

Exploring Spatial Distributions of Street Lighting Points and Night-Time Radiance Using Global and Local Measures of Spatial Autocorrelation

Kekula František^{1,#}, Kosovec Bernard², Hrubeš Pavel³

¹ Department of Transport Telematics, Faculty of Transportation Sciences, Czech Technical University in Prague, Prague, 11000, Czech Republic, kekulfra@fd.cvut.cz

² Department of Traffic Signalling, Faculty of Transport and Traffic Sciences, University of Zagreb, Zagreb, 10000, Croatia, bkosovec@fpz.unizg.hr

³ Department of Transport Telematics, Faculty of Transportation Sciences, Czech Technical University in Prague, Prague, 11000, Czech Republic, pavel.hrubes@fcvut.cz

Abstract

Street lighting is a widespread urban infrastructure where its spatial distribution reflects settlement morphology, road network, and land-use patterns. Municipal lighting inventories provide detailed point-based information, but are often analysed without explicitly considering spatial dependence. Satellite-derived night-time radiance products offer spatially continuous measurements of artificial light emissions and may capture broad patterns related to lighting density and installed power. This study examines the spatial structure of aggregated street lighting points and night-time radiance using exploratory spatial data analysis, focusing on global and local measures of spatial autocorrelation. Four urban areas in the Czech Republic were analysed. Street lighting places were aggregated into a regular grid aligned with the resolution of NASA Black Marble VNP46A3 radiance composites, and global and local Moran's I values were calculated under alternative spatial weight specifications. Results revealed statistically significant positive spatial autocorrelation in most study areas, with the strongest dependence observed in the largest urban area. Local Indicators of Spatial Association (LISA) identified dominant High–High clusters in central zones and Low–Low clusters mainly in peripheral or rural areas. Radiance showed similar clustering patterns, suggesting that night-time radiance may be a useful proxy for broad-scale characterisation of street lighting infrastructure.

Keywords: street lighting points, night-time radiance, global spatial autocorrelation, local indicators of spatial association.

Introduction

Street lighting constitutes a widespread urban infrastructure where its placement and technical characteristics reflect the settlement morphology, road network configuration, and the patterns of functional and land use. Municipal lighting inventories provide detailed point-based descriptions of lighting places, yet these datasets are often analysed only locally and without explicit consideration of spatial dependence.

Satellite-based night-time radiance products provide spatially continuous measurements of artificial light emissions. Although radiance is not a direct measure of street lighting infrastructure, it reflects aggregated light intensity and may correspond to spatial patterns of light density and installed power.

The objective of this study is to analyse the spatial structure of aggregated street lighting points and night-time radiance using exploratory spatial analysis methods. The paper focuses on spatial aggregates derived from street lighting places and examines their spatial dependence and clustering behaviour, since their patterns could be captured in spatial patterns of radiance values.

Data and Method

Study Areas

The analysis considered four urban areas in the Czech Republic: Study Area 1 - Hradec Králové, Study Area 2 - Dolní Čermná, Study Area 3 - Frenštát pod Radhoštěm, and Study Area 4 - Nové Sedlice. The main rationale for selecting these areas was their geographical locations and spatial extents in order to make the selection more representative.

