| Problem Chosen | 2023 MCM/ICM Summary Sheet | Team Control Number |
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# Less Lights & More Stars


## Summary

With the widespread use of artificial light, light pollution becomes more and more serious, causing problems in the ecological environment and human health. In this paper, we establish an evaluating model and a programming model to determine the risk level of light pollution and the best intervention strategy for different locations.

**For problem 1**, we propose a model for evaluating light pollution risk level with wide applicability. First, we consider that the light pollution risk level of an area is influenced by its current **Light Pollution Degree(LP)**, its **Natural Factors(NF)** and **Human Factors(HF)**, and find a total of six secondary indicators from them. Then, we combine the Analytic Hierarchy Process(**AHP**) with the Entropy Weighting Method(**EWM**) to calculate the weights of the indicators, thus obtaining the formula to calculate the light pollution risk score. After obtaining data and calculating scores for 14 regions in China and the US, the **Hierarchical Clustering Algorithm** is used to divide the light pollution risk level into three categories: **low, medium and high**. Besides, we make a **correlation analysis** of the secondary indicators, showing the rationality of our index system.

**For problem 2**, we choose Jiuzhaigou, Xiaogang Village, Fengxian District and Xinjiekou in China to represent four different areas in the question. After obtaining and processing the relevant data, we find that Jiuzhaigou has a total light pollution risk score of about **26.28**, which is a **low**risk area, followed by Xiaogang Village with a score of **37.68**, which is a **medium** risk area. Fengxian District is **76.70** and Xinjiekou is **90.21**, both are **high** risk areas. According to the scores of each indicator, we analyze the factors affecting their light pollution risk levels separately. To eliminate the influence of chance factors such as local peculiarities, we select four more representative areas in the U.S. for analysis, and the total score increases **in an ascending order from protected areas to urban community**, which is consistent with the actual situation. This again shows the reasonableness of our indicators and the universality of our model.

**For problem 3**, with the aim of **diversified governance**, we propose strategies in three aspects: **artificial light improvement, government policy intervention** and **public awareness education**, and **11 practical actions** from them are discussed. In addition, we analyze **the potential impacts** of certain measures in different areas, such as increasing safety risks on suburban roads, increasing economic burdens in rural areas, and inhibiting the development of nighttime economies in urban areas.

**For problem 4**, to determine the most effective intervention strategy, we establish a **light pollution treatment programming model**. we take Xinjiekou and Jiuzhaigou as examples, and the results show that the most effective intervention strategy in both places is to improve artificial light sources. Scores are reduced by **23.5%** and **13.9%** respectively after implementation. Moreover, this strategy reduces the light pollution risk level mainly by reducing the LP score in both places, and the NF score in Jiuzhaigou is also reduced. Finally, we conduct a **sensitivity analysis** and conclude that our model is stable.

**At last**, we produce **a 1-page flyer** to promote the most efficient strategy for Xinjiekou to reduce its light pollution risk level.



**Keywords**: Light Pollution Risk Level Evaluation Model, Light Pollution Treatment Programming Model, AHP, EWM, Hierarchical Clustering Algorithm

# Contents

# 1 Introduction

## 1.1 Problem Background

The colorful night lighting can beautify the image of the area and enhance the living service environment. People are also accustomed to taking the degree of night scene lighting as one of the criteria to measure the level of regional development. However, unreasonable night lighting leads to light pollution. Light pollution refers to the phenomenon of adverse effects on human life and the surrounding environment due to excessive or poor use of artificial lights. It may not only lead to traffic accidents, but also affect biorhythms and human health both physically and mentally. In order to raise people's awareness of light pollution and develop strategies to mitigate the negative effects of light pollution, we decide to establish a model to assess a location's risk level of light pollution, and then put forward relevant measures to deal with light pollution in different regions.

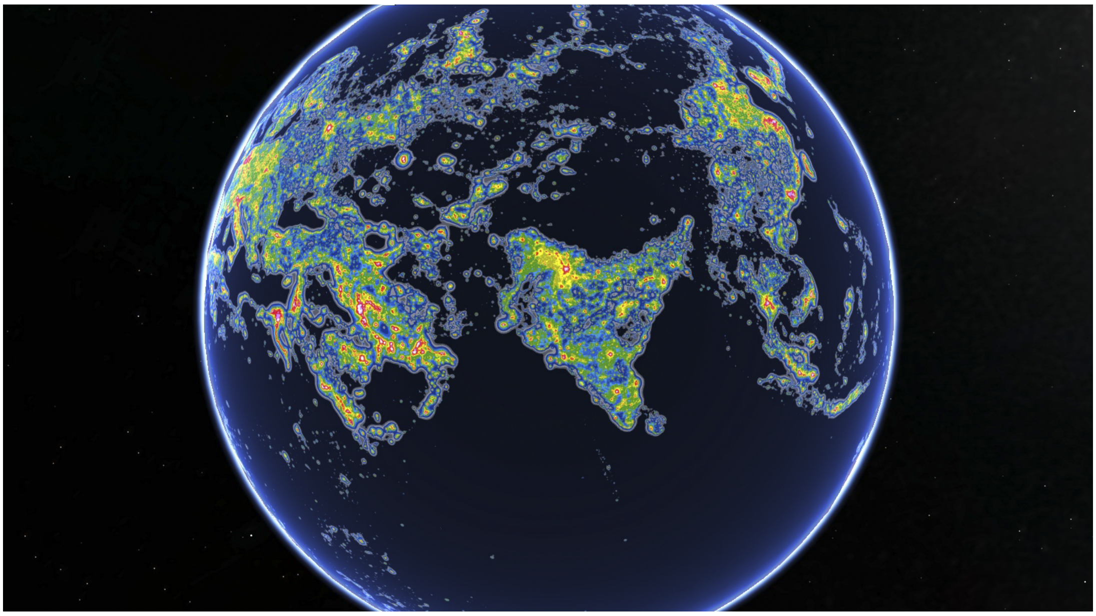

Figure 1: The new world atlas of artificial night sky brightness[1]

## 1.2 Restatement of the Problem

Having understood the problem and considered the background information, we're required to do the following work:

- Design a light pollution risk evaluation model with wide applicability.
- Apply our model to four different kinds of locations then explain and analyze according to the corresponding results.
- Based on the indicators and the analysis of the situation in the four regions, propose three possible intervention strategies to solve light pollution. Then discuss the specific actions related to each strategy and their potential impacts on general light pollution.
- Select two locations and determine the most effective intervention strategy for each. Discuss how the selected intervention strategy influences the risk level of the location.

- Create a one-page flyer to promote the most effective intervention strategy for one of the identified locations.

## 1.3 Our Work

First, we design **the Light Pollution Risk Level Evaluation Model**. We classify the light pollution risk level into the following three dimensions: **Degree of Pollution, Natural Factors and Human Factors**, followed by six secondary indicators. We quantify the qualitative indicators and then process the data set. A combination of **AHP** and **EWM** are used to derive the weight of each indicator, and a formula to calculate the total light pollution risk score is obtained. We also conduct a **correlation analysis** of the indicators to confirm the rationality of the selected indicators. Finally, the light pollution risk scores are classified into **3 levels** according to the **hierarchical clustering algorithm**.

Then, we select four different types of locations and use Light Pollution Risk Level Evaluation Model to analyze their light pollution risk level respectively.

