www.gi.sanu.ac.rs, www.doiserbia.nb.rs
J. Geogr. Inst. Cvijic. 2022, 72(1), pp. 51–66

*Original scientific paper*

UDC: 911.3:312.8
https://doi.org/10.2298/IJGI2201051P



Received: October 7, 2022
Reviewed: February 28, 2022
Accepted: March 15, 2022

# NIGHTTIME LIGHTS—INNOVATIVE APPROACH FOR IDENTIFICATION OF TEMPORAL AND SPATIAL CHANGES IN POPULATION DISTRIBUTION

*Milena Panić[1]*, Marija Drobnjaković[1], Gorica Stanojević[1], Vlasta Kokotović Kanazir[1], Dejan Doljak[1]*

[1]Geographical Institute "Jovan Cvijić" SASA, Belgrade, Serbia; e-mails: m.panic@gi.sanu.ac.rs; m.drobnjakovic@gi.sanu.ac.rs; g.stanojevic@gi.sanu.ac.rs; v.kokotovic@gi.sanu.ac.rs; d.doljak@gi.sanu.ac.rs

**Abstract:** Nighttime lights represent the result of satellite observation of the artificial lighting of human activities on the Earth from space during the night, which provides the excellent opportunity to determine their position, pattern, density, and spatial distribution. Such data have a high detail spatial and temporal resolution, which opens a wide range of possibilities for quantitative and qualitative analysis. In this paper, nighttime lights are used as a highly accurate dataset for indirect tracking of changes in temporal and spatial patterns of population distribution and activity in Serbia. Two indicators were applied—Lighted area and Sum of lights. They are calculated for local government units in Serbia, for 2015 and period 2015–2019. The results of the conducted analysis follow the conclusions of the existing knowledge on population distribution based on the official statistical data. Areas with a high share of lighted areas are dominantly urban and the most populated, while traditionally depopulated areas are with a low share of lighted areas. Sum of lights highlighted the distinction between developed and populated north and depressive and depopulated south of Serbia. General conclusion is that "dark has fallen in Serbia", not only in peripheral and rural parts of the country, but in the smaller urban centers as well, and it is steadily spreading toward bigger urban areas. With nighttime lights application, this kind of process in terms of spatial disparities, its scope and dynamics can be easily identified, analyzed, and monitored.

**Keywords:** nighttime lights; spatial and temporal changes; population distribution; population activity; territory of Serbia

## 1. Introduction

Social phenomena, processes, and events are complex, changeable, diverse, dynamic, and multidimensional (Knežić, 2004) and require the application of a wide range of approaches and methods toward their identification, comprehension, and monitoring, as well as their spatial or temporal aspect, or both. Some of these approaches and methods are traditional, based on statistical data, which are evaluated as insufficiently accurate, so the need for the introduction of more innovative approaches arose (Bruederle & Hodler, 2018; Chen, 2020; Hall et al., 2019).

[1]*Corresponding author, e-mail: m.panic@gi.sanu.ac.rs

As an alternative tool for studying and tracking social processes and phenomena, remote sensing has been introduced, providing the possibility of using satellite-based indicators with high spatial resolution (e.g., from a few to several hundred meters) and time resolution (daily, monthly, and annual level).

Nighttime lights mean observing the artificial lighting of human activities on the Earth from space during the night, which provides an excellent opportunity to observe their position, pattern, density, and spatial distribution (Chen & Nordhaus, 2011; Levin & Duke, 2012). Such data open a wide range of possibilities for quantitative and qualitative analysis. Potential problems within nighttime light images is the level of their clarity due to different factors: blooming effects, atmospheric conditions, auroras, gas production, mining, warehouse hub expansion, and geometric errors, which can be fixed by filtering the obtained data. Additionally, some underestimation persists due to the time when the satellite images are collected—about or after local midnight when a certain decline in human activities exists (Dou et al., 2017).

Early recognition of nighttime lights within social science date back to the 1980s when they were used as an inventory of human settlements (Elvidge et al., 1997), after which their use was rare for a long period of time (Hall, 2010). However, the applications of nighttime lights have intensified as a popular proxy since the early 2000s, as a result of the availability, global coverage, and free access (Bruederle & Hodler, 2018; Bustos, 2015; Chen, 2020; Hall et al., 2019).

Accordingly, the nighttime lights data have been used nowadays in wide range of scientific disciplines related to: economic development (Chen & Nordhaus, 2011; Coetzee & Kleynhans, 2021; Doll et al., 2006; Elvidge et al., 1997; Ghosh et al., 2010; Henderson et al., 2011, 2012), population (Doll, 2010; Elvidge et al., 1997; Pozzi et al., 2003; Sutton et al., 2001; Sutton, 1997; Sutton et al., 1997), poverty (Doll & Pachauri, 2010; Elvidge et al., 2009; Noor et al., 2008), urbanization (Bruederle & Hodler, 2018; Bustos, 2015; Elvidge et al., 2012; Elvidge et al., 2007; Henderson et al., 2003; Imhoff et al., 1997; Ma, 2018; Small et al., 2005), urban transition (Saksena et al., 2014; Tan, 2015), natural disasters (Akiyama, 2012; Kohiyama et al., 2004; Zhao et al., 2020), etc. As Elvidge, Baugh, et al. (2017) summarized, if one phenomenon can be measured or studied successfully with nighttime light data, then it can be used for measuring other related phenomena as well.

The application of nighttime lights in demographic studies is somewise limited, focused mostly on the population estimation (Bustos & Hall, 2015; Elvidge et al., 1997; Lo, 2001; Sutton et al., 2001), population density (Sutton et al., 1997; Tan et al., 2018), migration flows (Chen, 2020), as well as on population and income (Levin & Duke, 2012). The use of nighttime lights data is present in estimating such variables in countries where traditional economic and demographic data are missing or they are not accurate enough (Akiyama, 2012; Bustos, 2015). Thanks to the time and space accuracy, nighttime lights can be used to predict population processes in small areas (Chen, 2020). Some scholars have analyzed the relation between population distribution and light intensity in different regions, showing a significant correlation (Anderson et al., 2010; Bagan & Yamagata, 2015), while others observed spatial matching of the demographic data by using light image data (Amaral et al., 2005; Sutton, 1997).

Also, there is a very high correlation between nighttime lights and economic development of some countries, regions, etc. Elvidge, Baugh, et al. (2017) explain that in highly developed countries (e.g., USA or Japan) the satellite-observed lighting is stable on an annual level or in longer time series, while in developing countries the situation is quite opposite—changes in population or GDP are dynamic and with growing tendencies, which can be clearly noticeable.

In Serbia, nighttime lights data as a tool do not have wider application in social sciences, geography and spatial planning, nor do all the benefits that accompany it. Regional study of settlement networks on the territory of Vojvodina region for 2010 was performed, which showed domination of large cities and their surroundings, as well as of the areas along the infrastructure corridors (Krunić, 2012). Further, another research for Serbia was conducted regarding seasonally activated rural areas in the period 2015–2019 using nighttime lights as complementary tool to statistical analysis, indicating the scope, intensity, spatial dispersion of the studied phenomenon, and recognition of tourist activity as its main driving factor (Drobnjaković et al., 2022).

