Light pollution assessment study based on AHP-CI-VCW model

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Abstract. Light pollution has become increasingly serious in recent years. In order to better understand and mitigate the ecological and biological impacts of light pollution, a model was developed in this paper to measure the regional light pollution risk level. We developed the AHP-CI-VCW model. Based on the four main influencing factors of weather, reflection, air quality, and lighting, as well as the upper limit Ei for each indicator, we developed daytime and nighttime light pollution assessment models using hierarchical analysis and integrated index method, respectively. After that, we established the visual contrast weighting method, and assigned the scores of these two models to W1=1/7 and W2=6/7, respectively, and the two scores were summed to obtain the light pollution risk score of the region. We then selected protected areas such as the Grand Canyon of Colorado, rural Ashland, suburban Yonkers, and urban Washington to assess the light pollution risk level. We reviewed the local data and introduced them into the AHP-CI-VCW model and calculated scores of 1.117 for Colorado Grand Canyon, 1.975 for Ashland, 2.617 for Yonkers, and 2.815 for Washington, D.C. Using satellite light remote sensing maps, we validated the results and determined the light pollution risk levels for these four areas as none, low, moderate and high.

Keywords: Light pollution level, AHP-CI-VCW model, visual contrast, hierarchical analysis.

1. Introduction

At the IUCN World Conservation Congress (IUCN WCC) in September 2021, Proposal 84 on "Reducing Light Pollution" was adopted. By now, the negative impacts of light pollution have been widely recognized. The change in the understanding of light pollution is the result of continuous improvement in the way light energy is used. Therefore, it is important to study the measurement method of light pollution risk level and explore the environmental benefits of artificial light from the environmental perspective to provide scientific decisions for social development planning.

In this paper, a visual contrast weighting model (AHP-CI-VCW) based on AHP and composite index is developed to measure the risk level of light pollution in an area. Based on weather, light, reflection, air quality and other indicators, a daytime light pollution evaluation model and a nighttime light pollution evaluation model are established using AHP and composite index. Finally, we designed a visual contrast weighting method to combine the results of the two models to obtain the final light pollution score.

2. Establishing AHP-CI-VCW evaluation model

According to the four main influencing factors of weather, reflection, air quality and light and the upper limit value of each index , we have established the assessment models of light pollution in the daytime and at night by using the analytic hierarchy process and comprehensive index method. After that, we created the visual contrast weighting method to weight the scores of the two models. Add the two scores to get the risk score of light pollution in the region. This light pollution risk assessment model combines both hierarchical analysis, composite index method and visual contrast weighting method, so we named it as AHP-CI-VCW evaluation model.

2.1. Daylight environment light pollution risk evaluation model

2.1.1 Build the AHP model

Daytime light pollution phenomenon includes glass curtain wall, advertising lights, etc. The main influencing factors are weather, reflection and air quality.

The evaluation indicators are decomposed according to different levels to form a tree-like hierarchy. In which, the structure of the upper level has a dominant effect on the next level.

The daytime light pollution model can be decomposed into air quality, weather, reflective surface components for a total of three evaluation indicators. Three air quality level evaluation indicators: dust, PM2.5, water vapor; three weather evaluation indicators: sunny, cloudy, overcast; three reflective surface evaluation indicators: glass, water surface, ground. In this tree hierarchy, the bottom layer is the indicator layer for comprehensive evaluation [3].

(1) Build judgment matrix

Once the hierarchy of the upper part is determined, the affiliation between the upper and lower level indicators is determined, assuming that the upper level element is the criterion, denoted as B_{di}, and the lower level element it dominates is $C_1, C_2, C_3, \dots, C_n$. The n elements are compared against the criterion B_i, to determine which is more important, C_i or C_j ,relative to the criterion B_{di}.

(2) Consistency check

Due to the diversity of human perception and the complexity of objective things, the judgment matrix is not required to have complete consistency in the AHP hierarchical analysis method, but since the judgment matrix is the basis for calculating the weight ranking, it should be required to have the general consistency. Therefore, it is necessary to check the consistency of the judgment matrix of each layer.

After calculation, the consistency ratio CR values of target layer, criterion layer and indicator layer are all less than 0.10, which indicates that the consistency of each judgment matrix is good and can be used as the basis for calculating the weight value in the next step.

(3) Weighting calculation

In general, the weight calculation can be summarized as the problem of calculating the characteristic roots and eigenvectors of the constructed judgment matrix. According to the above-constructed judgment matrix, the maximum eigenvalue $\lambda_{max}$and eigenvector W_i of the judgment matrix are calculated based on the calculation method of linear an algebra, and after normalizing the eigenvector, the vector component W_i, which is the relative weight of the corresponding factor sought about the upper layer of factors, where $\sum W_i = 1$. The weight values of the criterion layer and the indicator layer are calculated according to this method. The indicator system weights are shown in Table 1 below.