Finally, we propose three possible intervention strategies to address light pollution and analyze their **potential impacts**. A **Light Pollution Treatment Programming Model** is developed to determine the most effective intervention strategy and their impacts at each location. Jiuzhaigou and Xinjiekou are selected for example analysis and **sensitivity analysis**.

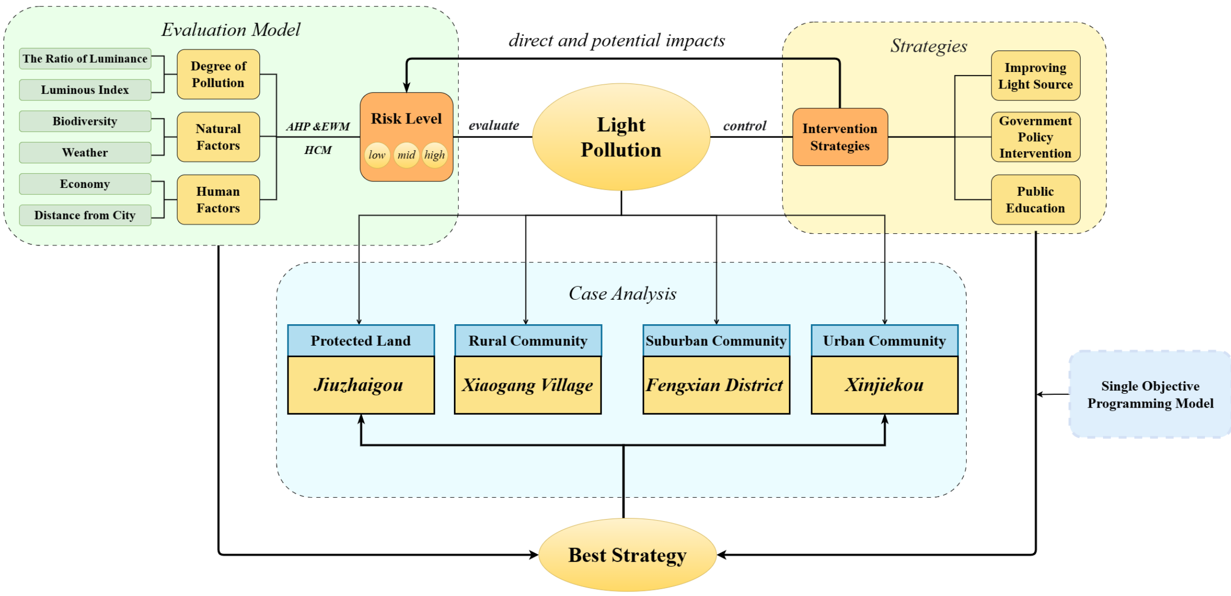


Figure 2: Our Work

# 2 Assumptions and Justifications

To simplify the problem, we make the following basic assumptions, each of which is properly justified. Other assumptions based on different models will be listed in the following model-related sections.

- **We assume that an area is not affected by the light source of its adjacent area**
  Since light is divergent, the light source in one region affects the level of light pollution

in adjacent regions. To emphasize the characteristics of an area itself, we ignore the small effect of light sources in adjacent areas to facilitate discussion of light pollution risk levels by region.

- **We assume that all departments are responsive to light pollution and actively implement various interventions**
  In order to judge the impact of the interventions on the level of light pollution risk, we assume that the interventions can all be implemented as specified.
- **We assume that the degree of various types of light pollution is the same**
  Light pollution is divided into glare pollution, infringement light pollution and spill light pollution, etc. Since what we need to get is the total degree of light pollution in an area, we ignore the differences between the degree of each type of light pollution and consider them as a whole.

# 3 Notations

Some important mathematical notations used in this paper are listed in Table 1.

Table 1: Notations Used in This Paper

| **Symbols** | **Description** | **Unit** |
|---|---|---|
| $P$ | The ratio of zenith luminance and natural night sky luminance | \ |
| $\phi$ | The total luminous flux of outdoor lighting | $lm$ |
| $B_i$ | The night sky luminance value in different weather conditions | $mcd/m^2$ |
| $Score$ | Total light pollution risk score | \ |
| $\alpha$ | The ratio of input capital to GDP | \ |
| $F_k$ | The actual capital of the *k*th index | billion |
| $\Delta S_k$ | The change of the *k*th index score | \ |

Note: There are some variables that are not listed here and will be discussed in detail in each section.

# 4 Light Pollution Risk Level Evaluation Model

In this section, we develop a model to identify the light pollution risk level of a location. Taking the **degree of light pollution, natural factors** and **human factors** into consideration, we select six secondary indicators. After that, we combine the Analytic Hierarchy Process(**AHP**) and the Entropy Weight Method (**EMW**) to calculate the weight of the indicators at all levels, and then obtain the light pollution risk score.

In order to ensure the rationality of the index selection and the universality of the model, we select 14 communities in China and the United States into our model. We analyze the correlation between the indicators according to the scores. Finally, referring to the light pollution risk scores of these communities, we use the **Hierarchical Clustering Method** to divide the light pollution risk into three levels.

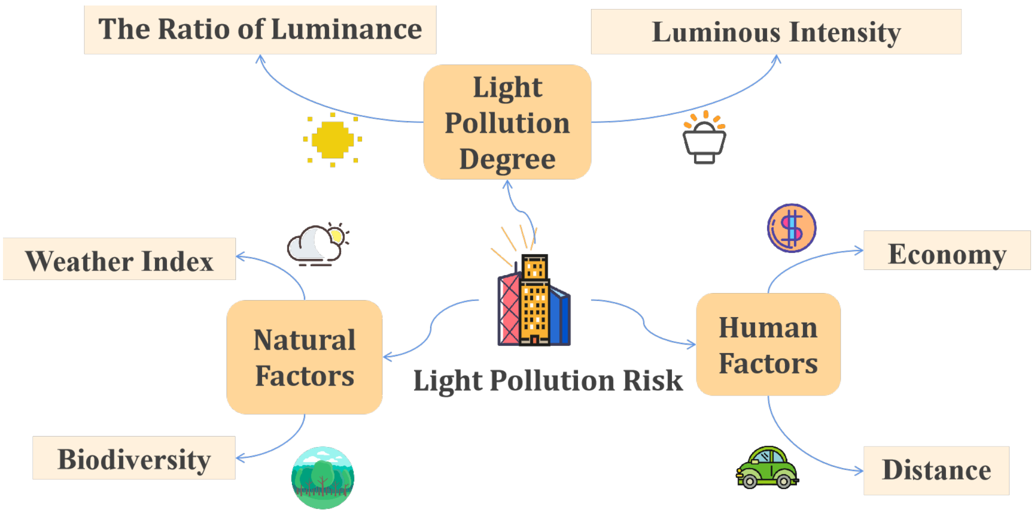


Figure 3: Indicators of light pollution risk

## 4.1 Selection of Indicators

### 4.1.1 Degree of light pollution(LP)

- **The Ratio of Luminance(RL)**

Zenith luminance is the distribution of solar radiation scattered by gas molecules and aerosols and the reflected light from the earth's surface, which is an important parameter to characterize the background light intensity of the sky. At night, when the sky background light is mainly contributed by artificial light increasing the reflected light from the Earth's surface, we ignore the effect of solar radiation. So the higher the zenith brightness, the more severe the light pollution. In order to eliminate the influence of the natural night sky luminance on the zenith luminance, we choose the ratio of zenith luminance and natural night sky luminance as an indicator of the degree of light pollution, noted as $P$, the formula is as follows:[2]

$$\log P = -4.7 - 2.5\log r + \log \phi \tag{1}$$

where $\phi$ is the total luminous flux of outdoor lighting, which is proportional to the population.$r$ is the distance from the light source to the observation point,according to the hypothesis, we set it as the distance from the observation satellite to the ground.