On the other hand, some interesting results for Serbia arose in a few international studies, which used nighttime lights as a main research tool and explored scientific justification for its application and consistency of the obtained results. Elvidge, Hsu, et al. (2017) conducted a thorough research in the spatial patterns of lighting as a result of change in population and GDP growth over the period 1992–2012 (on the national level). Territorial extent of the study implied Southeast Europe countries, among which was Serbia, too. The results of the study showed steady lighting growth over the mentioned period, with the emphasis on a second decade, when almost all of the cities experienced urban lighting growth, as well as some rural areas in the central part of Serbia (Elvidge, Hsu, et al., 2017). Another study was performed by Bustos et al. (2015) which monitors population change in Europe in the period 1992–2012 (on the national level), including Serbia as well. The results of this study pointed to a strong division in population change between Western and Eastern Europe, and then thoroughly examined the differences between the countries. Serbia belongs to the group of countries characterized by population change (growth then decline) growth then  decline, characteristic for other Eastern Europe countries (Bustos et al., 2015), and the same tendency is identified in lighted area change as well.

In this paper, nighttime lights served as an innovative but highly accurate tool for tracking changes and spatial patterns of population distribution and activity on the territory of Serbia. The main goal was to identify or indicate where development is concentrated, i.e., where the population and economic activities are in Serbia and where the opposite situation is, not just in the one moment of time (e.g., 2015) but over a longer period (2015–2019). As Bustos (2015) argues, a significant opus of knowledge exists regarding the effectiveness of nighttime lights as proxies for economic and demographic data in specific moments of time, without consideration of the complete temporal extent of the data available. An analysis of nighttime lights over a long period of time indicates the processes that take place in space. Where the intensity of lighting radians is weak, spaces are gradually "dying out" and population and economic activity are decreasing.

## 2. Method and data

The nighttime lights data were used for the identification and survey of temporal and spatial variations of population concentration as well as economic activity in Serbia. For this purpose, VIIRS Nighttime Day/Night Band Composites Version 1 (Earth Observation Group, Payne Institute for Public Policy, Colorado School of Mines, 2012-present; Elvidge, et al., 2013; Elvidge, Baugh, et al., 2017) dataset was used to calculate (i) the share of the light area—LA (%) in the total area of settlement/municipality and (ii) the sum of lights—SOL (nW cm$^{-2}$ sr$^{-1}$) for settlement/municipality. The LA showed areas with increased concentration of the population, as well as areas of depopulation, while the SOL is used for the analysis of the overall activity indicating the population concentration and the level of the economic activity and development of settlements/municipalities in Serbia.

Temporal framework encompasses the calculation of both indicators for 2015 as the initial year. Afterwards it was expanded to the period 2015–2019 (annual average) in order to track their dynamics, while the spatial resolution was ≈500 m. Both indicators were calculated for the level of a municipality first, but for deeper insight, the process included the level of settlement which made the obtained picture clearer. The boundaries of the administrative units were retrieved from the Open Data National Spatial Data Infrastructure (NSDI) service (Republic Geodetic Authority, n.d.).

Spatial extent of the research for the territory of Serbia includes 174 municipalities. However, for the settlement level, the territory of Kosovo and Metohija was excluded from the analysis due to data unavailability (the territory is under United Nations Security Council Resolution, No. 1244/99).

Data preparation and calculation of indicators were performed in the QGIS (Version 3.16). Two datasets were prepared: (i) average annual values for 2015 and (ii) mean monthly values of nighttime lights for the period 2015–2019. Original data were filtered to exclude the influence of stray light, lightning, lunar illumination, and cloud-cover, while the data set for 2015 is further filtered to fires and other ephemeral lights and with a background (non-lights) set to zero (Elvidge, Baugh, et al., 2013, 2017). Preparation of monthly values dataset for the period 2015–2019 involved the removal of negative values and interpolation of excluded pixels applying the Nearest-neighbor interpolation method. Additionally, both sets were checked on outliers that had been removed from the analysis. In the case of the dataset for 2015, areas with radiance of 0 nW cm$^{-2}$ sr$^{-1}$ were considered as unpopulated, while for the dataset 2015–2019, this threshold was set for the radiance ≤1 nW cm$^{-2}$ sr$^{-1}$.

## 3. Results and discussion

The obtained results, as well as interpretation and additional explanations are divided into two segments. The first segment is related to the indicator Lighted Area and the second is related to the indicator Sum of Lights.

### *3.1. Lighted area*

The obtained results of this indicator enable an overview of the actual spatial distribution of the population, where the share of lighted areas indicates increased concentrations of the population, or depopulated areas. According to the share of lighted areas at municipality level, it is possible to observe population distribution. Based on the data for 2015 (Figure 1A), regional disparities are evident. High share of the lighted areas (more than 70%) is registered in 17 municipalities (8.6%). These municipalities mostly encompass big cities' territory (Belgrade and Niš). Only eight municipalities are identified with highly lighted areas (90%–100%), which represent city core municipalities. Besides the regional disparities and a certain generalization in the derivation of the indicator (in relation to size of the local territory), this indicator also shows a population distribution within a municipal territory. High values of the lighted areas indicate a more balanced distribution of the local population, while low values indicate a concentration of the population in smaller areas, usually urban settlements that are characterized by higher population and housing density. In this regard, the aforementioned municipalities in the regions of the cities of Belgrade and Niš are highly populated and have good and balanced population distribution.

On the other hand, municipalities with a small share of lighted areas are dominantly located in the south of the country (Figure 1A). In 13 municipalities (6.6%), lighted areas cover less than 10% of the municipal territory. These municipalities are located in mountain and border areas. This fact shows that these municipalities are less populated with pronounced population concentration in municipal centers. About 80% of the municipalities in Serbia with less than 50% of lighted areas recorded a similar trend—population shrinkage and polarization at the local level. Also, central regions are usually characterized with prosperous economic, social, and cultural features, opposite to the periphery regions (Shishmanova, 2010).

Highly pronounced disparities are obvious observing the five-year average share of the lighted areas at the municipality level (Figure 1B). The areas with the largest representation of lighted areas are: the City of Belgrade (Surčin, Grocka, Barajevo, and Lazarevac), Novi Sad, Niš, and some municipalities in Kosovo and Metohija (e.g. Kosovo Polje). The share of the lighted area in these municipalities reaches more than 80% of the territory. In accordance with these results, identified municipalities are the most populated (cities' territory) or characterized by even distribution of local population. According to the Census 2011 (Statistical Office of the Republic of Serbia, 2014), the City of Belgrade recorded a population increase of 5% (Zemun, Zvezdara, Rakovica, and Surčin). Although this is the only region in which population growth occurs, the greatest contribution to the positive growth rate is the positive rate of the migration balance (Đurđev & Arsenović, 2015). However, in the period 2011–2018, an increase of only 18,000 inhabitants was recorded which indicates stagnation in the number of inhabitants.

More balanced population distribution within the municipality and a moderate share of the lighted areas are noticed in Pomoravlje, Mačva, and Kosovo and Metohija. Further from the central axis (corridor) and big cities, lighted areas are decreasing (Figure 1B). One quarter of the municipalities (49) are within less than 10% of the lighted area. Some of them are traditionally depopulated areas (Crna Trava, Gadžin Han, Bosilegrad, Kuršumlija, etc.), while others are located in the border zone (Trgovište, Bela Palanka, Krupanj, Ljubovija, Priboj, Gora, etc.), and in mountain areas (Nova Varoš, Sjenica, Ivanjica, Kučevo, Žagubica, Majdanpek, Svrljig, Blace, etc). Uneven distribution of the population in these municipalities, particularly in favor of urban areas, is obvious (Lukić, 2011). Rural areas have been depopulated as a result of previously unregulated development (Drobnjaković, 2019). As Shishmanova (2010, p. 93) refers, "the center–periphery problem arises when the integration, harmony, and balance are seriously disturbed or entirely missing in such relationships as: administrative center–the rest of the settlements, town–village or urbanized–rural regions, town center–suburbs, etc." These areas are affected with aging and depopulation processes, which is most obvious in Zaječar and Pirot districts with aging index higher than 1.8 (Magdalenić & Galjak, 2016). Low values of the lighted areas reflect the existence of the pronounced poles of the population concentration as well.

