



ЗБОРНИК РАДОВА

ГЕОГРАФСКОГ ФАКУЛТЕТА УНИВЕРЗИТЕТА У БЕОГРАДУ

COLLECTION OF PAPERS

FACULTY OF GEOGRAPHY AT THE UNIVERSITY OF BELGRADE

Свеска
Vol. **LXXIV**
Београд - Belgrade, 2026.

ISSN 1450-7552
UDC 911

УНИВЕРЗИТЕТ У БЕОГРАДУ - ГЕОГРАФСКИ ФАКУЛТЕТ
UNIVERSITY OF BELGRADE - FACULTY OF GEOGRAPHY

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Publisher

University of Belgrade - Faculty of Geography, Studentski trg, 3/III, Belgrade
scindeks.ceon.rs/journalDetails.aspx?issn=1450-7552

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100

ISSN 1450-7552

eISSN 2334-9441

Printing was supported by Ministry of education, science and technological development of the Republic of Serbia

Printed by

Planeta print d.o.o, Beograd

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Original scientific article

Received: 29.07.2025;

Received in revised form: 28.01.2026;

Accepted: 03.02.2026;

Available online: 28.10.2026.

UDC: 314.87(497.16)

doi: 10.5937/zrgfub26005P

DEMOGRAPHIC CHANGES IN PLJEVLJA MUNICIPALITY

Sladana Popović¹

Abstract: Demographic changes are influenced by a variety of factors — economic, migratory, ecological, political, and others. While the global population continues to grow overall, certain regions are experiencing a decline. The process of depopulation is particularly evident across Southeastern, Eastern, and Central Europe, including Montenegro. Negative demographic trends are especially pronounced in the northern municipalities of Montenegro, with the municipality of Pljevlja standing out. This paper analyzes recent demographic changes in Pljevlja within the broader context of depopulation processes in Montenegro. The aim of the research is to identify key population trends based on data from the 2023 census, in comparison with previous censuses dating back to 1948. The study applies statistical analysis methods, calculating various demographic indicators (natural increase, migration balance, aging index, dependency ratios, vital index, etc.), along with spatial analysis using GIS tools. The results indicate a continuous population decline in Pljevlja, accompanied by negative natural growth, significant emigration, and an intensified aging process. Dramatic shifts in age structure have been observed, including a reduction in the number of young and working-age individuals, and an increase in the share of the elderly. The findings point to a long-term negative demographic trend in Pljevlja, manifested through a sustained population decrease, accelerated population aging, and pronounced outward migration.

Key words: Pljevlja, depopulation, demographic aging, migrations, negative natural population growth

Introductory considerations

Although the world's population is constantly increasing, certain regions are facing depopulation. European countries have proportionally several times smaller growth in military service than some other parts of the world (Proroković, 2017). International organizations warn that Europe is facing serious demographic problems, which are reflected in the depopulation of rural, peripheral areas, and small and

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medium-sized cities (Navarro-Galera et al., 2024). It is expected that the number of inhabitants on the European continent will decrease by 157 million (21%) by the year 2100. Between 1950 and 2007, Europe lost 20 million inhabitants living in rural areas. In 1950, the total share of the rural population was 45%, which decreased to 36% by 2007 (Pinilla & Sáeza, 2021).

There are various reasons why certain areas face depopulation. At the beginning of the 20th century, depopulation affected the mountainous, rural areas of the Mediterranean, such as Spain, Portugal, Italy and Greece. The primary causes of depopulation were agrarian overpopulation, emigration to the USA, etc. In the middle of the 20th century, depopulation became pronounced in the continental areas of Eastern and Southeastern Europe (Joksimović et al., 2023). The decrease in the absolute size of the population is connected with changes in its demographic composition as well as with the social, cultural and economic characteristics of the population. Depopulation has a negative impact on economic growth and productivity and social equality (in terms of age structure, gender, qualifications) (Newsham & Rowe, 2025; Pinilla & Sáeza, 2021).

Permanent depopulation of large areas is often considered an inevitable consequence of global processes, such as accelerated urbanization, mass migration, sectoral economic changes and crises that further aggravate the vulnerability of peripheral regions. The structural deterioration of these areas is accelerated by major shocks such as the world economic crisis, natural disasters and pandemics, because such events deepen territorial differences and accelerate the aging of the population (Lucchetti & Morettini, 2025). Solving the problem of depopulation requires a combination of different academic disciplines and areas of government based on complete knowledge of the facts and through a holistic, comprehensive and interdisciplinary approach (Pinilla & Sáeza, 2021).

Experiences from Spain show that depopulation cannot be viewed exclusively through the number of inhabitants, but through the broader framework of quality of life and territorial cohesion. Their strategies include economic diversification, encouraging innovation and digital connectivity, strengthening endogenous development based on local resources, as well as preserving cultural and natural values. A special emphasis was placed on support for families, youth and women, tax incentives to retain the population, improvement of infrastructure and basic public services, and the development of sustainable tourism and ecological transition (Sáeza & Pinilla, 2024).

Depopulation also affects the countries of Central Europe. On the example of Slovakia, it can be seen how larger cities record an increase in the number of inhabitants at the expense of smaller ones, which face depopulation, low natural growth and migration. Small mining towns especially face these problems. Cities

around the world are facing problems after the shutdown of the mining industry. Their efforts are mainly focused on economic diversification (especially the development of tourism and services), protection of cultural heritage, ecological revitalization and improvement of the quality of life of the remaining residents. In order to mitigate economic and social decline, local authorities are implementing new development policies: spatial planning, encouraging employment through retraining, supporting small businesses, investing in education and community initiatives. These approaches combine national regional policies with local initiatives and the search for new potentials, as well as the reuse of existing capacities in an innovative way. The experiences of former mining towns in Slovakia show that, although they have similar problems, development patterns can be different depending on geographical factors, proximity to larger urban centers and the ability of local governments to use available support instruments. In some cities, depopulation has been alleviated thanks to a combination of economic restructuring, ecological rehabilitation, preservation of cultural and technical heritage and active involvement of the local community in planning. The importance of governance at multiple levels (local, regional, national and EU) and decentralization, which enabled cities to develop their own policies adapted to local conditions, is particularly emphasized (Bleha & Buček, 2024).

Depopulation caused by migration and negative natural growth is also characteristic of countries that were once part of Yugoslavia. A significant percentage of the population left the newly formed countries. The reasons for emigration were mostly war, political and economic (Orlović & Kovačević, 2022). However, the roots of depopulation arose in the middle of the last century, when the population began to leave rural areas and move to cities, abandoning agricultural production and working in industrial enterprises (Despotović et al., 2015).

The decrease in the number of inhabitants and the depopulation of certain areas are one of the dominant demographic processes that affected the municipality of Pljevlja. In this regard, many other areas of Montenegro did not remain isolated either (Despotović et al., 2015). Uneven regional development also contributed to depopulation and underdevelopment of the economy in the northern parts of the country. Regional development as a whole, in the Yugoslav territories in general, including in Montenegro, has not been viewed as an integral part of the overall socio-economic development for several decades. This led to the uneven development of certain regions within the same country, which was reflected in the fact that problems of a different nature arose that had a negative effect on the overall development of certain cities, regions and, ultimately, the entire country. As a consequence of the branch approach, and not the regional-spatial approach in development policy, spontaneous deagrarianization and depopulation took place, which led to the deepening of regional and structural development problems.

Strategically important areas remained unpopulated, and on the other hand, there was an excessive concentration of population and economy in the developed centers. When it comes to the regionalization of Montenegro, it is most often divided into three large regions: Northern (Mountain), Central (Central) and Southern (Seaside) (Milanović et al., 2010). According to the latest indicators of development - GDP per capita, unemployment rate and poverty risk rate - all 13 municipalities of the Northern Region are below 90% of the national development average. The unemployment rate in the Northern region in 2021 was 37.3%, in the Central region 9%, while in the Southern region it was only 5.1%. In the same year, the highest poverty risk rate was recorded in the Mountain region (40.8%), while it was significantly lower in the Central region (14.7%) and the Primorje region (10.5%). When it comes to demographic changes, in the period from 1991 to 2020, the number of inhabitants of the Northern region decreased by almost 50,000, while in the Central region it increased by the same amount (Government of Montenegro, Ministry of Economic Development and Tourism, 2023). Many local self-government units, primarily those in the Mountain region (Žabljak, Šavnik, Plužine) have been affected by the process of depopulation. The combined effect of low fertility, disturbed age structure and emigration, especially of young people of reproductive age, led to the beginning of the extinction of many areas in Montenegro (Doderović and Ivanović, 2018).

According to the first organized population census, which was conducted in 1921, when Montenegro was part of the SHS Kingdom, 26,798 people lived in the Pljevlja County (Census, 1921). However, according to the last population census (2023), Pljevlja has 24,134 inhabitants. So, after more than a century, Pljevlja has fewer inhabitants.

The process of depopulation, similar to that in the mountainous, rural parts of European countries, was also observed in Pljevlja, which confirms that local demographic challenges have a wider scope.

The territory of the municipality of Pljevlja occupies the extreme north of Montenegro. It stretches between the mountain Kovač in the north, the mountains Ljubišnja, Lisca and the Tara canyon valley in the southwest and west. On the southern and eastern sides are the Bjelopolje region, i.e. Prijepolje and Priboj region (Minić and Popović, 1999). Tara, Ćehotina, Vezišnica and Breznica flow through Pljevlja (Jovanović et al., 2024). The importance of the geographical location of Pljevlja has changed throughout history. In the Roman period as well as during the Middle Ages, important trade routes passed through the Pljevlja region (Vasović et al., 2009). However, today Pljevlja occupies a peripheral position in relation to the main traffic and tourist routes of Montenegro. This position had a significant impact on the economic development of the municipality, regardless of significant natural potentials and mineral wealth, and caused specific demographic conditions,

especially at the end of the 20th and the beginning of the 21st century (Mijanović et al., 2023).

In addition to its peripheral location, which negatively affects the development of the municipality, Pljevlja also faces environmental problems. The air quality in the urban settlement of Pljevlja is characterized by frequent exceedances of permitted concentrations of PM10 particles, especially in the autumn and winter months when unfavorable meteorological conditions (temperature inversions, high atmospheric pressure and long-lasting fogs) contribute to the retention of pollutants in the basin (Mijanović et al., 2023). Annual mean concentrations of PM10 particles in Pljevlja are almost twice as high as those in other Montenegrin cities. In Pljevlja, Nikšić and Podgorica, the mean daily concentrations of PM10 particles are higher than 50 µg/m³ for 64-217 days per year, which is much more often than allowed by the EU Air Quality Directive (35 days per year) or recommended by the WHO AQ Guidelines for mean daily concentrations of PM10 particles (3 days per year) (Krzyzanowski, 2016). According to the available data, the number of foggy days has been increasing since the 1970s, which is associated with the construction of industrial facilities and the operation of the thermal power plant, while since 2009, air quality has been continuously monitored in accordance with European standards. Extreme air pollution ranks Pljevlja among the most polluted municipalities in Montenegro (and beyond), and expert services of health institutions have been warning for years about the increase in respiratory diseases, especially among children, where there is an increase in obstructive syndrome and asthma (Ministry of Sustainable Development and Tourism, 2013; Mijanović et al., 2023; Green home 2024). Although no comprehensive research has been conducted so far that would directly prove the correlation between pollution and depopulation, numerous studies confirm that poor air quality has negative consequences for people's health, which can indirectly affect the population's decision to move out. Therefore, in addition to environmental problems, Pljevlja is also facing pronounced demographic changes.

The experiences of other European countries, which managed to reduce the depopulation of certain areas to a certain extent, can serve local and state decision-makers in Montenegro to find a way of revitalization through a combination of state support, local initiatives and the valorization of existing resources, starting from the industrial base and natural potentials to cultural heritage, which can be the basis for new development strategies.

This paper presents an analysis of demographic changes in the municipality of Pljevlja, with special reference to the process of population aging, depopulation and their causes. It also aims to show the consequences of these processes on the economic and social development of the municipality. Through the analysis of data from the census, statistical and comparative analysis, and the use of GIS, the paper

presents the movement of the population and its distribution, the demographic age and migration flows are analyzed. In addition to the analysis of current demographic trends, the work provides insight into possible strategies for mitigating the negative effects of depopulation and encouraging regional development. The results of this research can serve as a basis for further analysis and adoption of strategies to mitigate negative demographic trends.

Material and methods

Pljevlja is located in the northern part of Montenegro, in the Northern (Mountain) region, on an area of 1,346 km². The municipality is the third largest municipality in Montenegro (after Nikšić and Podgorica) and consists of 159 settlements, one of which has the status of a city settlement. It is located in the peripheral, border area of the country and borders the Republic of Serbia (JLS Priboj and JLS Prijepolje) and the Federation of Bosnia and Herzegovina (JLS Foča and JLS Čajniče).

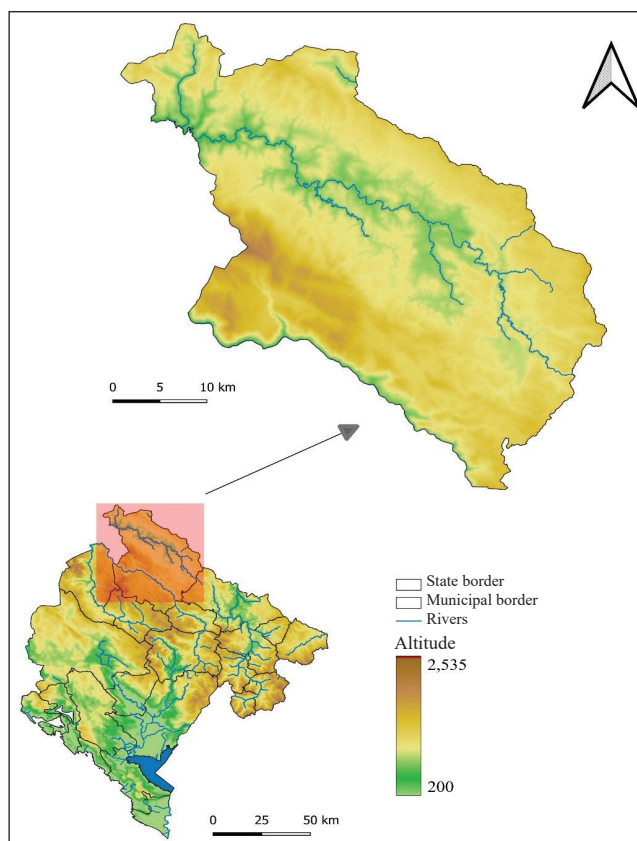


Figure 1. Physical-geographical map of Montenegro showing the municipality of Pljevlja (Source: author's processing based on a digital relief model (DEM))

For the purposes of this work, data from the census of population, apartments and households from 1948-2023 were used. year, as well as data on the natural and mechanical movement of the population, which are available on the website of the Administration for Statistics of Montenegro (MONSTAT). The time span from 1948 to 2023 includes all post-war censuses in Montenegro, which enables an overview of long-term demographic processes. Also, data on the number of households over a period of time were analyzed, as well as additional statistical indicators that more closely explain the demographic processes in Pljevlja. It should be borne in mind that statistical data from the census cannot fully show the internal connections between the population and the area, which must be determined by analyzing the area itself.

The methods of descriptive statistics and dynamic statistical analysis as well as comparative analysis were used in the analysis. Methods of calculating basic and chain indices, as well as the average annual population growth rate, were used to monitor demographic changes. Indicators such as the index of population change through the analyzed census cycles, the average size of households, the aging index, the aging coefficient, the average age of the population and the coefficient of total dependency of the population were processed. Diagrams were created for the graphic presentation of certain indicators (natural and mechanical movement of the population). Cartographic analysis was performed with the help of the QGIS software package. The years 1971 and 2023 were singled out for the cartographic display, because the first represents the middle of the post-war period when demographic changes were intense, while the second represents the latest census cycle, which enables comparison of long-term changes in the spatial distribution of the population. For the purposes of creating these maps, data on the number of inhabitants per settlement for 1971 and 2023, which are available on the website of the Statistics Authority (MONSTAT), were used. Based on the mentioned data, the author proceeded to calculate the population density, after which maps were created in QGIS. In addition to statistical and cartographic analysis, the paper also used a comparative approach when comparing certain data of the population of Pljevlja (natural and mechanical movement of the population, average household size, average population density) with other units of local self-government and at the level of the state itself. This paper aims to provide a clearer picture of the demographic processes in the municipality of Pljevlja through the integration of statistical and cartographic analysis and to indicate their causes and consequences.

Results and discussion

Trends in the number of inhabitants and households 1948-2023, index of population change and spatial distribution

The end of the 20th and the beginning of the 21st century were marked by political and socio-economic changes in Montenegro, which affected demographic trends (Katnić and Olandić, 2018). Events during the 1990s led to major changes in the country's economy, which largely affected demographic development. The closure and privatization of numerous companies, as well as the loss of jobs, resulted in the migration of residents (Mijanović et al., 2023). The biggest changes in the number of inhabitants in Montenegro occur in its Northern region. The municipalities of this region are recording a decrease in both the urban and rural population. This is a consequence of the fact that economic parameters and quality of life indicators in the Northern region lag behind those in the Central and Southern regions. People from rural parts of the country do not even go to their native urban units, but to other parts of Montenegro or even to other countries. The decrease in the number of inhabitants in northern Montenegrin municipalities is not only influenced by migration, but also by low or negative natural growth (Golubović et al., 2018).

The development of industry in Pljevlja began after World War II, during Yugoslavia. The first industrial company was founded in 1948 and it was the forest-industrial complex "Velemir Jakić" (Industrija, 2011). Soon after, in 1952, organized production of coal began, with the opening of a mine (Pljevlja Coal Mine, n.d.). The following year, the lead and zinc mine "Šuplja stijena" was opened. In 1975, a cement plant was opened as part of "Coal Mine", and in 1982, "TE Pljevlja" started operating. In addition to them, smaller companies "Elektrodistribucija", knitwear "Sloga", "Žitoprodukt" and others worked (Industrija, 2011). Until then, Pljevlja was one of the most underdeveloped municipalities in Montenegro. This city was engulfed by an intensive process of industrialization. Industrial development encouraged mass migration of the population from the rural parts of the municipality, which resulted in an increase in the number of inhabitants in the urban area. Regardless of the great industrial development, there were still large migrations outside the municipal borders, which the rates of natural increase could not compensate, so in the 1980s there was a greater decrease in the number of inhabitants (Mijanović et al., 2023). The depopulation of Pljevlja was primarily influenced by its border location, deagrarianization in terms of rapid industrial development, lack of quality infrastructure, economic opportunities, migration, etc. (Despotović et al., 2015).

According to the latest census, 24,134 inhabitants or 3.87% of the total population of Montenegro live in Pljevlja. Analyzing the data from the population census from 1948 to 2023, a constant increase can be observed from 1948 to 1971,

when Pljevlja experienced a peak in the number of inhabitants, after which a period of constant decrease began. During the mentioned period, the number of inhabitants increased from 35,926 to 46,843, which represents a growth of 30.4%. While population growth in the period 1948–1961 was primarily the result of high natural increase, subsequent growth up to 1971 was further fueled by industrialization and migration to urban areas. Pljevlja were part of a wider trend of demographic expansion that affected the whole of Yugoslavia during the period of recovery from the war and the revival of the country. The population census of 1981 recorded a decrease in the number of inhabitants for the first time. In the following inter-census periods, the number of inhabitants constantly decreased, and from 1971 to 2023 it decreased from 46,843 to 24,134, which is a percentage of 48.5%. So, in half a century, the number of inhabitants in the northernmost Montenegrin municipality has almost halved. These data clearly indicate the transition from the phase of growth to the phase of depopulation. A combination of factors, including the dissolution of the SFRY, industrial stagnation, job losses, declining birth rates, migration, environmental conditions, led to an intense population decline in Pljevlja.

Table 1. Comparative overview of the number of inhabitants of the municipality of Pljevlja, according to censuses (1948-2023)

year	1948	1953	1961	1971	1981	1991	2003	2011	2023
Pljevlja	35,926	40,876	46,677	46,843	43,316	39,593	36,913	30,764	24,134

Source: MONSTAT: Population Census 2003, Vol. 9; Population Census 2011; Population Census 2023

The population density in the municipality of Pljevlja, according to the 1971 census, was 34.8 people/km², while in 2023 it decreased to only 17.9 people/km². It is almost halved, which clearly indicates intensive processes of depopulation and emigration. Comparing population density maps from 1971 and 2023 clearly shows that population density has changed significantly in the past fifty years. The cartographic representation from 2023 indicates a significant spatial redistribution of the population on the territory of the municipality, with the highest concentration of residents in the urban settlement and its immediate vicinity. On the other hand, going from the center towards the peripheral parts of the municipality, the density drops sharply. These data confirm the pronounced depopulation of the rural areas of the municipality of Pljevlja, which is in accordance with the broader demographic analyzes presented in this paper. While in 1971 there were only two settlements in the municipality that belonged to the category of less than 5 people/km², by 2023 that number had grown to over fifty, which further confirms the degree of depopulation. In 1971, there was one settlement without permanent residents (Paljevina), as in 1981. According to the 1991 census, in addition to the settlement of Paljevina,

the settlement of Magžari also remained without residents. In 2011, the number of settlements without permanent residents increased to five (Klakorina, Magžari, Moćevići, Paljevina and Vukšići) and in 2023 to nine: Burići, Durutovići, Kotlajići, Moćevići, Magžari, Plakala, Tatarovina and Vukšići. In addition, in 2023, a “new” category appeared in the results of the census, “protected data”. Settlements with less than 10 inhabitants are included in the category of protected data and are marked with “z” in the census data, in accordance with the Law on Official Statistics and the System of Protection of Statistics, Article 54-61 (“Official Gazette of Montenegro”, No. 018/12 of 30 March 2012, 047/19 of 12 August 2019) (MONSTAT, 2024). Therefore, in 2023, 32 settlements with less than 10 inhabitants were registered in Pljevlja.

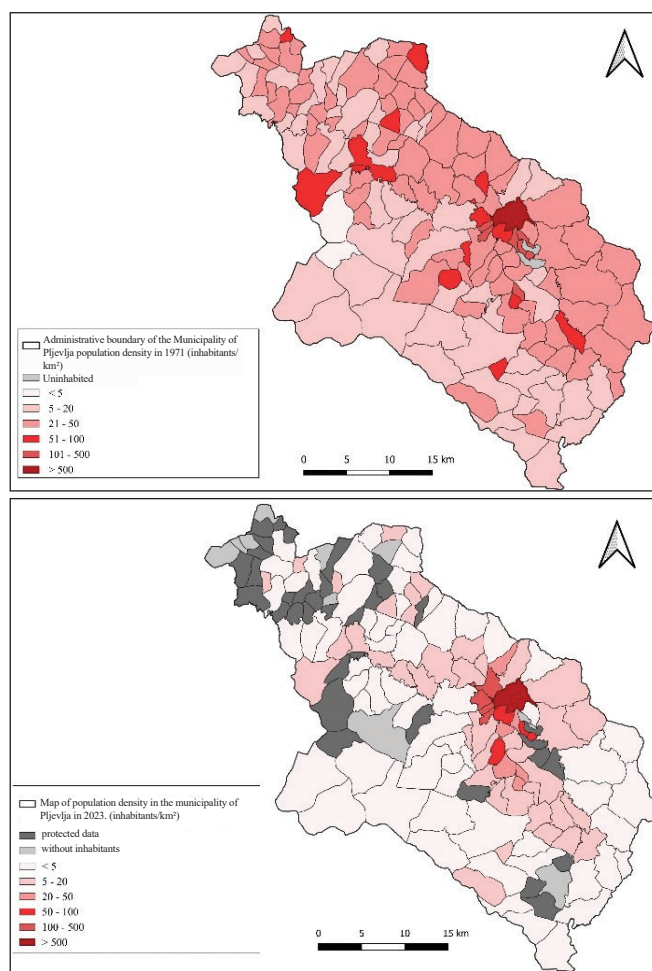


Figure 2. Map of population density in the municipality of Pljevlja in 1971 and 2023.
(Source: author's processing in the QGIS software package based on census data in 1971 and 2023)

Table 2. Population change index and average annual growth rate in the 1953-2023 period

year	1953.	1961.	1971.	1981.	1991.	2003.	2011.	2023.
Ip	113,8	114,2	100,4	92,5	91,4	93,2	83,3	78,5
Pavg	2.6%	1.7%	0.03%	-0.8%	-0.9%	-0.6%	-1.5%	-1.9%

Source: MONSTAT, edited by the author

Based on the index of change, it can be seen that the number of inhabitants of the municipality of Pljevlja, after increasing in the period from 1948 to 1961, began to gradually decrease in the following decades. The first decline was recorded between 1971 and 1981, and the negative trend intensified in later intercensal periods. The 21.5% drop in the period 2011–2023 is particularly worrying. year, which indicates a strong influence of migration and negative natural increase.

Data on the average annual growth rate (Psr, table 2) additionally confirm these trends. While positive growth was recorded in the first half of the 20th century, with a peak of 2.6% in the period 1953–1961, since 1971 the growth rate has stagnated, and since 1981 it has recorded a constant decline. Negative trends become more pronounced after 1991, and especially after 2011, when the rate of decline reaches -1.9% in the period 2011–2023. These data confirm the intense processes of depopulation, caused by the reduced birth rate, emigration and demographic aging of the population.

The structure and changes in households, as the basic units of society and economy, reflect key demographic processes, such as depopulation, migration and aging of the population, and represent an important segment of the overall analysis. Changes in the structure of households additionally reflect the demographic processes in the municipality.

Given that households represent the basic unit of society and the economy, their structures and changes over time may indicate deeper demographic and economic processes, including depopulation and emigration (Kaluderović, 2018).

The number of households increased from 6,843 to 9,136 or 33.51% from 1948 to 2023. From 1948 to 1991, the number of households was constantly increasing, when the largest number was recorded (11,431 households) and since then this trend has been slower, which is related to the decrease in the number of inhabitants. However, the 2003 census recorded a decline in the number of households, which continued in the next two censuses. In the period 2003-2023. the number of households decreased from 11,346 to 9,136, or 19.48%. Despite the overall growth in the number of households until 1991, the depopulation of Pljevlja after this period was also reflected in their number, which confirms the connection between demographic trends and socio-economic factors.

When urban and other, that is, rural households are compared, the conclusion is reached that from 1948 to 1981, rural households dominated. Since 1991, there are

more urban households in the municipality, which is connected with the decrease in the number of the population of rural areas and, therefore, the decrease in the number of households in the same.

Table 3. Comparative overview of the number of households in the municipality of Pljevlja, according to censuses (1948-2023)

year	1948	1953	1961	1971	1981	1991	2003	2011	2023
Pljevlja	6,843	7,641	9,109	9,980	10,550	11,431	11,346	10,627	9,136
city	1,673	1,976	2,886	3,876	4,902	6,076	6,696	6,401	5,981
other	5,170	5,665	6,223	6,104	56,648	5,355	4,650	4,226	3,155

Source: Population Census 2003; Vol. 10; Population Census 2011; TAB. DN1; Population Census 2023

In the observed period (1948-2023), the number of urban households increased from 1,673 to 5,981, which is an increase of as much as 257.5%. The growth in the number of urban households shows a clear trend of urbanization. The largest number of urban households was recorded in 1991 (6,076) and since then this number has stagnated and even decreased since 2003, which indicates negative demographic and economic changes. On the other hand, the number of rural households decreased from 5,170 (1948) to 3,155 (2023), which is a decrease of 38.9%. The decline in the number of rural households is associated with rural-urban migration and the economic decline and reduction in the rate of activity in rural areas.

Table 4. Average household size 1948-2023

year	1948	1953	1961	1971	1981	1991	2003	2011	2023
Ahs	5.3	5.4	5.2	4.7	4.1	3.5	3.3	2.9	2.6

Source: author's processing based on tables 1 and 3

The average household size in the municipality of Pljevlja indicates a trend of gradual reduction during the period from 1948 to 2023. At the beginning of the observed period (1948), the average household in the municipality of Pljevlja had 5.3 members, while that number decreased to 2.6 members by 2023.

According to research, Kaluđerović (2018) states that of all Montenegrin municipalities, the largest change in household size was recorded in Pljevlja. Apart from Pljevlja, other northern Montenegrin municipalities such as Žabljak, Plužine and Rožaje recorded a decrease in average household size by over 2 members during the observed period, while the coastal municipality of Tivat has the smallest decrease.

The analyzed trends show that there has been an increase in the number of households, but also a decrease in their size and structure. In other words, the number of single households and those with one family is increasing, which is in line with the trends that are present in the countries of Eastern and Southern Europe as well as in developed countries around the world (Kaluđerović, 2018).

The decrease in the average size of households in Pljevlja is in line with the broader European trends of demographic aging and individualization of households.

Natural increase and migrations for the period 2011-2023.

Changes in the number of inhabitants of the municipality are the result of both natural movements (birth rate and mortality) and migration flows, and a comprehensive analysis requires simultaneous consideration of these components over a longer period of time.

According to the data of the Administration for Statistics of Montenegro, a long-term trend of a decrease in the number of live births and an increase in the number of deaths in Pljevlja is noticeable. The number of deaths is significantly higher than the number of live births, which accelerates the decline of the population. Natural increase, in the intercensal period 2011-2023, is constantly negative, which confirms intensive depopulation processes. In the mentioned period, 2,480 people were born in the municipality, while 5,873 people died, which means that in twelve years the number of deaths was more than double the number of births. These indicators clearly confirm that the natural movement of the population has a decisive influence on the overall demographic trends of the municipality. The number of live births in that period varied between 155 (2023) and 225 (2014), while the number of deaths fluctuated, but on average was significantly higher, which indicates a continuous decline in the birth rate in Pljevlja. The most deaths occurred in 2021. This jump in mortality is largely related to the COVID-19 virus pandemic, but the trend of high mortality is present in other years as well.

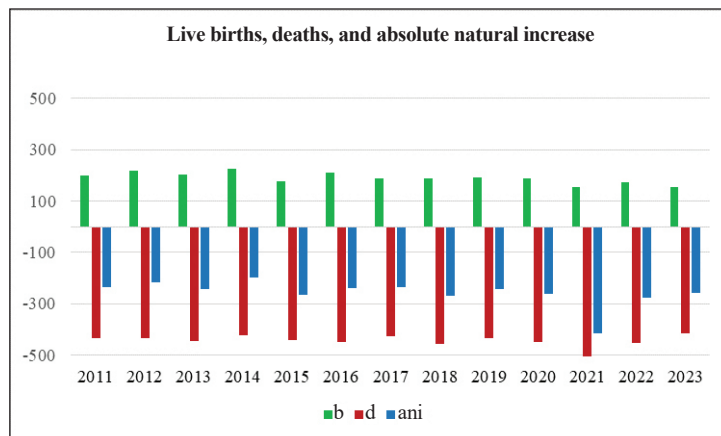


Figure 3. Trends in the number of live births and stillbirths and the absolute natural increase (2011-2023) (Source: MONSTAT, edited by the author)

Apart from the pandemic, one of the factors of high mortality in Pljevlja can be environmental pollution, which this city has been dealing with for decades, and which can negatively affect the health of the population. Calculations show that something close to 6% of all deaths caused by natural means in Podgorica, 12% of such deaths in Nikšić and 22% in Pljevlja can be attributed to air pollution that exceeds the WHO AQG values (Krzyzanowski, 2016). Such trends influenced the fact that in the observed period, the absolute natural increase in Pljevlja was negative for every year, with the worst situation occurring in 2021 (app=-417).

In 2011, the birth rate in Pljevlja was 6.53‰, while the mortality rate was 14.14‰, which resulted in a negative rate of natural increase of -7.60‰. In 2023, the situation further worsened - the birth rate fell to 6.42‰, while the mortality rate rose to 17.15‰, which led to a pronounced negative natural increase of -10.73‰. Such values indicate that there is no simple population reproduction in Pljevlja, which accelerates the depopulation process in the long term. Such demographic trends indicate an accelerated decrease in the number of inhabitants in the northernmost Montenegrin municipality. Vital index values confirm existing trends. A low vital index indicates that the number of deaths is greater than the number of births, which indicates a negative natural increase and the process of depopulation. The vital index in 2011 was 46.21 and will drop to 37.44 in 2023.

