SPATIAL AND SOCIO-DEMOGRAPHIC PATTERNS OF URBAN LIGHT POLLUTION AND FUTURE INTERVENTIONS

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Urban light pollution is an increasingly important environmental and public-health issue, yet its socio-demographic distribution within cities remains insufficiently explored. This paper presents an exploratory spatial comparison of nighttime illumination patterns and selected socio-demographic indicators in Győr, Hungary. The analysis draws on publicly available territorial statistics and mapped light-pollution data to examine whether areas with higher illumination intensity overlap with population groups that may be more vulnerable to nighttime environmental disturbance, particularly elderly and lower-income residents. Rather than testing causal relationships, the paper identifies indicative spatial patterns and evaluates the analytical potential of combining environmental and demographic datasets in urban research. The results suggest that the most intensely illuminated parts of the city are associated with the historical core, major transport corridors, and older high-density residential areas, which also show higher aging indices and less favourable income profiles. These findings point to a potential environmental inequality embedded in the city's socio-spatial structure. From a policy perspective, the paper argues that lighting strategies should incorporate socio-demographic considerations alongside efficiency and safety objectives in order to support more equitable and sustainable urban governance.

Keywords:
urban light pollution,
socio-demographics,
sustainable urban planning,
environmental justice,
spatial analysis

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1 Introduction

Cities play a central role in sustainability transitions, as they concentrate population, infrastructure, and resource consumption while also offering substantial potential for efficiency gains and environmental governance (Macher & Szigeti, 2025; Sipos et al., 2023). Consequently, integrating environmental considerations into urban planning and management has become a key objective of sustainable development strategies at local, national, and global scales (Macher & Beke, 2025; Magyar & Macher, 2023). Artificial light at night (ALAN) has become an integral component of contemporary urbanization, accompanying economic development, transport systems, and expanding service economies (Jiang et al., 2022). While urban illumination improves safety, mobility, and nighttime economic activity, its uncontrolled growth has also produced a distinct environmental externality in the form of urban light pollution (Bresson et al., 2023; Gaston & Sánchez de Miguel, 2022; Zielinska-Dabkowska et al., 2023).

Despite growing awareness of its ecological and health-related effects, the socio-spatial distribution of light pollution within cities remains comparatively underexplored (Gaston & Sánchez de Miguel, 2022; Zielinska-Dabkowska et al., 2023). In particular, fewer studies examine whether population groups with different socio-demographic characteristics are exposed to similar or unequal nighttime environmental conditions. This issue is especially relevant in urban areas where land use, transport infrastructure, service concentration, and housing-market dynamics shape both illumination patterns and residential structures.

This paper addresses that gap through an exploratory case study of Győr, Hungary. Rather than measuring causal effects, it asks whether publicly available territorial and illumination datasets reveal spatial overlaps between nighttime light intensity and selected indicators of potential social vulnerability, namely aging structure, population concentration, and income differences. Accordingly, the paper pursues three objectives:

1) to describe the intra-urban spatial pattern of nighttime illumination in Győr;
2) to compare this pattern with selected socio-demographic indicators; and
3) to discuss how such exploratory spatial evidence may inform more targeted urban lighting governance and future empirical research.

The remainder of the paper is structured as follows. Section 2 reviews the theoretical background on ALAN, environmental justice, and urban governance. Section 3 presents the methodology and data sources. Section 4 reports the empirical results, while Section 5 discusses their implications and limitations. Section 6 concludes.

2 Theoretical background

2.1 Artificial light at night as an urban sustainability challenge

Urban lighting reflects broader socio-economic processes, including mobility patterns, land-use intensity, and commercial concentration (Chang et al., 2025). From an environmental perspective, ALAN disrupts ecological cycles by altering species behaviour, migration patterns, and biodiversity composition. Landscape-scale analyses demonstrate that night lighting fragments habitats in ways comparable to transport infrastructure, creating barriers for nocturnal organisms (Challéat et al., 2021; Johnston et al., 2025; Sanders et al., 2020). Similarly, large-scale environmental assessments emphasize that nighttime illumination represents a cross-cutting pressure affecting terrestrial, freshwater, and urban ecosystems simultaneously (Gaston & Sánchez de Miguel, 2022). These findings position light pollution not merely as an aesthetic issue but as a structural ecological stressor (Hao et al., 2024).

