Light Pollution Mapping of Urban Human Activity and Land Zoning

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Abstract
Sky glow, a kind of light pollution, which brightens the night sky significantly results from the spill light of inappropriate or over-designed artificial lighting. It not only affects astronomical observations, but disturbs ecology system and wastes lighting energy. In fact, urban light pollution is related to artificial lighting made from human activities and nighttime urban facilities. However, former relative researches mostly concerned how to utilize remote sensing to evaluate large-scale sky glow for astronomy, not for urban or architectural lighting to improve the real environmental problem.

The purpose of this research is to find the relation between sky glow and urban planning, especially urban population and land zoning. The study surveyed the sky glow and then mapped it in Taichung City, Taiwan. Firstly, it measured sky glow by sky quality meter (SQM) across the whole metropolitan area by 133 points, and transformed GIS data into light pollution map with Surfer software. Secondly, it combined the light pollution map with local population density and land zoning to analyzing the local-scale sky glow causes. The result showed that high-density commercial areas have more severe light pollution, and the average brightness is 772 times of the natural moonless sky. This research provides an innovative methodology to estimate local-scale sky glow, and helps people recognize how the light pollution is to improve urban nighttime living environment in the future.

Keywords: light pollution, sky glow, GIS, sky quality mete

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Introduction

Negative environmental impacts generated by nighttime lighting system are collectively called light pollution, among which “sky glow” refers to the increase in brightness of the night sky due to the scattering of the ground artificial light through atmospheric dust and suspended materials to the sky. Italian scholar Cinzano synthesized night-sky brightness distribution map by satellite telemetry data. At present, about two-thirds of the current world population lives in areas of light pollution threat, a quarter of the people cannot directly view the Milky Way with their naked eyes（Cinzano et al., 2001）.

Light pollution in large cities is more severe, where natural moonless night-sky brightness average is 21.6 mag/arcsec^2, equivalent to the luminance value of 2.1×10^{-4} cd/m^2. The night-sky brightness in Beijing is 1.3×10^{-2} cd/m^2, the luminance value of Tokyo and Osaka is about 5.8×10^{-2} cd/m^2, and that in Shanghai’s commercial district is about is 1.0 cd/m^2（Li,2006）, all of which are a hundred times more than natural night-sky brightness. Increased night-sky brightness affects stargazing and means unnecessary lighting energy waste, increased CO_2 emissions and the impact of natural ecosystems.

Recent studies on the sky glow have been conducted. In addition to the first light pollution distribution map made by Cinzano using the US defense satellite DMSP and GIS（Cinzano et al., 2001）, there are studies using GIS and remote sensing method to study spatial distribution of the population and light pollution（Elvidge et al.,1997）. Regarding the prevention of sky glow, internationally, lamp “uplight pass ratio (ULR)” of No. 150 technical report（CIE, 2003） of International Commission on Illumination (CIE) is the specification recommendations.

Research Purpose

The sky glow is mainly caused by the “uplight” and “ground-reflected light.” The methods to determine sky glow in the past such as satellite telemetry mostly were proposed by astronomers. However, light pollution discussed in astronomy or physics presents the macroscopic results in the wide range, and cannot exactly reflect the detailed urban design and lighting plan relationship, therefore, the urban light pollution problem can be improved in smaller scale urban planning and lighting design.

On the other hand, nearly 60% of the population in Taiwan live in light-polluted areas of high night-sky brightness. Coupled with a particular phenomenon of Taiwan’s densely populated area and the mixed zoning of residential and commercial areas, urban light pollution is particularly serious. However, the study of urban light pollution in Taiwan is in an early stage. Therefore, it is necessary to understand the urban light pollution through sky glow survey and provides basic information to do the follow-up study. The purposes of this study are as follows: (1) To combine GIS to build urban night-sky brightness map ; (2) To analyze the impact of urban landmarks, main roads, and commercial centers on sky glow.