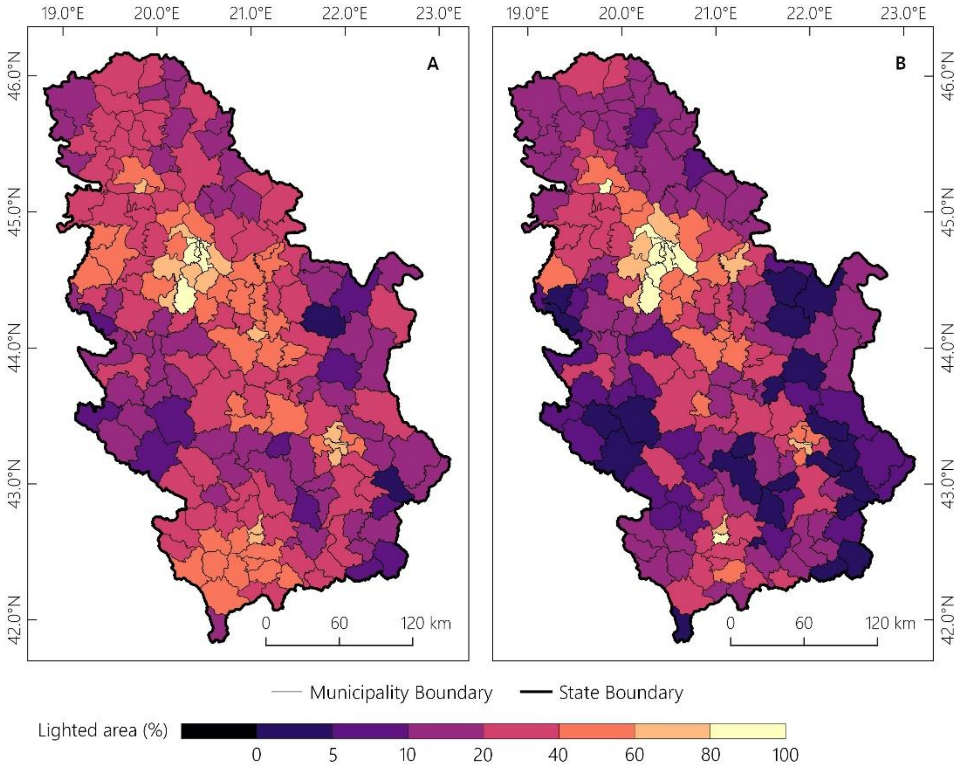


**Figure 1.** Lighted area at municipality level, 2015 (A) and Annual average of lighted area at the municipality level, 2015–2019 (B).

Observing the radiance of nighttime lights in Serbia at the micro level, it is obvious that the increased concentration of population is limited to the big cities' areas (Belgrade, Novi Sad, Niš, Priština, and regional centers) (Figure 3). Regarding regional perspective, the polarization is more emphasized in the southern regions of Serbia, while the lighting, as well as population distribution, is homogenized in Vojvodina region. Factors that lead to mention population distribution are various, related to the morphometry of the terrain, formation of the settlement, spatial organization, infrastructure, as well as some historical heritage (Drobnjaković et al., 2021; Gajić et al., 2018; Krunić, 2012). Furthermore, considering the spatial distribution of lighted areas in Figure 3 (spatial resolution ≈ 500 m), all the aforementioned factors and processes can be determined for areas independent of the official territorial organization (settlements, municipalities, etc.). Also, it can serve as a foundation for deriving new indicators regarding population distribution and activity. Concerning official population data in Serbia (e.g., Census), with decadal (or more) temporal dynamics of publishing, these data can help to better understand the spatial aspect and expression of the processes of interest.

According to the share of the lighted areas at a settlement level, about 9.45% of settlements (446) recorded more than 80% of settlements' territory (Figure 2). Urban settlements, municipal centers and peri-urban settlements dominated in this group of settlements, but some tourist centers, transit settlements, or industrial centers are embedded in this group as well. The nighttime lights are more intensive in these settlements, above 100 nW $cm^{-2}$ $sr^{-1}$ (Figure 3). That is especially related to peri-urban area of big cities, particularly to the City of Belgrade, which was, as Spalević (2013) explains, exposed to several phases of transformation in previous decades and today is characterized by continuous immigration process, functional transformation, unsupervised informal construction, conversion of agricultural land, and significant daily circulation of the population toward the city core. Once again, the results show that the level of urbanity is strongly related to the concentration of the population (Drobnjaković & Spalević, 2017).

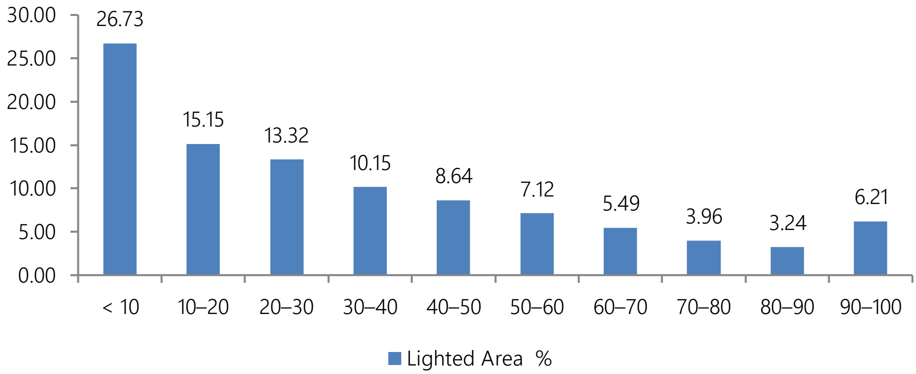


**Figure 2.** Share of settlements according to lighted areas (%), 2015.

Moderately lighted settlements, with a share of 50%–80%, cover 16.56% (782) of the total settlements in Serbia (Figure 2). They are characterized by a still substantial urbanity level and embedded in various settlement types—smaller municipal centers, local secondary developmental centers, or settlements with emphasized tourist and non-agricultural function (Drobnjaković, 2019).

On the other hand, a low intensity of nighttime lights dominates (Figure 3). Settlements with lighted areas less than 50% of territory counted for about 74% (3,493). Settlements with a low representation of lighted areas (26.73%, less than 10%), up to those in which they are almost not registered (13.4% have the value 0% and 20.31% have up to 5%), are most widespread in the peripheral and rural parts of the country. In that respect, the most affected settlements are in Southwest Serbia, in the contact zone with Kosovo and Metohija, Stara Planina Mt. area, the border area of Southeast Serbia, the Homolje Mt. area, Braničevo in Eastern Serbia, and Valjevo Mt. area in Western Serbia (Figure 3). Settlements with unfavorable natural characteristic, as well as with unfavorable age structure, are threatened by spontaneous abandonment (Penjišević, 2012), especially along the border and in the mountain areas (Babović et al., 2016; Milošević et al., 2010, 2011; Stamenković & Gatarić, 2006).

Similar tendency is noticed at the local level in the relation center–periphery of a municipality. Some of these settlements in the southern part of the country are traditionally depopulated (Drobnjaković, 2019; Ilić, 1989; Zdravković, 2016) and with the most unfavorable features regarding fertility rate, migration pattern, aging, and age population structure (Devedžić & Stojilković Gjatović 2015; Đurđev & Arsenović, 2015; Nikitović et al., 2015; Penev, 2005; Penjišević, 2012; Penjišević & Nikolić, 2011; Stojilković, 2011).