The level of natural increase in Montenegro has been low in recent years and its constant decline indicates that there is no simple reproduction, and the population is decreasing. The largest decline in live births was recorded in the Northern region and the smallest in the Southern region. On the other hand, all three regions recorded an increase in the mortality rate, with the municipalities in the north having the highest mortality (Katnić, 2018).

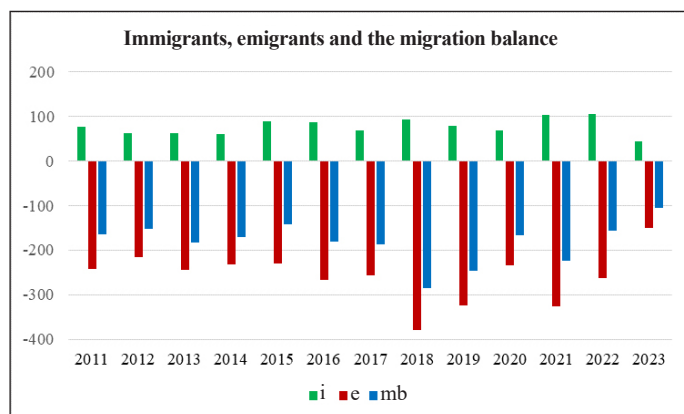


Figure 4. Trends in the number of immigrants and emigrants and the migration balance (2011-2023) (Source: Statistical Office, Department of Demographic Statistics and Population Census, edited by the author)

Another important aspect that contributes to the depopulation in Pljevlja is migration or the mechanical movement of the population.

The last century can be characterized as a century of intensive population emigration from the territory of Montenegro, conditioned by economic, natural and political factors (Katnić and Orlandić, 2018). These factors worked in the area of the municipality of Pljevlja, where many villages were left without inhabitants for decades precisely because of pronounced emigration in search of better living conditions. The departure of the young and able-bodied population from this municipality continued at the end of the 21st century, as a result of which the migration balance of Pljevlja has been consistently negative for several decades.

Analyzing the annual data published by MONSTAT, Pljevlja is in a pronounced phase of depopulation. In the past twelve years, the municipality recorded a constant negative migration balance. In the last inter-census period, 1,002 residents immigrated while 3,365 moved out at the same time, which means that between the two censuses, Pljevlja lost 2,363 residents through emigration. The combination of negative natural growth and constant emigration further accelerates depopulation processes and confirms that the municipality is facing multiple demographic pressures. The highest intensity of emigration was during 2018 (285) and 2019 (247). During 2020, the pandemic slowed down that process (166), but it intensified again in 2021, when 223 inhabitants left Pljevlja.

The results obtained from the previous analysis indicate that the municipality is losing its population both through natural and mechanical movement. For a better understanding of these processes, an analysis was also made of the general movement of the population. The general movement of the population represents the ratio of natural population change and migration in a certain period. Based on the migration balance, it is determined whether a place has emigration or immigration characteristics. They distinguish two types, emigration and immigration. Further, the emigration type is divided into four subtypes: emigration, depopulation, marked depopulation and extinction. Also, the immigration type has its four subtypes: increase by immigration, renewal by immigration, weak renewal by immigration and very weak renewal by immigration (Nejašmić, 2005). Based on the data from 2023, about the number of births, deaths, emigrations and immigrants, it was found that the general movement of the population is -15.08, which means that the territory of the Pljeval municipality belongs to the emigration type E4 with a trend of extinction. This classification confirms that Pljevlja shares characteristics with numerous rural and peripheral areas of Europe, where depopulation develops to the level of extinction of smaller settlements.

Demographic age of the population

The age structure of the population is one of the most important population structures for the population development process and for socio-economic implications. The age structure of the population has key demographic and socio-economic implications, as it affects the education system, labor market and health care (Katnić and Olandić, 2018).

The age structure of the population of Pljevlja is represented by age pyramids. Figure 4 shows the age pyramids for 2003 and 2023. Comparing these two pyramids, drastic changes in the number of inhabitants of certain age groups can be observed in the past twenty years. The age pyramid for 2003 is stationary but takes on the characteristics of a regressive type, while the pyramid for 2023 is of a regressive type, with a much narrower base than the one in 2003. The regressive shape of the pyramid indicates a decrease in the number of young and able-bodied population, which may have an impact on economic and social conditions in this city. These indicators clearly indicate a transition from a stationary to a regressive structure, which confirms the long-term aging trend. There is a large decrease in the number of the young population, in the category up to 30 years of age, and on the other hand, there is an increase in the share of the elderly population in the total population of the municipality. This further indicates that the northernmost Montenegrin municipality is in the process of deep aging of the population, which, among other things, fits with other parameters, i.e. with low rates of birth and natural increase and a negative migration balance.

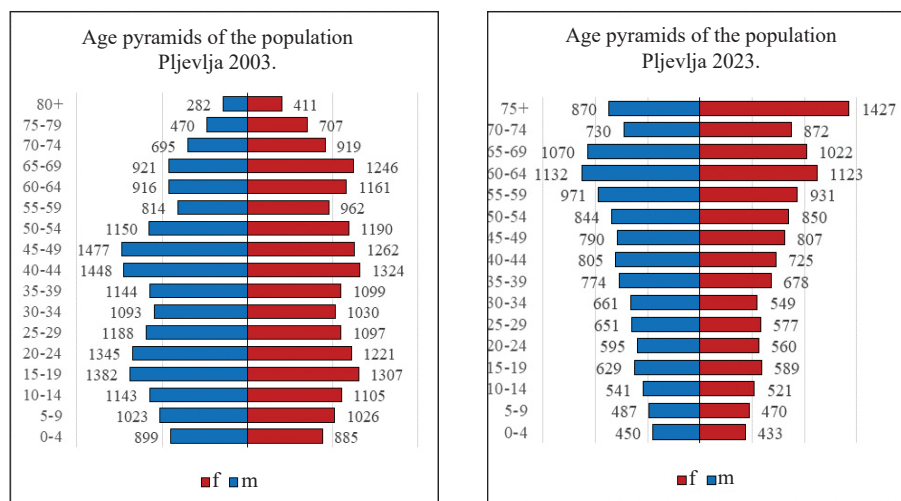


Figure 5. Age pyramids of the population of the municipality of Pljevlja for 2003 and 2023 (Source: MONSTAT - Population Census 2003, Vol. 2; Population Census 2023; author's work)

On the other hand, comparing the age pyramids for Pljevlja and Montenegro from the last census (2023), it is concluded that, although the country records a decrease in the number of young people, in Pljevlja this decline is much more pronounced. The base of the age pyramid for Montenegro is wider, which indicates that Pljevlja has a more pronounced decline in birth rates. This indicates that the majority of the young population is at the state level, which further implies that the decline in birth rates and migration are more pronounced in Pljevlja. In addition, Pljevlja has a larger proportion of elderly population, which indicates an intensive process of population aging. The number of elderly people in Montenegro is certainly high, but it is not as pronounced as in Pljevlja. When it comes to the working-age population, Pljevlja is also experiencing a decline, and if this trend continues, it will have greater pressure on the economy. Seen as a whole, the negative demographic trends in Pljevlja are more pronounced than at the state level.

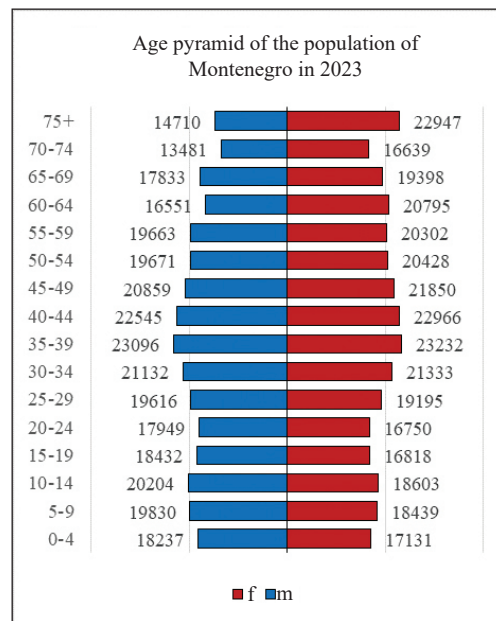


Figure 6. Age pyramid of the population of Montenegro in 2023
(Source: MONSTAT - Population Census 2023; author's work)

Whether a population has entered the aging process is determined based on the analysis of a number of indicators: aging index, average age, old-age dependency ratio, proportion of young, old and working population (Katnić and Olandić, 2018). The process of demographic aging has affected many countries of the world (Brajušković et al., 2018). In the analysis of the aging of the population of Pljevlja,

the aging index, the average age of the population, the coefficient of age and the coefficient of total dependency of the population were used.

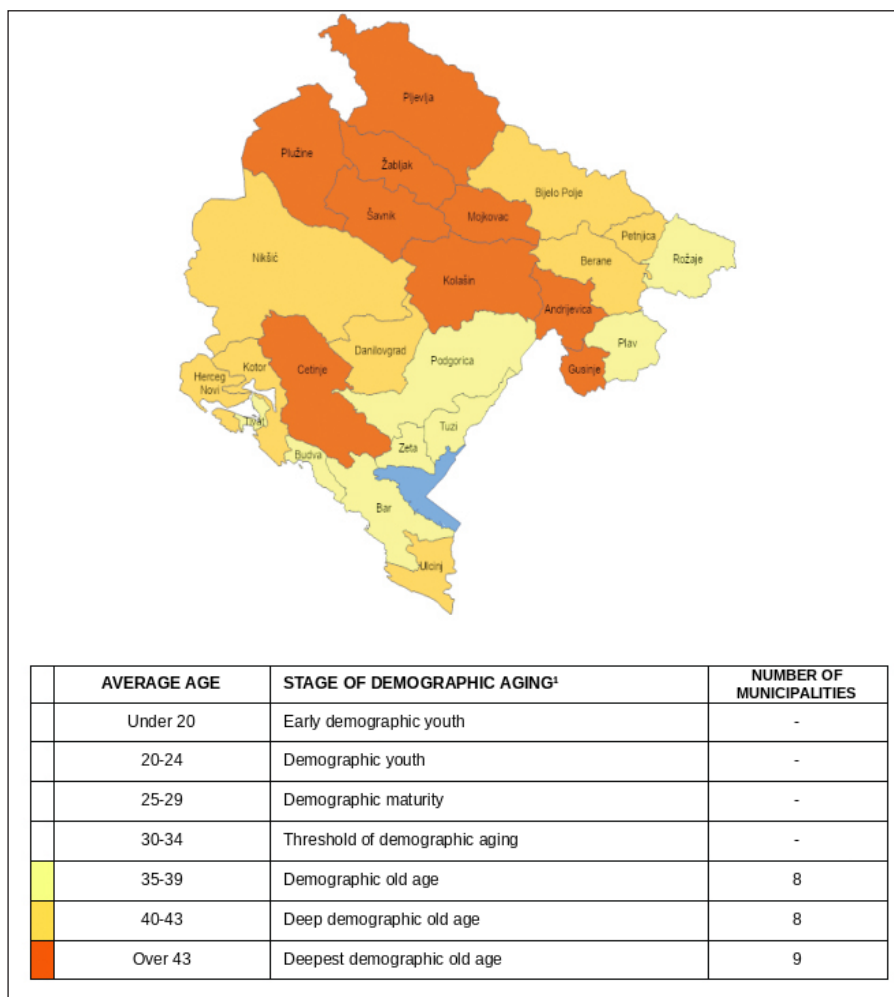


Figure 7. Demographic age stages of the population of Montenegro, by municipalities
(Source: MONSTAT)

Thanks to the aging index, any population can be classified into one of seven stages: early demographic youth, demographic youth, demographic maturity, demographic age threshold, demographic old age, deep demographic age and deepest demographic age (Milosavljević and Medojević, 2023). The aging index was calculated for the last intercensal period (2011-2023). On the basis of which it is concluded that Pljevlja is facing demographic extinction. Namely, in 2011 there

were 113.91 old residents per 100 young people, while in 2023 the number of old people per 100 young people increased to 200.15. This data points to a very intense process of population aging, which can have serious socio-economic consequences.

The age coefficient represents the share of the old population (60 or 65 and older) in the total population. The population begins to age when the share of the population over 65 years old reaches 8% (Nejašmić, 2005). The age ratio of the population increased from 18.26% in 2011 to 24.82% in 2023.

The average age in Pljevlja increased from 42.2 years (2011) to 46.1 years (2023). The average age of the population at the level of Montenegro in 2023 was 39.72. It is obvious that the average age in Pljevlja is far above the national average, which is not surprising if the previously stated indicators are taken into account.

The total dependency ratio of the population measures how many young residents (0-14 years old) and old residents (65 and over) there are per 100 working-age residents (15-65 years old). It consists of two integral parts: the dependency ratio of the young population and the dependency ratio of the old population. The dependency ratio of the young population represents the number of inhabitants aged 0-14 per 100 inhabitants aged 15-64. On the other hand, the dependency ratio of the old population is the number of inhabitants aged 65 and over per 100 inhabitants aged 15-64 (Grgur Drakić, 2018).

The coefficient of total dependency in Pljevlja in 2011 was 59.80 and in 2023 it dropped to 58.35. This further means that for every 100 inhabitants of working age, there were 59 economically dependent inhabitants in 2011, and 58 in 2023. Although the coefficient of total dependency is in a slight decline, its structure has changed significantly - the share of young dependents is decreasing, while the number of elderly dependents is increasing, which puts an additional burden on the working-age population. Analysis of the structure of the overall dependency ratio indicates a decrease in the dependency ratio of the young population in Pljevlja from 22.92 in 2011 to 19.04 in 2023, which is a consequence of the decrease in the number of children. The dependency ratio of the elderly population in 2011 was 27.47, and twelve years later it increased to 39.31. Therefore, the increase in the number of old residents in the total population of Pljevlja is evident. The divergent movement of these two values indicates an unfavorable growth trend in the burden of the working-age population. For the sake of comparison, the coefficient of total dependency in 2023 at the level of Montenegro was 53.54, which indicates that the pressures on the working-age population are more pronounced in Pljevlja. All the mentioned values confirm that Pljevlja is in the stage of deep demographic age, with pronounced pressures on the working-age population and long-term socio-economic implications.

Conclusion

Depopulation brings with it numerous challenges that affect all spheres of social life. The decrease in the number of inhabitants affects economic development, because the labor force decreases, the labor market weakens and local consumption decreases. At the same time, it is increasingly difficult to maintain public services such as education, healthcare and public transport, because their profitability is called into question due to the small number of users. The infrastructure in abandoned areas is deteriorating, and the cultural and social life of local communities is slowly dying out. Depopulation, especially in combination with the aging of the population, puts an additional burden on the health and pension systems, while local governments are left without the necessary human and financial resources to implement development policies. In the long term, such developments can lead to the permanent loss of vitality of entire regions, thus deepening regional differences and complicating the process of balanced development of the country.

Demographic trends in the municipality of Pljevlja indicate a long-term depopulation process, which is the result of the combined impact of low natural growth, negative migration balance and accelerated population aging. The analysis of the population census data from 1948 to 2023 shows a continuous decline in the number of inhabitants, with this trend further intensifying in recent decades. While the post-war period was marked by growth thanks to natural increase and industrialization, from the 1970s onwards a long-term process of depopulation dominated. The decrease in the number of inhabitants is particularly pronounced in rural areas, while the urban core records a slower depopulation. Natural increase is constantly negative in the observed period 2011-2023. year, and the number of deaths exceeds the number of newborns, which further accelerates the demographic aging process. The age pyramids for 2003 and 2023 indicate an increasingly unfavorable relationship between the working-age population and the old population, which may have long-term socio-economic consequences.

Along with negative demographic indicators, emigration also plays a significant role in depopulation, whereby the migration balance from 2011 to 2023 was consistently negative. The young and able-bodied population leaves in search of better life and economic opportunities, while the process of immigration cannot be compared with the intensity of emigration. These processes in Pljevlja fit into the broader European pattern of depopulation of peripheral, rural areas, which confirms that local challenges have a global dimension. These trends point to the need for strategic measures that could mitigate further depopulation, such as economic incentives for the youth to stay, improving infrastructure and developing sustainable economic sectors. The integrated statistical and cartographic analysis provided a clearer insight into the spatial distribution of the population and the intensity of

demographic changes, confirming that the municipality of Pljevlja is faced with serious demographic challenges that require an immediate response.

In order to alleviate negative demographic trends and encourage the revitalization of the area, it is necessary to implement comprehensive policies aimed at retaining the population, especially young and educated personnel. A special emphasis should be placed on improving the quality of life in rural areas, through the development of infrastructure, the availability of basic services, the stimulation of employment and the encouragement of entrepreneurship. Also, the valorization of natural resources and the development of sustainable forms of tourism, such as rural and ecotourism, can represent an important instrument for economic diversification and demographic stabilization. The experiences of European countries show that depopulation can be alleviated to some extent through integrated strategies that combine state support, local initiatives and innovative use of resources. In the long term, the success of any strategy will depend on the ability of local and state institutions to see demographic trends as a priority development challenge and to integrate them into all sectoral policies and planning documents.

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Sajtovi:

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<https://www.monstat.org/cg/>

<https://www.rupv.me>

Original scientific article

Received: 17.02.2026;

Received in revised form: 21.09.2026;

Received in second revised form: 02.10.2026.

Accepted: 02.10.2026;

Available online: 28.10.2026.

UDC: 631:502/504

doi: 10.5937/zrgfub26031M

MULTIFUNCTIONALITY AS A FRAMEWORK FOR CONTEMPORARY AGRICULTURAL TRANSFORMATION: GEOSPATIAL AND ENVIRONMENTAL CHALLENGES

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Abstract: Contemporary agriculture is changing under the combined influence of demographic decline, land-use pressures, climate-related risks and technological development. This paper examines multifunctionality as a framework for understanding these changes, with particular attention to the experience of Serbia. The analysis combines a comparative review of contemporary agricultural approaches with secondary statistical data from the 2012 and 2023 Censuses of Agriculture and other official sources of the Statistical Office of the Republic of Serbia. Between 2012 and 2023, the number of agricultural holdings declined from 631,552 to 508,325 (−19.5%), while utilised agricultural area decreased from 3.44 to 3.24 million ha (−5.8%). Over the same period, annual work units fell by 22.3%, whereas the average utilised agricultural area per holding increased from 5.44 to 6.37 ha. Demographic ageing remains an additional constraint: in 2023, 44.7% of holders of family agricultural holdings were in the oldest age group, while only 0.9% were aged 15–25. Data on farm diversification, irrigation, precision technologies and renewable-energy equipment indicate that these practices and technologies are present, but remain unevenly distributed. Taken together, the results point to a pattern of agricultural change characterised by fewer holdings, a declining agricultural labour input, an increase in average utilised agricultural area per holding consistent with a concentration of operated land, demographic ageing and selective diversification and technological adjustment. Complementary geospatial evidence from the peri-urban municipality of Grocka further shows that agricultural transformation is territorially differentiated and includes both conversion of agricultural land and internal restructuring of agricultural land use. In this context, multifunctionality provides a useful framework for linking agricultural production with environmental functions, rural livelihoods and territorial development, provided that these dimensions are examined through clearly defined indicators.

Keywords: multifunctional agriculture; agricultural transformation; farm structure; demographic ageing; sustainable agriculture; rural development; Serbia

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Introduction

Agriculture is simultaneously a production system, a major form of land use, and a source of environmental and social functions. The intensification of agricultural production during the second half of the twentieth century substantially increased food output, but also contributed to soil degradation, biodiversity loss, pressure on freshwater resources, and greenhouse-gas emissions (Tilman et al., 2002; Foley et al., 2005). These effects have encouraged a broader understanding of agricultural sustainability, in which agricultural systems are considered in relation to soil functions, ecosystem services, resource use, and wider socio-economic conditions (Bouma, 2014; HLPE, 2019).

This shift has been accompanied by the development of several approaches to agricultural production and management. These include integrated, organic and agroecological production, climate-smart agriculture, precision and digital agriculture, and circular approaches to resource use. Although they differ in their objectives and instruments, they share a broader concern with reducing environmental pressures, improving resource efficiency, strengthening adaptation and extending the role of agriculture beyond narrowly defined production goals (FAO, 2017; HLPE, 2019; Rockström et al., 2017; Schroeder et al., 2021). Their conceptual and practical differences are examined in greater detail in the following section.

Multifunctionality offers a framework for examining these changes without treating them as mutually exclusive models. In the OECD interpretation, agricultural activity may jointly produce market commodities and non-market outputs, including landscape maintenance, environmental services, and contributions to rural viability (OECD, 2001). Subsequent research has further linked multifunctionality with farm diversification, rural development, landscape management, and ecosystem services (van Huylenbroeck & Durand, 2003; Renting et al., 2009). Multifunctionality therefore does not represent a specific production technology or certification system. Rather, it provides a way of examining how productive, environmental, social, and territorial functions coexist and interact within agricultural areas. Recent evidence on agricultural diversification also indicates that diversified practices may provide environmental and socio-economic benefits when their effects are considered over longer periods, although outcomes remain dependent on local conditions and management practices (Raveloaritiana & Wanger, 2026).

Serbia provides a relevant setting for examining these relationships. Agricultural development is taking place under conditions of declining numbers of agricultural holdings, demographic ageing, marked regional differences, and continuing population loss in many rural areas. At the same time, agricultural land is exposed to pressures associated with peri-urban expansion, land-use change, climate variability,

and uneven access to technological innovation. Recent research in the Belgrade peri-urban area has shown that agricultural sustainability is strongly conditioned by the interaction of demographic, production, environmental, and spatial factors, illustrating the importance of analysing agriculture beyond production indicators alone (Mihajlović et al., 2026b). These conditions make it difficult to describe agricultural transformation in Serbia as a linear transition from a conventional towards a single alternative model. Previous research relevant to the Serbian context has addressed farm structure, agricultural sustainability, environmental pressures, land-use change and technological development from different analytical perspectives. However, these dimensions are less frequently considered together within a common multifunctional framework.

Against this background, the aim of this paper is twofold. First, it examines the relationship between multifunctionality and major contemporary approaches to agricultural development. Second, it analyses selected indicators of structural, demographic, environmental, technological and spatial change in Serbian agriculture using official secondary data and complementary previously published geospatial evidence. Rather than treating multifunctionality as a normative label, the analysis considers the extent to which its individual components can be identified through measurable indicators. Three questions guide the analysis: (1) which structural and demographic changes have characterised Serbian agriculture in the period covered by the available census data; (2) what do official data indicate about farm diversification, irrigation, precision technologies, and renewable-energy equipment; and (3) how do national statistical trends and complementary peri-urban land-use evidence reveal the spatially differentiated character of contemporary agricultural transformation in Serbia?

Conceptual Framework: Agricultural Approaches and Multifunctional Outcomes

Contemporary agricultural approaches should not be treated as mutually exclusive models. At farm and territorial level, production systems often combine elements of several approaches, depending on resource availability, environmental conditions, market orientation, institutional support, and access to knowledge and capital. Conventional agriculture remains primarily oriented towards productivity and market output and, particularly in intensive systems, may rely heavily on external inputs (Tilman et al., 2002). Integrated production retains the objective of economically viable production while seeking to improve input management and reduce environmental pressures through measures such as integrated pest management and more targeted resource use (Therond et al., 2019). Organic and agroecological approaches place greater emphasis on ecological processes, diversity, soil functions,

and reduced dependence on synthetic inputs, although their implementation remains conditioned by labour requirements, market access, knowledge, and institutional settings (FAO, 2017; HLPE, 2019).

Climate-smart agriculture introduces a different analytical emphasis by linking agricultural productivity with adaptation and mitigation. Rather than constituting a single production system, it represents a context-dependent approach in which different practices may contribute to one or more of these objectives (FAO, 2013). Irrigation, drought-tolerant varieties, soil conservation, and improved nutrient management may contribute to adaptation or mitigation, but their effectiveness depends on local climatic, production, and socio-economic conditions (IPCC, 2022). Digital and precision agriculture introduce a technological dimension through spatially targeted management, sensors, monitoring systems, and data-supported decision making. Their potential contribution lies primarily in more precise resource use and improved monitoring, although adoption remains constrained by investment capacity, farm structure, infrastructure, and skills (Schroeder et al., 2021). Circular approaches focus on keeping nutrients, biomass, organic residues, and energy in productive use for longer through recovery, reuse, and recirculation. Nutrient recovery from manure, crop residues, wastewater, and other waste streams illustrates this logic, although individual practices should be interpreted as components of a broader circular transition rather than evidence that an entire farming system is circular (Shrivastava & Laasri, 2025).

These approaches differ in their primary objectives, but they increasingly overlap in practice. Their main analytical emphases are summarised in Table 1. The comparison is intended to distinguish their principal areas of emphasis rather than to establish a hierarchy among them. Instead, it highlights the different productive, environmental, and wider multifunctional functions that may coexist within the same farm or territory.

Multifunctionality differs from the other approaches because it does not prescribe a particular production technique. It refers instead to the coexistence and interaction of several functions generated by agricultural activity. Alongside commodity production, these functions may include landscape maintenance, biodiversity conservation, ecosystem services, employment, income diversification, cultural continuity, and contributions to rural viability (OECD, 2001; van Huylenbroeck & Durand, 2003; Renting et al., 2009). A farm may therefore combine conventional production methods with tourism or processing activities, while an organic or digitally equipped farm may remain highly specialised in economic terms. Multifunctionality is thus more appropriately understood as an analytical framework for examining the interaction of functions than as a distinct production model.

*Multifunctionality as a framework for contemporary
agricultural transformation: geospatial and environmental challenges*

Table 1. Main agricultural approaches and their analytical emphasis

Approach	Main focus	Environmental/ resource emphasis	Wider multifunctional relevance
Conventional	Yield and market output	Frequent reliance on external inputs in intensive systems	Mainly productive- economic
Integrated	Input optimisation and integrated pest management	Reduced input losses and improved resource management	Productive-economic and environmental
Organic	Biological processes and restricted synthetic inputs	Soil quality, biodiversity and reduced synthetic- input dependence	Environmental and market differentiation
Agroecological	Ecosystem- based design and diversification	Biodiversity, soil functions and ecological regulation	Environmental, social and local-knowledge functions
Climate-smart	Productivity, adaptation and mitigation	Climate resilience, water and nutrient efficiency, emission reduction	Productive-economic and environmental
Digital / precision	Data-supported and spatially targeted management	Improved monitoring and potentially more efficient input use	Productive-economic and technological
Circular	Recirculation of nutrients, materials and energy	Nutrient cycling, biomass use and waste reduction	Environmental- resource and local value-chain linkages
Multifunctional	Combination of commodity and non- commodity functions	Ecosystem services and landscape management	Productive, environmental, social and territorial functions

Source: authors' synthesis based on OECD (2001), van Huylenbroeck and Durand (2003), Renting et al. (2009), Tilman et al. (2002), FAO (2013, 2017), HLPE (2019), Therond et al. (2019), IPCC (2022), Schroeder et al. (2021), and Shrivastava and Laasri (2025).

For the purposes of this study, these functions are organised into four interrelated dimensions: productive-economic, environmental-resource, demographic-social, and spatial-territorial. The productive-economic dimension refers to farm viability, market orientation, and income diversification. The environmental-resource dimension includes soil and water management, biodiversity, ecosystem services, and resource efficiency. The demographic-social dimension concerns labour availability,

ageing, succession, and rural livelihoods, while the spatial-territorial dimension captures land-use change, rural-urban relations, and regional differentiation. The analytical relationship between contemporary agricultural approaches, these four dimensions, and the empirical indicators used in the Serbian case is presented in Figure 1. The framework treats the four dimensions as parallel and interrelated rather than hierarchical. Individual processes may contribute to more than one dimension: diversification may affect farm income and rural employment, irrigation has both productive and resource-management implications, and renewable-energy technologies may influence economic as well as environmental performance.

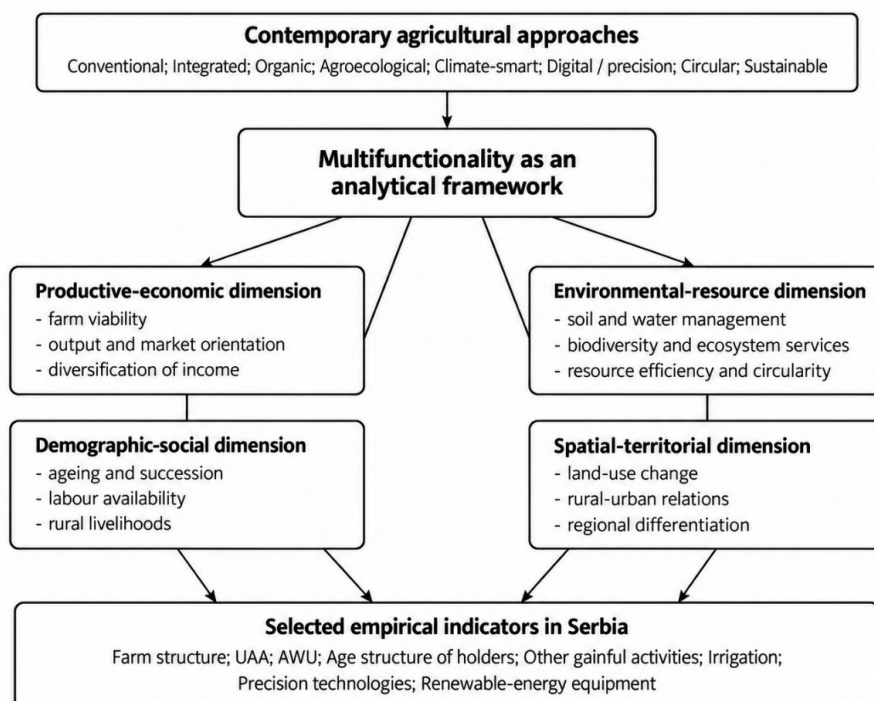


Figure 1. Conceptual framework linking contemporary agricultural approaches, multifunctional dimensions, and selected empirical indicators in Serbia.

The framework shown in Figure 1 provides the link between the conceptual and empirical parts of the study. Contemporary agricultural approaches are treated as overlapping sets of practices, while multifunctionality provides the analytical structure through which their wider effects can be examined. The final layer identifies the indicators used in the empirical analysis of Serbia: farm structure, utilised agricultural area (UAA), annual work units (AWU), age structure of holders,

other gainful activities, irrigation, precision technologies, and renewable-energy equipment. Spatial evidence on land-use change is examined separately through the peri-urban case study presented later in the paper. The indicators are used to examine specific components of agricultural transformation rather than to classify Serbian agriculture as multifunctional, climate-smart, digital, or circular as a whole. The following methodological section explains their sources, comparability, and treatment.

Materials and Methods

The study combines a focused review of scientific and institutional literature with a descriptive analysis of official secondary statistics for Serbia. The literature component was used to establish the conceptual basis for distinguishing multifunctionality from related agricultural approaches, including agroecology, climate-smart agriculture, precision agriculture, and circular agriculture. Priority was given to peer-reviewed studies and institutional reports directly addressing agricultural sustainability, ecosystem services, rural development, resource efficiency, technological change, and multifunctionality. The review was not conducted as a systematic review or meta-analysis; its purpose was to define the analytical categories subsequently applied in the empirical analysis.

The empirical analysis is based primarily on data from the Statistical Office of the Republic of Serbia (SORS). Structural indicators were obtained from the 2012 and 2023 Censuses of Agriculture. These sources provide data on the number of agricultural holdings, utilised agricultural area (UAA), labour input expressed as annual work units (AWU), and selected structural characteristics of agricultural holdings. The 2023 Census was conducted between 1 October and 15 December 2023. For variables relating to land use, labour, machinery, and agricultural practices, the reference period covered the agricultural year from 1 October 2022 to 30 September 2023, while selected stock variables referred to the situation on 30 September 2023. The 2023 census methodology followed the relevant FAO and Eurostat methodological frameworks. To complement the national statistical analysis, previously published geospatial evidence from the Municipality of Grocka was used as a documented peri-urban case of land-use transformation (Mihajlović et al., 2026a, 2026b). No new remote-sensing classification was undertaken for the present study. The CORINE Land Cover (CLC) and Sentinel-2 results were used as secondary geospatial evidence to illustrate spatial processes that cannot be captured by national agricultural statistics alone.

