A Comprehensive Approach based on GIS-LP model on Light Pollution

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Abstract. The escalating global concern over light pollution necessitates a comprehensive framework for effective control measures. This paper proposes a novel approach by establishing an evaluation index model. Direct impact factors are graded through GIS analysis, while LP-AHP and LP-IEW models determine the weight of indirect factors. A comprehensive risk index is derived by combining these approaches using Euclidean distance. The evaluation index model is applied to analyze protected land, rural, suburban, and urban areas, resulting in the creation of a light pollution risk level distribution map.

Keywords: Light pollution, Evaluation index model, LP analysis, GIS analysis.

1. Introduction

1.1. Background

According to a study in September 2021, global light pollution has increased by at least 49% in the past two decades, and about one third of human beings cannot see the Milky Way[1]. The harm of visible light pollution has long been one of the major problems facing human society[2].

For example, in the United States, more than one third of the regions have laws and regulations on light pollution. Japan confirmed the existence of light pollution as early as 1994[3-4]. In 2002, the Czech Republic formulated the world's first light pollution prevention regulation [5]. From both direct and indirect factors, this study evaluates and measures the level of light pollution risk in a region, making up for the shortcomings of previous studies that usually only focus on direct influencing factors.

1.2. Literature review

Some studies have shown that light pollution has an impact on people's rest state. For example, Gomes et al. studied the impact of indoor dynamic light on people's rhythm. Gensen et al [6]. studied the impact of dynamic light on Melatonin and sleep quality in the hospital. Later, Yu Juan et al. divided light damage into brightness, light color, and dynamic interference according to Confounding [7].

It can be seen that existing research focuses on the nature of the impact of light pollution, but lacks quantitative research, and lacks consideration of indirect influencing factors in measuring the level of light pollution risk. Thefore, we develop an index that can reasonably describe the risk level caused by the excessive use of artificial light. We select the appropriate sample location, apply the light pollution evaluation index to measure, and explain the reasons for this result by taking four reginons with different density of population as an example.

1.3. Our work

Firstly, establish the GIS evaluation model and clustering the test area to realize the index calculation and grade establishment of the direct impact factors of light pollution. Then Determine the index weight of indirect factors by the LP-AHP and LP-IEW models combined with the power index synthesis method. Finally, the direct and indirect methods are combined by Euclidean distance method to obtain an index that comprehensively considers the risk of light pollution.

Then, we collected four types of protected land, rural, suburban and urban areas.

According to the index determined in the first question, the risk degree of light pollution in four regions was analyzed using the evaluation index model of the first question, and then the light pollution risk level distribution map was established with direct factors as the abscissa and indirect factors as the ordinate .Meanwhile, the risk degree of light pollution in different regions is analyzed and explained from the perspectives of the distance between different regions and ideal points (origin of coordinate axis), main influence factors and regional type differences.

2. Evaluation of Light Pollution Level

As shown in Figure 1, the risk level of light pollution is analyzed from both direct and potential impacts.

Direct effects: A linear regression model based on glare pollution, light intrusion pollution and light spillover pollution is proposed, through the analysis of street lamp pole height, ground average illumination and other factors[8-9].Potential impacts: The indirect impact index is based on a multi-level model combining subjectivity and objectivity, taking development level, population, biodiversity and climate as the first-level indicators, and selecting the corresponding second-level indicators, using the power average synthesis method combined with the entropy weight method and the analytic hierarchy method to analyze and explain the indicators, comprehensively considering the subjective and objective factors, revealing the possible impact of each index.