Theory and Method

“Sky glow” is the night sky brightness increase. In general, night-sky brightness is used to assess the degree of sky glow in the measurement unit of luminance (cd/m^2) or equal per square arcsec ($mag/arcsec^2$), which means every level magnitude differs by 2.512 times in brightness. International Astronomical Union (IAU) established in 1979 “International Standards of Dark Sky Night”. It defines the natural moonless night-sky brightness in the case of no light pollution is $21.6 mag/arcsec^2$. In full moon, the natural night-sky brightness is $16 mag/arcsec^2$. At present, CIE 150-2003 technical report is generally used as the main basic specifications of sky glow (CIE, 2003). Its “ULR” is defined as the ratio of “light uplight flux against the total flux of all lamps” to limit the spill light of the lights to avoid light pollution.

The most direct way to observe sky glow is “the computation of the number of visible stars”. The observer computes the number of stars in the night sky of a certain region in accordance with the magnitudes of well-known stars. The method can be applied in the observation of a wide range. However, naked eye observation is not suggested as there will be a considerable degree of error (CIE, 1997).

Walker’s Law （Walker, 1977）is generally used to estimate the night-sky brightness. By using the scientific quantitative formula and the “urban population” and “distance from the urban center” as the assessment factors of sky glow, the increase in night-sky brightness from the 45° perspective of the observer in the direction of the urban center can be measured. In general, Walker’s Law is applicable to the assessment of various types of sky glow. However, it is not suitable for the densely populated Asian cities without obvious boundaries.

Satellite telemetry can obtain light pollution distribution of a wide range. Many studies have used the night satellite photos taken by DMSP for wide range light pollution mapping and analysis(Cinzano et al.,2001; Garstang, 1986; Elvidge et al.; 1997 Chalkias et al.,2006). Satellite telemetry can measure the light divergence of the common outdoor lighting fixtures, such as mercury vapor, high pressure sodium vapor lamps, and low pressure sodium vapor lamps. Moreover, it can display the ratio of “artificial sky brightness light” and “natural sky brightness” by different colors.

Sky Quality Meter (SQM) is an economic and convenient night-sky brightness measurement tool with the measurement unit of $mag/arcsec^2$. SQM sensor combines near-infrared filters, so that results are similar with the perceptions of the human eye(Cinzano et al.,2005). At the same time, a small induction range can avoid the influence of ambient lighting. Due to small size, easiness to carry, it has recently become one of the commonly used instruments in night-sky brightness measurement and astronomical events.

Night-Sky Brightness (NSB) measurement

According to literature, the sky glow assessments from the astronomy perspective mainly display the wide-range phenomena of a wide range by using satellite telemetry. Most of studies in urban architecture fields have used handheld photometer to measure the small field (Pun & So, 2012）. As this study focuses on the urban architecture research field, the latter investigation method was adopted. Meanwhile, based on geopolitical relations, Taichung, the third-largest city in Taiwan was selected as the research subject.

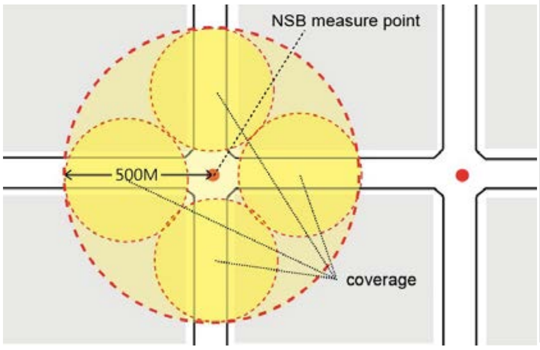
For the convenience and accuracy of measurement, this study used SQM as the instrument to measure night-sky brightness. Smaller readings of SQM mean greater light pollution. In addition, due to the building density in Taiwan's cities, the field view of the sky from the ground is relatively smaller. To avoid excessive and unnecessary light, the instrument SQM-L of FWHM (Full Width at Half Maximum) at 20° was used in this study (Table 1).