Additional 2023 data from the SORS dissemination database were used to examine the age structure of holders and farm managers, other gainful activities directly related to the holding, selected precision and automated technologies, and equipment used for renewable-energy production. These indicators were

included because they provide measurable information on demographic change, diversification, technological adoption, and resource-related adjustment. They were analysed as individual components of agricultural transformation rather than as direct measures of multifunctionality or sustainability as a whole.

Data on irrigation were obtained from the annual SORS irrigation survey and were used as a complementary indicator of water-management practices. This source was treated separately from the agricultural census because its statistical coverage differs. The annual irrigation survey covers business entities and agricultural cooperatives engaged in agricultural production, agricultural services, and/or irrigation-system management. Irrigation data from this source were therefore not directly combined with census-based indicators unless the observation unit, denominator, and statistical coverage were methodologically compatible. For indicators available for both census years, absolute values were supplemented by relative change rates calculated according to Equation (1):

$$\text{Relative change (\%)} = \left(\frac{V_{2023}}{V_{2012}} - 1 \right) \times 100 \quad (1)$$

where V_{2012} and V_{2023} denote the values of the same indicator in the 2012 and 2023 agricultural censuses, respectively.

Average UAA per holding was calculated by dividing total utilised agricultural area by the total number of agricultural holdings for each census year. Indicators available only for 2023 were analysed as cross-sectional measures and were not used to infer temporal trends. The analysis is descriptive and does not estimate causal relationships, construct a composite sustainability index, or rank agricultural models.

Particular attention was paid to the comparability of statistical sources. The 2012 and 2023 agricultural censuses were used for long-term structural comparisons only where definitions and coverage were sufficiently consistent. Indicators derived from annual surveys or specialised statistical tables were treated separately when their observation units, reference periods, or statistical coverage differed from those of the agricultural censuses. The CLC and Sentinel-2 datasets were likewise interpreted separately because they differ in spatial resolution, classification scheme, and data-production methodology. National-level data were used to identify broad structural tendencies, while regional and local evidence was used to examine spatial differentiation where appropriate supporting data were available.

Several methodological limitations should be considered when interpreting the results. First, indicators such as irrigation, precision technologies, renewable-energy equipment, and other gainful activities describe specific practices or structural characteristics rather than complete agricultural models. Second, the availability and definition of individual variables differ across statistical sources and years, which limits the range of valid longitudinal comparisons. Third, national averages may

conceal substantial regional variation in farm structure, demographic conditions, land use, and technological adoption. Finally, the Grocka case provides a documented peri-urban example but is not intended to be statistically representative of Serbia as a whole. The results should therefore be interpreted as a descriptive assessment of selected dimensions of agricultural transformation rather than as a comprehensive measurement of sustainability or multifunctionality.

Agricultural Transformation in Serbia: Empirical Evidence

Structural and Demographic Change

The comparison of the 2012 and 2023 agricultural censuses shows a substantial decline in the number of agricultural holdings in Serbia. The number of holdings declined from 631,552 in 2012 to 508,325 in 2023, corresponding to a decrease of 19.5%. Over the same period, utilised agricultural area (UAA) decreased from 3,437,423 ha to 3,239,373 ha, or by 5.8%. Because the reduction in UAA was considerably smaller than the decline in the number of holdings, average UAA per holding increased from 5.44 ha to 6.37 ha, or by 17.1% (Table 2) (SORS, 2013; SORS, 2024a).

The change in farm structure was accompanied by a substantial reduction in agricultural labour input. Total annual work units (AWU) decreased from 646,283 in 2012 to 502,318 in 2023, a decline of 22.3% (SORS, 2013; SORS, 2024a). The reduction in labour input was therefore slightly stronger than the contraction in the number of holdings. Taken together, these changes show that the intercensal period was characterised by a reduction in both the number of holdings and the volume of agricultural labour, while the agricultural land base declined more moderately.

Demographic characteristics of family holdings add an important dimension to these structural changes. According to the final results of the 2023 Census of Agriculture, 44.7% of holders of family agricultural holdings were older than 65 years, whereas only 0.9% were aged 15–25 (SORS, 2024a). The contrast between these two age groups indicates a pronounced demographic imbalance and limited representation of young holders in Serbian agriculture. The structural and demographic indicators should be interpreted together. The increase in average UAA per holding is consistent with a concentration of operated agricultural land among a smaller number of holdings, but it does not by itself demonstrate higher productivity, profitability, or technological advancement. At the same time, the decline in labour input and the age structure of holders point to potential constraints on generational renewal and future labour availability. These processes correspond to the demographic-social and productive-economic dimensions of agricultural transformation defined in the conceptual framework.

Table 2. Structural and demographic indicators of Serbian agriculture, 2012 and 2023.

Indicator	2012	2023	Change
Agricultural holdings (number)	631,552	508,325	−19.5%
Utilised agricultural area (ha)	3,437,423	3,239,373	−5.8%
Average UAA per holding (ha)	5.44	6.37	+17.1%
Annual work units (AWU)	646,283	502,318	−22.3%
Holders of family agricultural holdings older than 65 years	-	44.7%	2023 only
Holders of family agricultural holdings aged 15–25 years	-	0.9%	2023 only
Women among farm managers	-	23.0%	2023 only
Average AWU per holding	-	0.99	2023 only

Source: authors' calculations based on SORS (2013, 2024a). A dash indicates that the indicator was not used for direct temporal comparison.

The different intensity of the intercensal changes is illustrated in Figure 2. Labour input recorded the largest relative decline (−22.3%), followed by the number of agricultural holdings (−19.5%), whereas UAA decreased by 5.8%. In contrast, average UAA per holding increased by 17.1%.

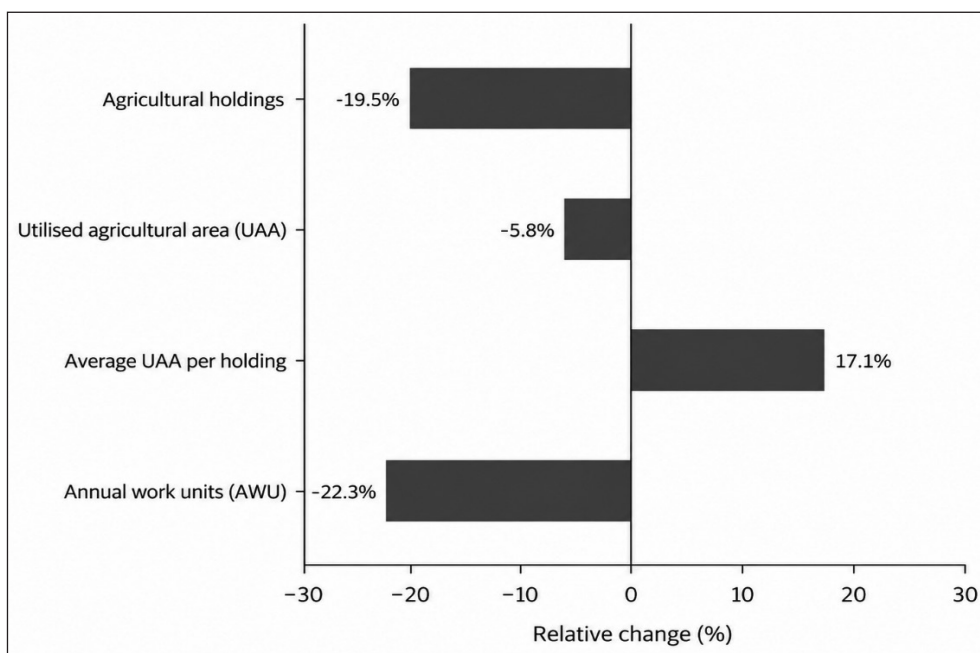


Figure 2. Relative change in selected structural indicators of Serbian agriculture, 2012–2023; Source: authors' calculations based on SORS (2013, 2024a).

Farm Diversification and Multifunctionality

Economic diversification represents one measurable component of agricultural multifunctionality. In the 2023 Census of Agriculture, the Statistical Office of the Republic of Serbia records other gainful activities related to the holding, referring to income-generating activities directly linked to the resources, products, or assets of the agricultural holding. In 2023, 63,684 agricultural holdings were recorded in this category, representing 12.5% of all agricultural holdings in Serbia (SORS, 2024a, 2024b). The main forms of these activities reported in the 2023 Census are summarised in Table 3.

Table 3. Selected other gainful activities related to agricultural holdings in Serbia, 2023

Activity	Share of holdings with other gainful activities (%)
Fruit and vegetable processing	26.2
Milk processing	26.0
Forestry activities	10.0
Meat processing	9.5
Tourism	1.4

Source: SORS (2024a, 2024b).

Note: The percentages refer to selected categories of holdings reporting other gainful activities and do not represent an exhaustive distribution of all such activities.

As shown in Table 3, processing accounts for a substantial part of the recorded diversification activities, particularly fruit and vegetable processing and milk processing. Forestry-related activities and meat processing are less frequent, while tourism represents only a small share. This distribution indicates that recorded diversification is concentrated mainly in activities connected with the processing and further use of agricultural products and farm resources, whereas tourism plays a much smaller role.

The overall share of holdings with other gainful activities indicates that diversification is present, but remains limited to a minority of agricultural holdings. It therefore represents one observable economic dimension of multifunctionality rather than evidence that multifunctionality characterises the agricultural sector as a whole. The indicator also does not provide information on environmental performance: a diversified holding may broaden its sources of income without necessarily improving resource efficiency or ecological conditions. Environmental and resource-related dimensions are considered separately in the following section.

Water Management and Resource Efficiency

Water management represents one of the most directly measurable environmental-resource dimensions of agricultural transformation in Serbia. According to the final results of the 2023 Census of Agriculture, 8.3% of utilised agricultural area (UAA) was irrigated during the 2022/2023 agricultural year. The proportion varied considerably across statistical regions: 20.4% in the Belgrade Region, 9.6% in Vojvodina, 6.7% in Šumadija and Western Serbia, and 5.2% in Southern and Eastern Serbia (SORS, 2024a). These figures demonstrate pronounced regional variation in the extent of irrigation.

The Census of Agriculture also shows that irrigation methods differ from those reported by the annual irrigation survey because the two sources cover different statistical populations and use different statistical bases. According to the 2023 Census summary, the distribution of irrigation methods was approximately 42% surface irrigation, 41% drip irrigation and 17% sprinkler irrigation. By contrast, the annual SORS irrigation survey reported that 47,579 ha were irrigated in 2023, with 91.0% of the total irrigated area irrigated by sprinkling, 8.7% by drip irrigation, and 0.3% by surface irrigation. The same survey recorded 70.429 million m³ of abstracted water, with 93.5% obtained from watercourses (SORS, 2024e). These figures should not be interpreted as contradictory. The annual irrigation survey covers business entities and agricultural cooperatives engaged in agricultural production, agricultural services, and/or irrigation-system management, whereas the census covers agricultural holdings more broadly. For this reason, the census is used here to describe the extent and regional distribution of irrigation at farm level, while the annual survey is used to characterise irrigated area, water abstraction and irrigation methods within its own survey population.

From the perspective of multifunctionality, irrigation is relevant primarily to the environmental-resource and productive-economic dimensions. It may reduce production risks under conditions of water deficit and support more stable output, but its effects depend on water availability, irrigation efficiency, crop structure, and local hydrological conditions. Accordingly, irrigation is treated here as a water-management indicator rather than as evidence, by itself, of climate-smart or environmentally sustainable agriculture.

Table 4. Share of irrigated UAA by statistical region of Serbia, 2022/2023

Statistical region	Irrigated UAA (%)
Republic of Serbia	8.3
Belgrade Region	20.4
Vojvodina Region	9.6
Šumadija and Western Serbia	6.7
Southern and Eastern Serbia	5.2

Source: SORS (2024a).

Table 4 shows a pronounced regional contrast, with the highest share of irrigated UAA recorded in the Belgrade Region and the lowest in Southern and Eastern Serbia. The regional values show that the national average conceals substantial spatial variation in irrigation intensity.

Digital and Precision Technologies

The 2023 Census of Agriculture provides a detailed picture of the use of selected precision and automated technologies on Serbian agricultural holdings. Among the recorded technologies, automatic feeding systems were the most widespread, with 2,893 holdings reporting their use. Precision-farming systems were recorded on 1,066 holdings, while 851 holdings used silo-mix feed trailers and 820 reported technologies for monitoring animal health and welfare. Precision crop-monitoring systems were used on 616 holdings, automatic regulation of temperature and humidity in livestock buildings on 472 holdings, and milking robots on 74 holdings (SORS, 2024c).

These values show that precision and automated technologies were present in Serbian agriculture in 2023, but their diffusion remained limited relative to the total of 508,325 agricultural holdings. Precision-farming systems, for example, were reported by only a small fraction of holdings. The data therefore indicate selective adoption of these technologies rather than their widespread use across the agricultural sector. The distribution of the selected technologies is presented in Figure 3.

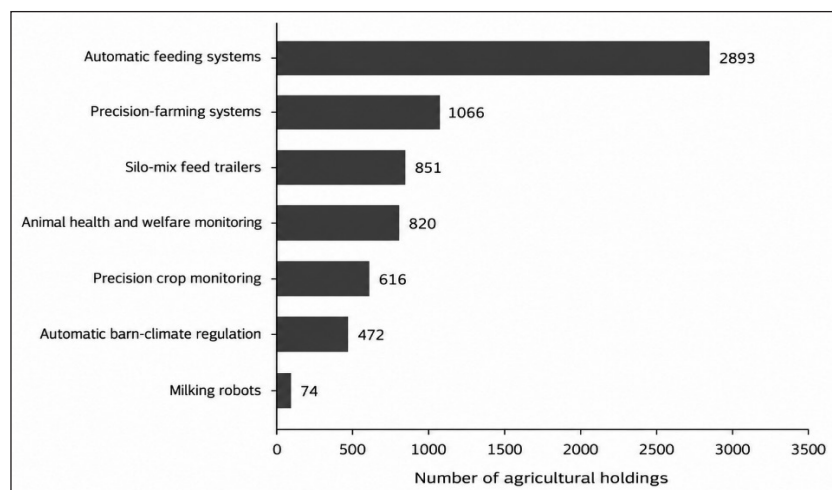


Figure 3. Agricultural holdings using selected precision and automated technologies in Serbia, 2023; Source: SORS (2024c), dissemination database, “Use of precision farming – Number of farms”.

The differences shown in Figure 3 also indicate that technological adoption is not uniform across production activities. Technologies associated with livestock feeding and monitoring were more frequently reported than systems for precision crop monitoring or robotic milking. The recorded pattern therefore reflects substantial differences in the uptake of individual technologies.

From the perspective of the conceptual framework, these technologies are relevant mainly to the productive-economic and environmental-resource dimensions. Precision systems may support more targeted use of inputs and improve monitoring, while automated systems may reduce labour requirements in specific production processes. However, the census data record the presence of equipment or systems, not their intensity of use, economic effects, or environmental performance. Accordingly, the data describe the extent of reported adoption, but do not allow assessment of the effectiveness or broader impacts of technological use.

Renewable-Energy Equipment and Resource Transition

The 2023 Census of Agriculture also provides information on equipment used for renewable-energy production on agricultural holdings. The largest number of holdings was recorded for wind-energy equipment (3,030), followed by solar photovoltaic equipment (1,758) and solar thermal equipment (1,563). Other renewable-energy sources were reported on 1,144 holdings, hydro-energy equipment on 891, biomass equipment on 670, and biogas-from-biomass equipment on 248 holdings (SORS, 2024d).

These categories should not be summed to estimate the total number of holdings using renewable energy, because a single holding may operate more than one type of equipment. The data are therefore best interpreted as the frequency of individual technologies rather than as a count of unique renewable-energy farms. The distribution of renewable-energy equipment is shown in Figure 4.

The pattern shown in Figure 4 indicates that renewable-energy technologies are present on Serbian agricultural holdings, with wind and solar equipment reported more frequently than biomass- and biogas-based systems. This distinction is relevant to the interpretation of resource transition. Solar and wind equipment contribute primarily to the energy dimension of farm modernisation, whereas biomass and biogas systems may additionally be associated with the utilisation of crop residues, manure, or other organic materials.

Renewable-energy equipment should therefore not be treated as a direct measure of circular agriculture. Its relevance depends on the type of technology and on how energy production is integrated with farm resource flows. Biomass and biogas systems have a potentially closer conceptual link with circular resource use

because they can incorporate organic by-products into energy production, whereas solar and wind systems primarily indicate the use of non-fossil energy sources. The census data do not, however, provide information on feedstock origin, material recirculation, or the degree to which these technologies are integrated into closed resource cycles.

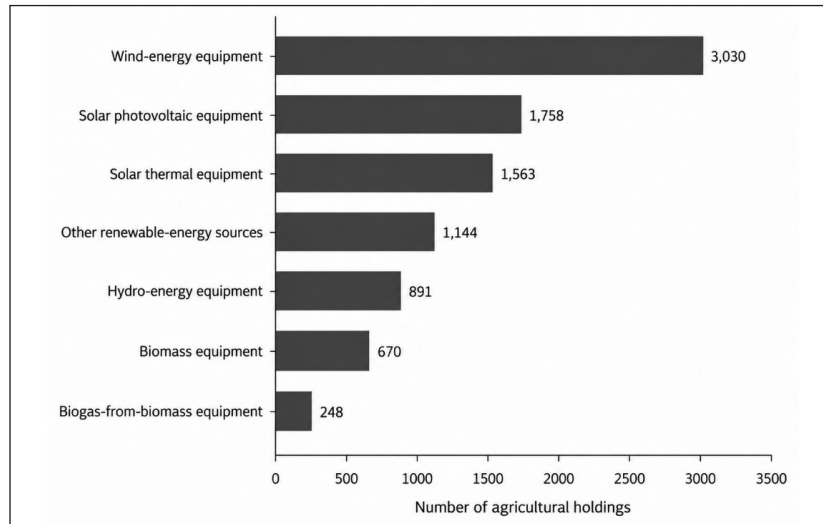


Figure 4. Agricultural holdings with equipment used for renewable-energy production in Serbia, 2023; Source: SORS (2024d), dissemination database, “Number of holdings with equipment used for production of renewable energy”. Categories are not mutually exclusive.

Spatial-Territorial Differentiation and Land-Use Pressure

Agricultural transformation in Serbia also has a spatial dimension that cannot be fully captured by national farm statistics. Changes in farm structure, labour input, diversification, and technology occur within territories that differ in urban influence, accessibility, demographic dynamics, land-use competition, and the physical organisation of agricultural land. Peri-urban areas are particularly exposed to these pressures because agricultural and urban functions overlap within the same space.

The Municipality of Grocka, located within the peri-urban zone of Belgrade, provides a documented example of such transformations. A GIS-based analysis of CORINE Land Cover (CLC) data for 1990, 2000, 2006, 2012, and 2018 identified substantial changes both within agricultural land categories and between agricultural and built-up uses (Mihajlović et al., 2026a). The most pronounced agricultural change was the decline in non-irrigated arable land, from 26.96 km² in 1990 to 7.22 km² in 2018, corresponding to a reduction of 73.22%. Complex cultivation patterns

decreased from 92.52 to 66.14 km² (–28.51%), while vineyard area declined from 7.10 to 5.12 km² (–27.88%). In contrast, fruit-tree and berry plantations expanded from 20.76 to 59.22 km², an increase of 185.26%. The same CLC analysis recorded expansion of built-up land. Discontinuous urban fabric increased from 31.44 to 35.15 km² (+11.8%), while industrial and commercial units increased from 0.83 to 1.60 km² (+92.77%). Transition analysis showed that part of this expansion occurred at the expense of non-irrigated arable land and complex cultivation patterns, particularly in settlements with stronger functional and transport links to Belgrade, including Kaluđerica, Leštane, and Vinča (Mihajlović et al., 2026a). The principal long-term land-cover changes relevant to agricultural restructuring are summarised in Table 5.

Table 5. Selected CORINE Land Cover changes in the Municipality of Grocka, 1990–2018

Land-cover category	1990 (km ²)	2018 (km ²)	Relative change (%)
Non-irrigated arable land	26.96	7.22	–73.22
Vineyards	7.10	5.12	–27.88
Fruit trees and berry plantations	20.76	59.22	+185.26
Complex cultivation patterns	92.52	66.14	–28.51
Discontinuous urban fabric	31.44	35.15	+11.80
Industrial or commercial units	0.83	1.60	+92.77

Source: Mihajlović et al. (2026a), based on CORINE Land Cover data.

Table 5 shows that peri-urban change in Grocka did not consist only of a reduction in agricultural land. It also involved internal restructuring of agricultural land use. The strong expansion of fruit plantations occurred simultaneously with the decline of arable land, vineyards, and mixed cultivation mosaics. The observed pattern therefore reflects both conversion to non-agricultural uses and reorganisation within the agricultural sector itself.

The same previously published analysis also used a Sentinel-2-based 10 m land-cover dataset for 2018 and 2024 to examine more recent spatial change. This dataset, derived from Copernicus Sentinel-2 imagery through the Esri/Impact Observatory product, was used as a supplementary high-resolution assessment of short-term land-cover change rather than as a direct continuation of the CLC time series (Mihajlović et al., 2026a). The Sentinel-based assessment identified a reduction in crop-covered surfaces from 128.98 km² in 2018 to 114.88 km² in 2024, a decrease of 14.10 km². Over the same period, built-up surfaces increased from 55.25 to 62.69 km² (+7.44 km²), tree-covered surfaces increased from 84.51 to 89.67 km² (+5.16 km²), and rangeland increased from 17.75 to 19.27 km² (+1.52 km²). Changes in water and flooded vegetation were small in absolute terms and should be interpreted cautiously because they may partly reflect seasonal or hydrological conditions at the time of image acquisition. These short-term changes are summarised separately in Table 6 because the Sentinel-2 and CLC datasets are not directly comparable.

Table 6. Selected Sentinel-2-based land-cover changes in the Municipality of Grocka, 2018–2024

Land-cover class	2018 (km ²)	2024 (km ²)	Absolute change (km ²)
Crops	128.98	114.88	–14.10
Built-up area	55.25	62.69	+7.44
Trees	84.51	89.67	+5.16
Rangeland	17.75	19.27	+1.52
Water	11.94	11.92	–0.02
Flooded vegetation	0.15	0.74	+0.59

Source: Mihajlović et al. (2026a), based on the Sentinel-2 10 m Land Use/Land Cover dataset (Esri & Impact Observatory, 2024; Copernicus Sentinel-2 imagery).

Note: Sentinel-2-derived classes are not directly equivalent to CORINE Land Cover categories. The two datasets differ in spatial resolution, classification scheme, and data-production methodology and are therefore interpreted separately.

The Sentinel-2 results show a more recent pattern characterised by an increase in built-up surfaces and a reduction in crop-covered surfaces, which is broadly consistent with the spatial pressures identified in the longer CLC analysis. However, the finer spatial resolution of the Sentinel-based product also captures short-term and small-scale changes that are not visible in the CLC series. For this reason, the two datasets provide complementary rather than interchangeable evidence.

The Grocka case should not be treated as representative of Serbia as a whole. Its relevance lies in showing how national structural changes may acquire specific spatial forms under peri-urban conditions. In this setting, agricultural transformation involves not only changes in the number and structure of holdings, but also land conversion and internal reorganisation of agricultural land use under peri-urban pressure. A separate GIS-based assessment of agricultural sustainability in Grocka also found marked differences among settlements when demographic, production, environmental, and spatial indicators were considered jointly, further confirming the importance of territorial differentiation in agricultural development (Mihajlović et al., 2026b).

Together with the regional differences in irrigation discussed in Section 4.3, these results show that agricultural transformation in Serbia is spatially uneven. National averages identify broad structural tendencies, while local and regional analyses are necessary to understand the territorial expression of land-use pressure, demographic constraints, and agricultural restructuring.

Discussion

The results indicate that agricultural transformation in Serbia is not occurring through the replacement of one production model by another. Instead, several processes are developing simultaneously: the number of agricultural holdings and total labour input are declining, the average area operated per holding is increasing, the age structure of holders remains unfavourable, while diversification, irrigation, precision and automated technologies, and renewable-energy equipment are present to varying degrees. This combination points to structural adjustment rather than to a uniform transition towards organic, agroecological, climate-smart, digital, or circular agriculture.

The structural changes observed between the two agricultural censuses are particularly important in this respect. The decline in the number of holdings was considerably greater than the reduction in utilised agricultural area, resulting in an increase in average UAA per holding. This pattern is consistent with a gradual concentration of operated land, but land concentration alone cannot be interpreted as evidence of improved economic or environmental performance. At the same time, the reduction in annual work units and the pronounced ageing of holders indicate that structural consolidation is occurring under conditions of declining labour availability and weak generational renewal. The Serbian pattern is therefore characterised by a combination of fewer holdings, less agricultural labour, and an ageing population of farm holders rather than by structural concentration alone. Generational renewal is relevant not only to farm continuity but also to the capacity of agricultural holdings to adopt new technologies, diversify activities, and respond to changing environmental and market conditions. Similar concerns have become prominent in European agricultural policy, where ageing, succession, access to land, and the limited entry of younger farmers are treated as structural constraints on the long-term viability of agriculture and rural areas (European Commission, 2025). Although the Serbian institutional and farm-structure context differs from that of the EU as a whole, the available data point to a comparable structural concern: the demographic basis for farm succession and long-term continuity is weak.

This demographic and structural context is also relevant to multifunctionality. Multifunctionality does not imply that every agricultural holding performs the same combination of productive, environmental, social, and territorial functions (OECD, 2001; van Huylenbroeck & Durand, 2003; Renting et al., 2009). In Serbia, other gainful activities related to the holding are present on a measurable but limited share of farms. Their structure is dominated by processing activities, particularly fruit and vegetable and milk processing, whereas tourism-related diversification remains much less frequent. This pattern suggests that diversification is more closely linked to value addition within or adjacent to primary production than to a broad expansion of

service-oriented farm activities. Diversification therefore represents one component of multifunctionality, rather than a sector-wide organisational pattern.

Water management illustrates a different dimension of agricultural adjustment. Irrigation can reduce exposure to rainfall variability and support production under water-limited conditions, but its effects depend on the availability and sustainability of water resources, irrigation efficiency, crop choice, soil conditions, and the local hydrological context (IPCC, 2022). The regional differences identified in Serbia are important because they show that irrigation capacity and intensity are spatially differentiated. In this respect, water management links the productive-economic and environmental-resource dimensions of agricultural transformation, although irrigated area alone is insufficient to assess the sustainability of water use. Technological change is similarly selective. The 2023 census records the use of precision and automated systems, but their overall diffusion remains limited relative to the total number of agricultural holdings. This is consistent with the international literature on digital agriculture. Schroeder et al. (2021) emphasise the importance of infrastructure, skills, finance, and access to information, while a recent systematic review and meta-analysis found that farm size, education, technical literacy, expected profitability, and managerial characteristics are among the factors associated with adoption of precision agriculture and digital technologies (Kroupová et al., 2025). Larger and better-capitalised farms are generally better positioned to adopt such technologies, although effects differ across technologies and empirical settings. In the Serbian context, this is particularly relevant because technological adoption is unfolding alongside demographic ageing and pronounced variation in farm structure.

The available census data nevertheless capture only the presence of particular systems or equipment. They do not show how intensively these technologies are used, whether they improve input efficiency or profitability, or whether they generate measurable environmental benefits. A relatively small number of technologically advanced holdings may therefore coexist with a much larger group operating with conventional machinery and management practices. This distinction between farm-level adoption and sector-wide transformation is central to interpreting the Serbian evidence. A similar distinction is necessary for renewable-energy equipment. Solar photovoltaic, solar thermal, and wind-energy systems indicate a change in the energy technologies available on some agricultural holdings, but circular agriculture places greater emphasis on the recirculation of materials and nutrients, reuse of residues, reduction of waste, and integration of biomass and organic by-products into new production cycles. Recent reviews identify anaerobic digestion, biomass utilisation, nutrient recovery, and reuse and recycling of agricultural waste streams as central components of circular agricultural systems (Peng et al., 2025; Shrivastava & Laasri, 2025). Biomass and biogas equipment recorded in Serbia may therefore have a closer

conceptual relationship with agricultural circularity than solar or wind systems, although even in these cases the census does not reveal the origin of the feedstock or the degree to which material loops are actually closed.

The spatial evidence from Grocka adds another dimension to this interpretation. The CLC analysis for 1990–2018 documents both conversion of agricultural land to built-up uses and substantial restructuring within agricultural land itself, including the expansion of fruit plantations and contraction of arable land and complex cultivation patterns. The supplementary Sentinel-2 assessment for 2018–2024 points to a more recent increase in built-up surfaces and reduction of crop-covered areas, although the two datasets must be interpreted separately because of differences in spatial resolution and classification methodology (Mihajlović et al., 2026a). These processes are characteristic of peri-urban environments, where agricultural land, settlement expansion, infrastructure, rural livelihoods, and environmental functions compete within the same territory. A recent systematic review of 137 studies likewise identifies peri-urban zones as particularly dynamic interfaces in which urban expansion, rural functions, land-use governance, and environmental pressures intersect (Salem et al., 2025).

The Grocka case also demonstrates why agricultural land loss should not be reduced to a simple urban-versus-agriculture dichotomy. Part of the observed change represents conversion to non-agricultural land uses, but another part reflects reorganisation within agriculture, including shifts between arable production, mixed cultivation, and permanent crops. The accompanying settlement-level assessment of agricultural sustainability further showed that demographic, productive, environmental, and spatial conditions vary substantially within the municipality (Mihajlović et al., 2026b). The local evidence is therefore not used here as representative of Serbia, but as an example of how national structural tendencies may take different spatial forms under specific territorial conditions.

This territorial differentiation has broader implications for interpreting agricultural transformation. An increase in average farm size at national level does not necessarily reflect the same process in all parts of the country. It may be associated with consolidation in some areas, declining agricultural activity in others, and conversion pressures in peri-urban zones. Similarly, the relevance of irrigation, diversification, digital technologies, or renewable-energy investment depends on the production system, accessibility, labour supply, infrastructure, and environmental constraints of individual territories. The results therefore support an interpretation in which agricultural transformation is spatially uneven and composed of multiple, partly independent processes.

Within this context, multifunctionality is useful primarily as an analytical framework rather than as a label for a particular type of farm. It allows structural, economic, environmental, demographic, technological, and territorial changes to be

considered within the same analytical structure without assuming that they develop simultaneously or in the same direction. A farm may adopt precision technologies without diversifying its income, install photovoltaic equipment without establishing circular material flows, or engage in processing while retaining conventional production practices. Conversely, holdings with limited technological investment may continue to contribute to employment, landscape maintenance, local food supply, or other territorial functions.

Overall, the Serbian evidence points to a differentiated agricultural transition in which structural concentration, demographic ageing, diversification, water management, technological adoption, renewable-energy use, and land-use change proceed at different rates and with different territorial expressions. No single indicator is sufficient to characterise the sustainability or multifunctionality of Serbian agriculture. Their analytical value lies in showing how these processes coexist, intersect, and sometimes develop independently, which is precisely why a multifunctional framework is useful for interpreting contemporary agricultural change.

Conclusions

The findings show that agricultural transformation in Serbia is characterised by the simultaneous operation of structural, demographic, technological, environmental, and spatial processes rather than by a uniform shift towards a single agricultural model. Between the two agricultural censuses, the number of holdings and total labour input declined substantially, while utilised agricultural area contracted more slowly and average UAA per holding increased. This pattern is consistent with a concentration of operated agricultural land, occurring alongside pronounced demographic ageing and limited generational renewal.

The empirical evidence also shows that diversification and technological adjustment are present, but unevenly distributed. Other gainful activities remain limited to a minority of holdings, precision and automated technologies are selectively adopted, and renewable-energy equipment represents a measurable but still limited component of agricultural resource and energy adjustment. Irrigation further illustrates marked regional variation in water management. Taken together, these findings indicate that structural change, diversification, resource management and technological adoption are proceeding at different rates rather than forming a single, uniform transition. The geospatial evidence from the peri-urban municipality of Grocka adds a territorial dimension to these national trends. Long-term land-cover change reflects both conversion of agricultural land to built-up uses and internal restructuring within agriculture, while the more recent Sentinel-based assessment shows further expansion of built-up surfaces alongside a reduction in crop-covered

areas. This local case does not represent Serbia as a whole, but illustrates how broader agricultural changes can take specific forms under peri-urban conditions and land-use competition.