Table 1. The weight of light environmental quality evaluation index system

Target layer	Guideline layer	Guideline layer weights	Indicator layer	Indicator layer weights
Sunlight Environment	Air Quality	0.2297	Dust	0.0752
			PM 2.5	0.1830
			Water vapor	0.7418
	Weather	0.6483	Sunny	0.7010
			Cloudy	0.1929
			Overcast	0.1061
	Reflection	0.1220	Glass	0.7306
			Water surface	0.1884
			Ground	0.0810

2.1.2 Comprehensive index evaluation model

The comprehensive index evaluation method is integrated on the basis of index single factor evaluation, reflecting the comprehensive, holistic and hierarchical nature of environmental quality standard evaluation, reflecting the common effect of each index factor on the environment.

The calculation formula is [4]:

$$Q_d = \sum_{i=1}^{n} W_{di} P_i \tag{1}$$

$$P_i = \frac{C_{di}}{\mathrm{E_i}} \tag{2}$$

$$\sum_{i=1}^{n} W_{di} = 1 \tag{3}$$

2.2. Night light environment light pollution risk evaluation level

2.2.1 Build the AHP model

Night light pollution contains sky shines, glare, etc. Its main influencing factors are lighting, reflection, air quality.

The process is the same as the daytime light pollution model, and the detailed process is not given here. The results are as shown in Table 2.

Table 2. The weight of light environmental quality evaluation index system

Target layer	Guideline layer	Guideline layer weights	Indicator layer	Indicator layer weights
Night Light Environment	Light Sources	0.6491	Street light	0.0752
			Car light	0.1830
			Advertising light	0.7418
	Reflection	0.2790	Glass	0.7010
			Water surface	0.1929
			Ground	0.1061
	Air Quality	0.0719	Dust	0.7306
			PM 2.5	0.1884
			Water vapor	0.0810

2.2.2 Comprehensive index evaluation model

The comprehensive index method of night light pollution model is roughly the same as that of daytimeThe calculation formula is:

$$Q_{\mathrm{n}} = \sum_{i=1}^{n} W_{ni} P_i \tag{4}$$

$$P_i = \frac{C_{ni}}{E_i} \tag{5}$$

$$\sum_{i=1}^{n} W_{ni} = 1 \tag{6}$$

2.3. Visual contrast ratio weighting method

2.3.1 Conceptual interpretation

The visual contrast ratio weighting method is a weighting method constructed according to the requirements of this question. In the actual use of urban lighting, the phenomenon of visual contrast

caused by light pollution is one of the main reasons for people's negative evaluation of artificial lighting. Taking the phenomenon in life as an example, visual contrast can be simply understood as the degree of blinding when a flashlight is turned on in a room. When there is no natural light in the room and it is dark, the flashlight is at a low illumination level, but it still feels blinding, which means that the visual contrast is relatively high. In the daytime when you open the flashlight does not feel blinding, the reason is that the visual contrast is relatively small. In modern cities, people mostly use natural light during the day, so there is no visual contrast ratio, so the contrast ratio can be set to 1. At night, because the natural light is weak, the city uses more artificial light, so the visual contrast ratio increases at night [5].

This method is applied in this question to normalize the visual contrast ratio between the same area in a night light environment and a daylight environment, and finally get the weight of the risk level of light pollution in the area, which provides methodological support for measuring and mitigating the impact of light pollution.

2.3.2 Formula calculation

After reviewing the data, we get the natural light intensity of 0.2 lx at night, and the average intensity of artificial light sources such as street lights, headlights and advertising lights is 1.2 lx.

In this method, the average light intensity of artificial light is set to l, l_n is the night natural light intensity, and the division of the two is the visual contrast ratio at night. So the formula is

$$r_n=\frac{l}{l_n}=6 \tag{7}$$

Since the visual contrast is weak during the day, r_d is obtained as 1.

$$r_d=1 \tag{8}$$

On the basis of calculating the visual contrast ratio of daytime and nighttime, the visual contrast ratio weight of daytime and nighttime is obtained by the following formula.

$$W_1=\frac{r_d}{r_d+r_n}=1/7 \tag{9}$$

$$W_2=\frac{r_n}{r_d+r_n}=6/7 \tag{10}$$

The total score is calculated as follows.

$$Q=W_1*Q_d+W_2*Q_n \tag{11}$$

3. Application of the model to analyze the risk level of light pollution in different types of areas

3.1. Preparation in advance

The International Illumination Commission(CIE) is a non-governmental and multidisciplinary international academic organization composed of light source manufacturing, lighting design, and light radiation measurement and testing institutions in the field of international lighting engineering. It is a non-profit organization in technology, science and culture.