In parallel, research increasingly identifies significant human health implications. Artificial nighttime exposure interferes with circadian rhythms by suppressing melatonin production, contributing to sleep disorders, metabolic disruption, and potentially elevated chronic disease risks (Moore-Ede et al., 2023). Epidemiological reviews link long-term nighttime illumination exposure to cardiovascular and psychological outcomes, especially among vulnerable populations (Jiménez et al., 2025; Zielinska-Dabkowska et al., 2023). Because sleep quality and biological rhythms are strongly tied to environmental conditions, urban lighting becomes a public-health concern rather than a purely infrastructural one (Bará & Falchi, 2023; Linares Arroyo et al., 2024).

2.2 Light pollution and environmental justice

Urban environmental hazards often follow patterns of environmental inequality, where disadvantaged communities experience disproportionate exposure to noise, air pollution, or heat stress (Nadybal et al., 2020). Recent studies suggest similar patterns for nighttime illumination: dense housing areas and lower-income neighbourhoods frequently experience higher luminance levels due to traffic corridors, commercial zoning, and infrastructural placement (Xiao et al., 2023). Such findings indicate that lighting infrastructure can unintentionally reproduce social inequalities within the urban environment (Tong et al., 2024). The environmental justice perspective therefore provides an important conceptual framework (Wilson et al., 2025).

Unequal exposure does not necessarily arise from intentional planning decisions but rather from the interaction of land-use zoning, market forces, and technological deployment (Eakin et al., 2022). Commercial districts tend to concentrate high-intensity lighting, while lower-income residential zones often border major transport routes or industrial areas (Silm et al., 2024). Consequently, socially vulnerable groups may experience disproportionate nighttime exposure. Urban environmental justice research increasingly calls for integrating demographic indicators into environmental assessments to identify these hidden inequalities (Helbich et al., 2024).

2.3 Governance and technological transition

Technological transitions further complicate the issue. The rapid adoption of LED lighting, often promoted as an energy-efficient sustainability solution, has paradoxically contributed to increased brightness due to rebound effects and higher blue-spectrum emissions (Schulte-Römer et al., 2019). While LEDs reduce energy consumption, their spectral composition enhances skyglow and biological impact unless carefully managed (Gaston et al., 2012). This demonstrates that sustainability interventions must consider environmental, social, and technological dimensions simultaneously.

In response, urban planning literature emphasizes smart lighting as a governance tool rather than a purely technical upgrade (Fazia et al., 2025; Munonye et al., 2025). Adaptive lighting systems can maintain safety while minimizing exposure. However, implementation requires coordination between municipalities, infrastructure operators, and communities, highlighting the importance of cross-sectoral governance (Jørgensen & Ma, 2025; Lewandowski et al., 2022). Without socio-spatial prioritization, technological solutions risk reinforcing existing inequalities rather than alleviating them (Giest, 2025; Moghayedi, 2025; Varzeshi et al., 2025).

The literature suggests that urban light pollution should be interpreted at the intersection of environmental sustainability, public health, and social equity. However, empirical studies still more often focus either on physical measurement or ecological impact, while fewer combine demographic variables with spatial urban analysis. This paper contributes to that gap through an exploratory, city-level comparison of socio-demographic and illumination patterns in Győr.

3 Methodology

This paper applies an exploratory and interpretative spatial research approach to assess whether existing publicly available datasets can support the identification of socio-spatial patterns of urban light pollution. The paper does not aim to estimate causal relationships, produce new remote-sensing measurements, or test statistical associations. Instead, it evaluates whether already available environmental and demographic data reveal plausible spatial overlaps that may justify more detailed future analysis. The empirical focus of the paper is the city of Győr, Hungary. The analysis is based on publicly available territorial statistics provided by the Hungarian National Spatial Development and Planning Information System (TEIR) (National Regional Development and Spatial Planning Information System, 2026). The database integrates census and administrative data and provides settlement-level and intra-urban indicators relevant for environmental and social assessment.

From this system, variables were selected that are theoretically linked to sensitivity to artificial light at night, including the aging index, permanent population distribution, and income-related indicators where available. These variables represent demographic vulnerability rather than environmental exposure itself, allowing the identification of groups that may experience different levels of impact under similar environmental conditions.

