_3 + B_4 \times Z_4 + B_5 \times Z_5 + B_6 \times Z6 + B7 \times Z_7 + B_8 \times Z_8 + B_9 \times Z_9 + B_10 \times Z_{10} + \varepsilon \quad (8)$$

The formula is as (8).

Figure 4 is the fitting result diagram, which shows that the fitting effect is good[8]:

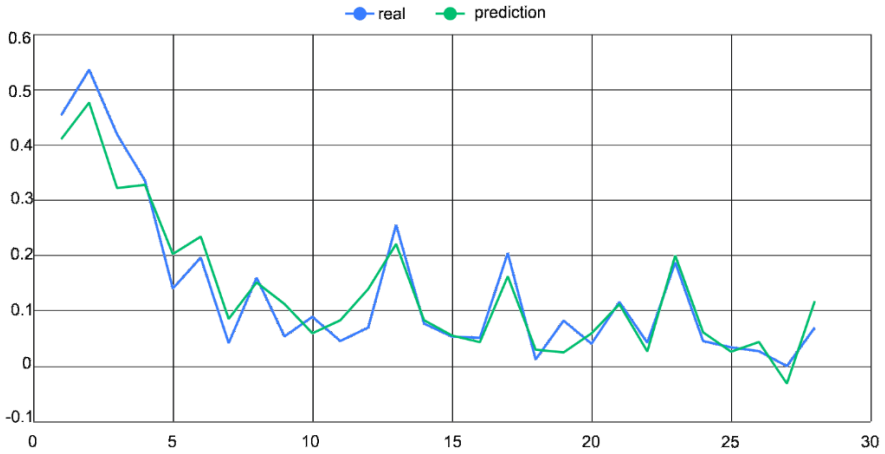


Figure 4: Fitting result diagram

Figure 5 is the CPLI ranking of the final provinces (municipalities and autonomous regions) obtained by fitting the model:

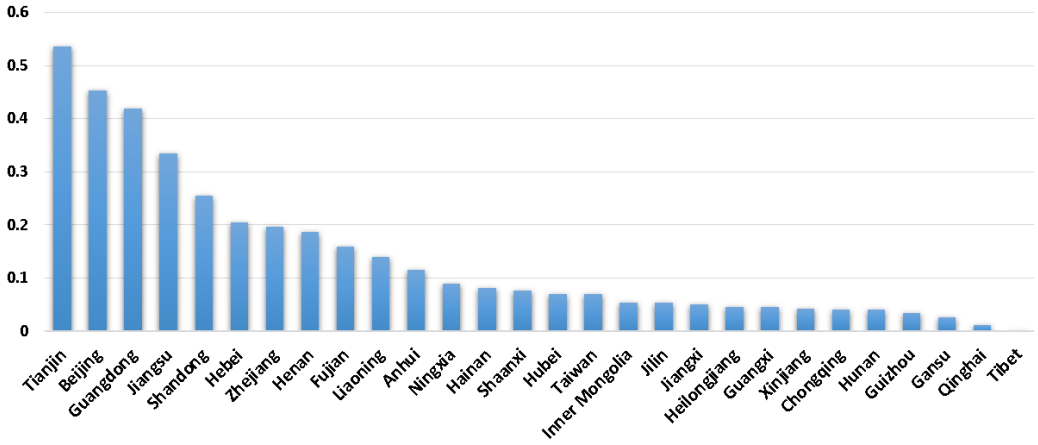


Figure 5: Rank by CPLI

2.2.4 Sensitivity Analysis

In the above model, we set the types of variables by ourselves and give each variable a weight in the score according to the program. We analyze the sensitivity of the CPLI to various indicators. The sensitivity of this light pollution model is tested, and the urbanization rate, light intensity, non-industrial electricity consumption and biodiversity are disturbed (increased or decreased) by 5%.The result is shown in the figure 6.