- **Luminous Intensity(LI)**

By acquiring the visible-near-infrared electromagnetic wave information emitted from the earth's surface, the nocturnal remote sensing satellite mainly reflects human activities, most notably human nighttime lighting. So we obtain remote sensing data of nighttime lights at each latitude and longitude from *the National Tibetan Plateau/Third Pole Environment Data Center(TPDC)*, [3]showing the luminous intensity(LI), to visualize the intensity of artificial light and thus the degree of light pollution.

Finally, we can obtain the degree of light pollution through the weighted combination of these indicators:

$$LP = w_{a1}RL + w_{a2}LI \tag{2}$$

where $w_{a1}, w_{a2}$ is the weight of the two indicators respectively.

#### 4.1.2 Natural Factors(NF)

- **Weather Index(WI)**

Clouds contain many tiny water droplets or ice crystals, which will enhance the scattering of artificial light at night. When it rains or snows, the accumulation of water or snow on the ground also makes the night sky luminance significantly higher. [3] So the weather conditions directly affect the night sky luminance. Therefore, we divide the night weather into sunny, cloudy and rainy-snowy days and calculate the Wheather Index (WI) to reflect the effect of night weather on night sky luminance. The larger the WI, the higher the risk level of light pollution. The formula is as follows:

$$WI = \sum_{i=1}^{3} W_i B_i \tag{3}$$

where $W_i(i = 1,2,3)$ is the weather state of the night weather throughout the year.$B_i$ is the night sky luminance value on sunny, cloudy and rainy-snowy days respectively. The specific value is $B_1 = 45mcd/m^2, B_2 = 104mcd/m^2, B_3 = 759mcd/m^2$.

- **Biodiversity(BI)**

Light pollution reduces biodiversity by affecting reproductive capacity, growth survival, interspecific relationships, biological rhythms, migration patterns of organisms and so on.[4] Therefore, we select biodiversity as an indicator to evaluate the light pollution risk level at a location. When describing the biodiversity richness of a region, the most commonly used indicator is species richness. We selected the Simpson Diversity Index to reflect the species richness. The larger the index, the richer the species. Its calculation formula is:

$$D = 1 - \frac{\sum n(n-1)}{N(N-1)} \tag{4}$$

where $D$ is the Simpson Diversity Index, $n$ is the number of individuals of a species, $N$ is the total number of individual species.

Also, we can obtain the natural factors by the weighted combination of these two indicators:

$$NF = w_{b1} WI + w_{a2} BI \tag{5}$$

where $w_{b1}, w_{b2}$ is the weight of the two indicators respectively.

#### 4.1.3 Human Factors(HF)

- **Economy(EI)**

By observing the global light pollution reflected by Light Pollution Map, we find that the areas with serious light pollution are often economically developed regions, such as western Europe, eastern and southern Asia, eastern North America and so on. Since nighttime lights are a reflection of surface human activities at night, which the primary industry in a region has almost nothing to do with, we do not take the primary industry into consideration. More precisely, we eliminate the effect of population density on total economic volume and use the GDP per capita of regional secondary and tertiary industries as the indicator of economic factors in the light pollution risk evaluation system.

- **Distance to urban community(DUC)**

A research study has shown that the degree of light pollution differs greatly between urban and suburban areas of the same city. This is due to the different urban functional areas caused by the distance from the central urban community.[5] So we select the distance from the location to urban community as an indicator in our model.

Thus, the calculation formula for human factors is

$$HF = w_{c1}EI + w_{c2}DUC \tag{6}$$

where $w_{c1}, w_{c2}$ is the weight of the two indicators respectively.

## 4.2 Determination of Weights

### 4.2.1 Weights Based on Analytic Hierarchy Process(AHP)

Analytic Hierarchy Process is a subjective empowerment method that addresses the process of quantifying qualitative problems in a more reasonable way.

First we normalize the data. Then we score and assign values to indicators at all levels, and construct a judgment matrix between each two of them, using the formula

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(EW)_i}{W_i} \tag{7}$$

to calculate the maximum eigenvalue of each judgment matrix. The consistency index CI and the random consistency index CR are used to test the consistency. The formula is as follows :

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{8}$$

$$CR = \frac{CI}{RI} \tag{9}$$

We calculate that the CR of each judgment matrix is less than 0.1, and the consistency test passes. According to the data, the corresponding hierarchy and total ranking are carried out, and finally the weight result is

$$w_{j,AHP} = (0.326041, 0.244959, 0.102102, 0.040898, 0.13013, 0.15587)$$

### 4.2.2 Weights Based on Entropy Weight Method(EWM)

The Entropy Weight Method is an objective weighting method applied to multiple indicators. Its results mainly depend on the discrete nature of the data itself and are not easily affected by human factors.

The Light Pollution Degree, Economy and Weather Index discussed above are positive indicators, while Biodiversity and Distance from urban community are negative indicators. Therefore, we have the formula

$$\begin{cases} y_{ij} = \frac{x_{ij} - \min(x_i)}{\max(x_{ij}) - \min(x_{ij})} \\ \\ y_{ij} = \frac{\max(x_i) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \end{cases} \qquad j = 1, 2, ..., n \tag{10}$$

where $y_{ij}$ represents the standardized value of each evaluation indicator. So the positive and negative indicators are standardized respectively. Then we introduce the following formula to calculate characteristic proportion:

$$p_{ij} = \frac{y_{ij}}{\sum_{j=1}^{n} y_{ij}} \tag{11}$$

According to

$$E_i = -\ln(n)^{-1} \sum_{j=1}^{n} p_{ij} \ln(p_{ij}) \tag{12}$$

we can calculate the information entropy of each evaluation index. On the basis of information entropy, we will further calculate the weight of each evaluation index we defined before.

$$w_{j,EWM} = \frac{1-E_i}{k-\sum E_i} \qquad j = 1,2,...,k \tag{13}$$

Finally the weight result is:

$$w_{j,EWM} = (0.16199, 0.32301, 0.1716, 0.0684, 0.209, 0.06325)$$

#### 4.2.3 Weights based on the Combination of AHP and EWM

Since the use of AHP to determine the weight of the standard is easily affected by human subjective factors, we adopt the combination of AHP and EWM to modify the index weight to ensure the objective and fair evaluation results.[6]So the new expression for weights is:

$$w_j = \frac{\sqrt{w_{j,AHP} \cdot w_{j,EWM}}}{\sum_{j=1}^{k} \sqrt{w_{j,AHP} \cdot w_{j,EWM}}} \tag{14}$$

The ultimate weights are as follows

Table 2: The weights of three first grade indicators and six secondary indicators

| | First Grade Indicators | Weights | Secondary Indicators | Weights |
|---|---|---|---|---|
| Light Pollution Risk | Degree of Light Pollution | 0.5305 | Luminous Intensity | 0.5504 |
| | | | The Ratio of Luminance | 0.4496 |
| | Natural Factors | 0.1868 | Weather Index | 0.7145 |
| | | | Biodiversity | 0.2855 |
| | Human Factors | 0.2827 | Economy | 0.6242 |
| | | | Distance to Urban Community | 0.3758 |

So we can obtain the formula to calculate the total score of light pollution risk:

$$Score = w_a LP + w_b NF + w_c HF \tag{15}$$

where $w_a, w_b, w_c$ is is the weight of first grade indexes.