Table 1: The characteristic of SQM-L

SQM-L	characteristic	Illustration
	Handheld	Unit： mag/ arcsec^2
	Narrow Field of view	HWHM ~10° , FWHM ~20
	Single reading	No continues reading
	Small &Portable	Monitor sky brightness in a few seconds

For the consideration of the convenience of mobile measurement, by following the concept of "urban road network", the 18 major roads running through Taichung were selected as the measurement routes. The measurement was taken at every 1 km to obtain the data of network distribution (Fig.1). This study also selected 6 representative urban landmarks to measure the NSB to supplement the road measuring points. The 6 landmarks were Taichung Metropolitan Park, Taichung Industrial Park, Phase 7 Central Business District, Yizhong Street Business Circle, Fengchia Night Market Business Circle, and SOGO Taichung Business Circle.

To reflect the real NSB, measurement should avoid direct exposure to artificial light and the shading of buildings or trees. SQM-L measuring points should be set at a distance equal to the height of the facility. If there were an artificial light source nearby, it should keep at least a distance of more than 10m (Fig.2)（Pun & So, 2012）. As NSB is mainly subject to the influence of "astronomical twilight", "cloudiness" and "moon phase", therefore, the measurement time was after 20: 30 and before 23: 00. In addition, to avoid the collection of data when cloudiness changes, the investigation was conducted in days between the new moon and the full moon of sunny weather.



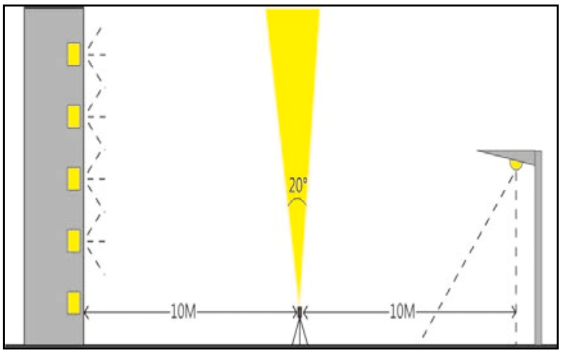
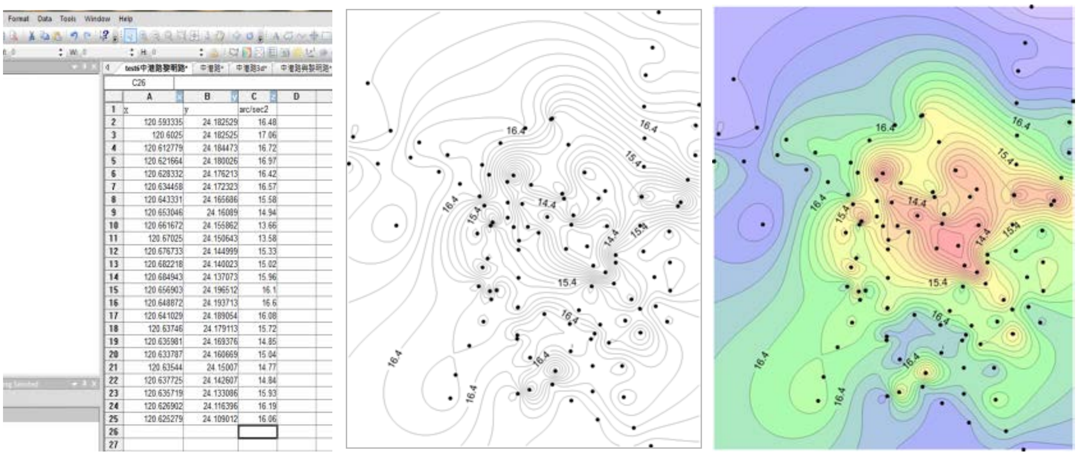


Figure 1: measurement point layout Figure 2: measure point

Establishment of NSB mapping

To combine the investigation results with GIS geographic information to facilitate the reading and interpretation of NSB, this study used Surfer software to describe investigation results and GIS in contour images to get the mapping of light pollution in a regional scale. Therefore, each measuring point of NSB was positioned by GPS to record the longitude and latitude of the location.The information of 133 measurement points were converted into XYZ three-dimensional coordinates. X represents longitude, Y represents latitude, and Z represents the measured NSB. Then, Surfer software was applied to convert the data into grid to plot the map of NSB (Fig.3).