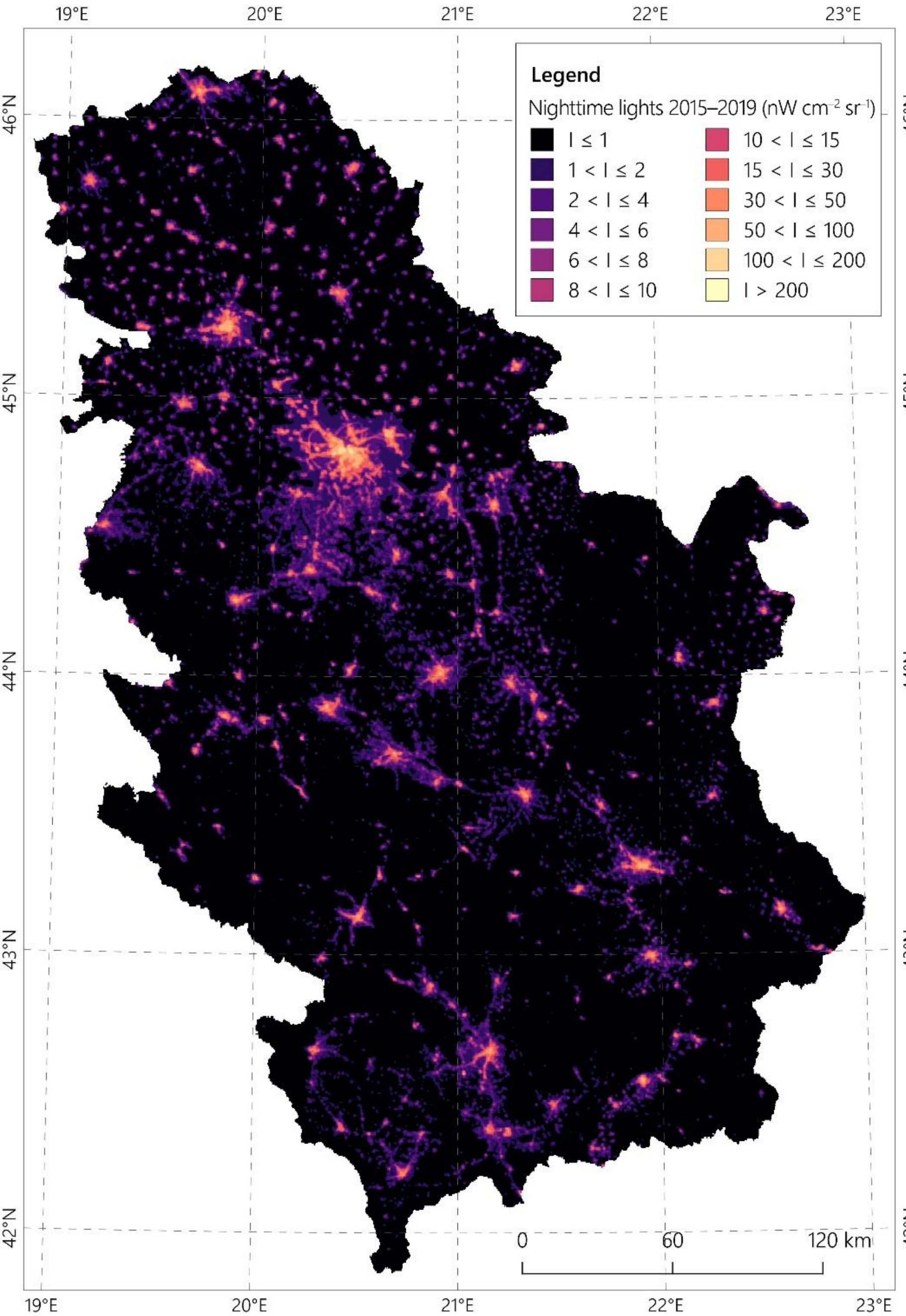


**Figure 3.** Nighttime lights, 2015–2019.

### *3.2. Sum of lights*

The second indicator—Sum of lights, shows the total radiance in an area, usually used to indicate population concentration and economic activity in an area. So, based on the intensity of the nighttime lights, spatial patterns have been identified (Figure 3). Observed in a longer period of time, this indicator highlights the directions of population and development expansion, as well as the abandoned and depressive areas.

According to the nighttime lights intensity in 2015 at the municipality level, the spatial units with the highest intensity were identified, as well as those in which the radiance is of the lowest intensity. A generalized image of Serbia is very heterogeneous according to this indicator. The highest light intensity according to data was identified in the City of Novi Sad, Pančevo, the municipalities of the City of Belgrade (Novi Beograd, Palilula, Zemun, Čukarica), Subotica, Kragujevac, and Kraljevo with more than 10,000 nW cm$^{-2}$ sr$^{-1}$ (Figure 4A). High nighttime light intensity (more than 5000 nW cm$^{-2}$ sr$^{-1}$) was recorded in 19 municipalities. Some of them are located in Belgrade region (Voždovac, Surčin, Lazarevac, Grocka, Zvezdara, Obrenovac), while the others are regional centers in different parts of Serbia (Valjevo, Čačak, Novi Pazar, Šabac, Sremska Mitrovica, Leskovac, Priština, Kruševac, and Zrenjanin). The concentration of population and activities identified in these municipalities are at the highest level in Serbia. The most populated municipalities are located in the City of Belgrade, which is generally ten times larger than the city Novi Sad (Drobnjaković & Spalević, 2017). Regional centers act as a pull factor in the previous internal migration movements (Nikitović et al., 2015). City' municipalities in Belgrade region have the highest net migration rate (Zvezdara 13.3, Voždovac 10.7, Surčin 8.9, and Palilula 8.8) (Statistical Office of the Republic of Serbia, 2020). Some of these municipalities represent unique vital parts of the country with rarely positive natural growth, like Novi Sad and Novi Pazar (Đurđev & Arsenović, 2015). On the other hand, the light intensity indicates activity concentration and indirectly a level of the development of the municipalities. The majority of the mentioned municipalities are strong economic and labor centers (Shishmanova, 2010; Drobnjaković et al., 2015) with achieved development level above the Republic's average (Uredba o utvrđivanju jedinstvene liste regiona i jedinica lokalne samouprave za 2014. godinu, 2014).

Municipalities with moderate intensity of nighttime lights are most representative with 52.79% (104). They are widespread all over the country (Figure 4A). However, in approximately 33% of all the municipalities, a low nighttime light intensity—below 1000 nW cm$^{-2}$ sr$^{-1}$—has been recorded. In this group, three municipalities recorded the lowest values, up to 100 nW cm$^{-2}$ sr$^{-1}$ (Novo Brdo, Crna Trava, and Žagubica). These municipalities are demographically endangered due to economic motivated migration abroad, continuous negative natural growth, and low fertility rate (Arsenović et al., 2018). There are 19 municipalities with low nighttime light intensity—100–500 nW cm$^{-2}$ sr$^{-1}$. This group embedded municipalities which are small by population size and with insignificant economic development (Ražanj, Ljubovija, Ćićevac, Žitorađa, Blace, Bojnik, Gadžin Han, etc.), border municipalities (Krupanj, Bosilegrad, Trgovište, Medveđa, Mali Zvornik, etc.), and some of them located in Kosovo and Metohija (Štrpce, Štimlje, Kosovska Kamenica). Their economic development does not attract a massive population, which reflects in insignificant radiance. In 21.83% of all the municipalities, a nighttime light intensity of 500–1000 nW cm$^{-2}$ sr$^{-1}$ was recorded. This group is characterized by unfavorable economic development (former industrial centers—Priboj, Majdanpek, Nova Varoš, Vladičin Han, etc.) and low centrality level (Lapovo, Malo Crniće, Titel, Čoka, Plandište, Osečina, Vladimirci, Sečanj, Mionica, Istok, etc.). They were faced with intensive emigration in the previous period or a development limited by big cities' influence (Kokotović Kanazir, 2016;

Lukić, 2011). For that reason, concentration of population and activities is low, as well as the identified radiance.