### 4.3 The Universality and Correlation Analysis of Indicators

Among the indicators we selected, those in the Degree of light pollution(LP) can directly and accurately reflect the light pollution in various each place. To determine the reasonableness and broad applicability of other indicators, we choose 14 regions of China and the United States.

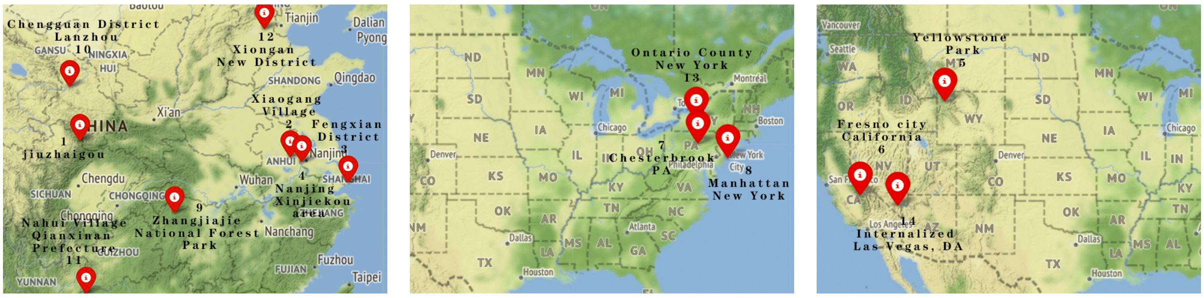


Figure 4: The selected 14 regions

The scores of each index are calculated according to the obtained data.[7–9] And the scores of indicators in Natural Factors(NF) and Human Factors(HF) are compared with those in LP.

From the following picture, we can see that the indicators in NF and HF all have almost the same or opposite trend with RL and LI, indicating that these indicators are related to the degree of light pollution. And the indicators of each region have a good degree of discrimination, indicating that the index system can reflect the different factors affecting the risk level of light pollution in different regions, and has wide applicability.


Figure 5: The relationship between LP, RL and other indicators.The sequence number along the abscissa axis represents the country: No.1 Jiuzhaigou; No.2 Xiaogang Village; No.3 Fengxian District; No.4 Nanjing Xinjiekou area; No.5 Fresno city; No.6 Chesterbrook; No.7 Manhattan; No.8 Manhattan; No.9 Chengguan District; No.10 Nahui Village; No.11 Xiongan New District; No.12 Ontario County; No.13 Internalized Las Vegas

To verify the correctness of the above analysis, we conduct a quantitative correlation analysis to discuss the correlation between each secondary index and RL and LI. We calculate their Spearman correlation coefficients and significance levels.

Table 3: Correlation coefficient between light pollution degree and each index

| | BI | WI | DUC | EI |
|---|---|---|---|---|
| LI | 0.946(0.000***) | 0.937(0.000***) | 0.671(0.069*) | 0.087(0.000*) |
| RL | 0.762(0.028**) | 0.714(0.047**) | 0.728(0.047*) | 0.667(0.071*) |

From the above table, we clearly see that the selected indicators have a great correlation with the degree of light pollution. For example, the correlation coefficients of Biodiversity, Weather Index, Economy and Luminous Intensity are **0.946, 0.937 and 0.97**, respectively.

In summary, we verify the rationality and broad applicability of the selected indicators.

## 4.4 Classification of Light Pollution Risk Level

Combined with the light pollution risk evaluation model we established, the total light pollution risk score is calculated for each region. Then, we use Hierarchical Clustering Method and divide the risk level of light pollution into three categories: **high, medium and low**.

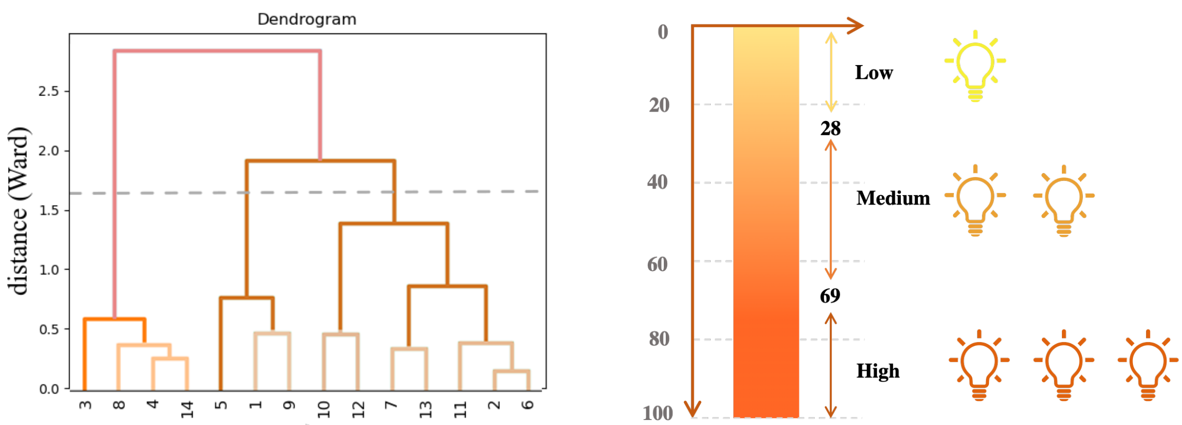


Figure 6: Clustering results of light pollution risk score

Then we calculate the total score range of light pollution risk corresponding to each level as follows. Therefore, once we get the total score of light pollution risk in the region, we can determine its risk level.

# 5 Case Study Based on Four Types of Locations

First, we select four representative regions in China to bring into the model for analysis.

As for **protected land location**, we select **Jiuzhaigou** located in Sichuan Province, which is a national nature reserve. For **rural community**, we choose **Xiaogang Village** in Anhui Province, which is called the first village of rural reform in China. We choose **Fengxian District** of Shanghai as the representative of **suburban community**. It is easily accessible from an urban community and the population is moderate compared to the surrounding area. Finally, we pick **Xinjiekou** in Nanjing, known as the biggest business circle in China, as the representative of **urban community**, which is densely populated and economically developed.

By searching and calculating the corresponding data of the ratio of luminance, luminous intensity, per capita GDP of secondary and tertiary industries, distance from urban community, weather index and biodiversity in these four regions, we bring them into the model for light pollution risk assessment. The results are as follows :

Table 4: Index scores of four different regions in China

| | LI | RL | BI | WI | DUC | EI | LP | NF | HF | Score |
|---|---|---|---|---|---|---|---|---|---|---|
| Jiuzhaigou | 53.47 | 11.74 | 46.68 | 0.10 | 50.25 | 0.10 | 34.70 | 13.40 | 18.95 | 26.28 |
| Xiaogang Village | 84.22 | 0.10 | 90.17 | 6.25 | 38.32 | 18.98 | 46.70 | 30.21 | 26.25 | 37.68 |
| Fengxian District | 94.29 | 84.60 | 99.03 | 58.02 | 97.65 | 31.39 | 89.93 | 70.02 | 56.30 | 76.70 |
| Xinjiekou | 99.10 | 61.53 | 99.06 | 99.01 | 93.63 | 99.10 | 82.76 | 99.09 | 97.67 | 90.21 |

From the data in the graph we can see that Jiuzhaigou has a total light pollution risk score of about **26.28**, with a low light pollution risk level, followed by Xiaogang Village with **37.68** points and Fengxian District with **76.70** points. Xinjiekou got the highest score of **90.21**, with a high light pollution risk level.