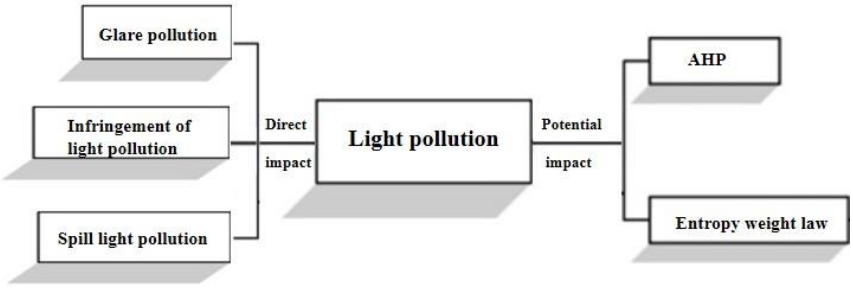


Figure 1: Light pollution risk level assessment model

2.1. Direct effects

Light pollution can be divided into three types: glare pollution, light damage pollution and light spill pollution[10], and through the average analysis of the three types of light pollution, a linear regression model of light pollution based on GIS (Artificial-Light-Harm) light pollution is proposed. To embrace a more detailed description of the measurements of GIS. It is shown in Figure 2.

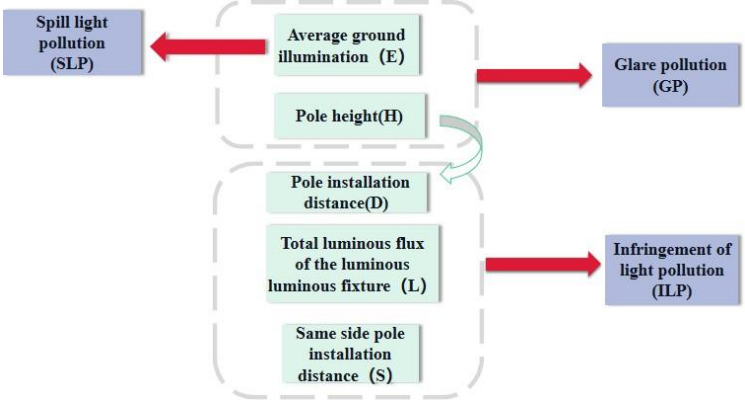


Figure 2. GIS light pollution construction

Light invasion pollution refers to unrelated light entering residential or work areas, disrupting people's normal life and work; light spillage pollution refers to light escaping from lighting fixtures, causing unnecessary energy waste; glare pollution refers to intense light causing discomfort or visual impairment.

$$GP = 57.004 + 2.882E - 8.011H \tag{1}$$

$$ILP = 32.285 + 0.002L - 1.935S + 2.719\text{-}0.62\mathrm{D} \tag{2}$$

$$SLP = 95.399 - 29.466\,E \tag{3}$$

GP is the comprehensive brightness glare evaluation index (glare) of residential roads, E is the average illumination of the ground, and H is the height of the roads lamp pole. ILP is the degree of light infringement of residential buildings along the street;L is the total luminous flux of the lamp, unit lm ; S is the distance between the road and the dwelling, unit m; H is the height of the pole in m.; D is the installation distance of the same side lamp pole, unit m. SLP is the light overflow; E is the average illumination of the ground, in lx.

Starting from the direct factors of light pollution, a GIS (Artificial-Light-Harm) light pollution model including glare pollution, light infringement pollution and light diffusion pollution is proposed.