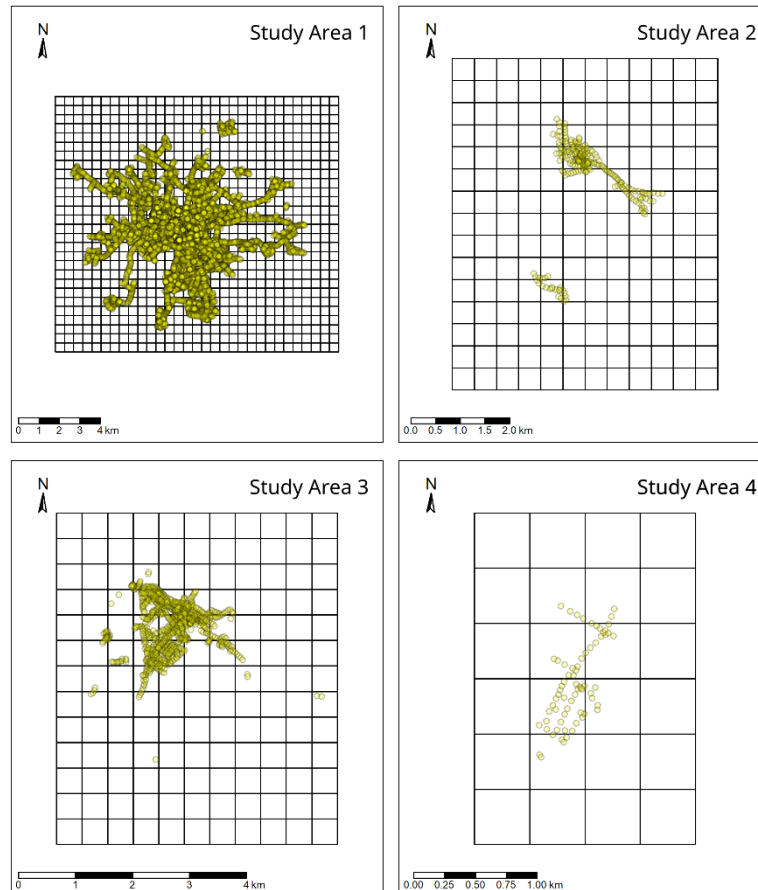


Fig. 1. Street lighting places within their square grids (source: authors).

Data sets

Vector and raster data sets were used for the purpose of this study. First, the monthly nighttime radiance product VNP46A3 was used from the NASA Black Marble VNP46 product suite. This product is derived from the VIIRS Day/Night Band sensor onboard the Suomi-NPP satellite and provides radiance values in units of $\text{nW} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1}$ (Wang, Shrestha Román and Kalb, 2022). In this study only snow-covered conditions were considered. The product is distributed in the standard land Hierarchical Data Format-Earth Observing System (HDF-EOS) format and was downloaded using the command-line utility wget from the Level-1 and Atmosphere Archive and Distribution System Web Interface (LAADS DAAC, 2026). Second, the street lighting places of selected study areas were obtained in comma-separated value files through geoportals of the respective municipalities as open data. These files were then imported into Quantum GIS (QGIS) as ESRI Shapefile point layers (QGIS.org, 2024). From the attribute tables of the layers, the three attributes were selected due to their availability and consistent values across all the places: (i) number of lighting points, (ii) nominal power, and (iii) pole

height. However, based on the results of the correlation analysis conducted in our previous work (Kekula and Hrušeš, 2023), only the first two were considered.

Raster preprocessing

Radiance values, covering the Czech Republic within two tiles (h19v03 and h19v04), were exported from HDF-EOS format to GeoTIFF, mosaicked, reprojected from WGS 84 to S-JTSK/Krovak East North, and clipped in order to obtain raster layers that fit each study area. Missing radiance values, caused mainly by clouds and stray light, were replaced using a spatio-temporal gap-filling method based on quantile regression and neighbourhood observations (Gerber, Jong, Schaepman, Schaepman-Strub and Furrer, 2018). The composites in which more than 50 % of pixels were missing were excluded from further analysis.

Vector preprocessing and spatial aggregation

In addition to the point layers of street lighting places, the administrative boundaries of the study areas were also considered. A regular square grid that matches the spatial resolution of the raster layers of radiance values was created using the QGIS algorithm Create grid. Zonal statistics were applied to compute the radiance per grid cell. Selected street lighting attributes were aggregated into the square grids by summing their values per each grid cell, producing the final aggregates denoted as variables y_1 (total number of lighting points per grid cell), and y_2 (total nominal power per grid cell). In this study we considered only the variable y_1 .

Exploratory spatial analysis

Spatial analysis was focused on the investigation of spatial autocorrelation of street lighting points and radiance values aggregated into spatial units as shown in Fig. 1. The degree of autocorrelation was measured through the calculated global and local Moran's I where their statistical significance was assessed based on the Monte Carlo method. All calculations were performed in R with the use of the spdep package. Global Moran's I was calculated according to the following formula (Cliff, 1981):

$$I = \frac{\sum_{i=1}^N \sum_{j=1}^N W_{ij} \cdot (z_i - \bar{z}) \cdot (z_j - \bar{z})}{\sum_{i=1}^N (z_i - \bar{z})^2} \quad (1)$$