- **Jiuzhaigou**

Jiuzhaigou is a national reserve with a good ecological environment, excellent climatic conditions and very rich biodiversity, thus scoring low in the natural factor index. The sparse population and restricted economic development make it score low in the human factor index. In terms of light pollution level, Jiuzhaigou scores **34.70**, with a small amount of lighting pollution, which we speculate is most likely due to human activities bring about by the development of tourism. Therefore, on balance, Jiuzhaigou is a low risk area for light pollution.

- **Xiaogang Village**

Xiaogang village is far away from the central city and has a small population. The primary industry accounts for a large share, and the level of economic development is relatively low. Therefore, its contribution to light pollution risk in human factors score is low compared with the other two indexes. The topography is dominated by low hills, with more crops and richer biodiversity, and the natural factors score is low. The degree of light pollution is **46.40** points, which may be caused by production activities in farmland, house lights, and road lights. Combined, Xiaogang Village belongs to the medium risk area of light pollution.

- **Fengxian District**

Fengxian District is a suburban area of Shanghai, easily accessible to the central city. As we can see from the data in the table, the area is influenced by the metropolis and has a serious light pollution score of **89.93** points. The proximity to the ocean, more cloudy and rainy days, and less biodiversity make natural factors contribute more to the risk of light pollution. Therefore, Fengxian District is a high risk area for light pollution.

- **Xinjiekou**

Xinjiekou is located in the central city of Nanjing, with large shopping malls and high-rise buildings, compact road layout, high population density and high level of economic development, which is a typical urban community. It has a developed commercial economy at night and serious light pollution. The urban construction makes the vegetation coverage and the biodiversity low. Therefore, Xinjiekou scores high in all indicators of light pollution level, natural and human factors, and is a high risk area for light pollution.

Then, in order to eliminate the influence of chance factors such as regional specificity, we also pick four locations in the United States: Yellowstone Park, Fresno, California, Chesterbrook, Pennsylvania, and Manhattan, New York. They respectively represent the protected land location, rural community, suburban community, and urban community.

The relevant data are brought into the model and the following scores are obtained. By observing and comparing the indicators, we find that the results are similar to those of the four regions we select in China:

Table 5: Index scores of four different regions in America

| | LI | RL | BI | WI | DUC | EI | LP | NF | HF | Score |
|---|---|---|---|---|---|---|---|---|---|---|
| Yellowstone Park | 0.10 | 12.86 | 0.10 | 0.51 | 0.1 | 10.89 | 5.84 | 0.39 | 6.84 | 5.10 |
| Fresno | 76.09 | 3.43 | 91.41 | 5.53 | 51.95 | 17.55 | 43.42 | 30.05 | 30.48 | 37.26 |
| Chesterbrook | 96.09 | 38.70 | 99.36 | 41.02 | 39.03 | 51.18 | 70.29 | 57.80 | 46.61 | 61.26 |
| Manhattan | 99.10 | 99.01 | 99.01 | 97.59 | 99.01 | 87.51 | 99.01 | 98.31 | 92.24 | 97.55 |

In general, protected land location scores low for all three indicators. As for rural community and suburban community, all three indicators results in moderate or high risk of light pollution level to some extent. Additionally, urban community scores high for all three indicators, with high light pollution and high risk of light pollution.

The eight regions are viewed together as shown in the figure below. This can show that our model is relatively reasonable and of broad applicability.

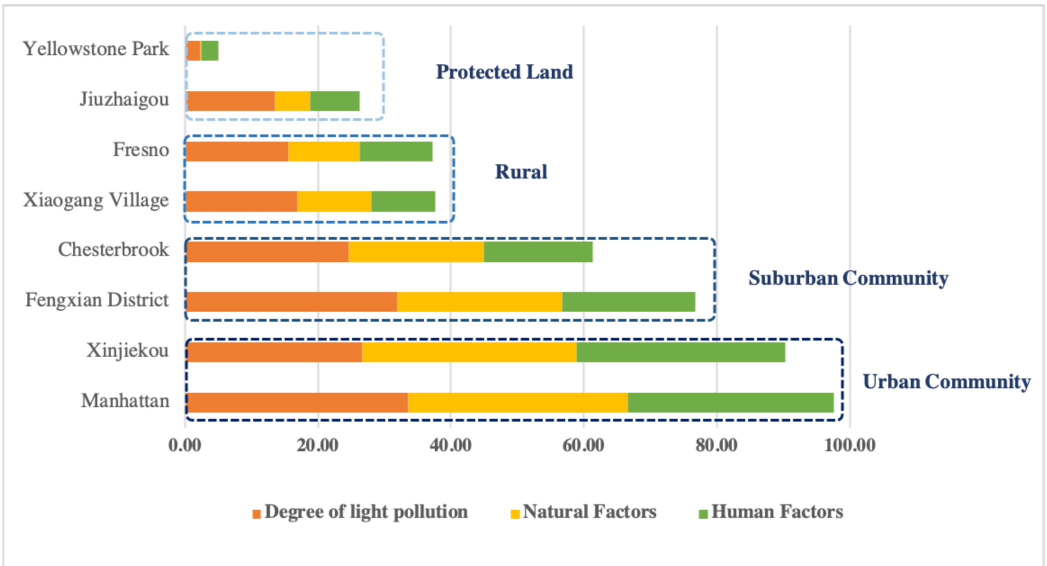


Figure 7: Light pollution risk scores of eight representative locations

# 6 Intervention Strategies and Potential Impacts

## 6.1 Three Possible Intervention Strategies

With the acceleration of global urbanization and the construction of urban lighting projects, the problem of light pollution is becoming more and more serious. It has threatened the normal survival and development of human beings and other living creatures. Therefore, the treatment of light pollution has no time to delay. However, the governance of environmental problems can not be blind, it should start from a number of aspects scientifically and reasonably.

Aiming at the diversification of governance methods, we put forward the following **three aspects of intervention strategies** and discuss specific actions for different types of locations.