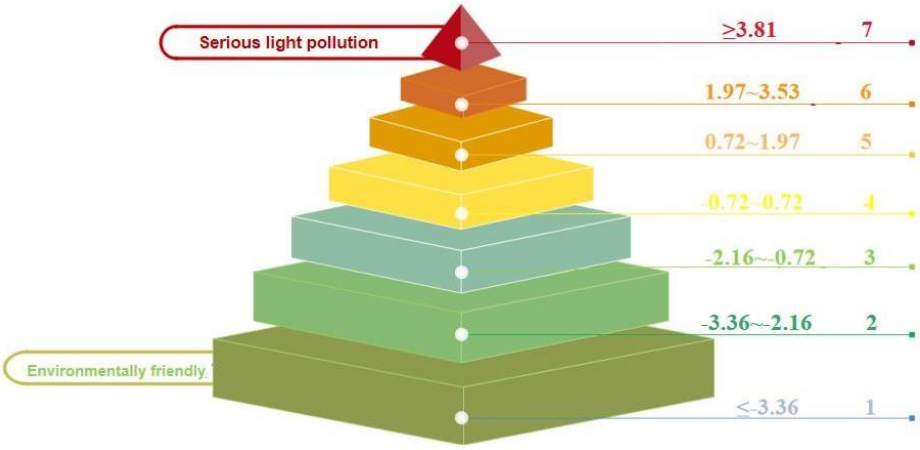


Figure 3: Light pollution is graded

$$GIS = GP + ILP + SLP \tag{4}$$

$$GIS = 187.688 - 26.584\,E - 5.292\,H + 0.002\,L - 1.935S - 0.62D \tag{5}$$

Normalizing the range of GIS indicators of light pollution convert GIS indicators into a standardized range with a mean of 0 and a standard deviation of 1. The standardized light pollution index is classified by grade using clustering. The values of standardized light pollution GIS are divided into 7 categories, and 7 GIS values are randomly selected as the initial cluster center, the distance of the remaining GIS data to the 7 initial cluster centers is calculated, the GIS data is assigned to the cluster where the nearest center is located, the new class is adjusted and the center of the new class is recalculated. Cycle until convergence, ending clustering, and the results are shown in Figure 3.

2.2. Potential effects

In addition, due to the level of development, population, biodiversity, climate and other reasons, it will also have a certain impact on light pollution [11].

Light pollution is an important aspect of environmental pollution, but it is not a pollutant, but a physical phenomenon. Due to the increase in night activities of urban residents, people cannot completely avoid the influence of light sources on their surrounding environment when they are outdoors at night; At the same time, with the increasing number of electronic products and cars in the city, the problem of light pollution is be- coming more and more prominent[12][13].

We decided to analyze the potential factors affecting light pollution using a combination of subjective and objective forms.

2.2.1 Model II-1: LP (light-pollution) AHP Model

First, in order to find the indicators that can accurately evaluate light pollution, we establish a standard layer analytic hierarchy method, select nine indicators for analysis, and establish LP (light-pollution) AHP model. Figure 4 shows the indicators of model.

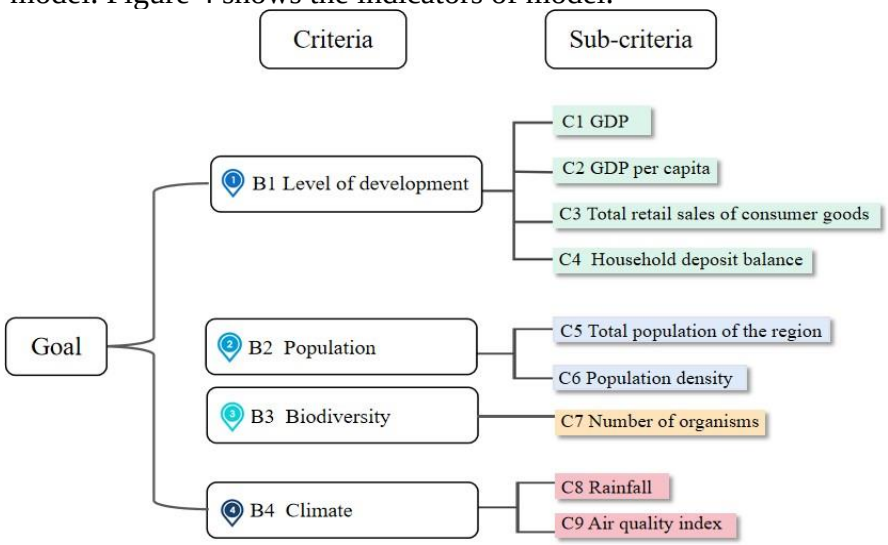


Figure 4 The Indicators

Through the form of information inquiry, determine the scale value of comparison among elements, establish the judgment matrix, and use YAAHP software to compare the eigenvector of the matrix by establishing the judgment matrix. *Wi* is calculated and the consistency of the matrix is checked. In which the target layer is aligned. Then the judgment matrix A-B between layers and the judgment matrix *B-C* between the criterion layer and the scheme layer are shown in the following table. Solving the eigenvalue of judgement matrix is easy to get *λmax*, which is calculated by the formula.

$$CR = \frac{\lambda_{\max} - n}{n - 1} \tag{6}$$

So according to $_{\max}$, $CR < 0.1$ is obtained, which has passed the consistency test. A comprehensive subjective and objective assessment of various possible factors affects light pollution. We apply the principle of best possible protection of the natural environment and economic development without causing light pollution. In this paper, eight indicators were selected to evaluate the city's light pollution, including GDP, per capita GDP, total retail sales of consumer goods, household savings balance, regional population, population density, biomass, rainfall, and air quality.