Multifunctionality is therefore useful primarily as an analytical framework for interpreting the coexistence of productive-economic, environmental-resource, demographic-social, and spatial-territorial functions. Its value lies in connecting these dimensions without assuming that they develop simultaneously or that the adoption of a particular practice represents a complete transformation of the farming system. The Serbian evidence consequently points to a territorially differentiated agricultural transition in which structural, demographic, technological, resource-related and land-use processes do not necessarily progress in parallel. Future research should extend the analysis through more detailed regional and local comparisons, longer time series for technological and environmental indicators, and farm-level data capable of linking structural change with economic performance, resource efficiency, and environmental outcomes. Such evidence would enable more direct assessment of the relationships among farm structure, multifunctionality and sustainability across different agricultural and territorial contexts in Serbia.

Acknowledgements

The authors acknowledge institutional support from the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract Nos. 451-03-34/2026-03, 451-03-137/2025-03/200123, and 451-03-33/2026-03/200091).

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Original scientific article

Received: 27.04.2026;

Received in revised form: 08.06.2026;

Received in second revised form: 24.06.2026;

Accepted: 24.06.2026;

Available online: 28.10.2026.

UDC: 711.4:314(497.6)

doi: 10.5937/zrgfub26055M

**PERI-URBAN AND DEMOGRAPHIC
TRANSFORMATION OF SLATINA
SETTLEMENT WITHIN THE FUNCTIONAL
SYSTEM OF BANJA LUKA**

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Abstract: This study analyzes the process of peri-urban and demographic transformation of the Slatina settlement within the functional system of Banja Luka. The main objective of this study is to examine spatial, demographic, and functional transformation processes in Slatina and to identify the key drivers of its transition from a rural to a peri-urban settlement within the functional system of Banja Luka. The research is based on the integration of spatial analysis, demographic indicators, and the concept of peri-urbanization. The results indicate that Slatina is transforming from a rural to a peri-urban settlement under the strong influence of the urban center, Banja Luka. This process is accompanied by significant demographic changes, characterized by population aging, a decline in the proportion of younger residents, and negative demographic trends. Simultaneously, changes in the functional structure of the area are observed, involving a weakening of agricultural functions and a strengthening of residential and service functions. The theoretical framework of the study is grounded in the concept of peri-urbanization and contemporary urban geography, which conceptualizes urban systems as dynamic and functionally integrated spaces. In this context, Slatina is defined as a peri-urban zone within the broader functional system of Banja Luka. The conclusions indicate that Slatina's transformation results from long-term processes of urban expansion, demographic change, and the redefinition of relations between the city and its periphery.

Keywords: peri-urbanization, demographic transformation, Slatina, Banja Luka, urban system

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Introduction

Contemporary spatial development is characterized by the intensive transformation of relations between urban centers and their immediate surroundings, with peri-urban zones emerging as a central focus in settlement geography and regional planning. Peri-urbanization processes, as spatial expressions of urban expansion, gradually blur the boundaries between the city and the countryside, forming hybrid spaces with mixed morphological, functional, and demographic characteristics (Tacoli, 2003; Simon, 2008; ESPON, 2017). In this context, urban systems are increasingly viewed as functionally integrated entities, where peripheral settlements play an active role in the spatial, economic, and demographic dynamics of the broader urban region (Brenner, 2004; Pacione, 2009).

Post-socialist areas are of particular importance in contemporary research, where urban transformation processes occur under particular socio-economic contexts. In these environments, peri-urbanization is often accompanied by rapid residential expansion, functional fragmentation, and significant demographic shifts, including population aging, declining birth rates, and intensified migration flows (Stanilov, 2007; Seto et al., 2012; UN DESA, 2018). Demographic transition in these conditions takes on a particular characteristics, heavily influenced by external factors, especially urban attraction and economic migration (Castles & Miller, 2009).

A key problem in contemporary peri-urban research lies in the insufficiently defined functional boundaries between urban and rural systems, which makes it difficult to clearly interpret spatial, demographic, and functional transformations in transitional settlements. In many cases, including post-socialist urban regions, peri-urban areas evolve in a fragmented and uncoordinated manner, driven by simultaneous processes of suburban expansion, migration, and economic restructuring. Possible approaches to addressing this issue include the application of functional urban region concepts, integrated spatial-demographic analysis, and comparative case-study frameworks, which allow for a more precise understanding of urban influence on peripheral settlements and their transformation dynamics.

Within the regional context of the Republic of Srpska, peri-urbanization processes are most pronounced in the sphere of influence of Banja Luka, the primary urban center. Its spatial expansion and functional dominance lead to the gradual transformation of surrounding rural settlements into peri-urban zones, which assume residential, service, and some recreational functions (Mandić, 2013; 2019). This process is accompanied by the redefinition of the traditional agricultural structure, an increase in daily commuting, and a increased reliance of peripheral settlements on the urban core.

In this study, the Functional System of Banja Luka is conceptualized as a hierarchically organized and spatially integrated urban region, in which Banja Luka functions as the dominant core, while surrounding settlements operate as peri-urban and suburban nodes connected through daily mobility, labor-market interactions, and service dependency flows. This system is characterized by continuous functional interactions that transcend administrative boundaries and define a dynamic urban–rural interface. Within this system, peripheral settlements such as Slatina and other settlements of the Laktaši municipality perform complementary residential, service, and recreational functions while remaining strongly dependent on the urban core. The concept therefore emphasizes functional relationships rather than administrative boundaries and provides the analytical framework for understanding the spatial and demographic transformation of peri-urban settlements in the Banja Luka region.

Previous studies in post-socialist urban regions have shown that peri-urban transformation is commonly associated with suburbanization, functional diversification, increased daily mobility, and demographic restructuring. Research on the daily urban system of Belgrade highlights the growing functional dependence of surrounding settlements on urban cores and the role of demographic processes in shaping spatial change (Filipović et al., 2022). Similar patterns have been observed in metropolitan regions such as Sofia, where urban expansion has been accompanied by land-use change and settlement restructuring (Slaev et al., 2018), as well as in Zagreb and Ljubljana, where peri-urban areas have undergone significant functional and morphological transformation under post-socialist transition dynamics.

However, existing research has predominantly focused on large metropolitan systems, while considerably less attention has been given to smaller spa settlements within the functional influence zones of regional urban centres. As a result, the interaction between demographic change, functional restructuring, and peri-urbanization processes in such contexts remains insufficiently explored. This gap is particularly evident in the case of settlements such as Slatina, which operate within a non-metropolitan but strongly urban-influenced functional system.

Slatina, as a spa settlement in the immediate zone of influence of Banja Luka and functionally linked to the municipality of Laktaši, represents a typical example of such transformations. Its development is characterized by a long historical continuity of settlement, gradual valorization of natural resources (thermal mineral waters), and contemporary processes of suburbanization, decline of agriculture, and functional diversification. Simultaneously, demographic indicators reveal a pronounced process of population aging, a decrease in the proportion of young residents, and an growing migration-driven dynamic of population change.

Based on the theoretical and regional framework, the aim of this study is to analyze the peri-urban and demographic transformation of Slatina within the

functional system of Banja Luka, with the aim of identifying key directions of spatial and demographic development and examining the mechanisms driving the settlement's transformation from a rural to a peri-urban model; accordingly, the study sets the following objectives: to analyze the historical and functional development of Slatina, to determine demographic changes and trends, to identify peri-urbanization processes, and to examine the role of Banja Luka and Laktaši in shaping the functional system of the area.

Based on the theoretical and regional framework, this study analyzes the peri-urban and demographic transformation of Slatina within the functional system of Banja Luka, aiming to identify key spatial and demographic development trends and the mechanisms of its transition from a rural to a peri-urban model, while also addressing its historical-functional development, demographic changes, peri-urbanization processes, and the role of Banja Luka and Laktaši in shaping the functional system of the area.

Based on the theoretical and regional framework, the objective of this study is to analyze the peri-urban and demographic transformation of Slatina within the functional system of Banja Luka, with the aim of identifying key directions of spatial and demographic development and examining the mechanisms driving the settlement's transformation from a rural to a peri-urban model; accordingly, the study sets the following objectives: to analyze the historical and functional development of Slatina, to determine demographic changes and trends, to identify peri-urbanization processes, and to examine the role of Banja Luka and Laktaši in shaping the functional system of the area.

Based on these objectives, the following hypotheses were formulated:

H1: Slatina is developing as a peri-urban settlement under the dominant influence of Banja Luka.

H2: Demographic development is characterized by population aging and negative natural growth.

H3: Migration processes are a key factor in spatial transformation.

H4: The functional structure of the settlement is shifting from agricultural to mixed peri-urban.

The scientific significance of the study lies in its contribution to understanding peri-urbanization processes in smaller spa settlements, which have been significantly underrepresented in the literature compared with large urban systems. The research also highlights key demographic risks in urban influence zones and provides a foundation for further spatial planning and regional development studies.

Methodology

The research is based on a mixed-method approach that combines quantitative and qualitative methods to achieve a comprehensive analysis of historical, spatial, demographic, and functional processes. The spatial scope of the study includes the settlement of Slatina and nearby settlements such as Malo Blaško within the administrative area of the municipality of Laktaši. The settlement of Slatina is located within the municipality of Laktaši in the Republic of Srpska (Bosnia and Herzegovina), positioned in the immediate functional sphere of influence of the city of Banja Luka. It is situated within a lowland corridor that forms part of the broader urban–peri-urban transition zone connecting Banja Luka with its surrounding municipalities. Due to its geographical proximity and strong functional linkages with the urban core, Slatina has undergone gradual integration into the peri-urban system of Banja Luka, particularly through residential expansion and daily commuting flows.

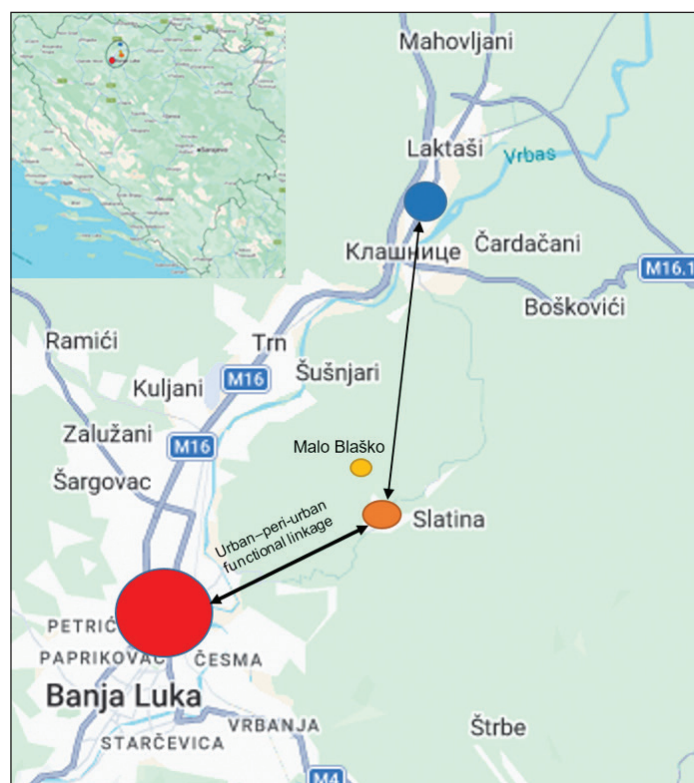


*Figure 1. Location of Slatina within the functional system of Banja Luka
(schematic representation based on Google Maps)*

The Banja Luka–Slatina corridor represents a strategically important spatial zone where processes of urban expansion, demographic redistribution, and functional restructuring are most clearly expressed. This corridor is characterized by intensive interaction between the urban centre and peripheral settlements, making it a key analytical unit for understanding peri-urban transformation processes in the region. Within this framework, Slatina is interpreted as a representative peri-urban settlement undergoing transition from a rural to a functionally integrated urban-influenced system.

In addition to traditional descriptive and statistical data processing, visual analysis was employed using line graphs and stacked bar charts to illustrate age groups, gender structure, and temporal trends of the population, as well as the comparative household structure. These visualizations facilitate the assessment of population dynamics, demographic aging, and migration flows. The study relies on population census data from 1879 to 2013, statistical yearbooks of the Republic of Srpska Institute of Statistics, spatial and urban plans of the municipalities of Laktaši and the settlement of Slatina, and relevant scientific and professional literature.

Through the analysis of these data, temporal comparisons of population dynamics by settlements and age groups were conducted, and growth rates, aging indices, age and youth coefficients, as well as annual rates of change, were calculated. At the same time, demographic indicators were integrated with household structures and migration flows, enabling a integrated synthetic interpretation of spatial-demographic processes in the peri-urban context. In this way, the research results provide a more complete picture of the transformation of rural settlements under the influence of urban centers, highlighting how both natural demographic dynamics and migration processes shape the contemporary population structure.

Research Results

Spatial-Historical Evolution of Slatina

The area of Slatina represents a long-term settled geographic complex in the northeastern peri-urban area of Banja Luka, whose development has been shaped by the interaction of natural factors (thermal mineral springs, morphological position within the Banja Luka basin) and anthropogenic processes of spatial organization. In the contemporary peri-urban context, Slatina can be considered part of the functional urban region of Banja Luka, dominated by the transformation of rural structures under the influence of the urban center (Brenner, 2004; ESPON, 2017).

Although systematic archaeological research has not been sufficiently conducted, indirect archaeological and historical evidence suggests a long continuity

of settlement dating back to the prehistoric period. This area belongs to the broader cultural-geographical zone of northwestern Bosnia, characterized by early and stable settlement patterns in areas with favorable environmental conditions (Group of Authors, 1985).

During the medieval period, Slatina developed as a dispersed type of village settlement, characteristic of the Dinaric region. The spatial structure was dominated by family cooperatives and a settlement model in which the basic organizational unit was the cooperative, featuring a well-defined internal hierarchy (Cvijić, 1918). This model resulted in a dispersed spatial structure, where family cores later became the basis for forming hamlets and local settlement nuclei.

During Ottoman rule, Slatina fell within the administrative jurisdiction of the Kobaš kadiluk and later the Banja Luka captaincy. The area retained a distinctly agrarian character based on livestock farming, fruit cultivation, and subsistence agriculture (Popović, 2002). At the same time, early forms of empirical utilization of thermal mineral waters appeared, marking the initial stage of its future spa function. However, this potential remained uninstitutionalized and functionally underdeveloped within the traditional rural system.

With the arrival of Austro-Hungarian administration at the end of the 19th century, systematic modernization of the area began. Geodetic and cadastral surveys (1880-1883) provided the basis for more rational land management and the introduction of planned spatial relations (Group of Authors, 1985). Of particular significance was the activity of the Trappist order, which introduced modern agricultural techniques, improved transport connectivity, and strengthened the link with Banja Luka as a growing urban center. This marked the beginning of the functional integration of Slatina into the broader urban system (Bertaud, 2004).

In the first half of the 20th century, the development of transport infrastructure and the gradual growth of the spa function intensified. The construction of transport and bridge structures at the beginning of the 20th century (1904) facilitated stronger spatial and economic connectivity. In the interwar period, the following developments were observed: the beginning of planned interventions in the spa area, the development of hospitality and recreational facilities, and the formation of early forms of tourist activity. This phase represents a typical “transitional spa” model, in which rural space gradually becomes functionally specialized (Hall & Page, 2014).

After the Second World War, the area underwent reconstruction and institutional reorganization. Industrialization in the wider Banja Luka region led to functional differentiation, while Slatina retained its agrarian base but strengthened its service and public functions (Urban Plan of Slatina 2007–2022). The 1969 earthquake marked a turning point in spatial reconstruction, after which the development of public infrastructure intensified, and the educational and healthcare functions of the settlement were strengthened.

From the end of the 20th century, Slatina entered a phase of pronounced peri-urbanization, dominated by the influence of Banja Luka as a regional center. This process is characterized by intensive daily commuting to Banja Luka, the transformation of rural areas into peri-urban residential space, the weakening of primary agricultural functions, and the strengthening of service and commercial activities. In the contemporary context, Slatina is defined as a peri-urban settlement within the functional urban region of Banja Luka, with partial administrative influence from the municipality of Laktaši (ESPON, 2017; Spatial Plan of Laktaši Municipality 2014–2034).

Functional Transformation of Slatina

Transport, Commerce, and Educational-Cultural Development

The functional transformation of Slatina represents a second key dimension of its peri-urban evolution, in which the spatial structure gradually reshapes from predominantly agricultural to multifunctional one. This process is directly influenced by strengthened transport connectivity with Banja Luka, the development of service activities, and the institutionalization of educational and cultural functions. Theoretically, this transformation corresponds to the model of peri-urban zones where functional hybridity of rural and urban spaces occurs (Antrop, 2004; ESPON, 2017).

The functional transformation of Slatina from a predominantly agricultural settlement into a multifunctional peri-urban centre has been driven by the development of several key economic and service sectors. These include local retail activities, small business services, educational institutions, and healthcare facilities, which collectively contribute to the diversification of the settlement's functional structure. In addition, the proximity to Banja Luka has stimulated daily mobility and increased demand for non-agricultural services, further strengthening Slatina's role within the peri-urban system.

The transport function constitutes the primary factor integrating Slatina into the functional system of Banja Luka. A main and local transport axis, Banja Luka–Slatina–Klašnice, passes through the inner urban area and serves as the principal structural line of the settlement's spatial organization. The development of transport infrastructure has enabled the intensification of daily commuting, integration into the labor and educational system of Banja Luka, and improved accessibility to the spa complex. At the same time, transit traffic through the central zone represents a spatial conflict, as it leads to decreased environmental quality and functional deterioration of the central urban core.

Commerce in Slatina has a long historical trajectory, traceable to the late 19th century. Its initial development was directly linked to the spa function and the emergence of early forms of tourism, which represented the first drivers of non-agrarian economic activity in the settlement. In the contemporary period, the commercial function is characterized by the predominance of small mixed-use retail facilities, a limited diversity of goods and services, and a strong local market orientation. Although it adequately satisfies the basic needs of the resident population and spa visitors, commerce has not developed into a secondary service center of wider significance, indicating a low level of urban economic specialization.

The educational function represents one of the most stable and structurally significant components of Slatina's functional system. The establishment of a school in the early 20th century marked the beginning of the institutionalization of education at the local level (Popović, 2002). Over time, the school evolved into a center of educational centrality for the surrounding area, a focal point of cultural activity, and an important generator of daily commuting among the student population. In parallel, cultural life—although uneven in intensity—has been sustained through school-based initiatives, amateur associations, sports organizations, and occasional community events, which is typical for peri-urban settlements with limited institutional infrastructure (Hall & Page, 2014).

In addition, the development of both commercial and educational functions has contributed to the gradual strengthening of Slatina's social cohesion and its functional dependence on the wider urban system of Banja Luka. Despite these developments, the overall functional structure remains spatially and sectorally unbalanced, with clear dominance of transport-related functions and only partial consolidation of service-oriented activities. This reinforces the interpretation of Slatina as a peri-urban settlement in a transitional phase, characterized by incomplete functional integration and ongoing reconfiguration of its urban-rural interface.

Tourism and the Spa Function of Slatina

Tourism and the spa function represent a specific developmental layer in the evolution of Slatina, conditioned by the presence of thermal mineral springs and their gradual functional valorization. Unlike classical rural functions, the spa function in Slatina exhibits a form of “induced spatial specialization,” developing under the influence of external factors, primarily the urban center of Banja Luka and land-use change dynamics (Hall & Page, 2014). Within the theoretical framework, the spa area is regarded as a specific type of functional zone where health, recreational, and tourism functions overlap, placing it within the category of hybrid peri-urban spaces (ESPON, 2017).

The first forms of utilization of thermal mineral waters in Slatina date back to the Ottoman period, but lacked institutional organization and infrastructural development. During this period, the spa function had an exclusively local and empirical character, based on traditional forms of natural resource use. This phase can be considered a “proto-spa period”, in which resources existed but a structured functional system was absent. Systematic valorization of spa potential began during the Austro-Hungarian period, when elements of a planned approach to spatial organization were first introduced (1880–1883). Although the spa function was not fully institutionalized at that time, it became a recognizable element of the spatial structure.

In the interwar period, the following developments occurred: the emergence of the first hospitality facilities, the development of recreational amenities, and the initial formation of a tourism function. This phase represents a transition from natural resource use to a functional spa system. After the Second World War, the spa function entered a phase of institutional reconstruction.

Much of the physical infrastructure was damaged, but facilities were gradually restored, and public health and recreational functions were introduced. A major reconstruction phase followed the 1969 earthquake, modernizing the spa complex. Today, Slatina’s spa develops amid pronounced peri-urban transformation. Proximity to Banja Luka strongly shapes demand, spatial organization, and functional orientation. Health and rehabilitation services have grown, while tourist commercialization remains limited. Day visitors dominate, and supporting infrastructure is underdeveloped. Urban plans include Slatina in a broader spa-recreational system for Banja Luka, though spatial and environmental limits persist. Spa and tourism functions are unevenly developed, with natural potential underexploited. Fragmented functional use restricts comprehensive tourism specialization. Slatina can thus be described as a peri-urban spa dominated by regional health functions with limited tourism capacity.

Demographic Transformation of Slatina

Demographic change represents an integral component of the overall functional transformation of Slatina, reflecting the interaction between spatial mobility, urban influence, and natural population dynamics. In peri-urban contexts such as Slatina, demographic processes are closely linked to the functional integration with nearby urban centers, particularly through migration flows, changes in household structure, and shifts in the age composition of the population. These processes are strongly influenced by the gravitational pull of Banja Luka, which acts as the primary driver of population redistribution in the area. Consequently, Slatina exhibits characteristics of demographic ageing, a decline in younger cohorts, and a gradual restructuring of its

population base. These trends highlight the interdependence between demographic and functional changes within peri-urban systems and provide important insights into future spatial development and planning challenges.

The data presented in Table 1 indicate the long-term, phased demographic dynamics of Slatina and Malo Blaško in the period from 1879 to 1931. These areas developed as rural settlements with a relatively stable population structure, although with notable fluctuations in total population. In the first phase (1879–1885), moderate population growth is evident, reflecting stable living conditions and the absence of major migratory disturbances. This period is characterized by a traditional agrarian structure in which demographic growth primarily depended on natural increase. The data for 1895 show a sudden decline in the population of Slatina, representing a pronounced demographic anomaly compared to the previous census cycle, likely related to administrative, territorial, or socio-economic factors. At the beginning of the 20th century (1910 and 1921), a gradual recovery and renewed population growth can be observed, indicating a stabilization of demographic processes and a re-establishment of rural settlement continuity. This phase represents a period of relative demographic equilibrium within the framework of the traditional agrarian economy. A particularly notable data point is that of 1931, which records an exceptionally high population in Slatina compared to previous censuses. This abrupt increase may indicate methodological differences in census enumeration or the territorial expansion of the settlement. Regardless, it is evident that, during this period, Slatina emerged as a more significant rural settlement with pronounced demographic potential.

Table 1. Population Dynamics of Slatina and Malo Blaško (1879–1931)

Census Year		Area		
		Slatina	Malo Blaško	Total
1879	Total	985	221	1206
	Male	543	131	674
	Female	442	90	532
1885	Total	1140	285	1425
	Male	625	169	794
	Female	515	116	631
1895	Total	301	249	550
	Male	168	134	302
	Female	133	115	248

1910	Total	405	371	776
	Male	220	184	404
	Female	185	187	372
1921	Total	492	369	861
	Male	-	-	-
	Female	-	-	-
1931	Total	4861	-	4861
	Male	2607	-	2607
	Female	2254	-	2254

Source: Census books from 1879 to 1931

Overall, the relationship between Slatina and Malo Blaško indicates a functionally interconnected spatial unit, forming a coherent local community with shared demographic development. Throughout the period, a predominantly rural settlement type prevailed, although with a gradual strengthening of internal demographic differentiation. Table 1 demonstrates that Slatina developed as a stable rural settlement in the period 1879–1931, exhibiting phased demographic fluctuations and a long-term increase in population potential, which laid the groundwork for subsequent urban and peri-urban transformations in later historical periods.

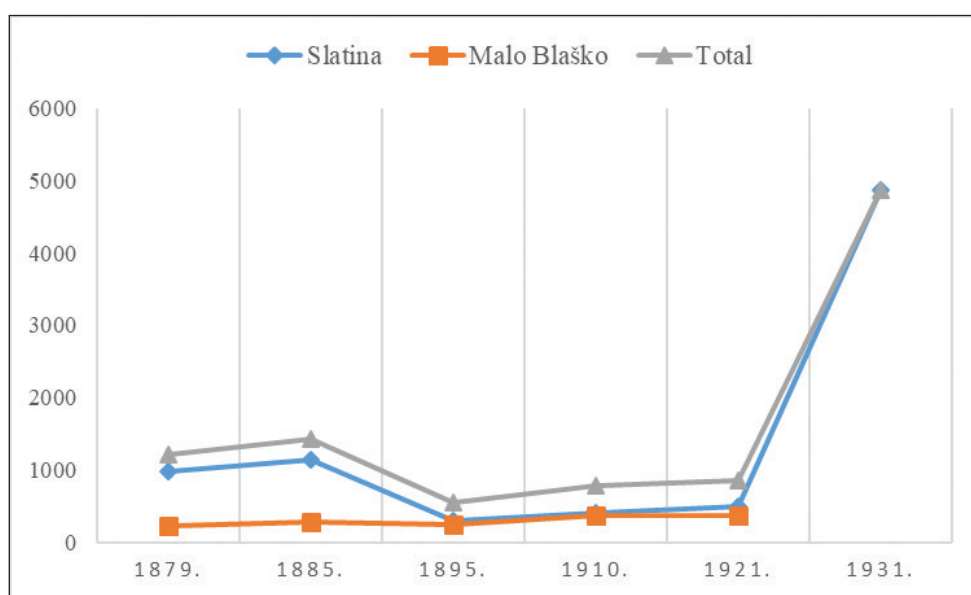


Figure 2. Line Chart – Population Trends in Slatina and Malo Blaško

The line chart illustrates the total population of Slatina and Malo Blaško across census years, enabling a clear visualization of long-term demographic trend.

The phased dynamics are evident: moderate growth in the period 1879–1885, a sharp decline in 1895, gradual recovery from 1910 to 1921, and a pronounced increase in 1931 for Slatina. The chart also highlights the difference in population size between the two settlements, with Slatina exhibiting greater demographic stability and a significantly higher population compared to Malo Blaško. Although Malo Blaško shows its own phases of growth and decline, its demographic potential remains considerably lower, confirming a persistent functional asymmetry within the shared local system. The line chart further facilitates the visual identification of anomalies and discontinuities, such as the abrupt population decrease in 1895 and the marked increase in 1931, which may be associated with administrative changes, migration processes, or territorial expansion of Slatina. In addition, the visualization clearly indicates the long-term dominance of Slatina within the local demographic system and its role as the primary population center in the micro-regional context. Thus, the chart complements tabular data by providing an intuitive overview of long-term demographic evolution and enhancing interpretability without requiring extensive statistical elaboration in the text. It also allows for a more direct comparison of temporal dynamics between the two settlements, reinforcing the interpretation of their divergent developmental trajectories.

Table 2. Population Dynamics of Slatina and Malo Blaško (1948–2013)

Census Year	Slatina	Malo Blaško	Total
1948	930	631	1561
1953	1054	672	1726
1961	1139	638	1777
1971	1188	589	1777
1981	1180	571	1751
1991	1153	591	1744
2013	1344	666	2010

Source: Census books from 1948 to 2013

The data from Table 2 show the demographic dynamics of Slatina and Malo Blaško during the period 1948–2013, a key phase marking the transition from a traditional rural to a peri-urban space under the influence of urbanization in Banja Luka. In the first post-war census period (1948–1961), moderate but stable population growth is observed, characteristic of demographic recovery following the Second World War. This growth reflects relatively favorable socio-economic conditions and the persistence of traditional rural functions in the settlements. However, from 1961 onward, stagnation in the total population becomes evident, with minor fluctuations across individual census years. This stabilization, without significant growth, indicates the onset of demographic transition and the gradual weakening of natural increase.

The period 1971–1991 is characterized by pronounced demographic stagnation, with slight declines in some census counts. This phase can be associated with intensified urbanization processes in Banja Luka, leading to the out-migration of younger and working-age populations from peripheral rural settlements toward the urban center. At the same time, Slatina maintains a certain level of stability due to its geographical proximity and its emerging role as a suburban settlement. The 2013 census shows a significant increase in population compared to previous periods, marking a major turning point in demographic dynamics. This population increase can be further interpreted through the distinction between natural population change (birth and death rates) and migration balance, where migration processes are identified as the dominant driver of population growth in the peri-urban context. Although detailed vital statistics are not available at the settlement level for all periods, available demographic trends strongly suggest that spatial mobility and in-migration from the urban center of Banja Luka played a more significant role than natural increase in shaping the observed population dynamics. This growth can be interpreted as a result of peri-urbanization, i.e., the expansion of Banja Luka's residential zones into peripheral areas, attracting new inhabitants to Slatina as a residentially attractive area near the urban center. Malo Blaško follows a similar, though slightly less pronounced, trend, reflecting the functional connection between the two settlements within the same local system, as well as differences in the intensity of urban influence. Table 2 demonstrates Slatina's transition from a phase of demographic stagnation to a phase of moderate growth driven by peri-urbanization after the 2000s. This pattern confirms that contemporary demographic development is not primarily driven by natural increase, but by spatial expansion from Banja Luka and the transformation of Slatina into a peri-urban residential settlement.

Table 3. Annual Population Growth and Decline Rates of Slatina and Malo Blaško (1948–2013)

Area	Census period					
	1948-1952	1953-1960	1961-1970	1971-1980	1981-1990	1991-2013
Slatina	2,6	1,0	0,4	-0.07	-0,2	0,7
M. Blaško	1,3	0,2	-1,4	-0,3	0,3	0,5
Total	2.7	0.7	-0.2	-0.1	-0.04	0.7

Author's elaboration based on Table 2.

Table 3 shows annual population growth and decline rates for 1948–2013, providing a more precise view of demographic phases than absolute numbers alone. In the early post-war period (1948–1952), Slatina experienced strong positive growth (2.6%; overall 2.7%), reflecting recovery and natural increase. Growth slowed in

1953–1960, marking the start of demographic transition and initial migration to urban centers. Between 1961 and 1970, rates approached zero or turned negative (-0.2%), indicating demographic stagnation and urbanization-driven outflow from rural areas. From 1971 to 1980, growth remained near zero or negative, exemplifying peri-urban pressure and rural depopulation. The 1981–1990 period saw continued low or negative rates, confirming prolonged stagnation. After 1991, positive growth resumed (0.7%) due to the expansion of residential areas and peri-urban settlement in Slatina. Overall, Table 3 highlights a cyclical demographic pattern—from post-war expansion, through stagnation, to renewed growth—demonstrating the non-linear impact of urbanization and peri-urban transformation.

Migration processes represent a key explanatory mechanism behind the observed demographic dynamics of Slatina, although direct migration statistics at the settlement level are not available for all census periods. Therefore, migration intensity is inferred indirectly through the relationship between natural population change, total population trends, and age-structure shifts.

The post-1961 stagnation and decline in growth rates (Table 3) indicate a continuous out-migration of younger and working-age population toward Banja Luka, driven by employment opportunities, education, and urban amenities. This process contributed significantly to the progressive aging of the population and the weakening of the reproductive base of the settlement. In the post-1991 period, population growth resumes despite low natural increase, which suggests a dominant influence of in-migration rather than endogenous demographic reproduction. This is consistent with peri-urban residential expansion from Banja Luka, where Slatina becomes an attractive settlement for daily commuters and relocated households.