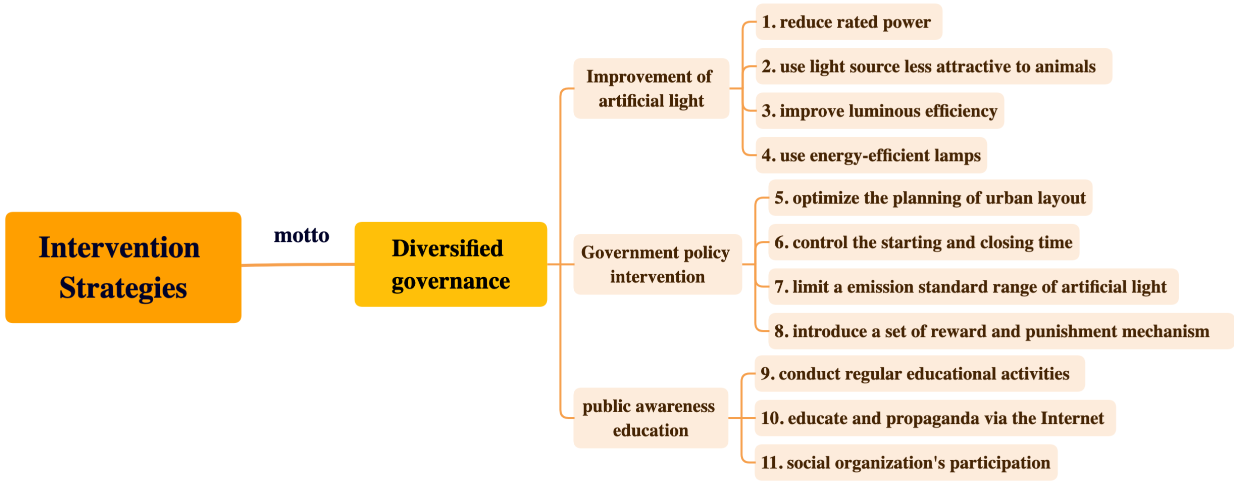


Figure 8: Three possible intervention strategies

- **Improvement of artificial light**

With the acceleration of global urbanization and the construction of urban lighting projects, the problem of light pollution is becoming more and more serious. It has threatened the normal survival and development of human beings and other living creatures. Therefore, the treatment of light pollution has no time to delay. However, the governance of environmental problems can not be blind, it should start from a number of aspects scientifically and reasonably. Aiming at the diversification of governance methods, we put forward the following three aspects of intervention strategies and discuss specific actions for different types of locations. The control of environmental pollution should start from the treatment of pollution sources. Only by limiting the source of light pollution can we fundamentally reduce light pollution.

Urban community is densely populated and has a large lighting demand. On the premise of meeting the lighting demand, the rated power of the artificial light source can be reduced. Flash or intermittent lighting systems can be used in its economically prosperous business district at night. This is to reduce the level of light pollution by reducing RL and LI.

As for the biodiversity-rich rural community and protected land, light pollution can seriously affect the survival and development of living things, light sources that are less attractive to animals or less damaging to plants should be designed and adopted.[10]

In addition, energy-saving light sources can be mass produced and promoted. Road lighting in various areas, especially in urban or suburban communities with high traffic volumes, can use energy-efficient lamps such as LEDs, which reduce energy consumption, extend their service life, and have a greater range of light color variation compared to traditional lamps. The use of technology to improve the luminous efficiency of lamps is also an effective countermeasure to reduce light pollution.

- **Government policy intervention**

The local government is the executor and manager of the environment protection. The government's introduction of policies and the formulation of laws or regulations are the most powerful measures to control light pollution.

Urban community has a compact road layout and gathers commercial and residential areas, where a large amount of commercial lighting and landscape lighting cause serious light pollution at night. Therefore, for urban communities, the government should strengthen the planning of urban layout, optimize the structure of urban functional areas, and reasonably arrange light sources.

In suburban communities and rural communities where the population distribution is relatively less dense, the government can compulsorily control the starting and closing time of lamps, and turn off some or all of the lamps during the time of low usage frequency, so as to avoid long time or even all-night lighting at night. This can save a lot of energy and reduce the impact on nocturnal biological activities. In each region, the relevant departments should limit the emission standard range of artificial light sources, both to meet normal lighting needs and to reduce light pollution.

Moreover, higher authorities can introduce a set of reward and punishment mechanisms, which is one of the most effective means to combat light pollution.[11] Only by rewarding companies or individuals who actively participate in the prevention and control of light pollution, and punishing those who violate environmental standards, can people be fully motivated.

- **Public awareness education on addressing light pollution**

The fundamental of environmental protection is to raise public awareness. Light pollution endangers everyone, and everyone should be a practitioner to reduce the harm of light pollution. Strengthening public awareness education is conducive to the formation of a good fashion for the participation of the whole society.

To improve public awareness of light pollution prevention and control, relevant departments should conduct regular educational activities on environmental protection awareness. In today's world with developed internet, local media can use the internet to carry out light pollution education and propaganda work. Additionally, some social organizations can call for public attention and participation in combating light pollution. These specific actions are applicable in any location.

## 6.2 Potential Impacts

However, for some areas, not all impacts of the interventions are necessarily positive. For example, in suburban community with a moderate population density and traffic flow, mandatory control of light activation hours may lead to low road visibility resulting in safety accidents and an increase in crime incidents. In rural community, due to the low economic level, the cost of implementing technologically advanced luminaires is high, which increases the local economic burden. For urban communities, controlling the intensity and time of nighttime lighting may limit the development of nighttime economy to some extent, while excessive restriction of lighting in protected locations may also adversely affect the living habits of certain creatures.

Hence, to manage light pollution, we must weigh the pros and cons and choose the most appropriate intervention strategy according to the actual situation of different regions.

# 7 Determining the Best Strategy: Light Pollution Treatment Programming Model

In order to determine the most effective intervention strategies for different regions and their impacts on light pollution risk level, we establish a **light pollution treatment programming**

**model**, and then obtain the investment funds and index scores of each specific measure. **The effectiveness of the strategy** is judged by an overall consideration of score changes and governance costs.

## 7.1 Establishment of the Programming Model

Due to the differences in the economic strength of each location, the funds that can be used to reduce the risk of light pollution are not the same. In order to discuss the effectiveness of the intervention strategy, we established a **single objective programming model** to minimize the risk level of light pollution. We set the constraints as investment funds, that is, all intervention strategies in the region do not exceed the total funds that the region is able to invest.

We use the GDP of each location to reflect the total capital that is capable to be invested in each region, recorded as F. The calculation formula is as follows :

$$F = \alpha \mathrm{GDP} \tag{16}$$

Where $\alpha$ is the ratio of input capital to GDP.

In the previous chapter ( Section 6 ), we proposed 11 specific measures to reduce the risk level of light pollution. We record the capital for each of them as $C_i(i = 1,2,...11)$, and use $P_{ik}$ to indicate the ratio of the cost of the $k(k = 1,2,...,6)$indicator to the $i$th measure. It can be concluded that the actual capital $F_k$ of the $k$th index is :

$$F_k = \sum_{i=1}^{11} P_{ik} C_i \tag{17}$$

According to the economic law of marginal cost[12], we get a simplified calculation formula when reducing the $k$th index score by 1 point :

$$f_k = \beta_k (S_k' - S_k) \qquad k = 1,2,...6 \tag{18}$$

where $\beta_k$ is the linear coefficient, $S_k$ and $S_k'$ are the scores of each index when no funds are invested and when funds are invested to improve the risk level of light pollution.

Since $f_k$ is the funds when $\Delta S = 1$ so we can get $F_k$ when the $k$th index score changes from $S_k$ to $S_k'$ :

$$F_k = \int_{S_k}^{S_k'} f_k(s) ds \tag{19}$$

Then the change of the index score can be obtained:

$$\Delta S_k = S_k' - S_k = 0.1 \sqrt{\frac{F_k}{\beta_k}} \tag{20}$$

According to the above analysis, we get the light pollution treatment programming model :

$$\min \quad Score = \sum_{k=1}^{6} w_k F_k$$
$$s.t. \quad \begin{cases} \sum_{k=1}^{6} F_k \leq F \\ 0 \leq F_k \\ 0 \leq \Delta S_k \leq S_k \end{cases} \tag{21}$$

## 7.2 Strategy analysis: Xinjiekou and Jiuzhaigou

We choose Xinjiekou and Jiuzhaigou to use the programming model to plan the specific action of the intervention strategy. The GDP of Xinjiekou and Jiuzhaigou are **$ 2.1823** and **$ 0.4513 billion**, respectively. Assuming $\alpha = 0.01$, that is, the funds that can be used to improve the risk of light pollution in both regions are up to 1 % of GDP. In the sensitivity analysis part, we will change the value of $\alpha$ to show the improvement of each index.