CIE formulates basic standards and measurement procedures in the field of lighting.We looked up the data to get different upper limit indicators of illumination in the protected areas, rural areas, suburbs and cities. According to the formula in the model, we calculated E_i.

Some natural indicators, such as sunny, cloudy, rainy and water surface, are not formulated by legal persons, so I set these indicators as 1.

We analyzed the light pollution levels in four types of areas: protected areas, rural areas, suburban areas and urban areas by calculating the weather index, reflection index, air quality index and light index in four areas, and the results are shown in Table 3 below.

Table 3. Light pollution risk level scores for different types of areas

Areas	Protected areas	Rural areas	Suburbs	Cities
Scores	1.1175	1.9757	2.6174	2.8151

3.2. Model Validation and risk level classification

We converted the optical radiation remote sensing black and white images of four regions to RGB images. The grayscale value is the color depth of the points in the black and white image, generally between 0 and 255, with 255 for white and 0 for black. we used JET color mapping to map the pixel grayscale values to RGB, and finally plotted the color image as in Figure 1.

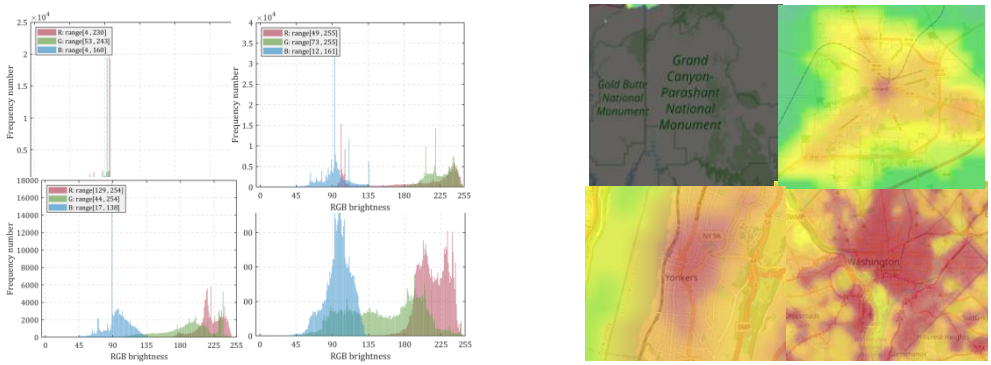


Fig. 1 Colorful ages of remote sensing of light radiation in four regions

In the color map, we can see that the Colorado National Park with an AHP-CI-VCW model score of 1.1175 is dark, while the Washington area with an AHP-CI-VCW model score of 2.8151 is bright red. The brighter the color, the stronger the radiation and the higher the degree of light pollution. Therefore, we believe that there is no light pollution risk in the black area in the color map, the light pollution risk in the green area is low, the light pollution risk in the yellow area is high, and the light pollution risk in the red area is high. We divided the score range according to Table 4.

Table 4. Light pollution risk level scoring

Light pollution risk level	Score of the AHP-CI-VCW model
No light pollution	0-1.4
Low light pollution	1.4-1.8
Medium light pollution	1.8-2.5
High light pollution	Above 2.5

In Summary, Colorado National Park has no light pollution, Ashland is moderate light pollution, and Yonkers and Washington are high light pollution levels.

4. Summary

We use hierarchical analysis and comprehensive index as the evaluation model of light pollution risk level. Since the main causes of daylight pollution and nighttime light pollution are very different, we discuss daylight pollution and nighttime light pollution separately, and the model is more convincing. In addition, the visual contrast weighting model based on hierarchical analysis and comprehensive index is constructed to normalize the visual contrast of the same area under nighttime light environment and daytime environment based on the visual contrast theory, and finally get the weight of the light pollution risk level of the area, which provides a more scientific and effective method for the comprehensive evaluation of the light pollution risk level. Finally, we verify the

accuracy of our AHP-CI-VCW model by comparing the model evaluation results with RGB images from the National Oceanic and Atmospheric Administration's nighttime light remote sensing images.

However, the assumptions of the model ignore other manifestations of light pollution and the impact of interventions on the overall environment, for example, we ignore light pollution indoors, the impact of interventions on animals, and the urban landscape. Influenced by the data search, it is not comprehensive enough in considering light pollution risk evaluation factors. If more data can be found, as many factors as possible should be selected for comparative screening. The applicability of the model was tested in only four regions, and if there is time, more regions can be tested to improve the applicability and accuracy of the model.

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