Environmental exposure is represented through an existing mapped source of nighttime illumination intensity. In this paper, the light-pollution map is used as a secondary visualized environmental dataset rather than as a newly processed remote-sensing product. Accordingly, the paper interprets relative spatial differences in illumination intensity in relation to the socio-demographic indicators. The analysis does not distinguish between public lighting, commercial lighting, transport-related lighting, or household-level emissions; instead, it examines the aggregated spatial pattern of nighttime illumination visible at the city scale.

The analysis therefore compares two independent but spatially interpretable data domains: socio-demographic indicators derived from TEIR and mapped nighttime illumination patterns derived from the selected light-pollution source. The aim is to assess whether their spatial distributions plausibly overlap in ways that may indicate uneven exposure conditions across the city. The analytical framework follows a qualitative comparison logic. Rather than testing statistical correlations, the paper examines whether areas characterized by higher illumination appear to correspond to locations with socially sensitive populations, such as a higher share of elderly residents, lower income levels, or higher residential concentration. These relationships are treated as indicative spatial patterns rather than measured effects, and they are interpreted as hypothesis-generating observations.

Accordingly, the results are not presented as causal evidence but as an assessment of the analytical potential of territorial data integration. The methodology demonstrates how environmental and demographic datasets can inform urban environmental governance even in the absence of advanced modelling. The approach highlights the role of publicly accessible spatial information in supporting early-stage planning discussions, identifying priority areas, and framing future research directions.

The paper also has clear limitations. First, it is a single-city exploratory case study and therefore does not support generalization to Hungary as a whole. Second, the analysis is descriptive and interpretative; it does not quantify exposure, health outcomes, or statistical significance. Third, the light-pollution source captures aggregated nighttime illumination patterns and does not allow the separate identification of specific light sources. The purpose of this preliminary step is therefore to support subsequent research phases involving spatial statistics, exposure modelling, and targeted intervention evaluation.

4 Results

4.1 Urban morphology and social zoning

The spatial datasets indicate that the city follows a layered urban structure typical of medium-sized Central European cities. A compact inner core of dense, closed urban fabric is surrounded by large housing estate areas, which transition into lower-density suburban neighbourhoods dominated by detached housing. Although this pattern initially appears purely morphological, the demographic indicators reveal that it simultaneously functions as a social zoning mechanism. The central districts concentrate permanent residents and everyday urban activity, while the outer zones function primarily as residential environments with a stronger daily commuting rhythm. This functional differentiation implies that environmental exposure in the city is shaped less by simple distance from the centre and more by the intensity of urban use. The city therefore operates not only as a density gradient but also as an activity gradient, which is particularly relevant when assessing nighttime environmental pressures (Figure 1.).

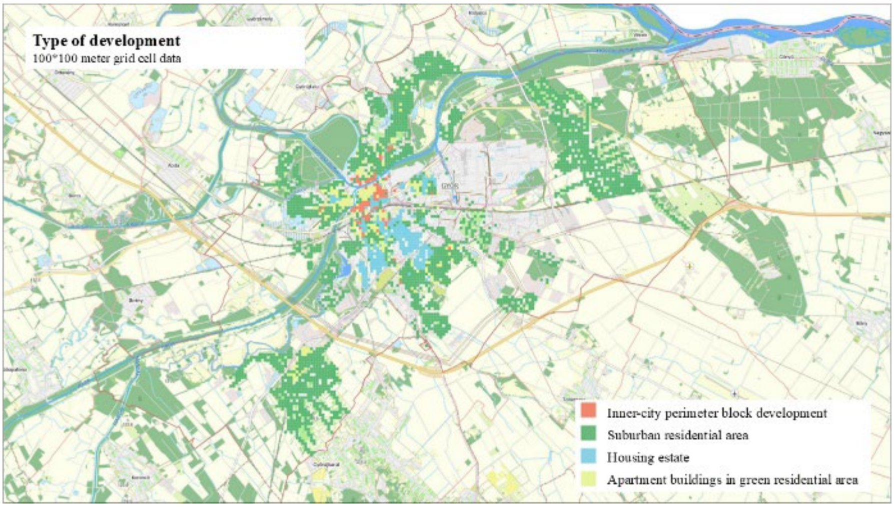

Figure 1: Type of development
Source: National Regional Development and Spatial Planning Information System, 2026