where N is the total number of observations, W_{ij} is the element in the spatial weights matrix that corresponds to the observation pair i and j , z_i and z_j are the observations for the areas i and j with the mean value $\bar{z}$. The values of global Moran's I vary from -1 to +1 where these maximum values represent maximum negative and maximum positive spatial autocorrelation, respectively. Values that are close to a zero value indicate random pattern and one cannot suppose spatial autocorrelation. The results from global spatial autocorrelation are shown in Fig. 2. From the scatter plots it can be seen that the highest positive global spatial autocorrelation was observed in the study area 1 with the distance based spatial weights with the value of 0,75. The high values are also present in the case of contiguity based spatial weights. In contrast the lowest spatial autocorrelation was observed in the study area 4.

Local spatial autocorrelation was performed using the Local Indicators of Spatial Association (LISA). The information output of this statistic is two maps. One map represents spatial clusters, and the second represents the map of their statistical significance. Map of spatial clusters can contain up to 4 different types of clusters (or outliers) denoted as High-High (H-H), Low-Low (L-L), Low-High (L-H) and High-Low (H-L). The local Moran's I statistic for an area unit sample i in a given study area can be calculated according to the following formula (Anselin, 1995):

$$I_i = (z_i - \bar{z}) \cdot \sum_{j \in J_i}^n W_{ij} \cdot (z_j - \bar{z})^2 \quad (2)$$

where J_i denotes the neighbourhood set of area i , and the summation in j runs only over those areas belonging to J_i , $\bar{z}$ denotes the average of these neighbouring observations (Fischer and Wang, 2011).

Based on the results of global Moran's I we present the results of local Moran's I only for study area 1 as this area evinced the highest spatial global autocorrelation. The results are shown in Figs. 3 – 4. For all types of spatial weights, the H-H clusters are dominant and are concentrated in the central part of the study area. For the contiguity based spatial weights there are also sporadic occurrence of L-L clusters. All clusters can be considered statistically significant according to the statistical significance maps. The results for the radiance are similar since the H-H clusters are also dominant and their prevalence is concentrated in the centre of the study area. However, there are many L-L clusters in all spatial weights that surround the central part of the study area.