1) B1 Level of development

The degree of economic development of a city directly reflects the degree of development of a city. The overall economy of a city is also affected by the economic situation of per capita income and expenditure, which is shown in Table 1.

Table1: Level of development

Type	Score	Wi
GDP	3	0.27
GDP per capita	1	0.08
Total retail sales of consumer goods	5	0.53
Household deposit balance	2	0.12
CR=0.065<0.1, (Consistency test passed)		

2) B2 Population

In densely populated areas, light pollution of the same race is more serious. For example, within the same city, more "light pollution" will be generated because cities with high traffic need more artificial lights at night. On roads with sparse population and almost no foot traffic, too many street

lights are often not installed, so the degree of light pollution is not high. Figure 2 gives the specific numeric.

Table 2: Population

Type	Score	*Wi*	
Total population of the region		1	0.17
Population density		5	0.83
CR=0.00<0.1, (Consistency test passed)			

3) B3 Biodiversity

The biodiversity of an area is considered to be an important part of the area, and most plants will have strong "phototaxis", they will grow towards light during the day and dark at night, and in areas with high biodiversity, the amount of light transmission at night should be reduced.

4) B4 Climate

The effect of climate on light pollution, such as precipitation and air quality, will have a certain impact on light pollution. Precipitation and air quality are associated with high light transmittance, and buildings with low light transmittance (<20%) produce greater photochemical smog pollution. Except for a few climatic conditions, insufficient sunshine due to high rainfall and haze is the main cause of light pollution and photochemical smog pollution, which is shown in Table 3.

Table 3: Climate

Type	Score	Wi
Rainfall	3	0.75
Air quality index	1	0.25
CR=0.00<0.1, (Consistency test passed)		

5) A1 Potential effects

The underlying factors of light pollution are related to the level of development, population, biodiversity and climate. The study assessed the impact of light pollution on the level of social and economic development. We found that a combination of these factors may lead to higher levels of light exposure at night in urban areas, which can negatively impact residents' quality of life and health. In these areas, especially with the increase in the degree of economic development, the degree of light pollution also increases, which is shown in Table 4.

Table 4: Potential effects

Type	Score	Wi
Level of development	7	0.56
Population	5	0.26
Biodiversity	1	0.05
Climate	4	0.13
CR=0.065<0.1, (Consistency test passed)		

Finally, the weights of 8 second-level indicators and 4 first-level indicators calculated are shown in the Figure 5 below:

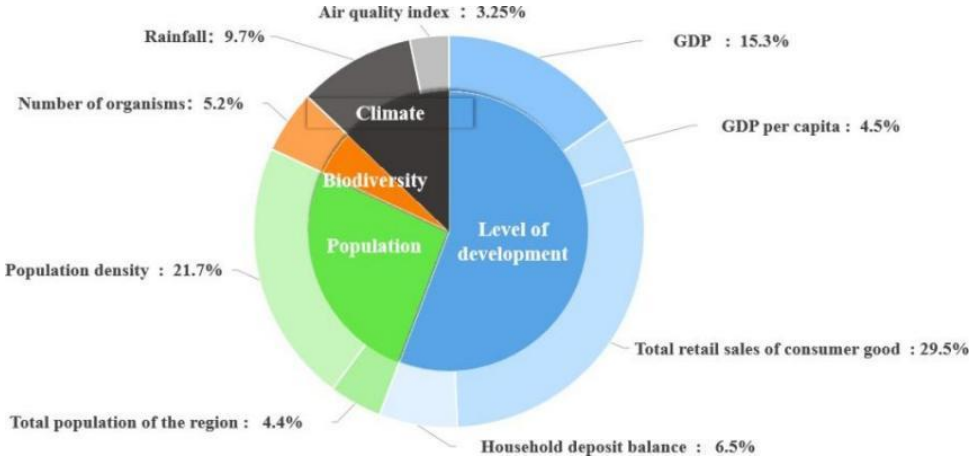


Figure 5: LP AHP Weight and score situation

2.2.2 Model II-2: LP (light-pollution) IEW Model

We selected 12 cities including Nanning, Beijing, Xi'an, Urumqi, Yinchuan, Xi Ning, Lanzhou, Lhasa, Guiyang, Chengdu, Xiamen and Ningbo, and still selected 8 indicators in 3.3.1. Let the city be *I* and the indicator be *j*.