4.2 Aging index: concentration of sensitive populations

Among the examined variables, the aging index presents the clearest spatial structure. Higher proportions of elderly residents appear consistently in the inner city and in earlier-developed high-density residential areas. Peripheral family-house districts show considerably lower values, indicating a younger demographic profile. This distribution reflects long-term residential stability. Older residents tend to remain in accessible, service-rich neighbourhoods where healthcare, shops, and public transport are available within short distances. Younger households, particularly families with children, are more strongly represented in newly developed suburban environments. The spatial consequence is that population groups that may be more sensitive to nighttime environmental disturbance are concentrated in the most continuously active parts of the city (Figure 2).

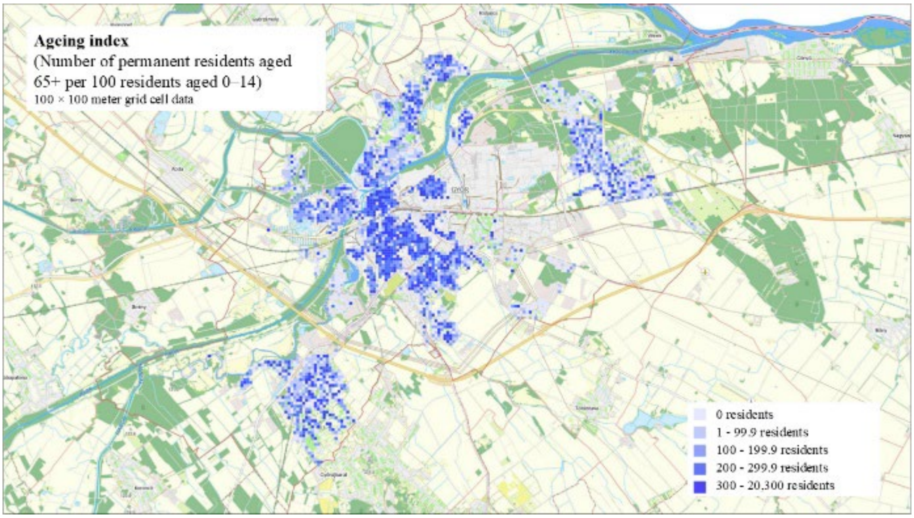

Figure 2: Ageing index
Source: National Regional Development and Spatial Planning Information System, 2026

4.3 Population density and activity intensity

The map of total permanent population shows a strong central concentration combined with secondary clusters along major transport axes (Figure 3).

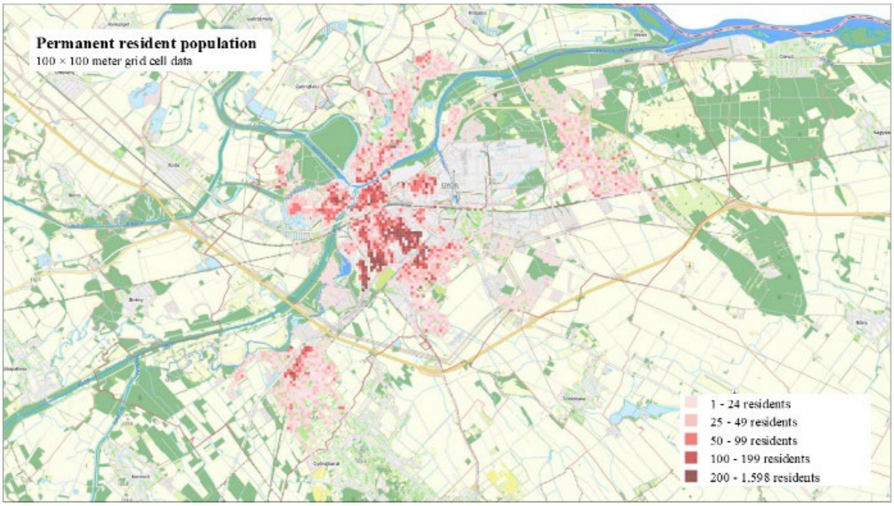

Figure 3: Population density
Source: National Regional Development and Spatial Planning Information System, 2026

Rather than forming a simple concentric decline, the pattern follows mobility infrastructure and service centres. This suggests that human presence is closely linked to accessibility and functional urban nodes. Such areas typically sustain activity beyond daytime hours due to commercial, transport and service functions. From an environmental perspective, the importance of this finding lies in distinguishing density from activity: areas with persistent human presence may also sustain nighttime functions associated with continuous urban operation and infrastructure use.