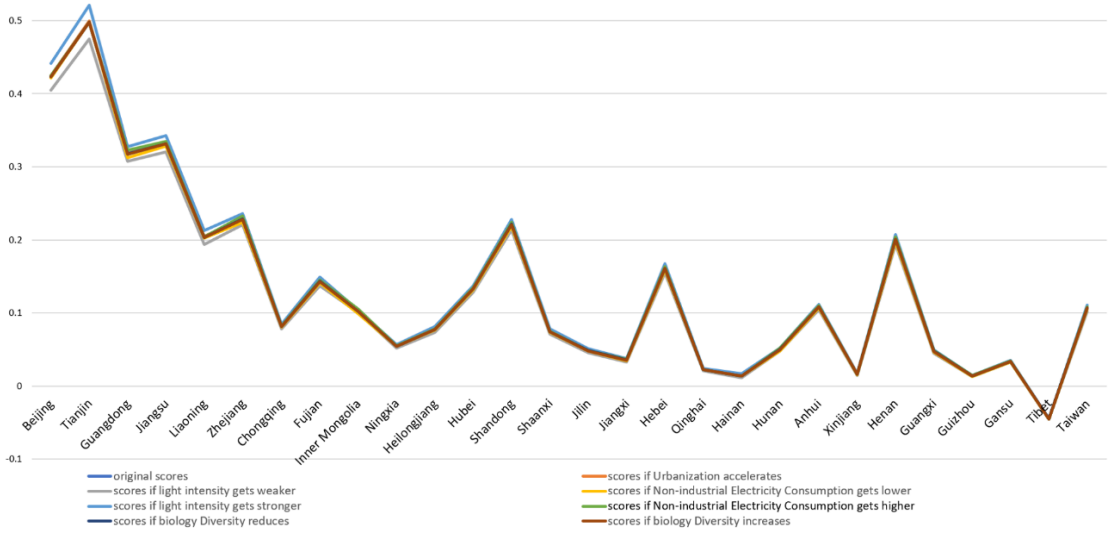


Figure 6: Sensitivity analysis

We found that when the light intensity was disturbed by 5% at night, the change of light pollution evaluation index was also close to 5%, which was sensitive. For other factors, the change of urbanization
rate, non-industrial electricity consumption and biodiversity is about 1%, which is relatively stable. The results of sensitivity and stability of the above factors also correspond to the fact that the light intensity at night is dominant in the influence of light pollution, and also reflect the rationality of the established model. Therefore, we believe that the determined model has passed the sensitivity test.

2.3. Verification of The Accuracy of The Original Model Data Based on Luojia–1 Data

2.3.1 Introduction of Luojia–1

”Luojia-1” is the world’s first professional luminous remote sensing satellite, which was jointly developed and produced by the team of Wuhan University and related institutions, and was successfully launched on June 2, 2018. It is equipped with a high-sensitivity luminous camera, and its accuracy will reach 100 meters on the ground. At night, all the lighted bridges on the Yangtze River can be seen, and at that time, night pictures with much higher accuracy than those of other countries’ satellites will be obtained. The satellite will be oriented to the National Development and Reform Commission and other departments to monitor the macro-economic operation in China and the world and provide objective basis for government decision-making.

2.3.2 Data Extraction and Transformation of Luojia–1

Our team downloaded China brightness data from official website[4]of Luojia–1 data center, and the downloaded Luojia–1’s data has not been scaled, so it can be scaled by radiance conversion formula:

$$L = DN^{3/2} \cdot 10^{-10} \tag{9}$$

The formula is as (9).

In the formula, L is the radiation brightness value after absolute radiation correction, and the unit is $W/(m2 \cdot sr \cdot \mu m)$. DN is the gray value of the image. The unit is the standard radiation measurement unit, and the radiation brightness is within the normal range.