Standardization of data. In order to eliminate the dimensional effect between indicators, we use the method of data normalization to deal with the comparability between indicators. In addition, as positive and negative indices have different meanings (positive indices: bigger is better; Negative exponent: smaller is better), we used different algorithms to process the data.

$$\text{Positive indicators:}\quad x^*_{ij} = \frac{x_{ij} - \min\{x_{1j},\ldots,x_{12j}\}}{\max\{x_{1j},\ldots,x_{12j}\} - \min\{x_{1j}\ \ldots,x_{12j}\}} \tag{7}$$

$$\text{Negative indicators:}\quad x^*_{\bar{ij}} = \frac{\max\{x_{1j},\ldots,x_{12j}\} - x_{ij}}{\max\{x_{1j}\ ,\ldots,x_{12j}\} - \min\{x_{1j},\ldots,x_{12j}\}} \tag{8}$$

Calculate the probability used in the entropy weight method, it is easy to verify that the sum of the probabilities corresponding to each index is 1. Determine the weight of the parameter. We can get the entropy weight for each indicator Then, combined with TOPSIS, we can get weighted scores for 8 metrics, which is shown in Figure 6.

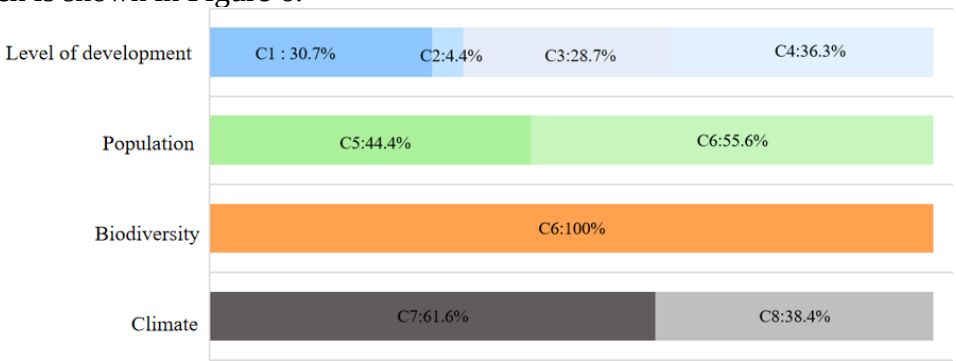


Figure 6: Scores for 8 metrics

2.2.3 Model II-3: LP (light-pollution) Model

Since the entropy weight method is based on the eight index weights derived from objective data, and the analytic hierarchy method is based on the experience and knowledge of experts to judge the index weights, it is necessary to integrate the two index weights into a "representative" result. We use power synthesis to combine entropy weights and analytic hierarchy.

3. Typical regional selection

3.1. Application of direct effects

We apply it from both direct and potential aspects. The direct aspect is that the selection Protected land 1, Protected land 2, Rural communities 1, Rural communities 2, Suburban community 1, Suburban community 2, Urban Community 1 and Urban Community 2.In the eight samples, *E* (average ground illumination), *H* (pole height), *L* (total luminous flux of lamps = power * luminous efficiency), *D* (installation distance of the same side lamp pole), *S* (distance between road and residence), a (lamp projection angle) were calculated for the corresponding G glare, T light infringement and S light diffusion degrees, the final scores of the three light pollution were solved, and finally normalized. Table 6 gives the effects of applications.