4.4 Age-group differentiation: children and elderly

The separation of younger (0–14 years) and older (63+ years) populations reveals a clear demographic inversion (Figure 4). Children are concentrated in suburban family-house neighbourhoods and newly developed residential areas, locations characterised by lower building height, reduced traffic intensity, and more regular daily cycles. In contrast, the elderly population overlaps strongly with the dense urban core and older housing estates. This spatial separation indicates that age groups experience fundamentally different urban environments. Younger populations inhabit areas designed primarily for residential use, while older residents remain embedded in multifunctional urban zones. The resulting pattern implies that exposure to continuous urban conditions is may not be evenly distributed across demographic groups.

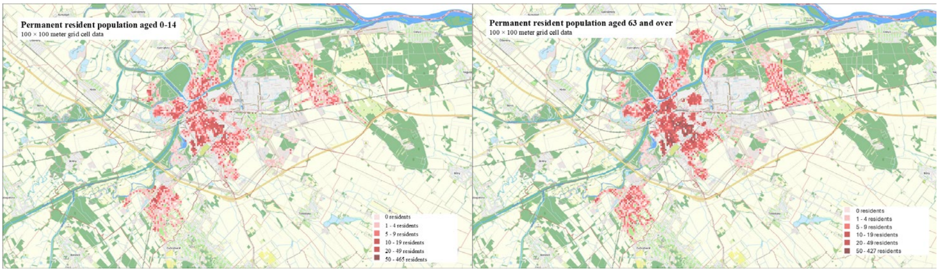

Figure 4: The separation of younger (0–14 years) and older (63+ years) populations
Source: National Regional Development and Spatial Planning Information System, 2026

4.5 Income structure and socio-economic differentiation

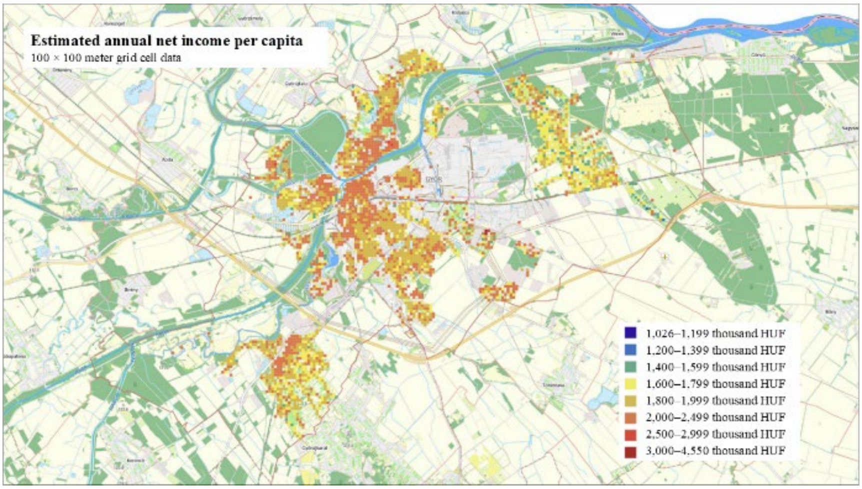

Figure 5: Income structure
Source: National Regional Development and Spatial Planning Information System, 2026

Estimated per-capita income further reinforces the socio-spatial differentiation. Higher income values are predominantly observed in suburban and garden-city areas, whereas central and earlier high-density residential districts show lower income levels. Consequently, accessibility to quieter residential environments appears to correlate with higher socio-economic status. The overlap between lower income and higher aging index in central zones suggests limited residential mobility for certain groups. Populations with fewer economic resources remain in locations shaped by historical development patterns and infrastructure concentration, while higher-income households relocate toward lower-intensity residential environments.