2.3.3 Determination of Light Intensity Index (LIl)

An index to determine the light pollution risk level of a site from the data of Luojia-1 is the Light Intensity Index (LIl), which combines the following factors:

Sky brightness: The brightness classification of light environment can effectively control the degree and scope of light pollution, improve the quality of light environment at night, ensure the light environment demand of urban residents in their normal life, study and workplace, and protect the

living environment and ecological balance. Therefore, we use John Bortle's dark sky classification for grading and scoring.The result are as table 2.

Table 2: John Bortle's dark sky classification

Dark sky Level	Visual Limit Magnitude	Location	Pollution Degree	Sky Color
Level 1	7.6 8.0	Original Dark Sky	Zodiacal light and starlight can be seen.	
Level 2	7.1 7.5	Typical Really Dark Sky	The airglow is faintly visible along the horizon.	
Level 3	6.6 7.0	Country Sky	There are some signs of light pollution near the horizon.	
Level 4	6.1 6.5	Sky in Rural-suburban Transition Zone	Light pollution can be seen in the direction of population gathering areas.	
Level 5	5.5 6.0	Suburban Sky	The starlight is very weak, and the horizon is invisible.	
Level 6	5.5	Bright Suburban Sky	You can't see zodiacal light even on the best night Only the starlight at the zenith can be seen.	
Level 7	5.0	Sky in suburban-Urban Transition Zone	The whole sky background appears fuzzy gray-white Starlight is invisible.	
Level 8	4.5	Urban Sky	The sky is grayish white or orange red.	
Level 9	4.0 or Less	Central Area and Main Urban Area	The whole sky is illuminated brightly.	

• Glare: This factor measures the amount of light scattered or reflected by the atmosphere or the ground, resulting in visual discomfort or damage. This can be measured by using a special glare meter or by analyzing satellite images.The earliest uncomfortable glare evaluation system is the GI glare index system summarized by British people Petherbrigde and Hopkingson in 1950s. That is, under the fixed background brightness, it is obtained by the subjective evaluation of the visual comfort of a light source by the subjects. The evaluation formula of this system for a single glare source is as (10):

$$G = (0.9L_s^{1.6} \cdot \omega^{0.8})/(L_b \cdot p^{1.6}) \tag{10}$$

In the formula above, LS = Brightness of glare source. Its unit is cd/m2. ω is solid angle of the glare source relative to the eyes. Its unit is ster. Lb is background brightness, its unit is cd/m2. P is the degree to which the glare source deviates from the line of sight, that is, the position index. GI system uses superposition method for multiple glare sources, and its formula is as (11):

$$GI = 10\,log_{10}\,(0.5\sum G) \tag{11}$$

The meaning of each symbol in the formula is the same as before. The value of GI is between 10 and 30, and the classification standard is as table 3.

Table 3: Classification standard

GI	Glare standard classification
Night Artificial Light Intensity	1.866
Sky Brightnesse	965-7
Glare Light Space Range	0.679 0.8187

We combine the data of Luojia–1 with the local report and analyze it to determine the final value of glare index GI.

• Spatial scope: This factor measures the size and degree of light pollution in the area. This can be measured using satellite images. Therefore, after SVD dimensionality reduction of Luojia No.1 image in matlab, our team used imread function to separate and extract the ratio of white pixels, and based on this, counted the light spatial range in this area.

• Artificial light intensity at night: This indicator measures the amount of artificial light emitted by outdoor light sources in a certain range at night, which can be measured by satellite images, so our team still uses matlab to process the images and count the size range of this indicator accordingly.

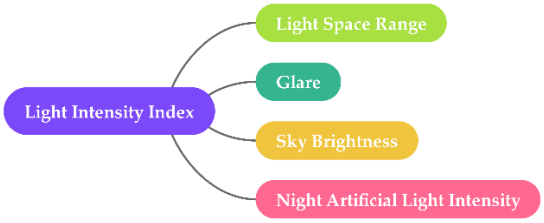


Figure 7: Indicators of LII

The classification of the indicators is shown in figure 7.