By solving the programming model, the total risk level scores of Xinjiekou and Jiuzhaigou are reduced by **21.23** and **3.65** respectively, and the reduction rates are **23.5%** and **13.9%**. The specific reduction values of each index are as follows :

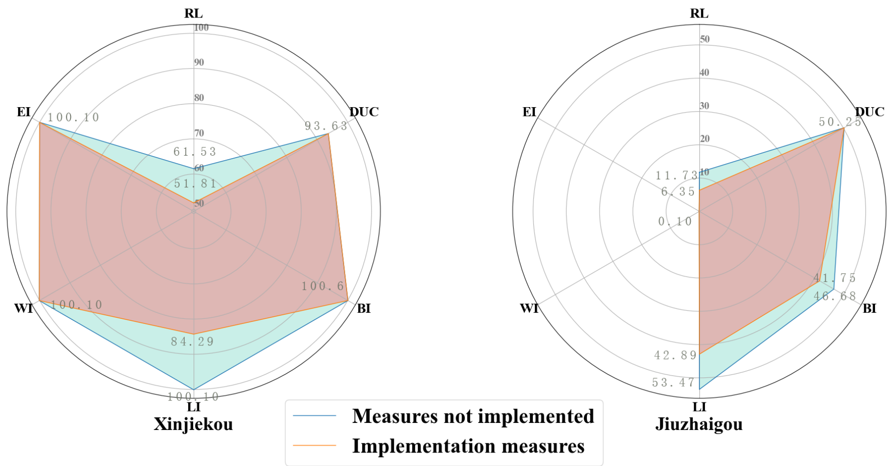


Figure 9: The change of each index after the implementation of the measures

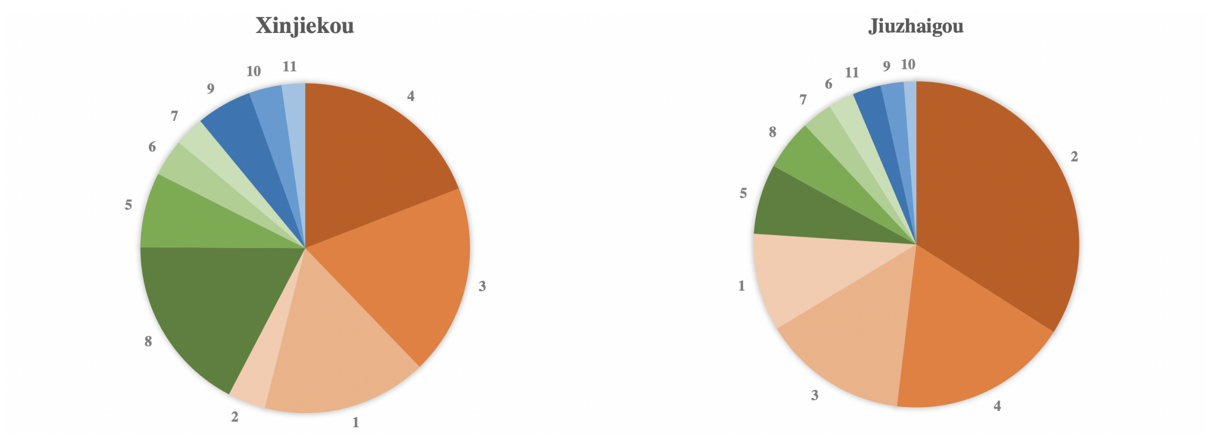


Figure 10: The proportion of investment funds for each measure(Figures indicate 11 specific measures)

From the above pictures, we can see that the change of Luminous index in Xinjiekou is the biggest. It has a large investment in various measures for the improvement of artificial light sources. This shows that for Xinjiekou, the most effective measure is to improve the artificial light source to reduce the score of light pollution index. So the risk level of light pollution is reduced.

Specific measures include: reducing the rated power of lamps in the business district, improving the efficiency of lamps and using energy-saving light sources.

The Luminous Index and Biodiversity of Jiuzhaigou change almost the same, and the investment in various measures to improve artificial light sources accounts for the vast majority of the total funds. Therefore, the most effective measure to reduce the risk level of light pollution in Jiuzhaigou is to reduce the degree of light pollution by using light sources that are less attractive to animals and energy-saving light sources. At the same time, biodiversity will increase with the improvement of light source, so the score of biodiversity index will decrease.

It is worth mentioning that since Jiuzhaigou is a national protected area, the government has carried out many interventions and protection measures, so strengthening government intervention will not have a great impact on the risk level of light pollution. This is consistent with the results in our pictures, which shows the rationality of our programming model.

# 8 Sensitivity Analysis

Finally, we perform a sensitivity analysis of the programming model by varying the parameters and comparing the differences between the original and changed results. We change the ratio of intervention strategy input to total GDP by raising it **from 0 to 0.03** in steps of **0.002** to obtain the change of total score of light pollution risk level in Jiuzhaigou and Xinjiekou.

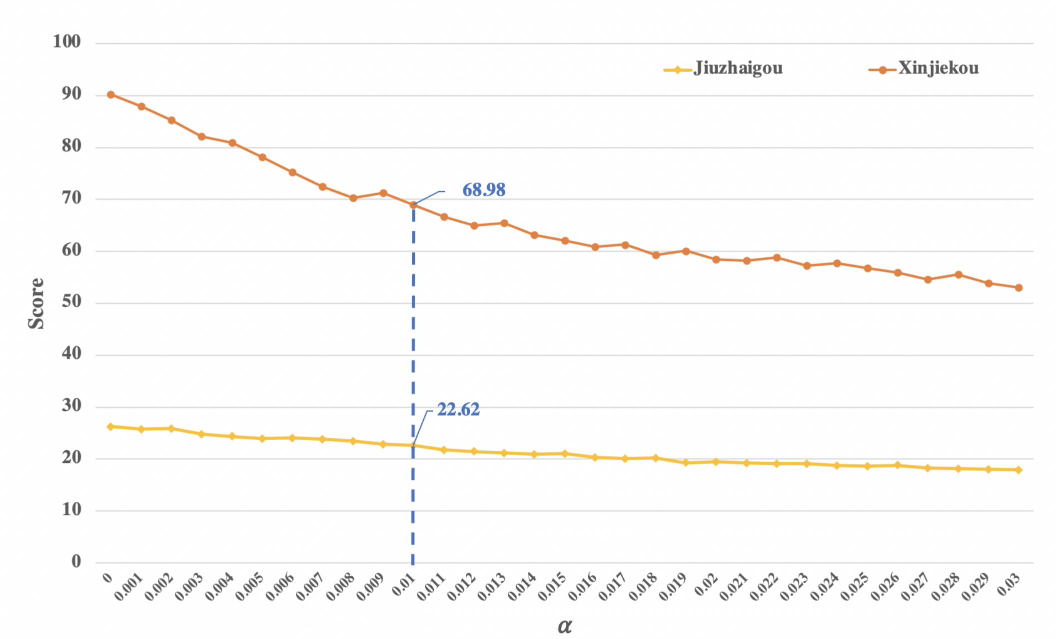


Figure 11: Sensitivity Analysis

As can be seen from the figure, the total light pollution risk scores in the two regions are not significantly changed by $\alpha$, indicating the high stability and wide applicability of our model. Moreover, the dashed line in the figure has an undulating trend, which is consistent with the conclusion that the intervention strategy has potential influence on the degree of light pollution risk.