Table 6 Application of direct effects

Sample	E	H	L	D	S	a	Score	Normalization
Protected land 1	2.54	8	9000	20	30	10	3.80	0.02
Protected land 2	2.79	8	9000	16	32	10	3.13	0.02
Rural communities 1	10	7	2500	30	16	30	45.0	0.23
Rural communities 2	12	7	2500	30	15	45	62.5	0.31
Suburban community 1	21	7	9000	20	10	45	117	0.56
Suburban community 2	20	7	9000	22	8	30	107	0.53
Urban Community 1	30	6	13000	12	6	30	159	0.79
Urban Community 2	32	4	12000	15	5	45	183	0.92

3.2. Application of potential effects

The potential aspect is that the selection Taibai Mountain, Changbai Mountain, Around Guazhang Village, Around Xuwang Village, urumchi, Guiyang, Ningbo and Xian. In the eight samples, C1(GDP), C2(GDP per capita), C3(Total retail sales of consumer good), C4(House- hold deposit balance), C5(Total population of the region), C6(Population density), C7(Number of organisms), C8(Rainfall), C9(Air quality index) were calculated for the final scores of the three-light pollution, and finally normalized. Table 7 shows the specific situations.

Table 7: Application of potential effects

region	C1	C2	C3	C4	C5	C6	C7	C8	C9	Score	Normalization
Taibai Mountain	20	0	0	0	0.3	92	3575	800	74	280.2	0.06
Changbai Mountain	8	0	0	0	1.3	7	2904	1000	36	244.3	0.05
Aruond Guazhang Village	893	1.7	240	482	52	89	1470	512	76	402.2	0.08
Aruond Xuwang Village	692	3.4	490	205	20	194	1397	685	78	423.3	0.08
urumchi	3337	8.2	964	3680	405	375	998	194	65	1383	0.28
Guiyang	4312	7.2	2188	3634	599	744	479	544	41	1913	0.38
Ningbo	12409	13	4238	8522	940	958	83	1527	65	4411	0.88
Xian	10020	7.8	4989	10913	1295	1282	86	648	84	4547	0.91

4. Results and Discussion

4.1. "W" --Indicator of light pollution

In order to better express it we just take the Direct impact as the x coordinate and Potential impact as the y coordinate to construct a Rectangular Coordinates and marked the distance of different areas' light pollution risk level point to the origin which represents ideal level of light pollution. It is shown in Figure 7.

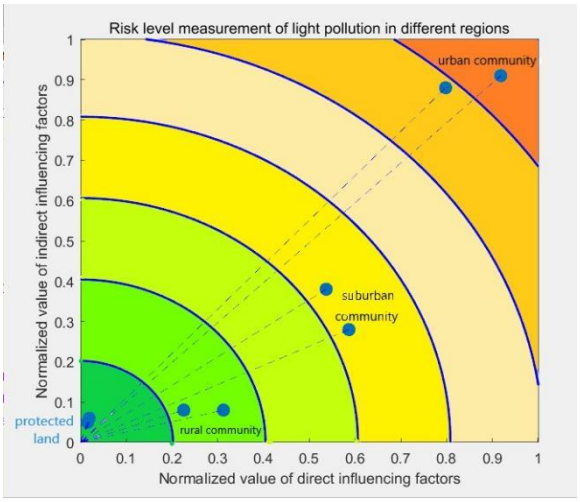


Figure 7: W --Indicator of light pollution

Therefore, to better recognize and manage the light pollution risk level we may again prefer to construct a multi-level model, which were combined with several circular arcs filled with gradient. The color changed from green to red gradually to express the light pollution risk level from slight to serious.

Green level: When all of those work were done, we now could see clearly that the sample Protected land 1 (N1), Protected land 2(N2), Rural communities 1(V1) and Rural communities 2(V2) were all located at green level, which means that their light pollution risk level were at a slight state.

Buff level: The sample Suburban community 1(S1) and Suburban community 2(S2) just at the state of buff level, which represented a medium level of light pollution risk level.

Orange and red level: While the sample Urban Community 1(U1) and Urban Community 2(U2) were at the orange and red level, which means they were really at a high-risk pollution of light in general.

4.2. GIS VS. LP

Besides using the distance to origin and the multi-level model to analyze the light pollution risk level in general, we also considered the value of Direct impact divided Potential impact, which reflected the leading aspect caused light pollution of the two aspects for an area.