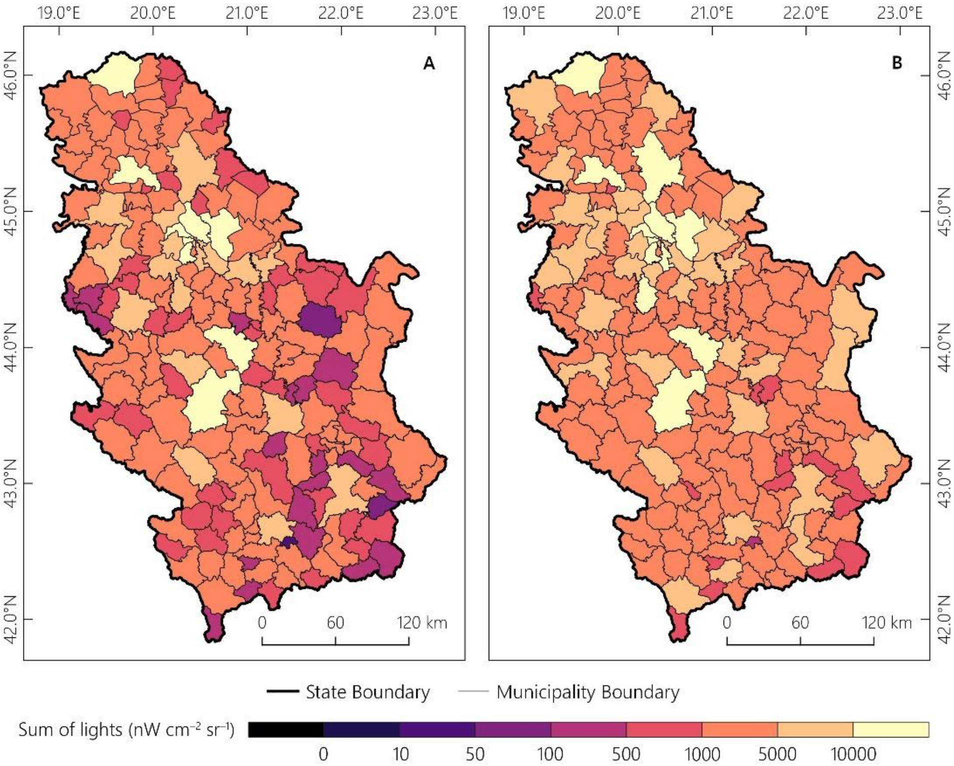


**Figure 4.** Sum of lights at the municipality level, 2015 (A) and Annual average of Sum of lights at the municipality level, 2015–2019 (B).

Annual average shows a more homogenized image of Serbia. Observed in a five-year period, the relation of developmental poles and less developed areas has been maintained, with a tendency to mitigate differences at the level of larger spatial units (Figure 4B). There is a somewhat increased intensity of light in significant regional centers (Užice, Čačak, Kraljevo, Kragujevac, Jagodina, Bor, Vranje, and Pirot) and in some economic transitional municipalities (Priboj, Nova Varoš, Kikinda, Zaječar, Negotin, Boljevac, Vršac, Kovin, Loznica, Sombor, etc.). It is obvious that the dispersion of population and activities is increasing and it is gradually shifting depopulation and economically depressed areas, which can lead to positive development transformations over a longer period of time.

The total radiance in the area of Serbia illustrates the clear difference between "developed north" and "undeveloped south" (Figure 3). In 77 settlements (1.63%) nighttime light intensity was more than 1000 nW cm$^{-2}$ sr$^{-1}$ (Figure 5). The strongest light intensity was registered in Belgrade and Novi Sad inner city areas and in Pančevo, with more than 10,000 nW cm$^{-2}$ sr$^{-1}$. In Subotica, Kragujevac, Čačak, Zrenjanin, and Kraljevo the light intensity was higher than 4000 nW cm$^{-2}$ sr$^{-1}$ and it was similar in some bigger regional centers (Smederevo, Valjevo, Požarevac, etc.), as well. In the south of the Peripannonian realm, the level of lighting decreases drastically, which indicates that the overall population and activity are concentrated around these two cities and labor centers, as well as several other regional centers (Niš, Kragujevac, Čačak, Kruševac, Priština, Leskovac, Novi Pazar, and Subotica).

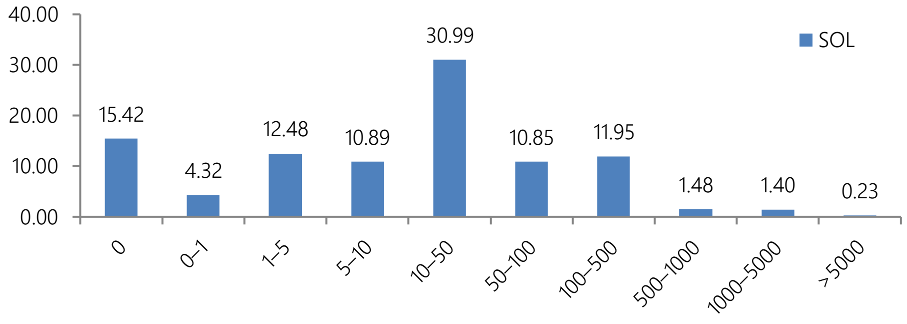


**Figure 5.** Share of settlements according to the intensity of nighttime lights (%), 2015.

In 84.94% of the recorded settlements' nighttime light, the intensity was up to 100 nW $cm^{-2}$ $sr^{-1}$ (Figure 5). The weakest radiance, up to 10 nW $cm^{-2}$ $sr^{-1}$, was recorded in 43.10% of settlements. The absence of radiance was noticed in 15.42% of settlements (728) and insignificant radiance in 4.32% (204). These 932 settlements are located at the very south of the country—on the border line with Kosovo and Metohija, along the southeastern and southwestern border line, and in the mountain area of the Valjevo mt., Stara planina, and the Homolje mt. Selected areas are dominantly faced with depopulation and low economic activity. Highly representative are the settlements with still low radiance, 10–50nW $cm^{-2}$ $sr^{-1}$, about 31% (Figure 5). Moderate nighttime light intensity, 100–1000 nW $cm^{-2}$ $sr^{-1}$, was recorded in 13.43% of settlements. Generally, the territory of Serbia emitted low nighttime light intensity, except in the highly urban areas and peri-urban fringe (Figure 3). The given image is a product of a very complex interrelation of various factors, such as terrain morphometry (Milošević et al., 2010, 2011), historical circumstances and settlement genesis (Drobnjaković & Spalević, 2017), uncontrolled processes of urbanization, industrialization, and deagrarization (Shishmanova, 2010; Spalević, 2013), etc.

## 4. Conclusion

This paper is focused on the new possibilities and innovative research approaches for the identification of spatial and temporal patterns and changes in population distribution. The authors used nighttime lights to "catch" the population distribution and its changes in the territory of Serbia in a clear and colorful way.

The results of the conducted analysis follow the conclusions of already existing knowledge and research results on population and activities based on official statistical data. This research justified a complementarity between traditional and alternative data with higher temporal and spatial sensitivity and accuracy. As it is shown, areas with a high share of lighted areas are dominantly urban and the most populated, which indicate a positive relation between lighting and urbanity. Observing the period 2015–2019, the polarization in population distribution was emphasized, which was indicated by the share of lighted areas in the municipalities. On the other hand, traditionally depopulated areas were confirmed once again with a low share of lighted areas. The nighttime light intensity pointed to the division on the developed and populated north and depressive and depopulated south of Serbia. Nighttime light data showed that "dark has fallen in Serbia". Low nighttime light intensity was detected in peripheral and rural parts of the country, as well as in smaller urban centers.