After determining the index, we use AHP to establish the following evaluation index after data search and discussion,and the consistent matrix of indicators is as Table 4 :

Table 4: Consistent matrix

Indicator	NAL	Br	GI	LSR
NAL	1	1.667	3	2.425
Br	0.6	1	1.269	1.138
GI	0.333	0.788	1	0.811
LSR	0.412	0.879	1.233	1

And we obtain the results in table 5 by spsspro :

Table 5: AHP analytic hierarchy process results

Indicator	Eigenvalue	Weight value	Maximum Eigenvalue	CI
Night Artificial Light Intensity	1.866	43.1177		
Sky Brightnesse	965-7	22.2927	4.012	0.004
Glare Light Space Range	0.679 0.8187	15.698 18.893		

The weight calculation results show that the weight of Night Artificial Light Intensity is 43.117%, that of Sky Brightness is 22.292%, that of Glare is 15.698%, and that of Light Space Range is 18.893%.

The calculation results are ranked as Figure 8 :

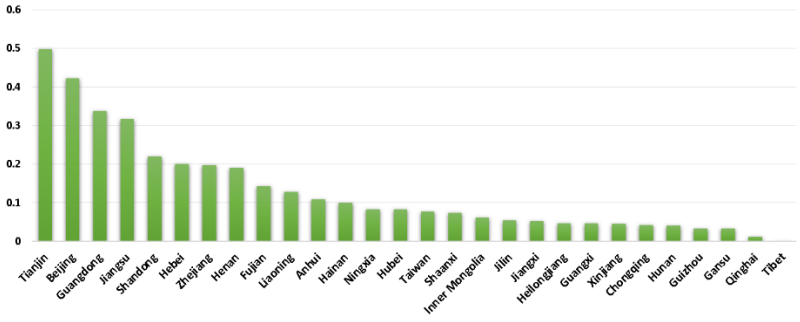


Figure 8: Rank of LII

The final results are basically consistent with the results in Figure 7, that is, the model in 3.4 is proved to be reasonable through inspection.

2.4. Improvement and Supplement of the Model

In the above analysis, we did not take Geography and Climate into consideration. In reality, these two indicators will have an impact on the degree of light pollution. In terms of geography, the shape and direction of the land will affect the spread of light – light pollution may be more concentrated in valleys and basins than in hilltops where light is more easily dispersed. In terms of climate, in areas with warm climate, people tend to spend more time outside, which may lead to an increase in the use of outdoor lighting. On the contrary, in a cold climate, people may spend less time outside, thus reducing the demand for outdoor lighting. The distribution model of the optimal temperature will have a bell curve, and the peak of the curve represents the optimal temperature range. The whole distribution conforms to the normal distribution, which represents the average temperature that people tend to spend more time outside, while the standard deviation represents people's different preferences for different temperatures. This shows that $22 \circ C\ (+-3 \circ C)$ is most likely the optimum temperature range. The formula 12 based on normal distribution illustrates the relationship between temperature and people's willingness to outdoor activities:

$$W_1 = \frac{1}{3\sqrt{2\pi}} e^{-\frac{(t-22)^2}{50}} \tag{12}$$

According to this, we can add the above indicators to the comprehensive evaluation system indicators and give them corresponding weights for calculation.

3. Conclusion

This paper is set up three first-level indicators which are regional development level, population, and biological environment, and set up two-level indicators under them like: urbanization rate, lighting intensity, biology diversity.etc,and use the light pollution index obtained by satellite detection, and get the final regression equation of light pollution index by ridge regression fitting with the data of 28 provinces, and then verify it with the image observed by Luojia --1, and determine the model equation of Light Pollution Index. Then we optimize the model through both geography and climate, and correct the provinces where the light pollution index fitted by the regression equation is different from the real light pollution index, making the model accuracy further improved.

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