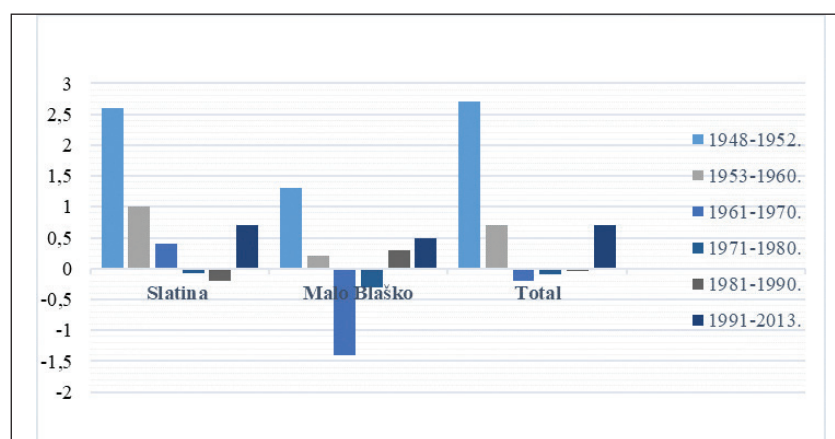


*Figure 2. Annual Population Growth and Decline Rates
of Slatina and Malo Blaško (1948–2013)*

Contemporary migration patterns are characterized by circular and daily mobility rather than permanent relocation. The settlement functions as part of the daily urban system of Banja Luka, with strong commuting flows toward employment, education, and services. This reinforces its role as a peri-urban residential zone within the functional system. Overall, migration emerges as the central driver of demographic restructuring in Slatina, mediating between urban expansion and local demographic aging. Although not directly measured through migration statistics, the combination of census dynamics and structural demographic changes provides robust indirect evidence of migration-led transformation.

The diagram shows that both Slatina and Malo Blaško experienced population decline until 1991, with Slatina stabilizing and slightly increasing afterward, while Malo Blaško exhibits a more pronounced and sustained decline, highlighting its weaker demographic potential and vulnerability to depopulation.

Table 4. Population structure of Slatina by age groups, according to the censuses 1971–2013

Census year	Total population		Age groups					
	Absolute	%	0-19	%	20-59	%	60+	%
1971	1777	100	730	41,1	851	47,9	196	11,0
1981	1751	100	629	35,9	902	51,5	220	12,6
1991	1744	100	503	28,8	949	54,4	292	16,7
2013	2010	100	424	21,1	1070	53,2	516	25,7

Source: Census books of 1971, 1981, 1991, and 2013.

Table 4 presents changes in the age structure of Slatina's population from 1971 to 2013, providing a direct insight into processes of demographic aging and the long-term consequences of peri-urban transformation. In 1971, the population structure shows a relatively favorable demographic balance, with a significant share of young people (0–19 years: 41.1%) and a stable proportion of the working-age population (47.9%). This structure is characteristic of a phase of demographic vitality under conditions of a still predominantly rural settlement. In the following decade (1981), a decline in the proportion of young people is observed (35.9%), accompanied by an increase in the working-age population (51.5%). This change indicates the onset of demographic transition, resulting from general demographic transition processes, including declining fertility rates and intensified migration flows toward urban centers.

The 1991 census shows a clearly pronounced trend of demographic aging: the share of young people falls to 28.8%, while the proportion of the population aged

60 and over rises to 16.7%. This structure reflects accelerated out-migration of the younger population and a weakening of the reproductive base. The most significant shift is observed in 2013, when the share of young people drops to only 21.1%, while the proportion of the elderly rises to 25.7%. Such an age structure represents a clearly regressive demographic model, in which the population has entered a phase of advanced aging. At the same time, a relatively stable or slightly increasing share of the working-age population (53.2%) indicates that part of the population is sustained by in-migration into the peri-urban area.

Table 4 unequivocally demonstrates the long-term process of demographic aging in Slatina, occurring in parallel with the peri-urban transformation of the area. The decline in the share of young people and the increase in the elderly population confirm the hypothesis of negative demographic trends (H2), while simultaneously indicating a change in the functional role of the settlement within the Banja Luka functional system.

Table 5. Detailed Age Structure of the Population of Slatina and Malo Blaško (2013)

	Sex	Years of age																		
		Tot.	0-4	5-9	10-15	16-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75-79	80-84	85+
M a l o B.	T.	666	23	35	24	51	59	50	33	36	39	55	61	44	43	30	29	30	16	8
	M.	334	17	18	10	21	34	25	16	22	16	31	33	26	20	10	14	12	6	3
	F.	332	6	17	14	30	25	25	17	14	23	24	28	18	23	20	15	18	10	5
S l a t.	T.	1344	58	61	79	93	80	70	66	96	95	110	98	76	99	82	83	60	27	9
	M.	642	25	32	35	52	41	33	37	50	44	54	50	36	42	36	37	25	8	5
	F.	702	33	29	44	41	39	37	29	48	51	56	48	40	57	46	46	35	19	4

Source: Census of Population, Households, and Dwellings in the Republic of Srpska, 2013, Republika Srpska Institute of Statistics, 2013

Table 5 presents the detailed age structure of the population of Slatina and Malo Blaško by five-year age groups according to the 2013 census, allowing a more precise insight into the internal demographic structure and the degree of population aging in the observed area. It is evident that the total population of Slatina (1,344 inhabitants) is significantly larger than that of Malo Blaško (666 inhabitants), confirming Slatina's dominance as the central settlement within the shared functional space.

The young population (0–19 years) in both settlements is moderate, without significant growth. In Slatina, young people are present but do not dominate, indicating low fertility and a weakened reproductive base. In Malo Blaško, their share is even smaller, suggesting stronger demographic stagnation and potential

depopulation, which poses challenges for future labor supply, education, and social services.

The working-age population (20–59 years) forms the majority in both settlements, concentrated in the 30–54 age intervals, reflecting a stable but demographically “mature” structure with limited generational renewal. This highlights their role as peri-urban areas with active commuting to Banja Luka and potential vulnerability if out-migration continues.

The elderly population (60+) is substantial, with notable shares in the 65+ and 70+ groups. Smaller cohorts persist in the oldest ages, indicating increased life expectancy but insufficient replacement. This aging trend raises dependency ratios and pressures on healthcare and local infrastructure, with a slightly higher female predominance consistent with general mortality patterns. Overall, Table 5 shows an aging and structurally imbalanced population in Slatina and Malo Blaško, dominated by working-age and older cohorts, with an insufficient share of youth. These patterns confirm that both settlements are in an advanced stage of demographic transition and peri-urban transformation, where natural population renewal is weakened and migration has become the key driver of demographic stability, emphasizing the need for integrated planning to address labor supply, social infrastructure, and long-term demographic aging.

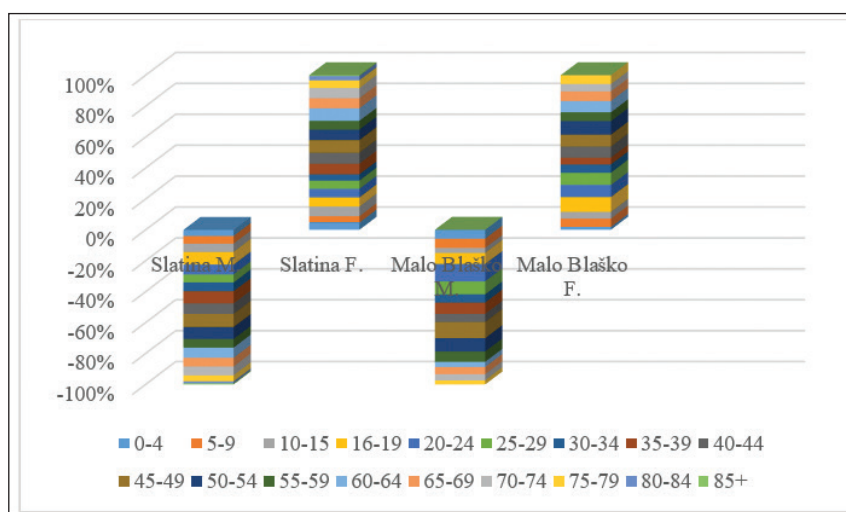


Figure 3. Age Structure of the Population in Slatina and Malo Blaško (2013) presented as a visual complement to Table 5 for easier interpretation of demographic composition.

Figure 3 visualizes the age structure of the populations of Slatina and Malo Blaško in 2013, with each column representing the total population of a settlement

and the segments within the columns indicating age groups. In both settlements, the working-age population (20–59 years) dominates, confirming a peri-urban functional orientation and strong links to migration toward the urban center. In Slatina, the column is noticeably taller than in Malo Blaško, reflecting a larger total population and its central role within the functional system. The younger age groups (0–19 years) occupy a smaller portion of the columns, indicating low fertility rates and a reduced reproductive base, while the older segments (60+) account for a relatively larger share, particularly in Slatina, pointing to pronounced population aging. In Malo Blaško, shorter columns and an even smaller share of youth highlight demographic stagnation and relative depopulation compared to Slatina.

The figure provides a clear visual representation of the age distribution, indicating a predominance of the working-age and elderly population, alongside a relatively lower share of younger cohorts, which may have implications for long-term demographic renewal. This pattern confirms an advanced stage of demographic transition and peri-urban transformation, where migration and population aging strongly shape demographic dynamics. It also reflects increasing structural imbalance within the age pyramid, particularly in the smaller settlement, where demographic sustainability is more fragile. Overall, the chart effectively distinguishes between the more stable and larger settlement of Slatina and the smaller and more aged Malo Blaško, highlighting key planning and sustainability challenges in the peri-urban area of Banja Luka.

Table 6. Aging Index, Age Coefficient, and Youth Coefficient of the Population of Slatina (1971–2013)

Census Year	Aging Index	Age Coefficient	Youth Coefficient
1971	24.8	10.2	41.1
1981	35.0	12.6	35.9
1991	58.0	16.7	28.8
2013	121.8	25.7	21.1

Source: Author's elaboration based on Table 4

Table 6 presents synthetic demographic indicators that allow for a quantitative assessment of the aging process of Slatina's population between 1971 and 2013. These indicators represent a high level of demographic analysis, as they integrate the relationship between young and old populations into a single structural framework. In 1971, the aging index was 24.8, indicating a relatively young population structure dominated by younger cohorts compared to the elderly. The age coefficient was low (10.2), while the youth coefficient was high (41.1), confirming a phase of demographic vitality and a relatively favorable age structure. By 1981, the aging

index had increased to 35.0, accompanied by a decline in the youth coefficient. This reflects the onset of accelerated demographic aging, driven by declining fertility rates and the initial intensification of migration flows toward urban centers.

The 1991 census shows a marked deterioration in the demographic structure. The aging index rose to 58.0, while the youth coefficient fell to 28.8. This clearly indicates entry into a phase of pronounced demographic transition, in which the elderly population occupies an increasingly larger share of the total population. The most drastic change is observed in 2013, when the aging index reached 121.8, meaning that the number of elderly residents is more than twice that of the younger population. The age coefficient increased to 25.7, while the youth coefficient declined to only 21.1, clearly indicating deep demographic aging and a regressive demographic regime.

Table 6 unequivocally demonstrates a continuous and accelerated process of population aging in Slatina, culminating in 2013 in an extremely regressive age structure. The increase of the aging index above 100 represents a critical demographic threshold, confirming that Slatina has entered a stage of advanced demographic aging. These results directly support the hypothesis of negative demographic trends (H2) and indicate a strong interdependence between demographic change and peri-urbanization processes within the functional system of Banja Luka.

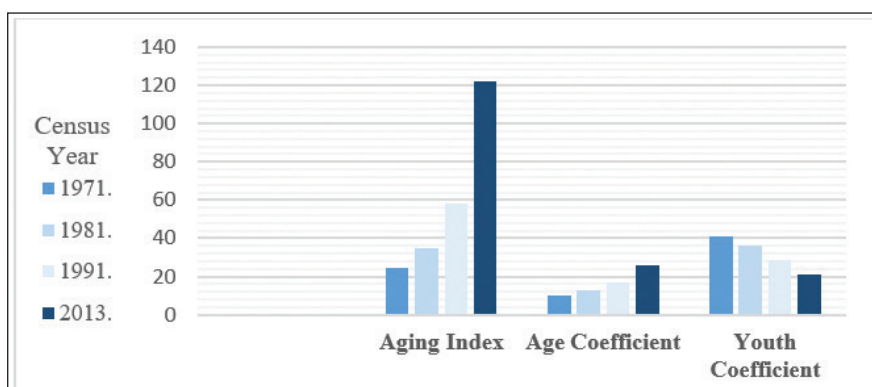


Figure 4. Diagram of the Aging Index, Age Coefficient, and Youth Coefficient of the Population of Slatina

The graph of the annual aging rate shows that demographic aging in Slatina accelerated over time, from about 1% annually in 1971–1981 to 2.2% in 1981–1991, reflecting declining fertility and youth out-migration toward urban centers. After 1991, the rate rises to nearly 3.0% per year, indicating intensified migration processes and peri-urban transformation within the Banja Luka functional system. This pattern confirms that aging is not linear but occurs in distinct phases with increasing intensity.

Table 7. Dependency Ratio of the Working-Age Population (1971–2013)

Year	Young Dependents (0–19)	Elderly Dependents (60+)	Working-Age Population (20–59)	Total Dependency Ratio (%)	Youth Dependency Ratio (%)	Elderly Dependency Ratio (%)
1971	41.1%	10.2%	47.9%	107.9	85.8	21.3
1981	35.9%	13.0%	51.5%	94.8	69.7	25.2
1991	28.8%	16.7%	54.5%	82.3	52.8	30.6
2013	21.1%	25.7%	53.2%	87.0	39.6	48.3

Source: Author's elaboration

The dependency ratios were calculated using standard demographic formulas: the youth dependency ratio as the share of the population aged 0–19 in relation to the working-age population (20–59), the elderly dependency ratio as the share of the population aged 60+ relative to the working-age population, and the total dependency ratio as their combined proportion. The results show a clear trend: the youth dependency ratio steadily declines due to a shrinking young population, while the elderly dependency ratio increases sharply, reflecting ongoing population aging. By 2013, nearly half of the working-age population supports elderly residents, indicating growing social and economic pressures on the demographic structure.

Table 8. Dynamics of the Number of Households and Average Household Size, 1948–2013

Year	Number of Households	Average Household Size
1948	290	5.4
1953	320	5.4
1961	372	4.9
1971	425	4.2
1981	449	3.9
1991	503	3.5
2013	677	2.9

Source: Census books, 1948–2013.

Table 8 presents the long-term transformation of household structure in Slatina from 1948 to 2013, using total households and average household size as key indicators of socio-demographic change. In the post-war period, larger extended households dominated (around 5.4 members), reflecting traditional rural family organization and strong intra-household economic cohesion. From 1961 onward, a steady decline in household size and a simultaneous increase in the number of households indicate the onset of nuclearization and demographic transition linked to modernization and changing socio-economic conditions.

By 2013, the average household size falls to 2.9 members, while the number of households reaches its maximum, confirming the dominance of small nuclear and single-person households. This reflects a significant reconfiguration of traditional living arrangements and a marked shift toward more fragmented household units with reduced intergenerational cohabitation. Overall, Table 8 shows a clear structural shift from extended to nuclear family forms, driven by urbanization, migration, and peri-urban transformation within the Banja Luka functional system. This process reflects not only demographic change but also deep social restructuring, including weakening of traditional family solidarity and increased household fragmentation, while also indicating growing individualization of living arrangements and gradual adaptation to urban-oriented lifestyles.

Table 9. Average Household Growth Rate in Slatina (1948–2013)

Household growth rate in %					
1948-1952	1953-1960	1961-1970	1971-1980	1981-1990	1991-2013
2.0	2.0	1.4	0.5	1.2	1.5

Source: Author's elaboration based on Table 8

Table 9 shows the average household growth rate in Slatina from 1948 to 2013, illustrating changes in family and housing structures across different socio-economic phases. In the early post-war period (1948–1960), growth was relatively high and stable (around 2.0%), reflecting demographic recovery and the persistence of traditional rural households. Between 1961 and 1970, the rate declined to 1.4%, indicating the onset of slower household formation due to urban migration and decreasing household size. The 1971–1980 period records a sharp slowdown to 0.5%, reflecting demographic stagnation and intensified out-migration toward urban centers. From 1981 to 1990, growth slightly increases to 1.2%, likely due to internal migration and partial stabilization of peri-urban settlement patterns. Finally, 1991–2013 shows moderate growth (1.5%), indicating the recovery of Slatina's residential function and its strengthening role within the Banja Luka peri-urban system. Table 9 demonstrates that household growth in Slatina followed a non-linear trajectory, with a clear slowdown in the second half of the 20th century and a moderate recovery in the post-socialist period. Overall, these fluctuations reflect the combined influence of demographic change, migration processes, and urbanization dynamics shaping household formation and spatial development.

The chart shows Slatina's household growth rate (1948–2013), with high post-war growth, a slowdown from the 1960s–1980s due to out-migration and smaller households, and moderate recovery after 1981 linked to peri-urban expansion.

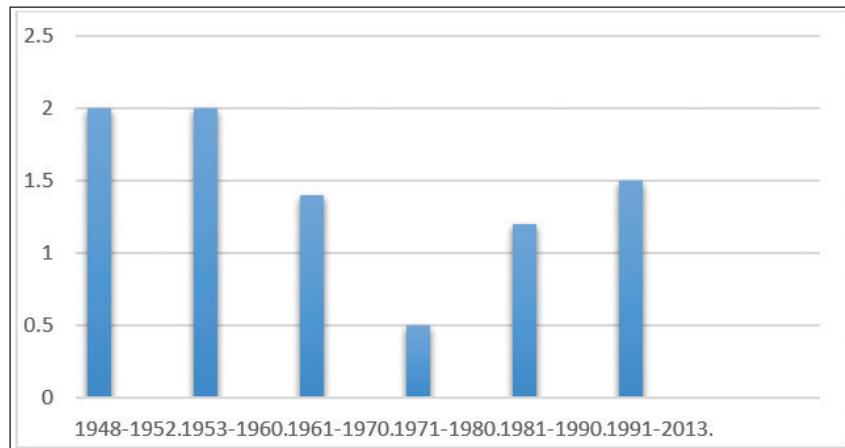


Figure 5. Chart of the Average Household Growth Rate (%) in the Slatina Area

Migration drives long-term demographic change in Slatina, shaping historical population structure and peri-urban transformation. Mid-20th-century outflow to Banja Luka and abroad accelerated aging, while the 1990s saw temporary inflows of displaced persons. Today, daily commuting and international migration reduce the reproductive base, reinforcing demographic fragility. Consequently, Slatina exhibits low fertility, population aging, high migration dependence, and heightened pressure on social and infrastructural systems within the peri-urban context.

Discussion

The results of the study indicate that the area of Slatina cannot be regarded as an isolated rural settlement, but rather as a functionally integrated component of the broader urban system of Banja Luka. Spatial and functional indicators consistently point to a long-term process of redefining relations between the urban center and its periphery, with Slatina acquiring the characteristics of a transitional peri-urban zone.

The observed peri-urban transformation of Slatina is consistent with established theoretical and empirical findings on urban expansion in post-socialist and global contexts. Previous research emphasizes that peri-urban zones represent dynamic interfaces between urban and rural systems, characterized by functional hybridization, land-use change, and increasing socio-spatial integration with urban cores (Tacoli, 2003; Simon, 2008; Pacione, 2009). In addition, broader models of global urban expansion confirm that peripheral settlements within metropolitan influence zones undergo structural transformation driven by demographic change, mobility patterns, and economic restructuring (Seto et al., 2012).

In this framework, Slatina exhibits the key characteristics of peri-urbanization processes, including increasing residential orientation, intensification of daily commuting toward Banja Luka, and gradual reduction of agricultural functions. These processes reflect the functional dependence of peripheral settlements on urban centers, which is a defining feature of contemporary urban systems in transition (Stanilov, 2007).

Table 9. Consolidated overview of key demographic and functional processes in Slatina

Indicator	Trend	Source
Total population	Relatively stable with a moderate increase after 1991	Table 2
Age structure	Decrease in the share of young population (0–19), increase in elderly (60+)	Tables 5, 6, 7
Households	Increase in number of households, decrease in average household size	Tables 8, 9
Migration	Migration – inferred from population trends and settlement-level demographic change; no direct quantitative migration data available	Sections on migration
Functional structure	Transition from agricultural to mixed peri-urban system	Discussion on functional transformation
Spatial integration	Slatina as a transitional zone integrated into the urban system of Banja Luka	Sections on functional dependence and hierarchy

The demographic development of Slatina is characterized by long-term structural change rather than simple population growth or decline. The age structure shows a continuous reduction in the proportion of younger cohorts and a corresponding increase in the elderly population, indicating a sustained process of demographic aging (Tables 5 and 6). This trend is reinforced by household transformation, where the decline in average household size and the increase in the number of households reflect a shift from extended to nuclear and single-person household structures (Table 8).

Migration processes represent a key explanatory factor for these transformations. Historically, Slatina has been influenced by both out-migration of younger and working-age populations toward Banja Luka and other destinations, and temporary in-migration flows during the post-conflict period in the 1990s.

In the contemporary phase, daily and circular migration dominates, reflecting the settlement's strong functional integration into the urban system of Banja Luka and its role as a residential component of the peri-urban zone.

The functional transformation of Slatina closely follows these demographic dynamics. Traditional agricultural activities have gradually declined in importance, while residential, service, educational, and recreational functions have strengthened. This has resulted in a mixed functional structure, characteristic of transitional peri-urban settlements. Within this system, Banja Luka acts as the dominant urban core, while Laktaši functions as a secondary administrative and service node, forming a hierarchical spatial organization: Banja Luka – Slatina – Laktaši.

Overall, the findings confirm that Slatina is part of a wider peri-urban system shaped by long-term urban expansion and socio-demographic restructuring. The observed patterns align with established theoretical frameworks of peri-urbanization and post-socialist urban transformation, where urban–rural boundaries become increasingly blurred and settlements are reorganized through functional integration with metropolitan centers (Tacoli, 2003; Stanilov, 2007; Simon, 2008).

Conclusion

The empirical results of this study demonstrate that Slatina can no longer be interpreted as a classical rural settlement but functions as an integrated component of the broader urban system of Banja Luka. Spatial and demographic indicators reveal a long-term reconfiguration of urban–rural relations, with Slatina increasingly exhibiting characteristics of a transitional peri-urban system.

Total population dynamics (Tables 1–2) indicate a generally stable trend, with a notable increase after 1991 corresponding to the temporary influx of displaced persons. Annual growth rates (Table 3) show phases of deceleration and partial stabilization, associated with declining fertility and out-migration of young and working-age cohorts. Age structure data (Tables 5–7) demonstrate a continuous decrease in youth (0–19 years) and an increase in the elderly population (60+ years), indicating a shift from a progressive to a regressive demographic profile. These trends are further corroborated by aging indices and dependency ratios, highlighting mounting demographic pressure on the working-age population.

Household dynamics (Tables 8–9) reveal a sustained increase in the number of households, accompanied by a consistent decrease in average household size, reflecting the transition from extended multigenerational households to nuclear and increasingly single-person forms. This pattern is closely linked to migration, urbanization, and evolving lifestyle patterns in the peri-urban context.

Migration emerges as the central driver of these demographic and functional changes. Historically, Slatina was shaped by complex migratory flows structuring the local ethnodemographic composition. Postwar economic migration to Banja Luka and abroad caused a continuous outflow of young and working-age residents. The 1991–1995 period saw the temporary settlement of displaced populations, resulting in a sudden population increase (Tables 2 and 6) without establishing a stable demographic base. Contemporary migration is dominated by daily commuting and circular movements within the Banja Luka functional area, reinforcing Slatina's peri-urban integration while intensifying population aging.

Functionally, Slatina has shifted from a predominantly agricultural settlement to a mixed peri-urban space, characterized by residential, service, and recreational functions, while traditional agriculture has gradually declined. The spatial expansion of Banja Luka has established a hierarchical functional organization: Banja Luka as the primary regional center, Slatina as a transitional peri-urban zone, and Laktaši as a secondary functional node. This structure reflects both demographic distribution and the spatial reorganization of households and economic activities.

Overall, the integrated analysis confirms theoretical frameworks of peri-urbanization and post-socialist urban transformation (Mandić, 2013; 2019). Slatina exemplifies a settlement where urban–rural boundaries blur, demographic aging accelerates, household structures transform, and functional diversification increases under metropolitan influence. From a planning perspective, these findings underscore the need for proactive management of peri-urban zones to ensure controlled spatial expansion, demographic sustainability, and balanced functional development.

In conclusion, Slatina represents a paradigmatic case of contemporary peri-urban transformation within the Banja Luka functional system. Empirical evidence of urban expansion, demographic restructuring, and household and functional changes provides a robust basis for theoretical interpretation and spatial planning interventions, emphasizing the interconnectedness of demographic, social, and functional dynamics in transitional peri-urban areas.

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Original scientific article

Received: 23.06.2026;

Received in revised form: 28.06.2026;

Received in second revised form: 07.08.2026;

Accepted: 09.09.2026;

Available online: 28.10.2026.

UDC: 338.48:640.412(497.11)

doi: 10.5937/zrgfub26083B

HOTELS, SHORT-TERM RENTALS AND SPATIAL TRANSFORMATION OF TOURIST ACCOMMODATION IN BELGRADE

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Abstract: This paper investigates how short-term rental (STR) platforms are reshaping the intraurban geography of tourist accommodation in Belgrade, a post-socialist city where tourism growth, hotel expansion, weakly regulated housing markets, and a recent boom in real-estate investment intersect. By comparing Airbnb listings with hotels, the study examines whether platform accommodation reproduces established tourist geographies or extends tourism into new areas. Kernel density estimation and Exploratory Spatial Data Analysis (ESDA) techniques are applied to hotel and Airbnb capacity at the level of statistical circles. The results reveal a pronounced centralisation of both accommodation types, but also important differences in their spatial distribution. Hotels remain concentrated in relatively limited clusters within the historic tourist core, New Belgrade business areas, and selected transport corridors. Airbnb, by contrast, forms a broader and more continuous central cluster, extending into prestigious residential neighbourhoods where hotel supply is weak. Bivariate spatial analysis identifies areas where Airbnb and hotel capacity co-locate in the old city centre, zones of Airbnb dominance in neighbourhoods such as Dorćol and Vračar, and peripheral areas with low accommodation intensity. The findings suggest that Airbnb has not dissolved the boundaries of the tourist city by enabling visitors to “live like locals”. Instead, it has largely reproduced and intensified centralised patterns of tourist demand, while taking advantage of weakly regulated housing markets and the locational flexibility of STRs. In Belgrade, Airbnb fills gaps in space left by the historically uneven development of hotels, but also contributes to touristification, commercial transformation of urban space, and housing financialisation.

Keywords: hotels; Airbnb; touristification; ESDA; Belgrade

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Introduction

The beginning of the twenty-first century has been marked by the emergence of tourism as one of the major forces reshaping the spatial and functional structures of many European cities (Sequera & Nofre, 2018; Alexandri et al., 2026). This transformation became particularly visible after the 2008 financial crisis, when many cities increasingly turned to tourism as a strategy for economic recovery and strengthening urban competitiveness (Lestegás, 2019). The intensification of tourism-led urban restructuring has consequently attracted growing scholarly attention to the processes and consequences of touristification and overtourism (Santos-Izquierdo et al., 2025). However, the impacts of touristification are not evenly distributed across urban space. Instead, urban tourism tends to concentrate in specific districts, which have been variously conceptualised in the literature as tourism business districts (Getz, 1993), tourist bubbles (Judd, 1999), tourist precincts (Hayllar & Griffin, 2005) and tourist-historic city (Ashworth & Tunbridge, 2000). This spatial selectivity reflects the distinctive nature of urban tourism: tourists often have limited knowledge of the city, stay for relatively short periods, and organise their movements around major attractions, central locations and clusters of urban amenities (Ashworth & Page, 2011). Tourist accommodation plays a central role in this process (Shoval et al., 2011). For example, hotels, as one of the few “pure” tourist facilities (Jansen-Verbeke, 1986; Timothy & Wall, 1995), are among the most visible spatial manifestations of urban tourism, unlike many urban services and facilities, which are used by both residents and visitors. Their location influences not only tourist mobility and expenditure, but also the functional structure, image, and symbolic meaning of particular urban areas and of the city as a whole (Wall et al., 1985; McKercher & Lau, 2008; Ashworth & Page, 2011; Shoval et al., 2011; Rogerson, 2012; Antić, 2021). By concentrating tourists in specific parts of the city, hotels may also contribute to the clustering of other tourism-related activities, such as restaurants, cafés, bars, cultural venues, and commercial services, thereby reinforcing existing touristified spaces and increasing pressure on already intensively used central areas (Gutiérrez et al., 2017).

Over the past decade and a half, however, the geography of urban tourist accommodation has been profoundly transformed by the rise of the sharing economy and STR platforms (Guttentag, 2015). Airbnb, as the most prominent global platform for peer-to-peer accommodation, has significantly expanded the supply of tourist accommodation by enabling property owners to rent apartments, rooms, and houses to visitors. Building on this model, Airbnb emerged in 2008 as the most prominent peer-to-peer accommodation platform and has since grown to 8.35 million listings worldwide, generating an estimated 436.8 million nights booked annually (Cruvinel & Cox, 2026). Originally promoted as a form of accommodation associated with everyday residential environments, local culture, and more “authentic” urban

experiences, Airbnb has become a major factor in the restructuring of urban tourism spaces (Gravari-Barbas & Delaplace, 2015; Gravari-Barbas & Guinand, 2017). The rise of platform-mediated STRs intensified the conversion of residential housing into tourist accommodation, linking tourism growth to processes of housing financialisation, rent increases and displacement pressures (Cocola-Gant et al., 2021). Consequently, tourism began to affect not only traditional visitor areas, but also everyday residential spaces, producing new conflicts over housing affordability, public space, local services, and the identity of neighbourhoods. Furthermore, the rapid expansion of STR platforms has challenged the traditional accommodation landscape, which was previously dominated by hotels and other formally categorised establishments. Unlike hotels, which are constrained by planning regulations, land-use zoning, investment costs, construction cycles, and the rigidity of purpose-built accommodation, STRs possess a high degree of spatial and functional flexibility, allowing them to enter existing residential buildings and neighbourhoods with limited physical transformation.

Against this background, this paper examines the intraurban geography of STRs in Belgrade and compares it with the spatial distribution of hotels. The aim is to understand how Airbnb is reshaping the geography of tourist accommodation in a city where tourism growth, recent hotel expansion, post-socialist urban transformation, and weakly regulated housing markets intersect. More specifically, the paper asks whether the geography of STRs in Belgrade follows a centralised centre-periphery pattern; whether Airbnb “activates” new parts of the city that were previously weakly integrated into the tourist accommodation system and follows the patterns of residential decentralisation; and how the spatial distribution of Airbnb listings compares with that of hotels.

Belgrade represents a particularly relevant case for examining the changing geography of urban tourist accommodation because the rapid expansion of Airbnb has occurred alongside broader tourism growth and the approximate doubling of hotel numbers over the past decade. Unlike more established European tourist cities, where Airbnb has often expanded within already advanced processes of touristification, Belgrade allows us to examine how STRs and hotels develop simultaneously in a still-evolving urban tourism market. This perspective also responds to the need to move beyond first-rank tourist cities, as empirical research on less-established urban destinations can generate novel insights into the diverse trajectories of platform-based accommodation and tourism-led urban change (Adamiak, 2022; Kadi et al., 2022). Second, the city’s hotel geography reflects its socialist urban legacy. During the socialist period, urban development encouraged the growth of areas beyond the historic core, including major modernist districts and business zones such as New Belgrade. As a result, hotel accommodation has not been confined exclusively to

the old city centre, but has also developed in areas associated with administrative functions, business zones, and major transport corridors (Budović et al., 2020). This historical spatial structure raises important questions about the contemporary relationship between hotels and STRs in Belgrade. Airbnb may be filling gaps in tourist accommodation within central residential areas where hotels are relatively scarce, but it may also be coexisting or competing with hotels in areas where formal accommodation is already present. New Belgrade is particularly important in this regard, as it functions primarily as a business district rather than as a tourist area. The comparison between hotels and Airbnb listings can therefore reveal whether STRs reproduce the established centre-periphery pattern of urban tourism, extend tourist accommodation into new residential zones, or create more complex spatial relationships of substitution, complementarity, and coexistence. Finally, the expansion of STRs in Belgrade is also facilitated by the specific characteristics of the local housing market. Tenant protection is weak in practice, public and social housing are almost absent, and most of the housing stock is privately owned (Vilenica et al., 2021; Musil et al., 2026). These conditions provide property owners with considerable freedom to commercialise housing assets through STR platforms. In addition, a substantial share of STRs operates in a grey zone, as many units are not officially categorised and hosts often do not fully comply with local tax and regulatory obligations. Consequently, Airbnb has not yet been widely perceived as a major threat either to the urban housing system or to the organisation of tourist space, and stronger regulatory constraints have remained limited.