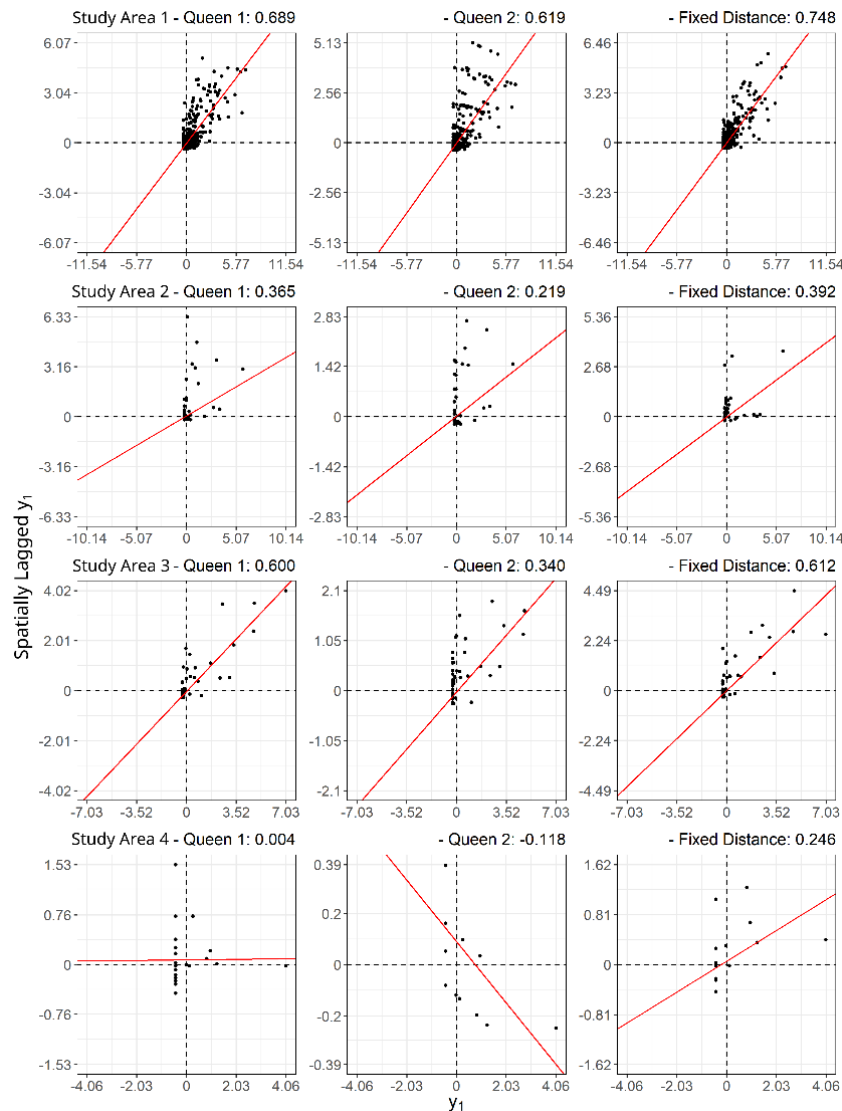


Fig. 2. Scatter point of global Moran's I for the total number of lighting points (source: authors).

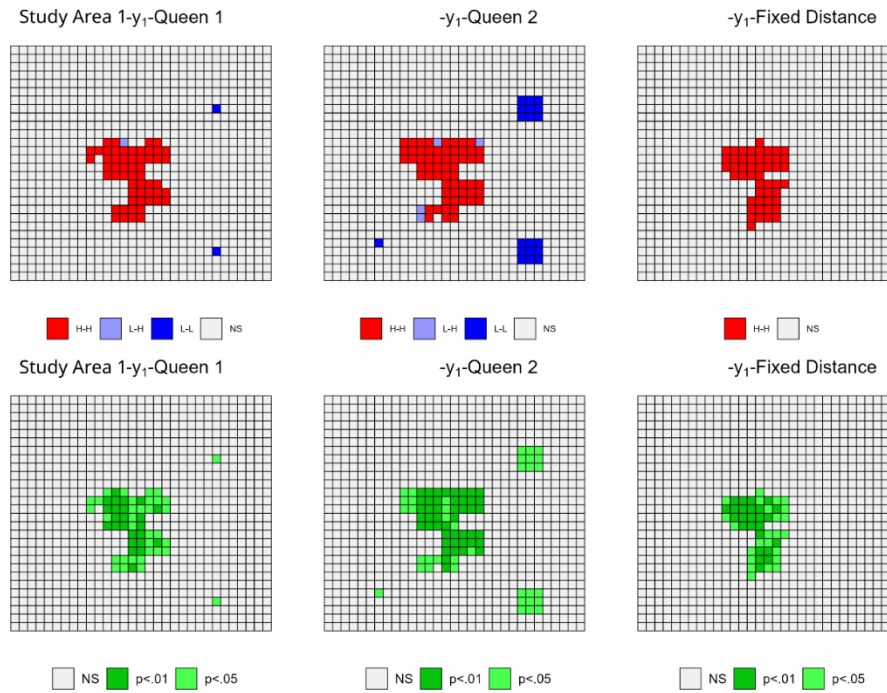


Fig. 3. Cluster and significance maps of total number of lighting points for study area 1 (source: authors).