4.6 Emerging vulnerability pattern

Taken together, the datasets describe a coherent spatial configuration. Central accessibility zones concentrate elderly and lower-income residents, while peripheral residential zones concentrate younger and economically stronger households. The spatial structure therefore aligns demographic sensitivity with urban intensity. Even without statistical testing, the territorial indicators reveal a differentiated vulnerability landscape at the level of descriptive spatial interpretation. The city's social geography suggests that any environmental pressure associated with continuous urban operation is unlikely to be evenly distributed across the population. Instead, it is expected to follow the same structural logic embedded in the urban fabric.

4.7 Light as a field of urban activity

The light pollution map does not display a simple concentric "centre–periphery" pattern. The highest radiance appears in the historical and functional core, yet not as a single concentrated point but as an extended field of activity stretching along the main transport corridors in several directions. Around the central area an intensive illumination zone emerges, connected through the housing estate belt to major commercial and mobility nodes. This suggests that nighttime light exposure primarily follows functional intensity rather than population size. The spatial distribution is shaped by the city's nocturnal infrastructure, roads, services, parking areas and commercial functions. Consequently, the highest exposure does not occur simply where the largest residential populations are located, but rather where the city operates most continuously after dark.

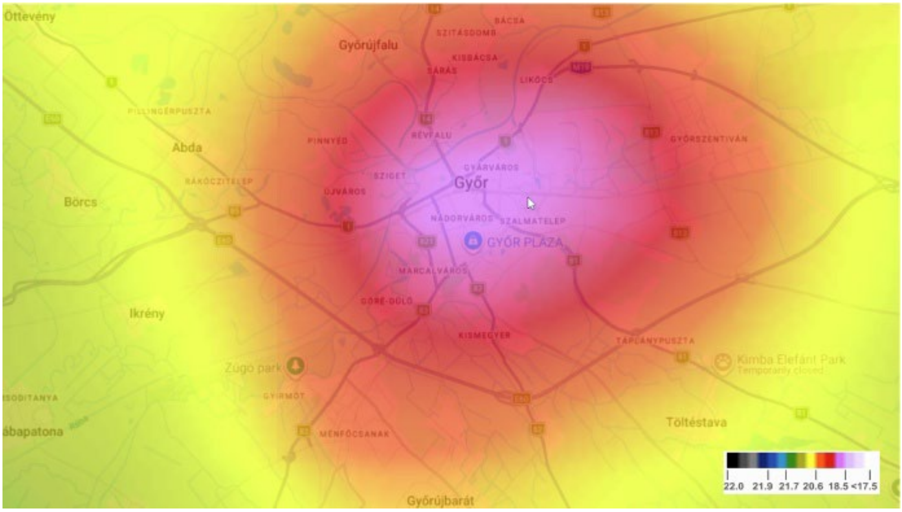

Figure 6: Light pollution in Győr
Source: https://www.lightpollutionmap.info

5 Discussion

When compared with the aging index, one of the clearest spatial relationships becomes visible. Areas with a high proportion of elderly residents largely overlap with the central high-intensity illumination field. The inner city and older housing-estate zones, which display the highest aging-index values, also appear among the brightest parts of the city. This overlap is relevant in light of previous studies suggesting that older populations may be more sensitive to circadian rhythm disturbance and may spend more time within their residential environment. On this basis, the findings do not demonstrate a measured health effect, but they do indicate a potentially relevant exposure configuration that warrants further investigation.

The spatial distribution of the 0–14 age group shows the opposite tendency. Households with children are predominantly concentrated in suburban and peripheral residential areas where illumination intensity appears lower. These neighbourhoods are primarily residential in function, with less nighttime activity and reduced traffic. This produces an inverse pattern: households with children are more frequently located in lower-exposure environments, while elderly populations remain concentrated in higher-intensity urban zones.

The income map adds another interpretative layer. Higher-income households are mainly located in peripheral residential belts, which also correspond to the lowest light exposure zones. The central and older high-density residential areas exhibit lower income levels while simultaneously representing the most illuminated urban environments. This configuration resembles a classic environmental inequality pattern in which higher environmental exposure is associated with fewer adaptive resources. Residential mobility therefore indirectly regulates access to lower-intensity nighttime environments. The maps suggest not only spatial correspondence but also a plausible structural mechanism. The historical development of the city has created a spatial structure in which:

- service-oriented zones remain continuously illuminated,
- these zones host stable, aging populations,
- newer and quieter residential environments are socially selective.