The remainder of this paper is structured as follows. The next section reviews the literature on the urban geography of hotels and STRs, with particular attention to centrality, tourist zones, spatial flexibility, and the relationship between Airbnb and hotels as a traditional form of tourist accommodation. The following section presents Belgrade as a case study and discusses the city's post-socialist urban transformation, tourism growth, housing-market conditions, and regulatory context. It then introduces the datasets on Airbnb listings and categorised hotels, followed by the methodological framework based on kernel density estimation, Global Moran's I, LISA, and bivariate Local Moran's I. The results section compares the spatial concentration, clustering, and local spatial associations of hotel and Airbnb capacity. Finally, the discussion and conclusion interpret these findings in relation to touristification, historical path dependency of hotel distribution, the housing boom, and financialisation.

Literature review

The urban geography of hotels

Research on the spatial distribution of hotels in cities has developed gradually. Early studies from the first half of the twentieth century were mostly descriptive and focused on recreational zones, tourism and hospitality facilities in urban environments (Smith, 1983). Later studies sought to explain the spatial patterns of the hotel industry by emphasising the historical evolution of cities and models derived from classical theories of urban land rent (Shoval, 2006). Evolutionary approaches, such as Ritter's model (1986), emphasise the importance of the development of transport technologies. According to this view, hotels were initially concentrated in historic cores, near city gates, markets or waterfronts; later around railway stations; and subsequently along major transport routes, on the urban periphery and near airports. A significant contribution was also made by Ashworth's tourist-historic city model, which identifies several types of hotel locations: traditional locations in the historic core, locations near railway stations and access roads, hotels along major transport routes, hotels in attractive and quieter locations, large modern hotels in the contact zone between the central business district and the historic core, as well as hotels on the periphery, near motorways and airports (Ashworth, 1989; Ashworth & Tunbridge, 2000). Although this model is primarily typological, it inspired numerous empirical studies that demonstrated that specific historical, economic, political and morphological conditions of a city can significantly modify general patterns of hotel distribution (Bégin, 2000; Shoval & Cohen-Hattab, 2001; Adam, 2013; Rogerson, 2014; Budović et al., 2020). The second group consists of models based on urban land rent and competition for central locations (monocentric models). Yokeno's model starts from the assumption that hotels tend to gravitate towards central areas because tourists, especially individual travellers, value proximity to tourist attractions, business functions, retail facilities and public transport (Yokeno, 1968; Shoval, 2006). Egan and Nield (2000) further elaborate this approach by introducing a spatial hierarchy of hotels, in which luxury hotels are concentrated in the centre, while cheaper and smaller hotels are located in the ring around the centre or on the periphery.

Since the 2000s, a distinct strand of research has examined urban hotel location in former socialist cities. During socialism, the hotel supply in these cities was limited, nationalised and strongly centralised in old urban cores (Matczak, 2004; Kowalczyk, 2004; Bučeková, 2007), although there is also evidence of the emergence of new tourist and hotel hotspots in newly developed socialist urban areas (Budović et al., 2020). Following political and economic transition, the number of hotels increased, ownership structures changed, international hotel chains entered the market, and hotel locations became more differentiated. Historic cores retained

their role as the most attractive zones, particularly for luxury and foreign-owned hotels, while smaller and cheaper establishments, often financed by domestic capital, increasingly appeared in peripheral parts of the city (Kowalczyk & Szkup, 2004; Bučková, 2007; Malarz, 2010; Matczak & Napierała, 2014; Włodarczyk, 2015; Budović et al., 2020; Kádár, 2023).

The urban geography of short-term rentals

Research on the spatial distribution of Airbnb has expanded rapidly in recent years. Much of this literature situates the urban geography of Airbnb in relation to classical models of accommodation location, particularly the monocentric model of hotel location proposed by Yokeno (1968) (La et al., 2022). Similar to hotels, Airbnb rentals tend to cluster in central urban areas, with their density generally declining toward the urban periphery (Adamiak, 2022; La et al., 2022; Zhang & Fu, 2022). The city centre and major tourist attractions² are widely identified as the main determinants of Airbnb's intraurban geography, functioning as key pull factors within urban space (Gutiérrez et al., 2017; Balampanidis et al., 2021; Ioannides et al., 2019; Quattrone et al., 2018; Ki & Lee, 2019; Lagonigro et al., 2020; Gyódi, 2024). Gyódi and Nawaro (2021), for example, found that proximity to tourist attractions is a crucial driver of Airbnb prices. Similarly, Zhang and Fu (2022), in their study of Airbnb supply in Los Angeles, showed that Airbnb listings are not only attracted to areas with a high concentration of points of interest, but are also more likely to be located in neighbourhoods with higher incomes, higher rents, and a larger stock of potentially rentable housing units. Conversely, areas with higher residential population densities were found to be less attractive for Airbnb activity.

A growing body of research also demonstrates that different types of Airbnb listings display distinct spatial patterns. Kadi et al. (2022), for example, show that "commercialised" apartments in Vienna, defined as units permanently used as STRs, are more spatially centralised than home-sharing units and occasional rentals. Studies such as Gyódi (2024), focusing on Barcelona, Berlin, and London, and Endrich et al. (2022), focusing on Brussels, show that professional and non-professional Airbnb hosts occupy different positions within the urban accommodation landscape. The geography of professional hosts largely mirrors the distribution of hotels, as these listings tend to cluster in central tourist areas and business districts. This pattern can be explained by the tendency of professional hosts to concentrate in the most

² Eugenio-Martin et al. (2019) show that the relative proximity of hotels and Airbnb rentals to tourist attractions differs by destination type: in beach destinations, hotels tend to be located closer to tourist attractions than Airbnb rentals, whereas in urban tourist destinations, Airbnb rentals are often located closer to major attractions than hotels.

popular and profitable urban locations, where tourist demand and expected returns are highest (Adamiak, 2022).

Several studies point to the expansion of Airbnb into central and inner-urban neighbourhoods located close to established tourist areas, including working-class or lower-priced residential areas with high potential for investors due to their proximity to tourist sites (Gutiérrez & Domènech, 2020). This spatial expansion can also be associated with the promise that Airbnb would enable tourists to “live like locals” by staying in residential neighbourhoods and engaging more closely with everyday urban life. However, Gyódi (2024) argues that Airbnb has not fulfilled this expectation of deeper integration into local residential environments or of dissolving the boundaries of the “tourist bubble”. On the contrary, Airbnb may reinforce uneven tourist development by commercialising residential dwellings in central and inner-urban areas and converting them into STRs.

Compared with hotels, Airbnb listings are often more spatially dispersed and cover a wider range of urban areas, including both tourist-oriented and residential neighbourhoods (Gutiérrez et al., 2017; Quattrone et al., 2018; Xu et al., 2020). Hotels, by contrast, tend to be more spatially concentrated and limited to specific areas of the city. The relationship between Airbnb and hotels has therefore become an important research topic, although empirical findings remain mixed. Some studies suggest that Airbnb and hotels serve partly different market segments and may therefore have a complementary relationship. Others argue that Airbnb has negative effects on hotels, particularly those oriented primarily toward leisure tourists (La et al., 2022). In many cases, Airbnb listings co-locate with hotels, further intensifying pressure on already saturated tourist areas (Gutiérrez & Domènech, 2020; La et al., 2022; Gyódi, 2024). A key distinction between hotels and STRs lies in their spatial flexibility. Hotels are constrained by planning regulations, land-use zoning, investment costs, construction cycles, and the relative rigidity of purpose-built accommodation facilities. STRs, by contrast, can enter existing residential buildings and neighbourhoods with limited physical transformation, often occupying already built-up housing stock in areas close to tourist attractions, cultural amenities, transport nodes, and other urban facilities. This flexibility allows Airbnb and similar platforms to penetrate, sometimes informally, parts of the city that were previously outside the formal geography of tourist accommodation, including residential neighbourhoods with little or no hotel presence. As a result, platforms such as Airbnb do not merely increase accommodation capacity. They reshape the relationship between tourism and residential space, blur the boundary between tourist and everyday urban environments, and contribute to new forms of touristification (Gutiérrez et al., 2017; Lagonigro et al., 2020; Xu et al., 2020).

Study Area, Data and Methodology

Belgrade as a post-socialist tourist city

The area covered by the General Plan of Belgrade 2041 (Urban Planning Institute of Belgrade [UPIB], 2022), which represents the study area of this research, has a population of approximately 1.38 million and functions as Serbia's main economic, cultural, educational, and tourist centre. The contemporary development of Belgrade can be understood in the light of post-socialist urban development as a transition from a city dominated by the functions of administration, industry and local consumption to a service-oriented urban economy, increasingly shaped by foreign investment and tourism. After the political changes in 2000, Belgrade gradually became more integrated into global economic, cultural, and tourist flows. Among other changes, transport connectivity, cultural infrastructure, hospitality services, and entertainment functions have been revitalised, accompanied by a growing number of flights, hostels, hotels, private apartments, and leisure spaces (Joksimović et al., 2014; Nicic & Iguman, 2019). This development has not been linear, yet tourism statistics indicate a clear long-term transformation. In 2000, Belgrade recorded around 796,000 tourist arrivals, of which only around 88,000 were foreign visitors (Figure 1). Although the COVID-19 pandemic caused a sharp decline in 2020, the recovery was relatively rapid. By 2024, the city recorded more than 1.5 million tourist arrivals and 3.7 million overnight stays, while in 2025 tourism remained at a broadly similar level, with foreign visitors clearly dominating the tourist structure (Secretariat for Administration – Sector for Statistics, 2000–2025). This indicates a major restructuring of Belgrade's tourism market, which is now

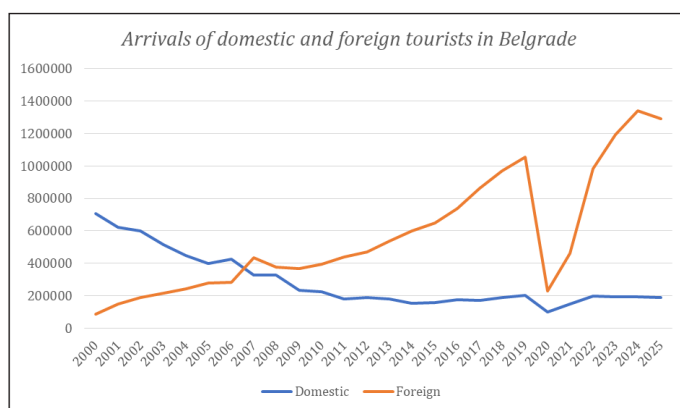


Figure 1. Arrivals of domestic and foreign tourists in the City of Belgrade, 2000–2025. (Secretariat for Administration–Sector for Statistics, 2000–2025)

increasingly driven by international demand. Although Belgrade has experienced rapid tourism growth, it still records fewer tourist arrivals than major regional urban destinations such as Vienna (9.1 mil. arrivals), Prague (8.3 mil.) and Budapest (4.8 mil.) (TourMIS, 2026). Precisely because of its rapid recent growth and

the perception that further expansion remains possible, tourism is increasingly framed in urban development strategies as one of the city's key economic sectors and as an instrument of economic growth and urban development (UPIB, 2022).

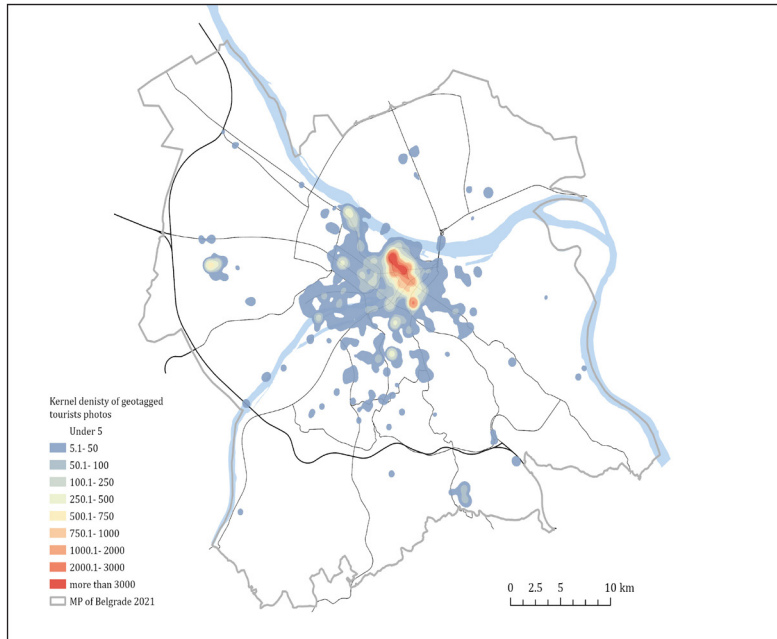


Figure 2. Kernel density estimation of geotagged tourist photos in Belgrade (2004–2026)

Figure 2 shows the density of tourist photo locations³, indicating the areas most frequently visited by tourists and the main tourist clusters in Belgrade. The spatial pattern confirms the strong centralisation of tourism in the city, with tourist activity primarily concentrated in the old urban core, especially along the tourist corridor extending from Belgrade Fortress to the Temple of Saint Sava. Beyond this

³ For this map, we applied kernel density estimation (KDE), as described in the methodology section, to geotagged Flickr photographs taken in Belgrade between 2004 and 2026 and retrieved through the Flickr API. Geotagged Flickr data have been widely employed in similar analyses of tourist spatial behaviour and urban visitation patterns (Kádár & Martins, 2026). Following Gutiérrez et al. (2017), users were classified as either visitors or residents according to the temporal span of their photographic activity within the study area, measured as the interval between their first and last recorded photograph. Users whose activity spanned 30 days or less were classified as tourists, whereas those with an activity span exceeding 30 days were classified as residents. To reduce potential spatial bias resulting from users taking multiple photographs at exactly the same location, we introduced an additional filtering criterion whereby only one photograph per user at each unique location was retained. After applying these criteria, the KDE was based on 10,686 geotagged photographs contributed by 1,203 unique Flickr users.

main central zone, secondary tourist concentrations can be observed in the historic core of Zemun, selected areas of New Belgrade, the Royal Palace, and the Museum of Yugoslav History. This spatial concentration of tourism should be understood within the broader post-socialist transformation of Belgrade. Central urban areas have increasingly been reshaped by consumption-oriented activities, nightlife, short-term stays, symbolic urban branding, and real-estate development. Formerly neglected, infrastructural, or underused parts of the city have gradually become attractive locations for cafés, restaurants, clubs, creative industries, and new real-estate projects, reflecting the growing role of tourism and leisure consumption in the restructuring of Belgrade's urban space (Jocić et al., 2017).

Housing-market conditions are also central to understanding the expansion of STRs in Belgrade (Ratkaj et al., 2024). A permissive attitude towards apartment renting, limited control over short-term accommodation and the growth of platforms such as Airbnb has increasingly encouraged the treatment of centrally located apartments as investment assets. Tourism is therefore closely associated with gentrification, as rising prices, the reorientation of commercial services toward visitors, and the displacement of residents' everyday needs by tourist-oriented amenities reshape the character of urban neighbourhoods. At the same time, the hotel offer is expanding. According to data from MTY, the number of hotels has almost doubled in the last decade, from 68 to 117 (MTY, 2016; 2026). Touristification in Belgrade should therefore not be understood simply as an increase in visitor numbers, but as part of a broader reorganisation of central urban space around mobility, consumption, real-estate valorisation, and rentier forms of urban development. Touristification in Belgrade functions less as a tourism problem alone and more as a symptom of speculative urbanism. Visitors, investors, digital nomads, and higher-income consumers increasingly contribute to the revaluation of central urban space, while long-term residents may face rising costs, displacement pressures, and the erosion of everyday neighbourhood life.

The private accommodation market still operates largely in a grey zone, with many owners, around 50% in 2022, according to YUTA (Gavrić, 2025), neither registering their accommodation nor paying taxes, which amount to approximately 15% of income. In order to operate legally, accommodation providers are required to register and categorise their property with the local administration, register the accommodation in the eTurista system⁴, and pay the tourist stay tax. However, controlling the legality of Airbnb and other forms of STRs in Belgrade has proven to be extremely difficult. The market is highly fragmented, monitoring individual listings is complex, and there are not enough tourism inspectors to effectively regulate and supervise the sector (YUTA, 2025).

⁴ The central information system for hospitality and tourism managed by the Ministry of Tourism and Youth.

Data

Since Airbnb does not publicly provide comprehensive data on its listings, most studies examining the intraurban geography of Airbnb rely on datasets obtained from specialised companies and web platforms that scrape, aggregate, and process Airbnb data, such as Inside Airbnb and AirDNA. These sources are among the most commonly used in intraurban analyses of Airbnb activity. However, Belgrade is not consistently covered by these databases. Therefore, this study uses data acquired from the newly launched Doorstep Analytics platform (2026). Doorstep Analytics collects data from multiple publicly accessible Airbnb API and HTML endpoints, formats and aggregates it into CSV files containing information on listing characteristics, calendar availability, pricing, reviews, host and business details, and further enriches the dataset with information from public sources such as OpenStreetMap. A methodological limitation of Airbnb data concerns the spatial precision of listing locations. Airbnb does not disclose the exact addresses of its listings; instead, it provides coordinates that are spatially displaced within a radius of approximately 0–150 m from the actual location in order to protect user privacy (Wachsmuth & Weisler, 2018). This form of spatial obfuscation is frequently identified as a limitation in microgeographical analyses of Airbnb activity (Gyódi, 2024). In the present study, the provided coordinates were treated as representative listing locations and were aggregated to the level of statistical tracts using geolocation procedures in ArcGIS Pro.

The dataset obtained from Doorstep Analytics included 6,068 Airbnb listings in Belgrade. In addition, 69 listings that were not included within the “Belgrade area” as defined by Doorstep Analytics, but which fall within the territory of the General Urban Plan of Belgrade 2041, were manually mapped and incorporated into the analysis. The estimated total capacity of Airbnb rentals in Belgrade is approximately 21,163 individual places. Around 70% of the listed apartments or homes are one-bedroom units, while approximately 20% are two-bedroom units.

The number of listings identified in this study is broadly comparable to estimates provided by other platforms, although these estimates vary because platforms differ in spatial coverage, data-collection procedures, and definitions of active listings. For example, Airbtics (2026) reported 5,523 active Airbnb listings in Belgrade for the period from October 2023 to September 2024, while AirDNA (2026), which includes data from both Airbnb and Vrbo (another short-term rental platform), reported a total of 7,617 properties. AirROI (2026) provides a lower estimate of 3,116 active listings, apparently based on listings active during the preceding year. A report by

Inside Airbnb estimates the number of listings in Belgrade at 4,950⁵ (Cruvinel & Cox, 2026).

Hotel location and capacity data were obtained from the database of categorised accommodation facilities published by the MTY for January 2026. Hotel addresses were geocoded in ArcGIS Pro using the address database provided by the Republic Geodetic Authority (2021). The hotel sector in Belgrade is dominated by four-star establishments, which account for approximately 70% of all hotels, followed by three-star hotels, which represent around 23%. Only six hotels are categorised as five-star establishments. In total, Belgrade has 110 hotels, with a combined capacity of 14,238 beds and an average capacity of approximately 130 beds per hotel. Total hotel bed capacity cannot be directly interpreted as equivalent or fully comparable to the capacity of Airbnb rentals. Hotel capacity is generally available throughout the year, whereas Airbnb listings often vary in availability due to seasonal, temporary, or host-specific patterns of use. Consequently, Airbnb capacity should be understood as a potential rather than continuously available accommodation supply.

Research Methods

The methodological framework consists of three main analytical steps. The first step involves the application of kernel density estimation (KDE)⁶. KDE is a non-parametric method used to analyse the spatial concentration of point phenomena in continuous Euclidean space, independently of administrative boundaries. It generates smoothed density surfaces that indicate the probability or intensity of occurrence of the observed phenomenon across space (Bailey & Gatrell, 1995). In this study, KDE was applied by placing a raster grid over the study area and calculating density values for each cell centroid on the basis of points located within a defined search radius. The size of the raster cell mainly affects the visual representation, while the bandwidth determines the balance between local spatial detail and the identification of broader spatial trends. Smaller bandwidths emphasise local hotspots but may produce excessive spatial noise, whereas larger bandwidths generate smoother surfaces but may overgeneralise spatial patterns. For this analysis, a bandwidth of 500 m was selected, as it provides an appropriate balance between detailed local variation and the generalised spatial patterns of both hotel and Airbnb capacity. Although KDE is useful for visualising the intensity and extent of spatial concentrations, it does not test whether observed clusters are statistically significant, which is why it is often combined with other spatial statistical methods.

⁵ The provided numbers for Serbia are 11,587 for listings and 406,348 for estimated overnight stays.

⁶ The “kernel” is the smoothing function or search window used to calculate density around each location.

In the second step, global and local indicators of spatial autocorrelation were applied. These methods⁷ are widely used in studies of hotel and STR geographies (Gutiérrez et al., 2017; Eugenio-Martin et al., 2019; Gutiérrez & Domènech, 2020; La et al., 2022; Zhang & Fu, 2022; Gyódi, 2024). Global spatial autocorrelation was used to examine whether the spatial distribution of hotel and Airbnb capacity⁸ in Belgrade follows a clustered, dispersed, or random pattern. In this study, Global Moran's I was applied as the main global indicator of spatial autocorrelation, as it measures the similarity of values among neighbouring spatial units through a spatial weights matrix (Getis, 2010). The analysis was conducted at the level of statistical circles⁹, with neighbourhood relations defined using queen contiguity. A positive Moran's I value indicates that statistical circles with similar values of hotel or Airbnb capacity are spatially clustered, while a negative value indicates spatial dispersion. Statistical significance was assessed using Monte Carlo permutations, which test the null hypothesis of spatial randomness.

Local spatial autocorrelation was analysed using Local Indicators of Spatial Association (LISA), which identify statistically significant local clusters and spatial outliers within the study area (Anselin, 1995; Anselin, 2003). Unlike global indicators of spatial autocorrelation, which provide a single value for the entire territory, LISA statistics reveal where specific patterns of clustering occur at the level of individual spatial units. In this study, the Local Moran's I statistic was applied to examine the spatial distribution of hotel and Airbnb capacity across statistical circles in Belgrade. The method compares the value of each statistical circle with the values of neighbouring statistical circles as defined by the spatial weights matrix. Based on this relationship, statistical circles can be classified into four categories: High–High, Low–Low, High–Low, and Low–High. High–High clusters indicate areas with above-average accommodation capacity surrounded by neighbouring areas with similarly high values, while Low–Low clusters indicate areas with below-average values surrounded by similarly low values. High–Low and Low–High categories represent spatial outliers, where the value of a statistical circle differs from the values observed in its surrounding neighbourhood. The statistical significance of local clusters was assessed using Monte Carlo permutations, allowing the identification of spatial patterns that are unlikely to result from a random spatial distribution.

Bivariate Local Moran's I (BiLISA) (Anselin, 2003) was used to analyse the spatial relationship between two different variables: hotel capacity and Airbnb

⁷ For the calculations, we used *GeoDa software*, while map visualization was performed in *ArcGIS Pro*.

⁸ Because hotel and Airbnb capacity variables are highly right-skewed and include many zero-valued statistical circles, the variables were transformed using $\ln(x + 1)$ prior to the analysis.

⁹ Data on statistical circles were retrieved from the Republic Geodetic Authority (2022). Peripheral statistical circles with no population, very low population density, or limited potential for the emergence of Airbnb accommodation were excluded from the analysis.

capacity. This method does not measure the correlation between the two variables within the same statistical circle, but rather compares the value of hotel capacity in one location with the Airbnb capacity of neighbouring locations. In this study, the x-axis of the bivariate Moran scatterplot represents hotel capacity, while the spatially lagged values of Airbnb capacity in neighbouring statistical circles are represented on the y-axis. The analysis identifies four types of local spatial association: High–High, Low–Low, High–Low, and Low–High. High–High clusters indicate areas with high hotel capacity located near areas with high Airbnb capacity, while Low–High and High–Low clusters indicate spatial mismatches between hotel and Airbnb capacity.

Results

The spatial distribution of hotels and Airbnb accommodation in Belgrade, presented through estimated kernel densities (Figure 3), reveals a high degree of concentration and centrality, as well as pronounced centre–periphery differences. Hotel capacity is primarily concentrated within the main tourist zone of the city, along the tourist corridor between Belgrade Fortress and the Temple of Saint Sava (Budović & Ratkaj, 2018), where approximately 40% of all hotels and total hotel capacity is concentrated. Other hotels are distributed across the wider historic city centre, parts of New Belgrade (around 16% of hotel capacity), and along major transport arteries in more peripheral areas of the city. Airbnb capacity is also strongly clustered in the city centre, particularly within the aforementioned tourist zone, with an additional concentration in the Belgrade Waterfront area. More than half of Airbnb listings and total Airbnb capacity are located in this central zone, after which densities decline rapidly toward the urban periphery. Secondary concentrations are also evident in areas such as the historic core of Zemun, an important tourist point of interest; the relatively recently developed Belville neighbourhood in New Belgrade; and the Surčin area near Belgrade Airport. Compared with hotels, Airbnb accommodation covers a considerably wider urban area, particularly residential neighbourhoods in the inner urban zone where hotels are largely absent.

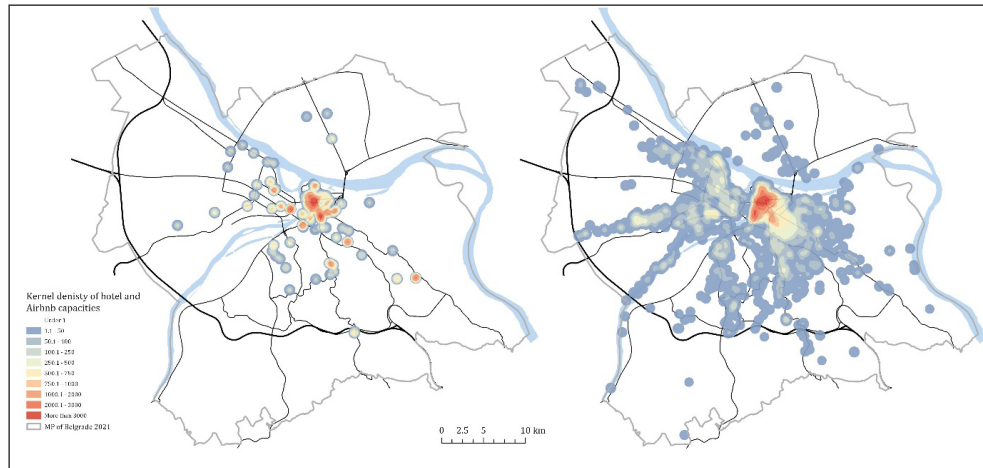


Figure 3. Kernel density estimates for hotel capacity (left) and Airbnb capacity (right) in Belgrade (2026)

The results of Global Moran's I for both hotels and Airbnb accommodation confirm the presence of spatial autocorrelation, indicating statistically significant clustering patterns. However, the strength of spatial clustering differs considerably between the two types of accommodation. Global Moran's I is substantially higher for Airbnb accommodation (0.872) than for hotels (0.360), which means that high and low values of Airbnb capacity are more strongly spatially concentrated than those of hotel capacity. This suggests that Airbnb accommodation exhibits a more strongly clustered spatial pattern, whereas hotel capacity is comparatively more dispersed across the study area. The LISA results further identify statistically significant local clusters for both types of accommodation (Figure 4). Both distributions contain High–High clusters in the historic centre of Belgrade. However, hotel clusters are spatially more limited, covering only 29 statistical circles, while Airbnb High–High clusters extend across 97 statistical circles, encompassing a much broader part of the historic city centre, including almost the entire municipalities of Stari Grad and Vračar, as well as older parts of Savski Venac and Palilula. A notable difference is the presence of High–Low clusters in the hotel distribution, indicating individual hotels with relatively high capacity located in areas where neighbouring statistical circles have lower values of hotel capacity. By contrast, the LISA results for Airbnb capacity reveal a wide Low–Low cluster in the peripheral parts of the city, separated from the central High–High cluster by a “ring” of statistically insignificant statistical circles. This pattern points to a strong spatial polarisation of Airbnb accommodation in Belgrade.

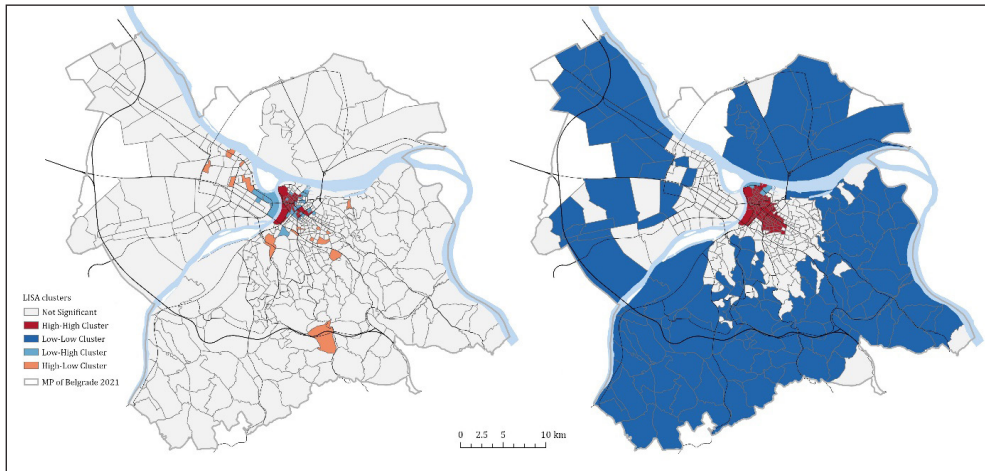


Figure 4. LISA for log-transformed hotel capacity (left) and Airbnb capacity (right) in Belgrade (2026)

Finally, Figure 5 presents the results of the bivariate Local Moran's I for hotel and Airbnb capacity, showing both spatial overlap and mismatch between the two forms of accommodation. In the old part of the city, High–High areas indicate the co-location of hotels and Airbnb accommodation, that is, areas where both variables display statistically significant positive spatial association. These areas cover the narrow core of the old city centre, extending from Belgrade Fortress and Upper Dorćol toward Savamala and Belgrade Waterfront, as well as physically separated areas around Slavija Square and Tašmajdan Park. Adjacent to these areas are Low–High clusters, where statistical circles with below-average hotel capacity are surrounded by neighbouring areas with above-average Airbnb capacity, such as Lower Dorćol and parts of Vračar. Peripheral parts of the city are predominantly characterised by Low–Low clusters, indicating that below-average hotel capacity is surrounded by below-average Airbnb capacity. In addition, several areas in the southern and south-eastern parts of the city contain relatively large hotels that function as isolated “islands” of higher hotel capacity within areas characterised by low Airbnb capacity (High–Low clusters).

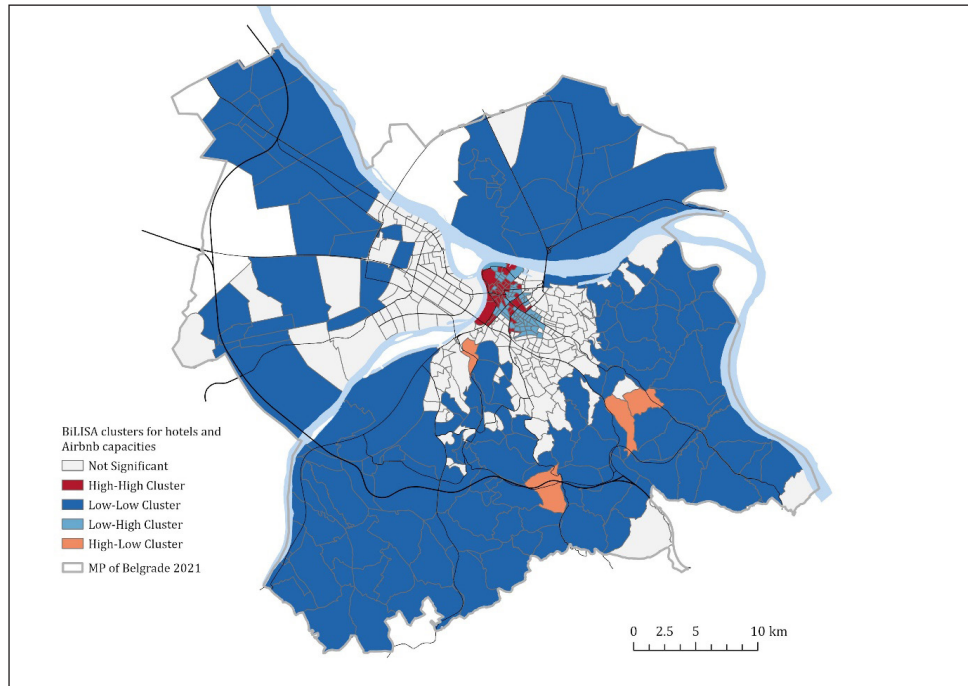


Figure 5. Bivariate Local Moran's I (BiLISA) for log-transformed hotel and Airbnb capacity in Belgrade (2026)

Discussion and Conclusion

This study examined the rapid expansion of STRs, particularly Airbnb, in urban areas and analysed their relationship with the spatial patterns of hotels as a more traditional form of tourist accommodation. The results show that Belgrade, although still a lower-tier tourist city in the European urban tourism hierarchy, is undergoing rapid touristification and displays spatial patterns of STR development similar to those observed in more established tourist cities. The geography of STRs in Belgrade is highly centralised and closely linked to the historic urban core, tourist attractions, nightlife, and other urban amenities. At the same time, STRs use their locational flexibility to penetrate central residential neighbourhoods where traditional tourist accommodation is limited or absent. Although STRs can be found across much of the urban space, it is difficult to argue that their geography in Belgrade is primarily driven by the promise of enabling tourists to “live like locals”. Rather, the spatial distribution of Airbnb suggests that STRs increasingly function as a commercialised and investment-oriented form of accommodation, closely connected to the financialisation of housing.