The additional contribution of this research, besides the results and conclusions mentioned above, is that the authors conducted the analysis at local or municipality level for the purpose of the review of population distribution and concentration. That is an important step toward better and more frequent use of this method, which has been generally used so far at the national or regional level. On the other hand, this research implicates the possibilities and advantages of the nighttime lights as an additional or alternative dataset for monitoring the population dynamics, which is complementary to traditional data sources but more temporally and spatially accurate.

The identified spatial and temporal patterns in population activity and distribution (Figure 1 and 4) validate the utilization of nighttime lights dataset in the population studies for the territory of Serbia. Besides, comparative use with the official statistics can bring new insight and can complete the existing resources for studying this issue. Nighttime light data (Figure 3) can fill potential gaps in data coverage from other sources and/or can be used for study areas defined according to special requirements. The annual average derived from monthly time series of nighttime lights implies their potential usage in studying more specified processes and phenomena with short-term dimensions. Limitations and shortcomings of nighttime lights are predominantly related to three research aspects. The first is the time coverage and short available time series (since 2012 VIIRS datasets are with higher resolution). The second is related to a certain level of noise in nighttime light data due to light contamination from various sources and/or capability of satellite sensors to capture individual sources of light, especially in low populated areas. The third limitation is hidden in the process of indicator derivation, which enhances a certain level of generalization for observing a phenomenon at a municipality level.

Additionally, these data can be used together with other georeferenced spatial layers (about physical and social environment) bringing new information in this research field. In this regard, the introduction of this tool in population studies offers a wide research insight into various phenomena and processes regarding population and human activities.

Extensive scholarly experience successfully confirmed the use of nighttime lights in various research fields, which contributed to methodological simplification for the verification of their use. The results of this research confirmed the assumption that nighttime lights could be used as an accurate and significant proxy for investigating population processes as well. The obtained results opened new research possibilities in the field of population distribution, dynamics, urban studies, spatial planning, etc.

**Acknowledgements**

This paper is a part of a research project "Remote detection of (de)population processes in Serbia", implemented with the financial support of the United Nations Development Programme (UNDP) in Serbia, United Nations Population Fund (UNFPA) and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

## References

Akiyama, Y. (2012, August 25–September 1). *Analysis of light intensity data by the DMSP/OLS satellite image using existing spatial data for monitoring human activity in Japan*. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Melbourne, Australia. https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/I-2/25/2012/isprsannals-I-2-25-2012.pdf

Amaral, S., Câmara, G., Miguel Vieira Monteiro, A., Alberto Quintanilha, J., & Elvidge, C. D. (2005). Estimating population and energy consumption in Brazilian Amazonia using DMSP night-time satellite data. *Computers, Environment and Urban Systems, 29*(2), 179–195. https://doi.org/10.1016/j.compenvurbsys.2003.09.004

Anderson, S. J., Tuttle, B. T., Powell, R. L., & Sutton, P. C. (2010). Characterizing relationships between population density and nighttime imagery for Denver, Colorado: Issues of scale and representation. *International Journal of Remote Sensing, 31*(21), 5733–5746. https://doi.org/10.1080/01431161.2010.496798

Arsenović, D., Nikitović, V., & Magdalenić, I. (2018). Spatial dimension of the second demographic transition in Serbia. *Zbornik Matice srpske za drustvene nauke, 167*, 499–514. https://doi.org/10.2298/ZMSDN1867499A

Babović, S., Lović Obradović, S., & Prigunova, I. (2016). Depopulation of Villages in Southeastern Serbia as Hindrance to Economic Development. *Journal of the Geographical Institute "Jovan Cvijić" SASA, 66*(1), 61–74. https://doi.org/10.2298/IJGI1601061B

Bagan, H., & Yamagata, Y. (2015). Analysis of urban growth and estimating population density using satellite images of nighttime lights and land-use and population data. *GIScience & Remote Sensing, 52*(6), 765–780. https://doi.org/10.1080/15481603.2015.1072400

Bustos, M. F. A. (2015). *Population, Demography and Nighttime Lights: An examination of the effects of population decline on settlement patterns in Europe* (CFE Working Papers series No. 53). Centre for European Studies at Lund University. https://www.cfe.lu.se/sites/cfe.lu.se/files/2020-12/cfewp53.pdf

Bustos, M. F. A., Hall, O., & Andersson, M. (2015). Nighttime lights and population changes in Europe 1992–2012. *Ambio, 44*, 653–665. https://doi.org/10.1007/s13280-015-0646-8

Bruederle, A., & Hodler, R. (2018). Nighttime lights as a proxy for human development at the local level. *PLoS ONE, 13*(9), Article e0202231. https://doi.org/10.1371/journal.pone.0202231

Chen, X. (2020). Nighttime Lights and Population Migration: Revisiting Classic Demographic perspectives with an Analysis of Recent European Data. *Remote Sensing, 12*(1), Article 169. https://doi.org/10.3390/rs12010169

Chen, X., & Nordhaus, W. D. (2011). Using luminosity data as a proxy for economic statistics. *Proceedings of the National Academy of Sciences, 108*(21), 8589–8594. https://doi.org/10.1073/pnas.1017031108

Coetzee, C., & Kleynhans E. (2021). Remote night-time light sensing: Investigation and econometric application. *Journal of Economic and Financial Sciences, 14*(1), 1–12. https://doi.org/10.4102/jef.v14i1.613

Devedžić, M., & Stojilković Gnjatović, J. (2015). *Demografski profil starog stanovništva Srbije* [Demographic profile of the old population of Serbia]. Statistical Office of the Republic of Serbia. https://publikacije.stat.gov.rs/G2015/Pdf/G20154007.pdf

Doll, C. N. H. (2010, August 9–13). *Population detection profiles of DMSP-OLS night-time imagery by regions of the world*. 30th Asia-Pacific Advanced Network Meeting. Hanoi, Vietnam. http://dx.doi.org/10.7125/APAN.30.22

Doll, C. N. H., Muller, J.-P., & Morley, J. G. (2006). Mapping regional economic activity from night-time light satellite imagery. *Ecological Economies, 57*(1), 75–92. https://doi.org/10.1016/j.ecolecon.2005.03.007

Doll, C. N. H., & Pachauri, S. (2010). Estimating rural population without access to electricity in developing countries through night-time light satellite imagery. *Energy Policy, 38*(10), 5661–5670. https://doi.org/10.1016/j.enpol.2010.05.014

Dou, Y., Liu, Z., He, C., & Yue, H. (2017). Urban Land Extraction Using VIIRS Nighttime Light Data: An Evaluation of the three Popular Methods. *Remote Sensing, 9*(2), Article 175. https://doi.org/10.3390/rs9020175

Drobnjaković, M. (2019). *Razvojna uloga ruralnih naselja centralne Srbije* [Development role of the rural settlements in Central Serbia]. Geographical Institute "Jovan Cvijić" SASA.

Drobnjaković, M., Panić, M., & Đorđević, J. (2015). Traditional undeveloped municipalities in Serbia as a result of regional inequality. *European Planning Studies, 24*(5), 926–949. https://doi.org/10.1080/09654313.2015.1129396

Drobnjaković, M., Panić, M., Stanojević, G., Doljak, D., & Kokotović Kanazir, V. (2022). Detection of the Seasonally Activated Rural Areas. *Sustainability, 14*(3), Article 1604. https://doi.org/10.3390/su14031604

Drobnjaković, M., & Spalević, A. (2017). Naselja Srbije [Settlements of Serbia]. In M. Radovanović (Ed.), *Geografija Srbije* [The geography of Serbia] (pp. 566–613). Geographical Institute "Jovan Cvijić" SASA.