(1) XYZ Data file (2) Post map (3) Contour map

Figure 3: Steps of NSB mapping

NSB analysis in Taichung City

In this study, NSB was used to assess the degree of sky glow in the unit of “mag/arcsec^2”. Smaller readings represent brighter sky and more serious light pollution. By integrating the investigation results of 133 measuring points of 18 main roads in Taichung, it is found that the NSB of “Gongyi Rd. (14.60 mag/arcsec^2)” is the highest, followed by “Daya Rd.-Zhongqing Rd. (14.73 mag/arcsec^2)”, which are the major traffic roads of Taichung (Fig.4). As the measurement range of this study has covered the range of Taichung, the average value of all measuring points at 15.78

mag/arcsec^2 can be regarded as the average NSB of Taichung. It is nearly 212 times of the natural moonless NSB, suggesting the light pollution is serious.

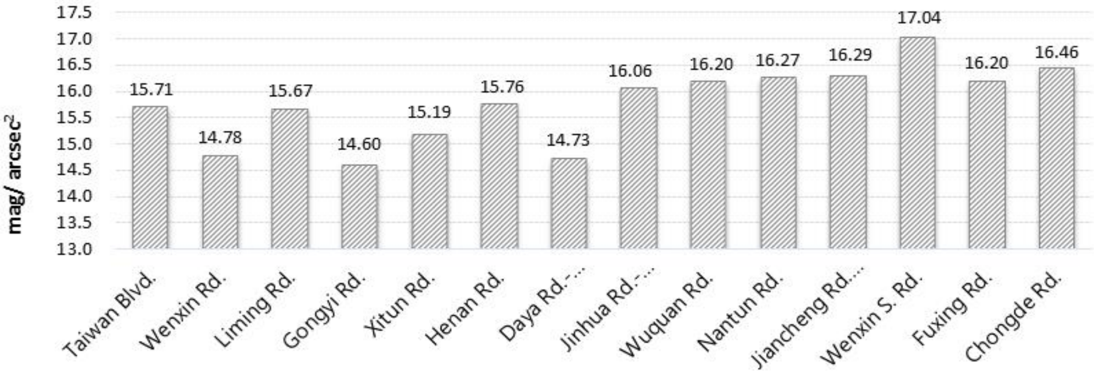


Figure 4: NSB of 18 main roads in Taichung City

Regarding the landmark measuring points, due to heavy human flow and more lighting equipment of signs and boards in the business area, the NSB of the four business areas is relatively high and the average NSB is up to 14.38 mag/arcsec^2. The average brightness is 772 times of the natural moonless NSB with the NSB of SOGO business area at 13.66 mag/arcsec^2 is the highest. The sky glow of Taichung Industrial Park and Taichung Metropolitan Park with fewer human activities is relatively lower. The NSB of them is 17.7 mag/arcsec^2 and 17.82 mag/arcsec^2 respectively, which is in the range of natural NSB(Fig.5).