The results confirm a high degree of spatial concentration of Airbnb listings in Belgrade, characterised by a pronounced centre–periphery gradient. This pattern is consistent with previous studies showing that Airbnb tends to cluster in central urban areas, especially in proximity to tourist attractions. More broadly, the findings support Law’s (2002) conceptualisation of the ideal tourist city as having a compact central area in which cultural and historical landmarks, major attractions, entertainment facilities, and other tourism-related amenities are concentrated, enabling visitors to move between them largely on foot. The spatial distribution of Airbnb in Belgrade strongly reflects this logic. Although STRs have considerably greater locational flexibility and a wider spatial coverage than hotels, this flexibility has not fundamentally decentralised the geography of tourist accommodation. Instead, Airbnb remains strongly dependent on the compact central tourist core, expanding the supply of accommodation within and around established tourism spaces rather than substantially extending tourism into new parts of the city.

However, the results also reveal important differences between the urban geographies of Airbnb and hotels. The main areas of hotel concentration, including the principal hotel cluster in the old city, largely overlap with the main areas of Airbnb concentration. These overlapping zones correspond to the city’s primary tourist areas, which attract both hotels and STRs. In this sense, Airbnb and hotels display a spatially co-existing relationship and may compete for similar urban spaces and partly overlapping tourist markets. This co-location may intensify tourism-related pressure in already saturated parts of the city, contributing to touristification and associated problems such as the reduced availability of housing for local residents, rising rents, commercial gentrification, congestion, noise, and the transformation of everyday urban spaces into consumption-oriented tourist environments. Future research should therefore examine more closely the competitive relationship between hotels and Airbnb in these central areas, particularly in terms of price, occupancy, target markets, seasonal dynamics, and differences in visitor profiles.

At the same time, STRs have contributed to the expansion of the tourist function beyond the traditional tourist zones of Belgrade into new urban areas, many of which are, or until recently were, primarily residential. As a result, the boundaries of the “tourist city” have increasingly extended from the historic city core into neighbourhoods that were not previously strongly associated with tourism, generating new social and spatial transformations. In some cases, this expansion may create conditions for the gentrification of residential areas, rising real estate values, and related processes; in other cases, tourism expands into neighbourhoods that are already socially prestigious or undergoing gentrification (Freytag & Bauder, 2018).

In Belgrade, these areas are mostly located within the wider historic city centre, where hotels have not expanded to the same extent. Many of these neighbourhoods,

such as Dorćol and Vračar, are still perceived as prestigious residential areas and are inhabited by higher social strata (Ratkaj et al., 2024). This makes Belgrade an interesting case, as Airbnb appears to be strongly concentrated in areas already attractive to higher-income residents, rather than functioning solely as an instrument of gentrification and displacement of lower-income groups in relatively poorer neighbourhoods, as has been observed in some other cities (Cocola-Gant & Gago, 2021). Nevertheless, the social effects of Airbnb expansion in Belgrade remain insufficiently explored. Further research is needed to determine which social groups are most affected by STR growth and whether Airbnb contributes to housing exclusion, displacement pressures, restructuring of residential neighbourhoods, or inclusive tourism (Kadi et al., 2022). Another important finding is the relationship between STRs and newly constructed high-end housing developments located close to the old city centre. For example, newly built luxury residential buildings in the Belgrade Waterfront area account for around 10% of total Airbnb capacity in Belgrade. In these areas, STRs can be interpreted not only as tourist accommodation, but also as part of an investment strategy linked to the profitability of STR markets. This suggests that Airbnb may contribute to broader processes of housing financialisation in Belgrade (Zeković et al., 2025), particularly where new residential developments are partly oriented toward rental income rather than long-term residential use.

The Belgrade case also demonstrates the importance of historical path dependency in shaping the contemporary geography of tourist accommodation. Airbnb has partly filled a spatial “void” created by the specific historical development of hotel locations in the city. Historically, hotels were concentrated on the Sava-facing side of the central city, while Dorćol, the former Ottoman part of Belgrade, remained relatively underdeveloped in terms of hotel accommodation during the second half of the nineteenth century. After Serbia gained independence in 1878, and following the subsequent formation of the Kingdom of Yugoslavia, the functional centre of the city gradually shifted away from Savamala, and hotel development followed this changing urban geography. Despite these broader transformations, Dorćol remained largely outside the main trajectories of new hotel construction. During the socialist period, hotel development shifted toward other parts of the city, while central hotel construction was limited¹⁰ (Budović et al., 2020). Since the 2000s, the availability of relatively larger development plots in the historic centre became restricted, preventing substantial new hotel construction in some highly attractive central areas. Airbnb was able to enter these spaces much more quickly and flexibly, making areas such as Dorćol one of the main focal points of STR expansion in Belgrade.

Other areas indicate a possible substitution relationship (La et al., 2022) between hotels and Airbnb, where STRs use their spatial flexibility as a competitive advantage.

¹⁰ Before the 2000s, the last hotel constructed in the historic city centre dated back to the 1930s.

Although these areas are not always statistically significant by LISA analysis, they are still linked to tourism-related spaces, such as Surčin near Belgrade Airport, where hotel supply remains limited, the historic core of Zemun, and riverfront areas along the Sava and Danube. The touristification of Belgrade's riverbanks, including accommodation in weekend houses and rafts, represents another topic that requires further analysis.

Overall, Airbnb is present across a much wider range of urban areas than hotels in Belgrade, particularly in residential neighbourhoods where hotels are absent. However, it would be difficult to argue that Airbnb simply follows residential housing preferences or that the desire to "live like a local" represents the dominant explanation for its geography. Rather, the spatial pattern of Airbnb in Belgrade suggests a combination of central tourist demand, proximity to attractions, investment opportunities in real estate and housing-market dynamics, as well as the flexibility of STRs in entering existing residential spaces.

Based on the study results, several policy recommendations can be formulated regarding the future development and spatial distribution of STRs in Belgrade. The findings suggest that neither urban tourism nor STR development should be governed through a laissez-faire approach. Instead, Belgrade would benefit from a spatially sensitive regulatory framework designed to maximise the benefits of STRs for different stakeholders, the urban tourism economy and visitors, while simultaneously minimising pressures on housing and limiting the excessive touristification of the historic city centre. A first priority should be the formalisation of the STR sector. Further assessment of Airbnb's effects on other tourism stakeholders, the housing market and urban tourism more broadly, as well as the development of an effective regulatory framework, requires bringing a substantial part of the sector out of the grey economy through mandatory registration and categorisation. Licences, listing activity and changes in the spatial distribution of STRs should subsequently be monitored continuously by city authorities. Secondly, the results indicate that Belgrade should introduce spatially differentiated regulation rather than applying a uniform policy across the entire city. The analysis shows that the strongest processes of touristification and STR concentration remain spatially concentrated in and around the historic urban core. In these high-pressure areas, city authorities could consider restricting the further expansion of professionally operated STRs, for example by capping the number of new commercial licences issued annually or establishing maximum STR densities. In other parts of Belgrade, where tourism and accommodation pressures remain considerably weaker, regulation could remain more permissive in order to retain the economic benefits of STR activity and potentially support a more spatially balanced development of the urban tourism economy.

This study has several limitations. First, the spatial precision of the available Airbnb location data is limited, which restricts the extent to which fine-scale intraurban patterns can be interpreted. More precise address-level data would allow for a more detailed examination of the relationship between STR expansion and specific urban development processes, including the concentration of STRs in newly built residential projects. Second, the study does not examine the locational determinants of hotels and STRs, such as agglomeration effects, proximity to points of interest, neighbourhood type, transport accessibility and walkability, and urban amenities. Third, the analysis treats hotels and Airbnb listings as internally homogeneous categories, although previous research has shown that different hotel categories and different types of Airbnb accommodation, particularly professional and non-professional hosts, may display distinct spatial patterns. Future research should therefore examine these differences and place STR expansion more explicitly within the broader nexus of gentrification, touristification, and housing financialisation.

Acknowledgements

The work was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract number 451-03-34/2026-03/200091). During the preparation of this work, the authors used *ChatGPT* to improve grammar and readability. The authors reviewed and edited the content and take full responsibility for the final manuscript.

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Original scientific article

Received: 26.06.2026;

Accepted: 12.07.2026;

Available online: 28.10.2026.

UDC: 504.1(497.11)

doi: 10.5937/zrgfub26111N

NATURAL HAZARDS VULNERABILITY ANALYSIS USING TRAPEZOIDAL FUZZY AHP AND TOPSIS: THE CASE OF THE ŠUMADIJSKI DISTRICT (SERBIA)

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Abstract: Natural hazards represent an increasingly important challenge for sustainable regional development and disaster risk management. Effective identification of vulnerable areas is essential for reducing potential losses and improving preparedness capacities at the local level. This study presents an integrated GIS-based multi-criteria decision-making framework for analyzing local self-government units vulnerability to natural hazards in the Šumadijski District, Serbia. Fifteen indicators were selected and grouped into three categories: natural hazard exposure, exposure of built-up areas to natural hazards, and demographic vulnerability. The indicators included flood-prone areas, landslide/rockfall susceptibility, seismic hazard, hail-prone areas, erosion and torrential flood potential, as well as selected demographic characteristics associated with increased vulnerability. Criterion weights were determined using the Trapezoidal Fuzzy Analytic Hierarchy Process (TF-AHP), while municipal ranking was performed using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Spatial analyses were conducted within a Geographic Information System environment using hazard datasets derived from the Spatial Plan of the Republic of Serbia and demographic data obtained from the 2022 Population Census. The results indicate that indicators related to natural hazards affecting built-up areas received the highest weights, highlighting the importance of considering potential impacts on populated zones. According to the TOPSIS results, Batočina was identified as the most vulnerable municipality, followed by Rača and Kragujevac, whereas Knić showed the lowest overall vulnerability. The proposed methodology successfully integrates spatial, environmental, and demographic dimensions of vulnerability and provides a transferable framework for supporting disaster risk reduction and spatial planning at the municipal level.

Keywords: disaster risk reduction; multi-criteria decision-making; hazard exposure; demographic vulnerability; relative closeness coefficient

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Introduction

Natural hazards have become one of the most significant challenges to sustainable development worldwide. Increasing frequency and intensity of extreme events, combined with growing population concentrations and expanding built environments, have considerably increased the vulnerability of local communities. Floods, landslides, earthquakes, hailstorms, and erosion-related processes frequently cause substantial economic losses, environmental degradation, and social disruptions. Consequently, the identification and assessment of vulnerable areas have become essential components of disaster risk reduction strategies and spatial planning policies (IPCC, 2022; UNISDR, 2009). Due to the complex influences of various factors, Serbian territory is prone to various natural hazards (Dragičević et al., 2011).

Geographic Information Systems (GIS) have become indispensable tools for natural hazard assessment due to their capability to integrate, analyze, and visualize large volumes of spatial information. GIS-based approaches have been widely applied in landslide susceptibility, flood risk, and environmental vulnerability assessments, often in combination with multi-criteria decision-making techniques (Malczewski, 1999; Malczewski, 2006; Feizizadeh et al., 2014). However, vulnerability assessment usually involves numerous heterogeneous indicators that differ in scale, units of measurement, and relative importance. Consequently, multi-criteria decision-making (MCDM) methods have become increasingly popular in hazard and vulnerability studies (Rashed & Weeks, 2003; Malczewski, 2006).

Among MCDM techniques, the Analytic Hierarchy Process (AHP) is one of the most frequently applied methods for determining criterion importance (Saaty, 1980). Nevertheless, conventional AHP relies on precise judgments that may not adequately reflect the uncertainty and ambiguity associated with expert evaluations. To address this limitation, fuzzy set theory has been integrated into the AHP framework. Fuzzy AHP allows decision-makers to express preferences through fuzzy numbers, thereby reducing subjectivity and providing a more realistic representation of human reasoning (Zadeh, 1965; Buckley, 1985; Kahraman et al., 2004). In particular, trapezoidal fuzzy numbers offer greater flexibility than triangular fuzzy numbers because they can represent a wider range of uncertainty and expert confidence (Wang et al., 2008; Kubler et al., 2016).

Another widely used MCDM technique is the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), which ranks alternatives according to their relative distances from ideal and anti-ideal solutions. TOPSIS has been extensively applied in environmental management, risk assessment, and spatial planning because of its conceptual simplicity and ability to incorporate weighted criteria (Hwang & Yoon, 1981; Chen, 2000).

Although numerous studies have applied GIS and MCDM techniques to hazard and risk assessment, relatively few investigations have simultaneously considered physical hazard exposure, vulnerability of built-up areas, and demographic characteristics at the municipal level in Serbia. Furthermore, applications of Trapezoidal Fuzzy AHP combined with TOPSIS in the assessment of natural hazard vulnerability remain limited. Previous studies conducted in Serbia have demonstrated the usefulness of integrating GIS and fuzzy multi-criteria decision-making approaches for natural hazard assessment. For example, fuzzy AHP and TOPSIS methods were successfully applied for forest fire susceptibility assessment in Nature Park Golija (Novkovic et al., 2021), confirming the applicability of these techniques in disaster risk management and spatial decision-making.

The main objective of this study is to analyze and rank the vulnerability of municipalities in the Šumadijski District to natural hazards using an integrated GIS–Trapezoidal Fuzzy AHP–TOPSIS framework. Specifically, the study aims to: (i) identify and quantify key indicators of natural hazard vulnerability, (ii) determine criterion weights using Trapezoidal Fuzzy AHP, (iii) rank municipalities according to their overall vulnerability using TOPSIS, and (iv) provide spatial planning and disaster risk management recommendations based on the obtained results.

Study Area

The Šumadijski District is located in central Serbia and covers an area of 2,386.82 km². According to the 2022 Population Census, the district had 269,728 inhabitants. Administratively, it consists of seven local self-government units: the City of Kragujevac and the municipalities of Arandelovac, Batočina, Knić, Lapovo, Rača, and Topola. The district occupies a central position within Serbia and represents one of the country's most important demographic, economic, and transportation regions. Kragujevac, the administrative center of the district, is the largest municipality, covering 834.70 km² and accommodating 171,186 inhabitants. In contrast, Lapovo is the smallest municipality, with an area of 54.88 km² and a population of 6,582 (Statistical Office of the Republic of Serbia, 2023).

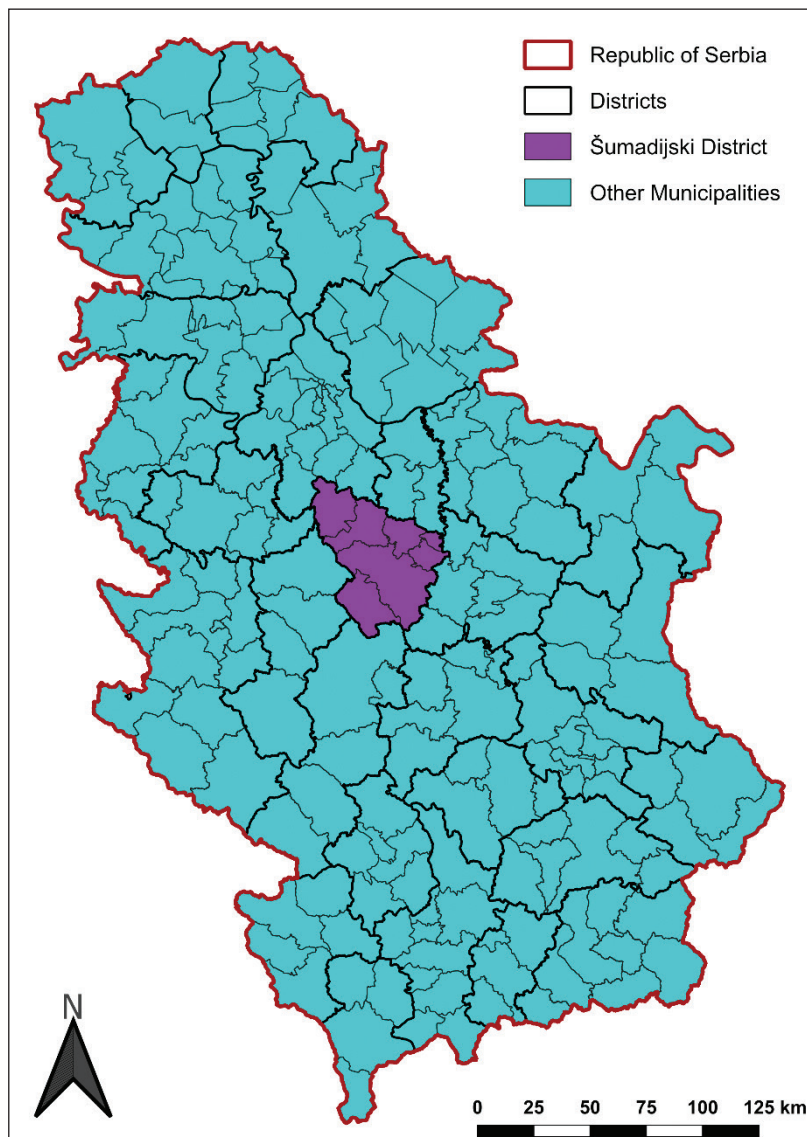


Figure 1. Location of the Šumadijski District in Serbia

Geomorphologically, the district is characterized by a combination of low mountains, hilly terrain, river valleys, and agricultural plains. Such terrain diversity contributes to the occurrence of various natural hazards, including floods, landslides, erosion processes, and torrential floods. In addition, the district is located within a seismically active part of Serbia and is periodically exposed to severe convective storms accompanied by hail.

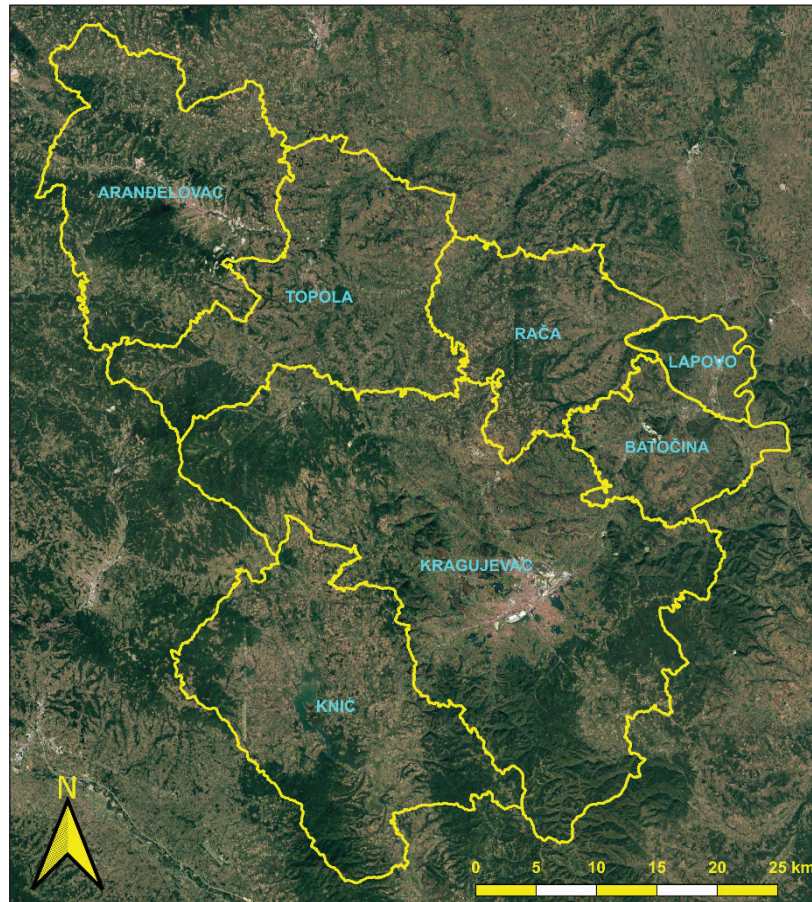


Figure 2. Local self-government units of the Šumadijski District

The spatial distribution of settlements is highly heterogeneous. GIS-based interpretation of satellite imagery indicated that built-up residential and commercial areas occupy approximately 141.67 km², representing 5.94% of the district's territory. These built-up areas constitute the most vulnerable spatial units because they concentrate population, economic activities, infrastructure, and public services. Due to the diversity of environmental conditions, settlement patterns, and demographic structures, the Šumadijski District represents an appropriate case study for evaluating municipal vulnerability to natural hazards through the integration of spatial and socio-demographic indicators.

Materials and Methods

The assessment of municipal vulnerability to natural hazards was based on the integration of spatial and demographic datasets within a Geographic Information System (GIS) environment. Natural hazard data were obtained from the Spatial Plan of the Republic of Serbia 2021–2035, which provides nationally harmonized information on areas exposed to major natural hazards. Five hazard categories were considered: flood-prone areas; landslide- and rockfall-prone areas; seismic hazard zones with expected earthquake intensity exceeding VIII degrees on the Mercalli–Cancani–Sieberg (MCS) scale for a return period of 475 years (Republic Seismological Survey of Serbia, 2023); hail-prone areas; areas with the highest erosion and torrential flood potential.

For each municipality, the proportion of territory affected by each hazard was calculated. In addition, the same indicators were determined exclusively for built-up residential and commercial areas identified through GIS analysis. Demographic data were obtained from the 2022 Population, Households and Dwellings Census (Statistical Office of the Republic of Serbia, 2023). Five demographic indicators associated with increased vulnerability were selected: percentage of persons with disabilities in the population aged two years and older; percentage of population aged 65 years and over; percentage of persons with primary education, incomplete primary education, or no formal education among the population aged 15 years and over; percentage of economically inactive population; percentage of elderly single-person households. The selected indicators represent demographic characteristics that may influence preparedness, response capacity, evacuation efficiency, and post-disaster recovery. Fifteen criteria were used for municipal vulnerability assessment and grouped into three thematic categories, hazard exposure indicators, hazard exposure in built-up areas and demographic vulnerability indicators, as shown in Table 1. All criteria were considered beneficial (positive) from the perspective of vulnerability assessment because higher values indicate greater vulnerability to natural hazards.

Spatial analyses were performed using Geographic Information Systems. Hazard layers were intersected with local self-government unit boundaries to determine the proportion of their territory exposed to each natural hazard. Subsequently, hazard layers were overlaid with mapped built-up residential and commercial areas to quantify hazard exposure within populated zones.

Table 1. Criteria used for municipal vulnerability assessment

Group	Mark	Criteria	Unit
A	A1	Flood-prone areas	%
A	A2	Landslide/rockfall-prone areas	%
A	A3	Seismic hazard zones exceeding VIII degrees on the MCS scale	%
A	A4	Hail-prone areas	%
A	A5	Areas with the highest erosion and torrential flood potential	%
B	B1	Flood-prone built-up areas	%
B	B2	Landslide/rockfall-prone built-up areas	%
B	B3	Seismic hazard zones exceeding VIII MSC in built-up areas	%
B	B4	Hail-prone built-up areas	%
B	B5	Built-up areas with the highest erosion and torrential flood potential	%
C	C1	People with disabilities in the population aged two years and older	%
C	C2	Population aged 65 years and over	%
C	C3	People lacking education among the population aged 15 years and over	%
C	C4	Economically inactive population	%
C	C5	Elderly single-person households	%

Criterion weights were determined using the Trapezoidal Fuzzy Analytic Hierarchy Process (TF-AHP), which extends the conventional AHP framework by incorporating fuzzy set theory (Zadeh, 1965). Unlike triangular fuzzy numbers, trapezoidal fuzzy numbers provide a plateau of maximum membership, enabling a more realistic representation of uncertainty in expert judgments (Buckley, 1985; Chang, 1996).

A trapezoidal fuzzy number is represented as: $\tilde{A} = (l_1, l_2, u_2, u_1)$, where $l_1 \leq l_2 \leq u_2 \leq u_1$ (Wang et al., 2008). Pairwise comparison matrices were constructed for each criterion group and for the groups themselves. Expert evaluations were expressed using trapezoidal fuzzy numbers. The synthetic extent values were calculated for each criterion following the extent analysis approach originally proposed by Chang (1996), followed by the determination of fuzzy priority vectors and normalized criterion weights.

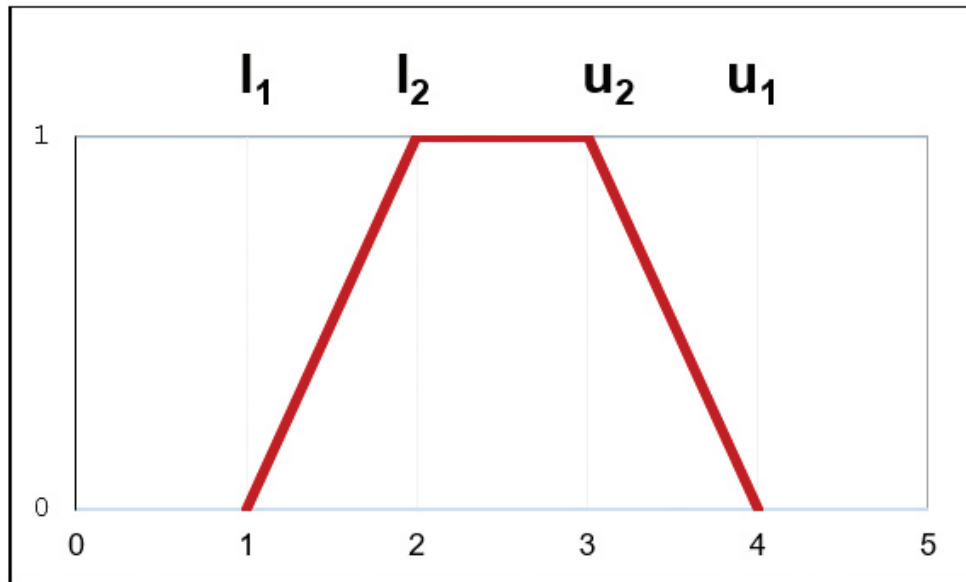


Figure 3. Trapezoidal fuzzy number

Table 2. Trapezoid fuzzy pairwise matrix for criterion group A

A	A1	A2	A3	A4	A5
A1	1,1,1,1	1.1,1.6,2.6,3.1	1.3,1.8,2.8,3.3	1.5,2,3,3.5	1.7,2.2,3.2,3.7
A2	1/3.1,1/2.6,1/1.6,1/1.1	1,1,1,1	1.2,1.7,2.7,3.2	1.3,1.8,2.8,3.3	1.6,2.1,3.1,3.6
A3	1/3.3,1/2.8,1/1.8,1/1.3	1/3.2,1/2.7,1/1.7,1/1.2	1,1,1,1	1.25,1.75,2.75,3.25	1.5,2,3,3.5
A4	1/3.5,1/3,1/2,1/1.5	1/3.3,1/2.8,1/1.8,1/1.3	1/3.25,1/2.75,1/1.75,1/1.25	1,1,1,1	1.3,1.8,2.8,3.3
A5	1/3.7,1/3.2,1/2.2,1/1.7	1/3.6,1/3.1,1/2.1,1/1.6	1/3.5,1/3,1/2,1/1.5	1/3.3,1/2.8,1/1.8,1/1.3	1,1,1,1

Table 3. Trapezoid fuzzy pairwise matrix for criterion group B

B	B1	B2	B3	B4	B5
B1	1,1,1,1	1.2,1.7,2.7,3.2	1.25,1.75,2.75,3.25	1.4,1.9,2.9,3.4	1.6,2.1,3.1,3.6
B2	1/3.2,1/2.7,1/1.7,1/1.2	1,1,1,1	1.2,1.7,2.7,3.2	1.3,1.8,2.8,3.3	1.5,2,3,3.5
B3	1/3.25,1/2.75,1/1.75,1/1.25	1/3.2,1/2.7,1/1.7,1/1.2	1,1,1,1	1.25,1.75,2.75,3.25	1.4,1.9,2.9,3.4
B4	1/3.4,1/2.9,1/1.9,1/1.4	1/3.3,1/2.8,1/1.8,1/1.3	1/3.25,1/2.75,1/1.75,1/1.25	1,1,1,1	1.3,1.8,2.8,3.3
B5	1/3.6,1/3.1,1/2.1,1/1.6	1/3.5,1/3,1/2,1/1.5	1/3.4,1/2.9,1/1.9,1/1.4	1/3.3,1/2.8,1/1.8,1/1.3	1,1,1,1

Table 4. Trapezoid fuzzy pairwise matrix for criterion group C

C	C1	C2	C3	C4	C5
C1	1,1,1,1	1.15,1.65,2.65,3.15	1.25,1.75,2.75,3.25	1.4,1.9,2.9,3.4	1.5,2,3,3.5
C2	1/3.15,1/2.65,1/1.65,1/1.15	1,1,1,1	1.2,1.7,2.7,3.2	1.3,1.8,2.8,3.3	1.4,1.9,2.9,3.4
C3	1/3.25,1/2.75,1/1.75,1/1.25	1/3.2,1/2.7,1/1.7,1/1.2	1,1,1,1	1.25,1.75,2.75,3.25	1.35,1.85,2.85,3.35
C4	1/3.4,1/2.9,1/1.9,1/1.4	1/3.3,1/2.8,1/1.8,1/1.3	1/3.25,1/2.75,1/1.75,1/1.25	1,1,1,1	1.2,1.7,2.7,3.2
C5	1/3.5,1/3,1/2,1/1.5	1/3.4,1/2.9,1/1.9,1/1.4	1/3.35,1/2.85,1/1.85,1/1.35	1/3.2,1/2.7,1/1.7,1/1.2	1,1,1,1

Table 5: Trapezoid fuzzy pairwise matrix for criterion groups

Group	A	B	C
A	1,1,1,1	1/2.7,1/2.4,1/1.6,1/1.3	1/2,1/1.7,1/1.3,1/1
B	1.2,1.6,2.4,2.8	1,1,1,1	1,1.2,1.6,1.8
C	1,1.3,1.7,2	1/1.8,1/1.6,1/1.2,1/1	1,1,1,1

The normalized weight of criterion i was calculated as:

$$w_i = d_i / \sum d_i$$

where w_i = normalized criterion weight, d_i = degree of possibility that criterion i is more important than the remaining criteria. The final global weight of each criterion was obtained by multiplying the local criterion weight (w) by the corresponding group weight (W) (Table 6). The resulting weights satisfy $\sum w_i = 1$, and were subsequently used within the TOPSIS procedure, that was used for municipal vulnerability ranking.