Light exposure therefore appears not as an isolated environmental factor but as a by-product of urban functioning that follows broader socio-spatial patterns. The analysis suggests that nighttime light exposure is unlikely to be evenly distributed across the population. Rather than random variation, the observed patterns point to a form of structurally differentiated exposure embedded in the urban fabric. Illumination intensity follows the logic of functional centrality, and because social groups are unevenly distributed within that structure, environmental burden may also become socially differentiated.

In this configuration, exposure is indirectly regulated by accessibility and housing market dynamics. Central areas, characterised by continuous services, transport infrastructure, and commercial activity, maintain higher levels of nighttime illumination. These same areas host a relatively stable population with higher average age and lower mobility. Peripheral residential zones, by contrast, offer calmer environmental conditions but require greater economic capacity and daily mobility, which selectively favours younger and higher-income households. Consequently, environmental conditions are not only spatially but also socio-economically stratified.

This pattern suggests that light pollution may operate as a form of secondary environmental inequality: it is not intentionally allocated, yet it may systematically affect groups with differing levels of vulnerability and adaptive capacity. The elderly population, which previous literature identifies as potentially more sensitive to circadian disruption, appears concentrated in the most persistently illuminated zones. Meanwhile, populations with greater residential choice and mobility are more frequently located in lower-exposure environments. The resulting configuration links demographic sensitivity, economic capacity, and spatial position.

From an urban governance perspective, this implies that lighting policies should not be evaluated solely through efficiency, safety, or energy considerations. Uniform technical standards may reproduce existing inequalities if they ignore demographic structure. Instead, nighttime lighting can be interpreted as a component of the urban welfare environment, similar to noise or air quality, where distribution matters alongside intensity. The findings therefore support the need for spatially differentiated lighting strategies that integrate demographic information into planning decisions.

At the same time, the present paper has clear limits. Because it relies on descriptive visual comparison within a single city, it cannot demonstrate causality, quantify the magnitude of exposure, or separate the effects of different light sources. These limitations should be addressed in future research through spatial statistics, source-specific lighting analysis, and health-relevant indicators.

6 Conclusions

This paper examined whether publicly available territorial datasets are sufficient to reveal potentially differentiated exposure to urban light pollution before more detailed quantitative modelling is undertaken. By interpreting socio-demographic indicators together with spatial illumination patterns in Győr, the analysis shows that descriptive spatial comparison can already generate relevant hypotheses for urban environmental research and planning. The results suggest that nighttime illumination in the city primarily follows functional urban structure rather than residential density alone. Areas characterized by continuous activity–especially the historical centre, transport corridors, and older high-density residential zones–exhibit the highest light intensity. These same areas also show higher aging indices and less favourable income profiles, while suburban residential zones with younger and economically stronger households correspond to lower illumination intensity.

Importantly, the observed pattern should not be interpreted as evidence of deliberate allocation, but rather as the outcome of historical urban development, housing-market dynamics, and infrastructure concentration. In this sense, light pollution appears as a secondary outcome of urban functioning that may reproduce broader socio-spatial patterns. From a planning perspective, the results imply that lighting policy should not be treated exclusively as a technical or energy-efficiency issue. Because illumination patterns appear to align with demographic vulnerability, uniform lighting standards may unintentionally reinforce unequal environmental conditions. Integrating demographic indicators into lighting management could therefore improve both environmental quality and social equity without compromising safety or functionality.

The paper makes three contributions. First, it demonstrates the analytical value of combining publicly available territorial data with mapped illumination patterns in an exploratory urban paper. Second, it identifies a plausible spatial overlap between nighttime illumination and socio-demographic vulnerability in Győr. Third, it outlines a planning-relevant framework for identifying priority areas for future intervention and measurement. At the same time, the paper remains limited by its descriptive design, its focus on a single city, and its inability to separate different sources of nighttime illumination or measure health effects directly. Future research should therefore build on this exploratory assessment through spatial statistics, exposure measurement, source-specific lighting analysis, health-related indicators, and the evaluation of targeted urban interventions.

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