Drobnjaković, M., Stojanović, Ž., & Josipović, S. (2021). Rural Areas and Rural Economy in Serbia. In E. Manić, V. Nikitović, & P. Djurović (Eds.), *Geography of Serbia. Nature, People, Economy* (pp. 289–305). Springer, Cham. https://doi.org/10.1007/978-3-030-74701-5_22

Đurđev, B., & Arsenović, D. (2015). Populaciona dinamika u međupopisnom periodu [Population dynamics in the inter-census period]. In V. Nikitović (Ed.), *Populacija Srbije početkom 21. veka* [Population of Serbia at the beginning of the 21st century] (pp. 41–60). Statistical Office of the Republic of Serbia.

Earth Observation Group, Payne Institute for Public Policy, Colorado School of Mines. (2012–present). *VIIRS Nighttime Day/Night Band Composites Version 1* [Dataset]. Retrieved from https://eogdata.mines.edu/products/vnl/

Elvidge, C. D., Baugh, K. E., Anderson, S. J., Sutton, P. C., & Ghosh, T. (2012). The Night Light Development Index (NLDI): A spatially explicit measure of human development from satellite data. *Social Geography, 7*(1), 23–35. https://doi.org/10.5194/SG-7-23-2012

Elvidge, C. D., Baugh, K. E., Kihn, E. A., Kroehl, H. W., Davis, E. R., & Davis, C. W. (1997). Relation between satellite observed visible near infrared emissions, population, economic activity and electric power consumption. *International Journal of Remote Sensing, 18(*6), 1373–1379. https://doi.org/10.1080/014311697218485

Elvidge, C. D., Baugh, K. E., Zhizhin, M., & Hsu, F. C. (2013). Why VIIRS data are superior to DMSP for mapping nighttime lights. *Proceedings of the Asia-Pacific Advanced Network, 35*, 62–69. http://dx.doi.org/10.7125/APAN.35.7

Elvidge, C. D., Baugh, K., Zhizhin, M., Hsu, F. C, & Ghosh, T. (2017). VIIRS night-time lights. *International Journal of Remote Sensing*, *38*(21), 5860–5879. https://doi.org/10.1080/01431161.2017.1342050

Elvidge, C. D., Hsu, F. C., Baugh, K. E., & Ghosh T. (2017). Lighting Tracks Transition in Eastern Europe. In G. Gutman & V. Radeloff (Eds.), *Land-Cover and Land-Use Changes in Eastern Europe after the Collapse of the Soviet Union in 1991* (pp. 35–57). Springer, Cham.

Elvidge, C. D., Safran, J., Tuttle, B., Sutton, P., Cinzano, P., Pettit, D., Arvesen, J., & Small, C. (2007). Potential for global mapping of development via a nightsat mission. *GeoJournal, 69*(1/2), 45–53. https://www.jstor.org/stable/41148175

Elvidge, C. D., Sutton, P. C., Tilottama, G., Tuttle, B. T., Baugh, K. E., Budhendra, B., & Bright, E. (2009). A global poverty map derived from satellite data. *Computers & Geosciences, 35*(8), 1652–1660. https://doi.org/10.1016/j.cageo.2009.01.009

Gajić, A., Krunić, N., & Protić, B. (2018). Towards a new methodological framework for the delimitation of rural and urban areas: a case study of Serbia. *Geografisk Tidsskrift-Danish Journal of Geography, 118*(2), 160–172. https://doi.org/10.1080/00167223.2018.1503551

Ghosh, T., Powell, L. R., Elvidge, C. D., Ebaugh, C., Sutton, P. C., & Anderson, S. (2010). Shedding Light on the Global Distribution of Economic Activity. *The Open Geography Journal, 3*, 148–161. https://www.ngdc.noaa.gov/eog/pubs/Ghosh_TOGEOGJ.pdf

Hall, O. (2010). Remote Sensing in Social Science Research. *The Open Remote Sensing Journal, 3*, 1–16. https://benthamopen.com/contents/pdf/TORMSJ/TORMSJ-3-1.pdf

Hall, O., Bustos, M. F. A., Olén, N. B., & Niedomysl, T. (2019). Population centroids of the world administrative units from nighttime lights 1992-2013. *Scientific Data, 6,* Article 235, 1–8. https://doi.org/10.1038/s41597-019-0250-z

Henderson, J. V., Storeygard, A., & Weil, D. N. (2011). A Bright Idea for Measuring Economic Growth. *American Economic Review, 101*(3), 194–199. https://doi.org/10.1257/aer.101.3.194

Henderson, J. V., Storeygard, A., & Weil, D. N. (2012). Measuring economic growth from outer space. *American Economic Review, 102*(2), 994–1028. https://doi.org/10.1257/aer.102.2.994

Henderson, M., Yeh, E. T., Gong, P., Elvidge, C., & Baugh, K. (2003). Validation of urban boundaries derived from global night-time satellite imagery. *International Journal of Remote Sensing, 24*(3), 595–609. https://doi.org/10.1080/01431160304982

Ilić, J. (1989). Teritorijalna rasprostranjenost i obim depopulacionog procesa u Jugoslaviji [Territorial distribution and scope of the depopulation process in Yugoslavia]. *Geografski godišnjak, 25*, 79–92.

Imhoff, M. L., Lawrence, W. T., Stutzer, D. C., & Elvidge, C. D. (1997). A technique for using composite DMSP/OLS "City Lights" satellite data to map urban area. *Remote Sensing of Environment, 61*(3), 361–370. https://doi.org/10.1016/S0034-4257(97)00046-1

Knežić, B. (2004). Od definicije do operacionalizacije, sa osvrtom na istraživanje nasilja [From definition to operationalization, with a focus on violence research]. *Temida, 1*, 45–50. http://www.doiserbia.nb.rs/img/doi/1450-6637/2004/1450-66370401045K.pdf

Kohiyama, M., Hayashi, H., Maki, N., Higashida, M., Kroehl, K. W., Elvidge, C. D., & Hobson, V. R. (2004). Early damage area estimation system using DMSP-OLS night-time imagery. *International Journal of Remote Sensing, 25*(11), 2015–2036. https://doi.org/10.1080/01431160310001595033

Kokotović Kanazir, V. (2016). *Mali gradovi - demografski potencijal Srbije* [Small cities - demographic potential of Serbia]. Geographical Institute "Jovan Cvijić" SASA.

Krunić, N. (2012). *Prostorno-funkcijski odnosi i veze u mreži naselja Vojvodine* [Spatial and functional relations and links in the network of settlements of Vojvodina] [Unpublished doctoral dissertation]. University of Belgrade, Faculty of Geography.