# 9 Strengths and Weaknesses

## 9.1 Strengths

1. In the model, our data were obtained from some authoritative official websites, so we guarantee the reliability of the model. Our results are accurate and have high reference values.

**2.** We comprehensively considered the factors that reflect the risk level of light pollution from the three aspects , and used correlation analysis to prove the rationality of the index selection.

**3.** In the light pollution risk level evaluation model, we used the combination of AHP and EWM to give weight to the indicators, optimizing the shortcomings of the existing literature research on the evaluation system of light pollution risk level, such as fewer selected indicators and certain subjectivity in the determination of weights, and finally we obtained a more reasonable weight.

**4.** We obtained the total score ranges corresponding to the three light pollution risk levels through hierarchical clustering, and realized the rating of each location.

**5.** We discussed the intervention measures and specific actions to solve light pollution in different regions, and realized the diversification of governance. Its direct and potential effects on light pollution are all analyzed.

## 9.2 Weaknesses

**1.** We only discussed light pollution at night, and did not consider the impact of day light pollution.

**2.** In the programming model, we only chose the most effective intervention strategy according to the risk level of light pollution, economic factors and regional characteristics, and we ignored the practical feasibility of the measures.

# 10 Promotion Flyer

# Less Lights More Stars

*When night falls, **Xinjiekou**, the busiest urban community in Nanjing, is harassed by "white night". Beautiful night lighting makes our nightlife colorful, but do you know that excessive use of artificial light leads to light pollution?*

## What is light pollution?

It is caused by excessive or poor use of artificial lights and is very common in our daily life. Its phenomena include light trespass, over-illumination, light clutter and so on.

## What are the serious hazards of light pollution?

Nowadays, when you look up at the sky at night in **Xinjiekou**, you will find that stargazing has become a luxury. But light pollution not only makes the stars disappear, but also increases energy consumption, causes traffic accidents, disrupts our circadian rhythm and damage ecosystem...

## What can we do?

After research, **improving the artificial light source** is found to be the **most efficient strategy** for **Xinjiekou** to mitigate light pollution hazards:

- *Use lights with reduced rated power on the building*
- *Improve the efficiency of lamps through technology*
- *Encourage residents to use energy-saving lamps at home*

In addition, we hope to see the introduction of relevant policies and education activities on light pollution.

***Everyone can contribute to make our community a better place to live. Let's do our part to return a bright starry sky to Xinjiekou from now on!***

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# Appendices

Code Listing 1: Hierarchical Clustering Algorithm

```
import numpy as np
import pandas as pd

data = pd.read_csv('find_ans.csv' , encoding='gb18030' , index_col=0)
indicator = data.columns.tolist()
project = data.index.tolist()
value = data.values
print(indicator)
print(project)
print(value)
data.head()

def std_data ( value , flag ):
   for i in range(len(indicator)):
      # print(flag[i])
      if flag[i] == '+':
         value[: , i] = (value[: , i] - np.min(value[: , i] , axis=0)) / (
               np.max(value[: , i] , axis=0) - np.min(value[: , i] , axis
                  =0)) + 0.001
      elif flag[i] == '-':
         value[: , i] = (np.max(value[: , i] , axis=0) - value[: , i]) / (
               np.max(value[: , i] , axis=0) - np.min(value[: , i] , axis
                  =0)) + 0.001
   # print(value)
   return value

flag = ["-" , "+" , "-" , "+" , "+" , "+"]
std_value = std_data(value , flag)
print(std_value)
std_value.round(3)
DF = pd.DataFrame(std_value)
DF.to_csv('value.csv')

def cal_weight ( indicator , project , value ):
   p = np.array([[0.0 for i in range(len(indicator))] for i in range(len(
      project))])
   # print(p)
   for i in range(len(indicator)):
      p[: , i] = value[: , i] / np.sum(value[: , i] , axis=0)

   e = -1 / np.log(len(project)) * sum(p * np.log(p))
   g = 1 - e
   w = g / sum(g)
   return w

w = cal_weight(indicator , project , std_value)
w = pd.DataFrame(w , index=data.columns , columns=['weight'])
print("######weight:#######")
print(w)
w.to_csv('weight.csv')
score = np.dot(std_value , w).round(2)
score = pd.DataFrame(score , index=data.index , columns=['score']).
   sort_values(by=['score'] , ascending=False)
score.to_csv('score.csv')
print(score)
```

Code Listing 2: Read data

```
from osgeo import gdal
import pandas as pd
import numpy as np

gdal.AllRegister()
filename_list = ['World_Atlas_2015.tif','
    GEDI04_B_MW019MW138_02_002_05_R01000M_MU.tif',
'gpw_v4_population_density_rev11_2015_2pt5_min.tif' ]
find_list = {'Nanjing Xinjiekou area': [32.0 , 118.0] ,'Fengxian District':
     [30.0 , 121.0] ,'Yellowstone Park': [44.3 , -110.3] , 'Fresno city':
    [37.0 , -119.0] , 'Chesterbrook': [41.1 , -77.1] ,'Manhattan': [40.0 ,
    -74.0] , 'jiuzhaigou': [33.1 , 104.1] , 'Xiaogang Village': [32.2 ,
    117.7]}

# for key in find_list.keys():
#    print('find ans of ' + key)
for filename in filename_list:
    filePath = r'D:\ICM2023\python_code\NewWorldAtlas/' + filename
    dataset = gdal.Open(filePath)
    adfGeoTransform = dataset.GetGeoTransform()
    nXSize = dataset.RasterXSize # x
    nYSize = dataset.RasterYSize # y
    print(nXSize , nYSize)
    im_data = dataset.ReadAsArray(0 , 0 , nXSize , nYSize)
    index = [] # loc
    columns = [] # iloc
    for j in range(nYSize):
        lat = adfGeoTransform[3] + j * adfGeoTransform[5]
        index.append(lat)
    for i in range(nXSize):
        lon = adfGeoTransform[0] + i * adfGeoTransform[1]
        columns.append(lon)
    data = pd.DataFrame(im_data , index=index , columns=columns)
    data.where(data >= 0 , data - data , inplace=True)
    print(filename + ' read done')
    for i in data.index:
        if -90 < i < 90:
            pass
        else:
            i = i / 100000
        data.rename(index={i: int(i)} , inplace=True)
    for j in data.columns:
        if -180 < j < 180:
            pass
        else:
            j = j / 100000
        data.rename(columns={j: int(j)} , inplace=True)
    print(data)
    for key in find_list.keys():
        print('find ans of ' + key)
        x = find_list[key][0]
        y = find_list[key][1]
        key_data = data.loc[(x,y)]
        print(key_data)
        key_data.to_csv(key+filename+'.csv')
```