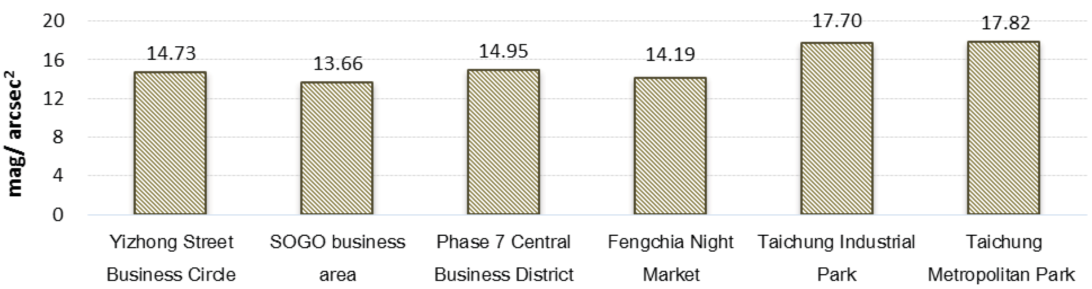


Figure 5: NSB of landmarks in Taichung City

NSB map and urban Light Pollution Analysis

The NSB data of 133 measuring points were plotted into Surfer to present the light pollution map of Taichung. Areas of bright colors and closer to the red color have higher NSB (Fig. 6). In the NSB map, the light pollution of Taichung City is separated by the outer ring road “Huanzhong Rd.” and “railway”. The downtown area to the east of Huanzhong Rd. and the west of the railway has the high NSB while the area to the west of Huanzhong Rd. has apparently low NSB. If the average NSB of the “downtown area” is 14.38 mag/arcsec^2, then the average NSB of “suburbs” represented by Taichung Industrial Park and Taichung Metropolitan Park is 17.76mag/arcsec^2. They differ by about 22.5 times in NSB. In addition, a few important roads such as Taiwan Blvd. have serious light pollution due to heavy traffic flow and human flux as well as booming business activities.

NSB of urban landmark distribution relationship is separated by Huanzhong Rd. The business areas to the east of Huanzhong Rd. are peak areas of high NSB and the most seriously light-polluted areas of Taichung. SOGO business area is the area of most serious light pollution in Taichung, and it expands along the neighboring 60m Taiwan Blvd. By comparison, Taichung Metropolitan Park and Taichung Industrial Park to the east of Huanzhong Rd. are relatively darker as compared to the neighboring area.

Taichung covers a total area of 163.42 square kilometers. The residential area is distributed in downtown and other outer areas. The commercial area is mainly distributed in the old city area and the area along Taiwan Blvd. The commercial area's NSB is roughly separated by Huanzhong Rd. The NSB of the business area to the east of the road is between 13 and 15 $mag/arcsec^2$ while the NSB of the commercial area to the west of the road is between 15 and 17 $mag/arcsec^2$. Although the area from the railway station to the downtown is a business area, it is decadent and thus the NSB is relatively darker (Fig.7).