Levin, N., & Duke, Y. (2012). High spatial resolution night-time light images for demographic and socio-economic studies. *Remote Sensing of Environment, 119*, 1–10. https://doi.org/10.1016/j.rse.2011.12.005

Lukić, V. (2011). Demographic problems in Carpathian Region of the Serbia. *Journal of the Geographical Institute "Jovan Cvijić" SASA, 61*(2), 85–95. https://doi.org/10.2298/IJGI1102085L

Lo, C. P. (2001). Modeling the Population of China Using DMSP Operational Linescan System Nighttime Data. *Photogrammetric Engineering & Remote Sensing, 67*(9), 1037–1047. https://www.asprs.org/wp-content/uploads/pers/2001journal/september/2001_sep_1037–1047.pdf

Ma, T. (2018). Quantitative Response of Satellite-Derived Nighttime Lighting Signals to Anthropogenic Land-Use and Land-Cover Changes across China. *Remote Sensing, 10*(9), Article 1447. https://doi.org/10.3390/rs10091447

Magdalenić, I., & Galjak, M. (2016). Ageing map of the Balkan Peninsula. *Journal of the Geographical Institute "Jovan Cvijić" SASA, 66*(1), 75–89. https://doi.org/10.2298/IJGI1601075M

Milošević, M., Milivojević, M., & Ćalić, J. (2010). Spontaneously Abandoned Settlements in Serbia – Part 1. *Journal of the Geographical Institute "Jovan Cvijić" SASA, 60*(2), 39–57. https://doi.org/10.2298/IJGI1002039M

Milošević, M., Milivojević, M., & Ćalić, J. (2011). Spontaneously Abandoned Settlements in Serbia – Part 2. *Journal of the Geographical Institute "Jovan Cvijić" SASA, 61*(2), 26–35. https://doi.org/10.2298/IJGI1102025M

Nikitović, V., Predojević-Despić, J., & Marinković, I. (2015). *Migrantsko stanovništvo* [Migrant population]. In V. Nikitović (Ed.), *Populacija Srbije početkom 21. veka* [Population of Serbia at the beginning of the 21st century] (pp. 98–127). Statistical Office of the Republic of Serbia.

Noor, A. M., Alegana, V. A., Gething, P. W., Tatem, A. J., & Snow, R. S. (2008). Using remotely sensed night-time light as a proxy for poverty in Africa. *Population Health Metrics, 6*(5), 1–13. https://doi.org/10.1186/1478-7954-6-5

Penev, G. (2005). Srbija u prvoj polovini 21. veka - da li se mogu izbeći depopulacija i intenzivno demografsko starenje? [Serbia in the first half of the 21st century - can depopulation and intensive demographic aging be avoided?]. In S. Stamenković & M. Grčić (Eds.), *Zbornik radova sa naučnog skupa Srbija i savremeni procesi u Evropi i svetu* (pp. 359–371). Faculty of Geography, University of Belgrade.

Penjišević, I. (2012). The directions of regional development of Raška Municipality. *Journal of the Geographical Institute "Jovan Cvijić" SASA, 62*(2), 33–48. https://doi.org/10.2298/IJGI1202033P

Penjišević, I., & Nikolić, M. M. (2011). Changes in population dynamics of Raška region. *Journal of the Geographical Institute "Jovan Cvijić" SASA, 61*(3), 81–94. https://doi.org/10.2298/IJGI1103081P

Pozzi, F., Small, C., & Yetman, G. (2003). Modeling the Distribution of Human Population with Night-time Satellite Imagery and Gridded Population of the World. *World Observation Magazine, 12*(4), 24–30. http://www.ciesin.org/pdf/Pecora2002_Pozzi.pdf

QGIS (Version 3.16) [Computer software]. (2020). https://qgis.org/en/site/forusers/download.html

Republic Geodetic Authority. (n.d.). *Open data of National Spatial Data Infrastructure (NSDI)* [Data set]. Retrieved from https://geosrbija.rs/en/services-eng/open-data-of-nsdi-eng/

Saksena, S., Fox, J., Spencer, J., Castrence, M., DiGregorio, M., Epprecht, M., Sultana, N., Finucane, M., Nguyen, L., & Vien, T. D. (2014). Classifying and mapping the urban transition in Vietnam. *Applied Geography*, *50*, 80–89. http://dx.doi.org/10.1016/j.apgeog.2014.02.010

Shishmanova, M. (2010). Central and peripheral regions – a topical problem in regional policy. *Journal of the Geographical Institute "Jovan Cvijić" SASA*, *60*(1), 87–105. https://doi.org/10.2298/IJGI1001087S

Small, C., Pozzi, F., & Elvidge, C. D. (2005). Spatial analysis of global urban extent from DMSP-OLS night lights. *Remote Sensing of Environment*, *96*(3–4), 277–291. https://doi.org/10.1016/j.rse.2005.02.002

Spalević, A. (2013). *Transformacija periurbanog prostora Beograda* [Transformation of peri-urban area of Belgrade]. Geographical Institute "Jovan Cvijić" SASA.

Stamenković, S., & Gatarić, D. (2006). O antropogeografskim istraživanjima naselja jugoistočne Srbije [About anthropogeographic researches of settlements in South Eastern Serbia]. *Bulletin of the Serbian Geographical Society*, *86*(1), 85–96. https://gery.gef.bg.ac.rs/bitstream/handle/123456789/172/170.pdf?sequence=1&isAllowed=y

Statistical Office of the Republic of Serbia. (2014). *2011 Census of Population, Households and Dwellings in the Republic of Serbia: Book 20. Comparative overview of the number of population in 1948, 1953, 1961, 1971, 1981, 1991, 2002 and 2011 – Data by settlements*. https://publikacije.stat.gov.rs/G2014/Pdf/G20144008.pdf

Statistical Office of the Republic of Serbia. (2020). Demografska statistika [Demographic Statistics], https://www.stat.gov.rs/publikacije/publication/?p=13351

Stojilković, J. (2011). Growing number of pensioners and population aging in Serbia. *Journal of the Geographical Institute "Jovan Cvijić" SASA*, *61*(2), 69–84. https://doi.org/10.2298/IJGI1102069S

Sutton, P. (1997). Modeling population density with night-time satellite imagery and GIS. *Computers, Environment and Urban Systems*, *21*(3/4), 227–244. https://doi.org/10.1016/S0198-9715(97)01005-3

Sutton, P., Roberts, D., Elvidge, C. D., & Bauch, K. (2001). Census from Heaven: An estimate of the global human population using night-time light satellite imagery. *International Journal of Remote Sensing*, *22*(16), 3061–3076. https://doi.org/10.1080/01431160010007015

Sutton, P., Roberts, D., Elvidge, C. D., & Meij, H. (1997). A Comparison of Nighttime Satellite Imagery and Population Density for the Continental United States. *Photogrammetric Engineering & Remote Sensing*, *63*(11), 1303–1313. https://www.asprs.org/wp-content/uploads/pers/1997journal/nov/1997_nov_1303-1313.pdf

Tan, M. (2015). Urban Growth and Rural Transition in China Based on DMSP/OLS Nighttime Light Data. *Sustainability*, *7*(7), 8768–8781. https://doi.org/10.3390/su7078768

Tan, M., Li, X., Li, S., Xin, L., Wang, X., Li, Q., Li, Y., & Xiang, W. (2018). Modeling population density based on nighttime light images and land use data in China. *Applied Geography*, *90*, 239–247. https://doi.org/10.1016/j.apgeog.2017.12.012

Uredba o utvrđivanju jedinstvene liste regiona i jedinica lokalne samouprave za 2014. godinu [Decree on establishing a single list of regions and local government units for 2014]. Službeni glasnik Republike Srbije, No. 104 (2014). https://www.pravno-informacioni-sistem.rs/SlGlasnikPortal/eli/rep/sgrs/vlada/uredba/2014/104/1

Zdravković, G. (2016). Demografske promene stanovništva Srbije između dva popisa, 2002–2011. godine [Demographic changes in the population of Serbia between the two censuses, 2002–2011]. *Timočki medicinski glasnik*, *41*(4), 293–301. https://doi.org/10.5937/tmg1604293Z

Zhao, N., Liu, Y., Hsu, F.-C., Samson, E. L., Letu, H., Liang, D., & Cao, G. (2020). Time series analysis of VIIRS-DNB nighttime lights imagery for change detection in urban areas: A case study of devastation in Puerto Rico from hurricanes Irma and Maria. *Applied Geography*, *120*, Article 102222. https://doi.org/10.1016/j.apgeog.2020.102222