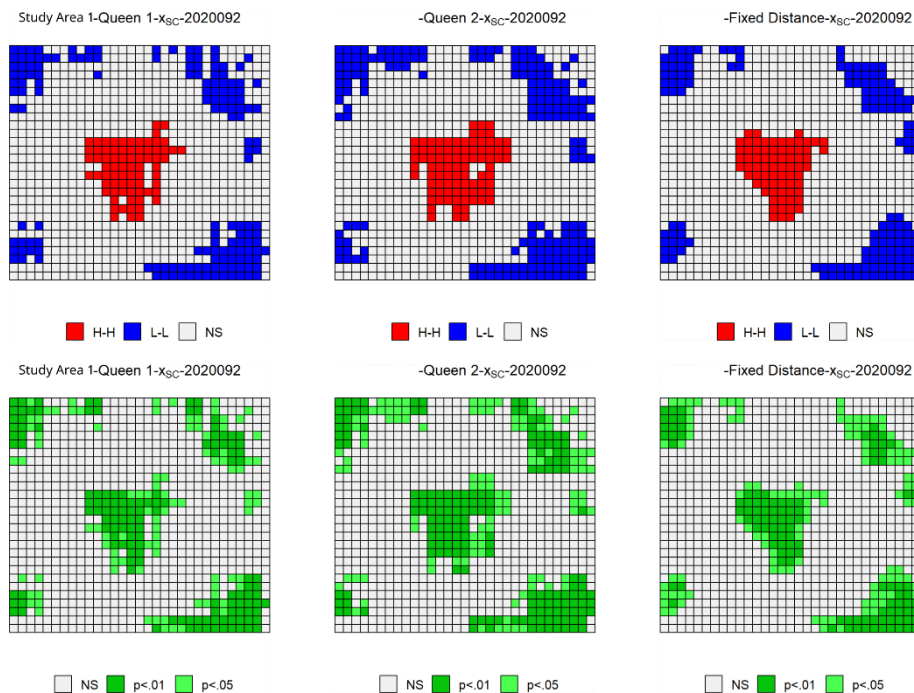


Fig. 4. Cluster and significance maps of night-time light radiance for study area 1 (source: authors).

Results

Exploratory spatial data analysis revealed statistically significant spatial autocorrelation almost in all study areas. However, the highest was observed in the study area 1. Global Moran's I indicated a strong positive spatial dependence for the number of street lighting points and thus rejected the null hypothesis of spatial randomness. Since the highest global spatial autocorrelation was observed in the study area 1, the results of local Moran's I was presented only for this area.

The local Moran's I identified H-H clusters of street lighting points predominantly in the central part of the study area, while L-L clusters were observed in peripheral or rural zones. The same was observed for the radiance. Therefore, the results demonstrate that both radiance and street lighting points form coherent spatial patterns rather than independent observations.

The results also highlight methodological constraints. Spatial dependence and the modifiable areal unit problem imply that effect sizes and cluster boundaries are sensitive to the chosen grid resolution. In addition, the large number of zeros occurring in street lighting points suggests that standard Gaussian assumptions are inappropriate and motivates count-based or hurdle modelling strategies in subsequent analyses.

Conclusion

This study demonstrated that night-time radiance appears to be meaningfully related to the number of street lighting points. Exploratory spatial analysis showed that both radiance and lighting points exhibit strong and statistically significant spatial clustering. The most prominent H-H clusters were located in central parts of the area, while peripheral zones were formed by L-L clusters.

Although the results may support the idea that the use of night-time radiance could be a good proxy for the broad-scale characterisation of street lighting infrastructure, the analysis also revealed important limitations. These include frequent zero values in aggregated street lighting points, sensitivity to a spatial aggregation unit, and the need to explicitly account for spatial dependence. Another limitation arises that the results were not good for smaller areas, as the authors expected.

Future work will be aimed at the analysis by applying spatial regression models, such as spatial lag and spatial error models, as well as count-data models with spatial structure. Such models can systematically quantify the relationships between radiance and the number of lighting points.

References

- Wang, Z., Shrestha, M. R., Román, M. O., Kalb, V. L. (2022) NASA's Black Marble Multiangle Nighttime Lights Temporal Composites. *IEEE Geoscience and Remote Sensing Letters*, 19, doi: 10.1109/LGRS.2022.3176616.
- LAADS DAAC. <https://ladsweb.modaps.eosdis.nasa.gov/search/>, 18.02.2026
- Kekula, F., Hruběš, P. (2023) An empirical study of relationships between urban lighting indicators and night-time light radiance. *Neural Network World*, 33, 375-396, doi: 10.14311/NNW.2023.33.021.
- Gerber, F., Jong, R., Schaepman, M. E., Schaepman-Strub, G., Furrer, R. (2018) Predicting Missing Values in Spatio-Temporal Remote Sensing Data. *IEEE Transactions on Geoscience and Remote Sensing*, 56, 2841-2853, doi: 10.1109/TGRS.2017.2785240.
- Cliff, A. D. (1981) *Spatial Processes: Models and Applications*. Pion, London.
- Anselin, L. (1995) Local Indicators of Spatial Association—LISA. *Geographical Analysis*, 27, 93-184, doi: 10.1111/j.1538-4632.1995.tb00338.x
- Fischer, M. M., Wang, J. (2011) *Spatial Data Analysis: Models, Methods and Techniques*. Springer, Heidelberg.