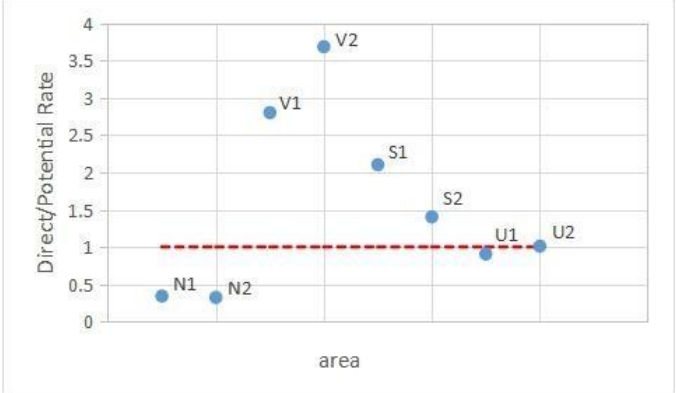


Figure 8: GIS VS. LP

From Figure 10, it can be concluded that Protected land 1 (N1) and Protected land 2 (N2) have the Potential impact as their leading factor for light pollution. These areas should pay more attention to addressing this potential impact. High wildlife numbers are the major reason for the light pollution in these areas, as it increases the risk of light pollution affecting the wildlife. On the other hand, Rural communities 1 (V1), Rural communities 2 (V2), Suburban community 1 (S1), and Suburban community 2 (S2) have the Direct impact as their leading factor for light pollution. This is mainly due to factors such as the height of street lamps and the proximity of roads and buildings, which contribute to light pollution in these areas. Finally, Urban Community 1 (U1) and Urban Community 2 (U2) require attention to both Direct impact and Potential impact, as they are at the baseline level for light pollution.

4.3. Regional characteristics

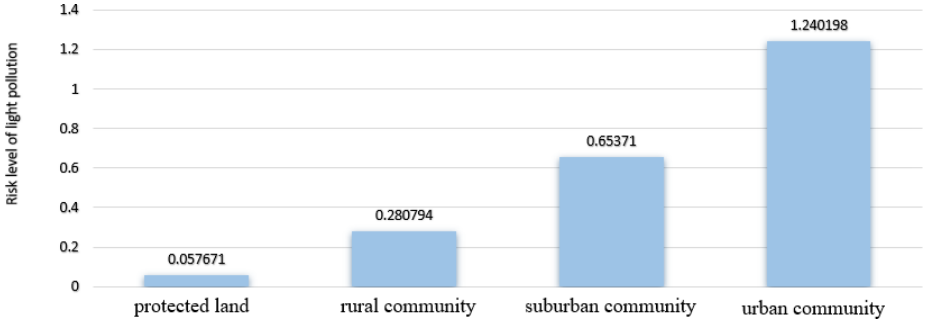


Figure 9: Comparison of light pollution risk levels in different types of regions

The protected area has the lowest risk level of light pollution among the different areas ,based on the given figure, This is due to indirect factors, such as limited human development activities, mini mal artificial light sources, and limited use of excessive lighting. In rural areas, there is also less lig ht pollution due to fewer people, less developed road traffic, and limited use of street lights. Direct f actors, such as rural road lighting, contribute to light pollution in these areas. Suburban communitie s have a moderate level of light pollution, with population density and light use falling between rura l and urban areas. Urban areas have the highest level of light pollution, driven by a combination of e xcessive use of urban lamps, dense population, and high demand for lighting due to economic devel opment.

5. Summary

A GIS evaluation model was established to assess the risk level of light pollution by considering both direct and indirect influence factors. The direct factors were evaluated using a clustering method, where a GIS light pollution model incorporating glare pollution, light infringement pollution, and light diffusion pollution was utilized. The standardized light pollution index was then classified into seven categories representing different levels of light pollution.

This comprehensive assessment provides valuable insights for policymakers in formulating light pollution prevention and control policies. It enhances their understanding of the complexity and causes of light pollution problems and guides the implementation of appropriate measures to reduce light pollution risks, thereby protecting the environment and human health.

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