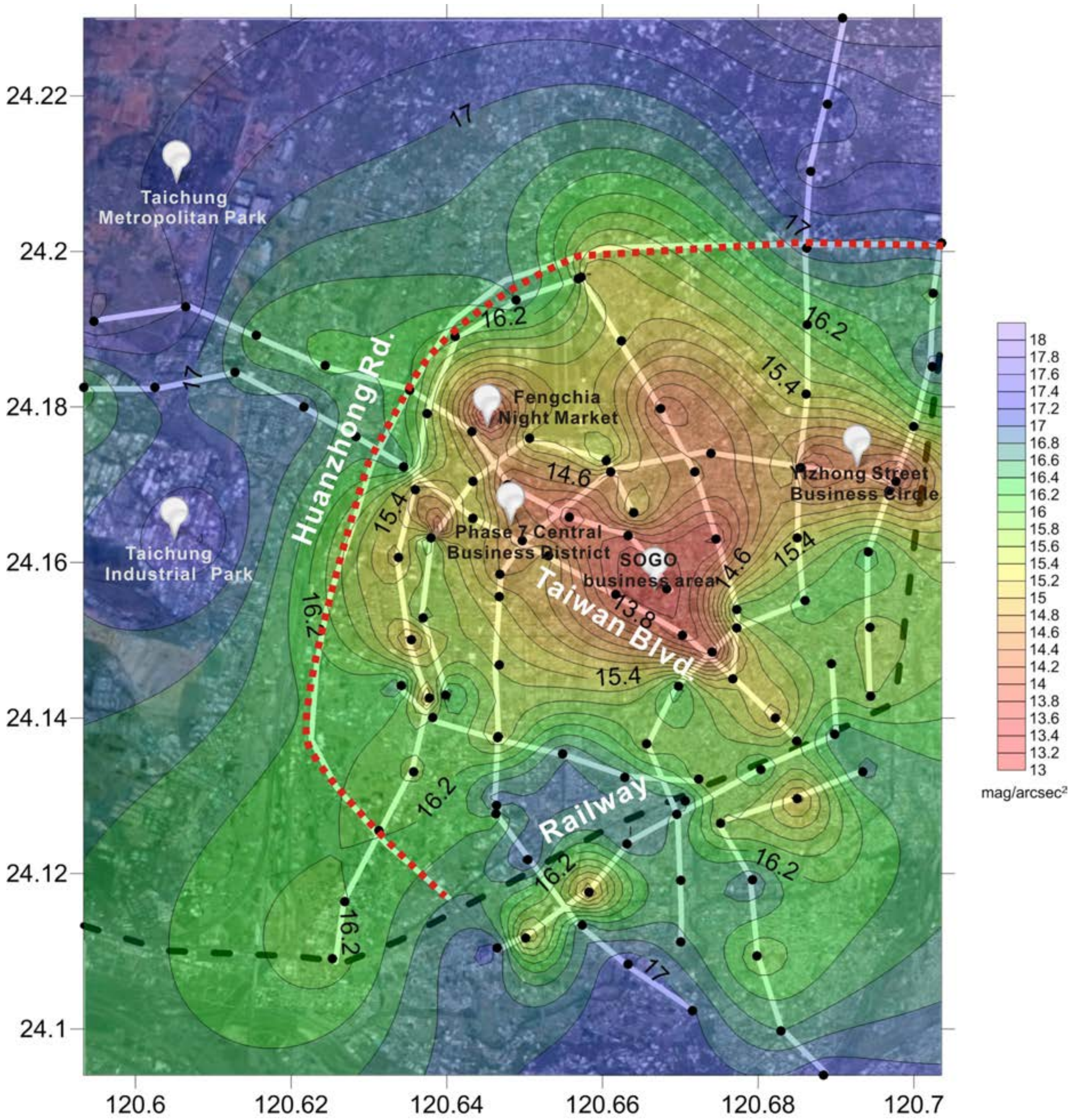


Figure 6: NSB map of Taichung City

On the other hand, the corresponding relationship of the residential area location and NSB distribution is not apparent. The NSB of the residential area to the east of Huanzhong Rd. is between 13 and 15 mag/arcsec^2, and it is between 16 and 18 mag/arcsec^2 in the area to the west of Huanzhong Rd. The area to the west of the road is low-density residential area with low building coverage ratio and floor area ratio as well as fewer artificial lighting sources. In the area to the east of Huanzhong Rd., the high-density residential area is close to the neighboring commercial area with high building coverage ratio and floor area ratio as well as more artificial lighting sources and more serious light pollution (Fig.8).

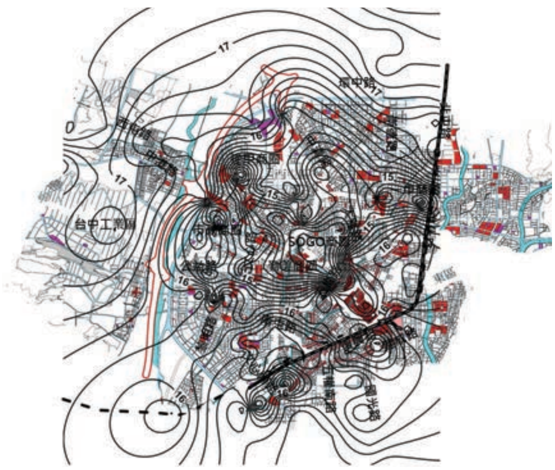


Figure 7: NSB map of commercial area

Figure 8: NSB map of residential area

Because urban lighting luminaires vary with land zoning, the NSB differs from zones, too. For example, besides basic road lighting, there are usually more lighting devices in commercial area, such as advertising lighting and landscape lighting. It makes the light pollution in commercial area worse than other urban zones. In this research, the NSB of commercial area in Taichung City was 15.08 mag/arcsec^2, of residential area was 15.71 mag/arcsec^2, and of industrial area was 16.76 mag/arcsec^2(Table 2) .

Table2 : NSB of different land zoning (mag/arcsec^2)

Commercial Area	Residential Area	Industrial Area	Agricultural Area
15.08	15.71	16.76	16.72

Conclusion

This study used SQM-L to measure Taichung's NSB. Furthermore, by combining with GIS to describe the light pollution map, this study analyzed the relationship between urban landmarks, main roads and the business area, and NSB while providing the research method to preliminarily getting the urban texture and light pollution relationship. It is suggested that subsequent studies may discs the correlation of population density, floor area ratio, road luminance and other urban composition factors with light pollution. A NSB forecasting model can be proposed as the basis for subsequent application and analysis.

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