Table 5: Weight coefficients for each criterion

Group	Mark	Local criterion weight (w)	Corresponding group weight (W)	Final global weight (w × W)
A	A1	0.341720	0.231348	0.079056
A	A2	0.254562	0.231348	0.058892
A	A3	0.184467	0.231348	0.042676
A	A4	0.130554	0.231348	0.030203
A	A5	0.088697	0.231348	0.020520
B	B1	0.339884	0.442208	0.150299
B	B2	0.250566	0.442208	0.110802
B	B3	0.185050	0.442208	0.081831
B	B4	0.132601	0.442208	0.058637
B	B5	0.091899	0.442208	0.040639

C	C1	0.336733	0.326445	0.109925
C	C2	0.250880	0.326445	0.081898
C	C3	0.184765	0.326445	0.060316
C	C4	0.131820	0.326445	0.043032
C	C5	0.095801	0.326445	0.031274

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is one of the most widely used multi-criteria decision-making (MCDM) methods. The method is based on the principle that the optimal alternative should have the shortest distance from the positive ideal solution and the greatest distance from the negative ideal solution (Hwang & Yoon, 1981). Due to its conceptual simplicity, computational efficiency, and ability to simultaneously evaluate multiple criteria, TOPSIS has been extensively applied in environmental management, risk assessment, spatial planning, and sustainability studies.

The method has also been successfully extended to fuzzy decision-making environments, allowing the incorporation of uncertainty and imprecision in the evaluation process (Chen, 2000). Consequently, TOPSIS is frequently combined with fuzzy weighting techniques, such as Fuzzy AHP, where fuzzy logic is employed to determine criterion importance, while TOPSIS is used to rank alternatives.

In this study, TOPSIS was applied to rank municipalities of the Šumadija District according to their overall vulnerability to natural hazards. The analysis was performed using criterion weights obtained through the Trapezoidal Fuzzy Analytic Hierarchy Process. The decision matrix was first normalized using vector normalization:

$$r_{ij} = x_{ij} / \sqrt{\sum x_{ij}^2}$$

where x_{ij} = value of criterion j for municipality i , r_{ij} = normalized value. The weighted normalized matrix was then obtained:

$$v_{ij} = w_j \times r_{ij}$$

where w_j denotes the TF-AHP weight of criterion j . The positive ideal solution (PIS) and negative ideal solution (NIS) were defined as:

$$A^+ = \{\max(v_{ij})\}$$

$$A^- = \{\min(v_{ij})\}$$

Because all criteria were beneficial from the vulnerability perspective, maximum values formed the positive ideal solution.

The Euclidean distances from the ideal and anti-ideal solutions were calculated:

$$D_i^+ = \sqrt{\sum (v_{ij} - v_j^+)^2}$$

$$D_i^- = \sqrt{\sum (v_{ij} - v_j^-)^2}$$

Finally, the relative closeness coefficient was computed:

$$CC_i = D_i^- / (D_i^+ + D_i^-)$$

Municipalities with higher closeness coefficients were considered more vulnerable to natural hazards and therefore received higher positions in the final ranking. Owing to its transparency and effectiveness in ranking alternatives based on multiple criteria, TOPSIS has become one of the most frequently applied MCDM techniques in environmental and hazard-related studies (Behzadian et al., 2012).

Results

The analysis of natural hazard exposure revealed considerable spatial variability among municipalities of the Šumadijski District. Flood hazard was most pronounced in the municipalities of Lapovo and Batočina, where flood-prone areas account for more than one-third of the municipal territory. In contrast, no significant flood-prone areas were identified within the municipality of Knić. The largest absolute flood-prone area was recorded in the City of Kragujevac due to its extensive territorial extent.

Landslide and rockfall susceptibility showed a different spatial pattern. The municipalities of Arandelovac and Topola exhibited the highest proportions of landslide-prone terrain, reflecting the influence of local geomorphological and geological conditions. The lowest susceptibility was identified in Lapovo. The seismic hazard analysis indicated that earthquakes represent one of the most widespread natural hazards in the district. Entire territories of Batočina, Lapovo, and Rača are located within the zone where earthquake intensities exceeding VIII degrees on the Mercalli–Cancani–Sieberg scale may occur during the considered return period. More than two-thirds of the district territory falls within this hazard category, making seismic risk one of the dominant environmental threats in the study area.

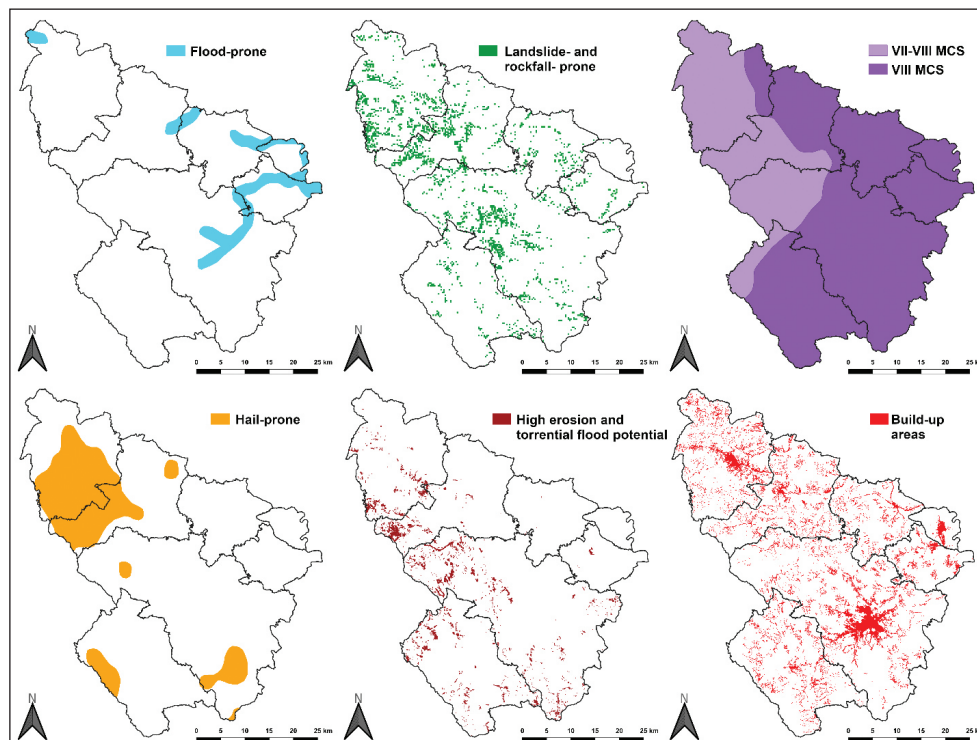


Figure 4. Spatial distribution of natural hazard exposure and build-up areas

Table 6. Natural hazard exposure in the Šumadijski District

Local self-government unit	Flood-prone [%]	Landslide- and rockfall-prone [%]	Seismic hazard over VIII MCS [%]	Hail-prone [%]	High erosion and torrential flood potential [%]
Arandelovac	2.63	11.90	15.06	52.27	2.95
Batočina	33.39	4.60	100.00	0.00	0.39
Knić	0.00	3.63	85.42	8.16	3.22
Kragujevac	6.57	7.22	76.17	6.51	2.90
Lapovo	35.64	0.28	100.00	0.00	0.00
Rača	13.56	5.31	100.00	0.04	0.03
Topola	2.34	9.24	54.37	33.00	3.04

The distribution of hail-prone areas was highly uneven. Aranđelovac and Topola displayed substantially larger shares of territory exposed to severe hail events than the remaining municipalities. Conversely, hail-prone zones were practically absent in several municipalities. Areas characterized by the highest erosion and torrential flood potential occupied a relatively small proportion of the district territory. Nevertheless, the spatial distribution of these areas indicates localized susceptibility that may significantly affect settlements and infrastructure under extreme hydrometeorological conditions. The analysis demonstrates that natural hazard exposure is not uniformly distributed across the district. Different municipalities are characterized by distinct combinations of hazards, highlighting the need for integrated multi-hazard assessment approaches.

Table 7. Natural hazard exposure of built-up areas in the Šumadijski District

Local self-government unit	Flood-prone [%]	Landslide- and rockfall-prone [%]	Seismic hazard over VIII MCS [%]	Hail-prone [%]	High erosion and torrential flood potential [%]
Aranđelovac	2.98	10.61	15.44	62.36	2.91
Batočina	48.56	5.32	100.00	0.00	2.88
Knić	0.00	3.65	88.63	8.77	3.44
Kragujevac	31.39	4.84	90.59	1.84	2.82
Lapovo	6.26	0.00	100.00	0.00	0.00
Rača	30.47	4.81	100.00	0.00	0.00
Topola	4.26	8.81	62.08	25.24	3.01

The demographic analysis revealed substantial differences in population characteristics associated with vulnerability to natural hazards. The highest proportions of persons with disabilities were recorded in Lapovo and Knić, whereas Aranđelovac exhibited the lowest share. Elderly population (65 years and over) was particularly prominent in Knić and Topola, indicating increased vulnerability due to reduced mobility and response capacity during emergency situations. Educational structure also showed notable spatial disparities. The highest percentages of persons with primary education, incomplete primary education, or no formal education were recorded in Rača and Topola, while Kragujevac displayed the most favorable educational profile. Educational attainment may influence risk awareness, access to information, and the effectiveness of preparedness measures.

Table 8. Demographic vulnerability in the Šumadijski District

Local self-government unit	People with disabilities [%]	Population aged 65+ [%]	People lacking education [%]	Economically inactive population [%]	Elderly single-person households [%]
Arandjelovac	4.79	22.59	23.21	58.70	13.89
Batočina	6.74	25.00	30.08	59.89	14.83
Knić	7.20	28.39	34.61	63.00	17.73
Kragujevac	5.75	21.98	18.80	56.25	12.06
Lapovo	7.90	25.71	28.25	61.35	15.24
Rača	5.93	26.17	42.18	59.42	14.48
Topola	5.47	26.18	37.57	61.93	14.36

The share of economically inactive population exceeded 56% in all municipalities and reached its highest values in Knić and Topola. Likewise, elderly single-person households were particularly common in Knić and Lapovo. Such households are often considered highly vulnerable because of limited social support networks and reduced capacity for self-protection during disasters. Although demographic indicators generally exhibit smaller variability than physical hazard indicators, they represent an important component of overall vulnerability. Their inclusion allows the assessment framework to account not only for exposure but also for the social capacity of local communities to cope with natural hazards.

The Trapezoidal Fuzzy Analytic Hierarchy Process produced differentiated weights for the fifteen vulnerability indicators, reflecting their relative importance in the decision-making process. The highest weight was assigned to criterion B1 (flood-prone built-up areas), with a value of 0.1503. This was followed by criterion B2 (landslide- and rockfall-prone built-up areas) with a weight of 0.1108 and criterion C1 (population with disabilities) with a weight of 0.1099. These results indicate that exposure of populated areas and the presence of socially vulnerable groups were considered the most influential determinants of municipal vulnerability. Within Group A, which represents overall hazard exposure, flood-prone areas received the highest weight, whereas erosion and torrential flood potential obtained the lowest importance. Similar patterns were observed within Group B, where flood and landslide exposure in built-up areas dominated the weighting structure.

The cumulative weights of Group B criteria account for approximately 44% of the total model weight, while demographic indicators contribute around 33% and general hazard exposure indicators approximately 23%. This distribution emphasizes

that vulnerability assessment should prioritize potential impacts on populated areas rather than considering hazard extent alone. The weighting results also demonstrate the advantages of the Trapezoidal Fuzzy AHP approach in representing uncertainty in expert judgments while maintaining consistency and transparency throughout the weighting process.

The final ranking of municipalities was obtained using the TOPSIS method and the criterion weights derived from the Trapezoidal Fuzzy AHP model. The municipality of Batočina achieved the highest closeness coefficient (0.6432) and was therefore identified as the most vulnerable municipality within the Šumadijski District. This result can primarily be attributed to the exceptionally high proportion of flood-prone areas, extensive seismic exposure, and high vulnerability of built-up zones. Rača ranked second with a closeness coefficient of 0.4870, followed closely by the City of Kragujevac (0.4857). Although Kragujevac exhibits lower percentages for several hazard indicators, its large, urbanized area and significant exposure of populated zones contribute substantially to its overall vulnerability score.

Next is Arandjelovac, whose ranking is strongly influenced by higher exposure to landslides and hail-prone areas, particularly within built-up zones. Topola ranked fifth despite relatively high values for several demographic and environmental indicators. Lapovo was classified as the sixth most vulnerable municipality. While it demonstrates high flood and seismic exposure, its overall ranking is moderated by lower values of several other indicators and its relatively small territorial extent. Knić achieved the lowest TOPSIS coefficient (0.2647) and was therefore ranked as the least vulnerable municipality among the analyzed local self-government units. Despite unfavorable demographic characteristics, lower exposure to several major hazards contributed to its comparatively lower vulnerability score.

Table 9. Relative closeness coefficient for local self-government units

Local self-government unit	Relative closeness coefficient (CC)
Arandjelovac	0.451108
Batočina	0.643240
Knić	0.264726
Kragujevac	0.485698
Lapovo	0.333231
Rača	0.486987
Topola	0.391288

The obtained ranking confirms that vulnerability results from the interaction between environmental hazards and demographic sensitivity rather than from the influence of any single factor. Consequently, municipalities with moderate hazard exposure but high social vulnerability may achieve vulnerability levels comparable to those of municipalities exposed to more intense natural hazards.

Discussion

The present study demonstrates the applicability of an integrated GIS–Trapezoidal Fuzzy AHP–TOPSIS framework for assessing municipal vulnerability to natural hazards. By combining spatial hazard indicators with demographic vulnerability characteristics, the proposed approach provides a comprehensive representation of vulnerability that extends beyond traditional hazard mapping.

The weighting results indicate that criteria describing hazard exposure within built-up areas exert a substantially greater influence on overall vulnerability than criteria describing hazard exposure across the entire municipal territory. In particular, flood-prone built-up areas (B1) and landslide-prone built-up areas (B2) received the highest weights among all analyzed indicators. This finding suggests that the potential impacts of natural hazards on populated areas are considered more critical than the total spatial extent of hazard-prone zones. The high importance assigned to demographic indicators further confirms that vulnerability is not determined solely by physical exposure. The relatively high weights obtained for the proportion of people with disabilities (C1) and elderly population (C2) emphasize the role of social sensitivity in disaster risk assessment (Fekete, 2009; Cutter et al., 2003). Individuals with limited mobility or reduced access to resources often experience greater difficulties during evacuation, emergency response, and post-disaster recovery. Therefore, the inclusion of demographic characteristics significantly improves the ability of vulnerability models to capture real-world conditions (Cutter et al., 2003; Cutter & Finch, 2008).

The obtained municipal ranking reveals substantial differences in vulnerability across the Šumadijski District. Batočina achieved the highest TOPSIS score and was identified as the most vulnerable municipality. This result primarily reflects the municipality's extremely high flood exposure, complete inclusion within the analyzed seismic hazard zone, and significant vulnerability of built-up areas. The ranking demonstrates that municipalities do not necessarily become highly vulnerable because of a single dominant hazard but rather because of the cumulative effects of multiple hazards combined with social vulnerability factors. Rača and Kragujevac occupied the second and third positions, respectively. Although Kragujevac exhibits lower values for several individual hazard indicators than some smaller municipalities,

its extensive urbanized area and concentration of population increase its overall vulnerability. This finding highlights the importance of considering exposure within built-up areas rather than relying exclusively on the proportion of municipal territory affected by hazards. In contrast, Knić was identified as the least vulnerable municipality despite exhibiting relatively unfavorable demographic characteristics. The result suggests that demographic vulnerability alone is insufficient to generate high overall vulnerability when physical exposure remains comparatively limited. This outcome confirms the multidimensional nature of vulnerability and demonstrates the usefulness of multi-criteria decision-making approaches for integrating diverse indicators into a single assessment framework.

An important methodological contribution of this study is the application of Trapezoidal Fuzzy AHP instead of the more commonly used Triangular Fuzzy AHP. While both approaches are based on fuzzy set theory, trapezoidal fuzzy numbers allow decision-makers to express uncertainty through a wider interval of maximum membership. Consequently, expert judgments can be represented more realistically, particularly when precise pairwise comparisons are difficult to establish (Kubler et al., 2016; Wang et al., 2008). The integration of Trapezoidal Fuzzy AHP and TOPSIS also offers several practical advantages. Trapezoidal Fuzzy AHP effectively addresses uncertainty in the weighting phase, whereas TOPSIS provides a transparent and computationally efficient ranking procedure based on distances from ideal and anti-ideal solutions. Together, these methods enable the generation of robust vulnerability rankings while maintaining methodological simplicity and interpretability (Behzadian et al., 2012; Opricovic & Tzeng, 2004).

The findings have important implications for disaster risk reduction and spatial planning in Šumadijski district. Local self-government units identified as highly vulnerable should receive priority in the implementation of preventive measures, infrastructure protection programs, and emergency preparedness activities. Particular attention should be directed toward settlements located within flood-prone and landslide-prone zones, as these criteria exerted the strongest influence on vulnerability assessment results. Furthermore, demographic vulnerability indicators should be incorporated into local disaster management plans to ensure that vulnerable population groups receive adequate support during emergencies (UNDRR, 2015).

Despite the advantages of the proposed methodology, several limitations should be acknowledged. First, hazard indicators were derived from nationally available datasets and therefore depend on the spatial accuracy and thematic resolution of the original sources. Second, the weighting process remains partially dependent on expert judgment despite the application of fuzzy logic. Third, the analysis was performed at the local self-government unit level, which may conceal significant intra-unit differences in vulnerability. Future research could address these limitations

by incorporating higher-resolution spatial data, additional socioeconomic indicators, and sensitivity analyses of criterion weights. Moreover, the proposed framework could be applied to other districts of Serbia, enabling comparative regional assessments and the development of a national vulnerability index.

Overall, the results confirm that the integration of GIS, Trapezoidal Fuzzy AHP, and TOPSIS provides a reliable and transferable approach for assessing vulnerability to natural hazards. The methodology successfully captures both environmental exposure and demographic sensitivity, thereby supporting evidence-based decision-making in disaster risk management and spatial planning.

Conclusion

This study proposed an integrated GIS-based framework for assessing municipal vulnerability to natural hazards in the Šumadija District through the combined application of Trapezoidal Fuzzy AHP and TOPSIS methods. The approach enabled the simultaneous consideration of environmental hazard exposure and demographic vulnerability, providing a comprehensive basis for municipal-level vulnerability assessment. The weighting results emphasized the importance of hazard exposure within built-up areas, particularly flood- and landslide-prone zones, while demographic indicators also contributed significantly to the overall assessment. The obtained TOPSIS ranking revealed notable differences among municipalities, identifying Batočina, Rača, and Kragujevac as the most vulnerable local self-government units within the district.

The findings confirm that vulnerability to natural hazards is a multidimensional phenomenon that cannot be adequately explained by physical hazard exposure alone. The integration of social and demographic characteristics substantially improves the representation of local vulnerability patterns and contributes to a more realistic assessment of potential disaster impacts. From a methodological perspective, the study demonstrates that the combination of Trapezoidal Fuzzy AHP and TOPSIS provides a transparent and effective decision-support framework for vulnerability assessment under conditions of uncertainty. The proposed approach can be easily transferred to other regions and adapted to different sets of indicators, making it suitable for broader applications in disaster risk reduction and spatial planning.

The results may support local authorities in prioritizing risk reduction measures, improving emergency preparedness, and incorporating vulnerability considerations into spatial planning and development policies. Future research should focus on the application of the methodology at finer spatial scales and on the inclusion of additional socioeconomic and environmental indicators to further improve assessment accuracy.

Acknowledgment

This research was supported by the Science Fund of the Republic of Serbia, Project ID: 7358, POPENVIROS – “Population dynamics under environmental challenges in Serbia”, as well as within the framework of the SRO (University of Belgrade – Faculty of Geography) funded by the Ministry of Science, Technological Development and Innovation for 2025 [contract number 451-03-137/2025-03/200091].

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Original scientific article

Received: 04.09.2026;

Received in revised form: 17.09.2026;

Accepted: 21.09.2026;

Available online: 28.10.2026.

UDC: 551.583(676.2)

doi: 10.5937/zrgfub26133C

CLIMATE CHANGE AND (SUSTAINABLE) DEVELOPMENT – CASE STUDY OF NAIROBI (KENYA)

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Abstract: The primary objective of this paper is to identify the most significant climate changes in Nairobi for the period 1993-2023. The final goal is to propose sustainable solutions to improve the city's resilience to climate change, including enhancing urban infrastructure, promoting use of renewable energy, and encouraging greener practices across various sectors to ensure a more sustainable and climate-resilient future for Nairobi. The Mann-Kendall test was used to analyze temperature and precipitation trends. The Rainfall Anomaly Index (*RAI*) indicator was used to rank years according to dryness, while the Gaussen index (*GI*) was applied to determine the dry months. Lang's rain factor (*LRF*), Emmanuel de Marton Drought Index (*DMI*), and the Pina Combined Drought Index (*PCI*) were used to identify drought in Nairobi. The main results shows statistically significant yearly increase in air temperature at the level of significance $\alpha = 0.001$, and decreasing of the precipitation which is not statistically significant. *RAI* indicate increasing extreme years for the last ten years. According to the results of the Gaussen Index for the Nairobi weather station, it was found that in the period 1993-2023, there were a five dry months (jun – october), while according to typology of climate season, there are six dry months. Nairobi belongs to dry climate type according to the *LRF*, between semi-dry and mediterranean type according to the *DMI*, and semi-dry according to the *PCI*. Climate change is affecting the lives and work of Nairobi's population, especially due to the large number of residents living in poor conditions.

Keywords: drought, extreme weather, season, Africa, Kenya, Nairobi, underdeveloped regions, Mann-Kendall test.

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Introduction

Intergovernmental Panel on Climate Change (*IPCC*) defines climate change as alterations in the climatic state caused by both natural processes and external anthropogenic forces such as land use and greenhouse gas emissions (IPCC, 2021). Climate change can affect physical environment, climate volatility, and relative accessibility of natural resources (Kumar et al., 2021), water resources (Burić et al., 2023), changes in hydrological processes and climate conditions (Doulabian, et al., 2021), population migration in lower development regions (Sedlak, Malinić & Joksimović, 2025), social, economic and ecological changes (Rajczak, Pall & Schär, 2013), poverty (Sedlak, Josifov & Malinić, 2025). Climate change also affects agriculture and thus dictates the prices of certain foods (Mio et al., 2020; Petrović et al., 2023), as well as food security (Mondejar et al., 2021). Climate change is listed as the most critical risk factor across the globe affecting urban areas where the rate of many impacts, such as higher temperatures, fluctuations in the pattern and intensity of precipitation, besides the occurrence of severe and extreme weather, has been estimated and noted (Kareem et al., 2020). Climate change in the form of frequent weather events (Papadopoulou et al., 2024), affect infrastructure (Yin et al., 2023), and tourism (Pandžić et al., 2022).

Unplanned urban growth amplifies the consequences of climate change, especially for low-income regions (Fekete, 2023). These issues are emerging more sharply as the city expands, and the infrastructure is already stretched to accommodate floods and heat waves (Li, Stringer & Dallimer, 2022). This occurs mostly in urban areas in the “Global South”, particularly Asia and Africa, since they face a “climate-urbanization nexus” as stated in The United Nations Human Settlements Programme (UN-Habitat, 2022). Research on African cities, such as Mombasa and Dar es Salaam, has found that they are more vulnerable to climate-related risks, such as floods and heat waves (Cabral et al., 2018). Other rapidly urbanizing regions in the developing world experiencing similar climate change impacts (Pelling, 2011; Lwasa, 2020).

Rising temperatures are associated with a trend toward aridification of the climate, so, in conjunction with global warming, drought is a growing problem in many parts of the world (Gadedjisso-Tossou, Adjegan, & Kablan, 2020; Rajić i Zemunac, 2017). This is especially evident in less developed parts of the world, where the population lives in informal settlements. Developing countries such as Kenya are gravely endangered by climate change due to geographic exposure, an impoverished economy, and high dependence on natural resources (Semplici & Campbell, 2023).

Over the last few decades, Kenya has undergone significant changes in seasonal rainfall patterns and increased occurrence of extreme weather conditions, including

prolonged droughts and floods (Ayugiet al., 2020). Drought, flood, and increasing temperatures seriously challenge Kenya's social and economic transformation and its citizens' well-being. Again, it is the needy populations living in slums and severe climatic areas that are mostly affected by these disasters (Nidhi & Charles, 2020). In Nairobi erratic climate systems reflected in droughts and floods are now apparent (Musyoka, 2019). This is due to an increase in fossil fuel usage, deforestation, and urbanization, which all lead to a decrease in the ability of the city to absorb carbon dioxide. Nairobi, like many cities in sub-Saharan Africa, faces increasing temperatures and unpredictable rainfall patterns, which contribute to poor air quality, especially in urban areas with high vehicular emissions (Kenya Meteorological Department, 2022). Climate change also threatens biodiversity, as ecosystems in the Nairobi region, including forests and wetlands, are increasingly vulnerable to shifts in temperature and rainfall. These environmental stressors, combined with the spread of vector-borne diseases like malaria due to changing climates, are escalating public health risks, particularly for vulnerable populations in informal settlements (World Health Organization, 2020). Vegetable production worse off from climate variability (Ogendi, Mukundi & Githiri, 2021). Climate change has greatly influenced this food productivity in Nairobi, especially in peri-urban regions of Njiru, Embakasi, Mihango, Ruai, Karen, Mukuru Kwa Njenga, Kawangware, and Pangani since different crops and livestock are produced. These effects can, for instance, be observed in cereals such as maize and beans, roots and tubers, and vegetables and fruits, which have a bearing on the dairy, poultry, and small ruminants subsectors, respectively (Abuje, 2021). The social-economic costs of climate change to residents in Nairobi mainly affect the needy groups, such as people in the slums and peri-urban areas.

The most important influences on the design of climate policy come not only from direct factors (greenhouse gas emissions), but also from indirect factors (primary energy consumption per capita and energy productivity) (Kluza et al., 2024). Different climatic conditions, climatic disasters and trends of the most significant climatic changes elements (temperature, precipitation) impose unique models of mitigation and adaptation to them (Sedlak, Josifov & Malinić, 2025). Nairobi, like most emerging cities, has also implemented various measures addressing climate change's impacts on physical planning, development controls, and disaster risk management frameworks (Muchiri & Opiyo, 2022). While the Nairobi has made strides in promoting green infrastructure and renewable energy adoption, challenges remain in scaling these solutions to the broader population (Wambugu, 2021). Local and national policies play a critical role in driving climate resilience, with Kenya's National Climate Change Action Plan (NCCAP) 2018-2022 providing a framework for addressing these issues. However, gaps in policy implementation, inadequate funding, and weaknesses in urban planning have constrained the effectiveness of

climate and urban development policies in Nairobi (Republic of Kenya, 2018; Nairobi City County Government, 2018).

This study is significant because it helps in the understanding of the urban dimension of climate change, since it has been left out in Kenya's environmental research, which mostly delves into rural settings. By focusing on Nairobi, this research adds valuable insights into how urban residents experience and adapt to climate-related risks. The findings can help inform policymakers, urban planners, and environmental agencies such as *NEMA*, *UNEP*, and the World Bank in designing inclusive, climate-resilient strategies for cities. Two of the impacts of climate change concerning Nairobi, which is the capital city of Kenya and also the largest city, include: regarding extreme weather conditions, where the city of Nairobi has experienced these impacts through changes in the physical structures of cities with an increase in instances of damage, and also infrastructural changes and disruption of critical sectors such as agriculture and water provision.

The primary objective of this paper is to identify the most significant climate changes in Nairobi for the period 1993-2023. The final goal is to propose sustainable solutions to improve the city's resilience to climate change, including enhancing urban infrastructure, promoting use of renewable energy, and encouraging greener practices across various sectors to ensure a more sustainable and climate-resilient future for Nairobi.

Materials and methods

Study area

Nairobi is located in the South-Central part of Kenya about 1,795 meters above sea level. Nairobi lies on several intercommunicating rolling hills, valleys, and a plateau offering different heights and contributing to its water drainage system and the city's varied micro-climates (Gitonga & Kanyepi, 2022). The city's daily temperatures range between 10°C and 26°C (Kiplimo, 2019), and it experiences two main rainy seasons (Mwangi et al., 2020): the long rains between March and May and the short rains between October and December (Abuje, 2021; Matsaba et al., 2020). Climate change has affected water resources in Nairobi's water supply (Nyiwul, 2021). The hydraulic system of Nairobi is based on several rivers with the Nairobi River being prominent among them alongside its branches, which is vital in providing water and supporting the ecological structure of Nairobi (Kumar et al., 2021). It is realized that these rivers are more commonly experiencing pollution and fluctuations in flow attributable to climate change and urbanization (National Environment Management Authority 2019-2021). The current environmental changes in Nairobi are being experienced as a threat to agriculture, water security,

and global health among urban and peri-urban dwellers (Adeyeye, Gibberd & Chakwizira, 2020). These vulnerabilities will be discussed in the framework of this study concerning the specified environmental and physical threats of climate change. Residents of Nairobi usually experience such consequences due to deflections in infrastructure for resource endowment (Adger et al., 2003; Satterthwaite, 2011). Drainage systems are poorly designed or maintained, and land-use regulation is often ignored in rapidly expanding suburbs (Bandauko & Arku, 2023). By understanding how these communities respond to climate stress, the study will complement the social understanding of climate resilience of urban areas (Dodman, 2017; Revi et al., 2014). Only about 50% of Nairobi's population has reliable access to piped water, while poor drainage and waste management systems increase the city's sensitivity to flooding and waterborne diseases (Water Services Regulatory Board [WASREB], 2024). While not all slum settlements have higher densities than their surrounding cities, most slum populations are typically denser than formal urban areas. In Nairobi, for example, an estimated 60% of the population (of all 4,4 millions residents) lives in slums (UN-Habitat, 2019), but slums occupy an estimated 6% of the urban land. Overcrowding is often associated with decreases in quality of living conditions and sanitation, and hence the rate of agent transmission is typically high in such urban neighbourhood.



*Figure 1. Study area: position of Nairobi in Africa (left), and map of Nairobi (right).
Source: Open Street Map (2026)*

Data source and conceptual model

Data on the amount and distribution of precipitation, fluctuations in temperature, and frequencies of storms and other climate-related extremes were gathered from the

Climate Change Knowledge Portal of the World Bank and Kenya Meteorological Department databases, NEMA, and UNEP reports on how climate change has impacted weather systems in Nairobi. Also, data on maize production was collected from the KilimoStat, which helped determine climate variability's effect on maize production and agriculture practices.

Data was collected from the Nairobi meteorological station ($\phi = 1.30169^\circ\text{S}$; $\lambda = 36.75919^\circ\text{E}$; 1,795 m a.s.l.). Nairobi has a subtropical highland climate with dry winters (*Cwb*) according to the Koppen classification. Seasonal values were created based on four distinct annual seasons, which are classified according to rainy and dry periods (Table 1). The duration and timing of these seasons varies across the region of East Africa, driven principally by the movement of the intertropical convergence zone (*ITCZ*) (Palmer et al., 2023), and modern climate changes (Choi, Campbell & Eltahir, 2023).

Table 1. Climate seasons in Nairobi

Season	Months	Main characteristics
Shorter dry season (<i>JF</i>)	January	Which is also the warmer part of the year. Temperatures are slightly higher than during the rainy months.
	February	
Long rains (<i>MAM</i>)	March	With the most rainfall usually in April. Due to the abundance of rainfall, the vegetation flourishes, and the conditions are favorable for agriculture.
	April	
	May	
Drier period (<i>JJAS</i>)	June	Characterized by little precipitation, drier conditions, more cloudiness and relatively lower temperatures. Lower temperatures than at the beginning of the year, especially at night and in the morning. During September, temperatures begin to rise.
	July	
	August	
	September	
Short-term rains (<i>OND</i>)	October	Most pronounced in November. Temperatures are relatively pleasant and moderate. Rains are often short-lived and showers, but less abundant than in the long rainy season.
	November	
	December	

Source: Choi, Campbell & Eltahir, 2023; Dyer & Washington, 2021; Kotikot, S. Smithwick & Greatrex, 2024; Nicholson, 2017; Palmer et al., 2023; Yang et al., 2015;

The results of this paper are interpreted from several parts. The first part provides an analysis of descriptive statistics related to air temperature and precipitation in Nairobi for the period 1993-2023. In the second part, an analysis of air temperature trends and precipitation on an annual, seasonal and monthly level was performed. In the third part, a typology of dry and wet years and months with transitional varieties was made. In the fourth part, an analysis of various climate indices was performed for the period 1993-2023, as well as sub-periods: 1993–2002, 2003–2012. and 2013–2023. The results are interpreted through their analysis through the prism of socio-economic consequences on the case study of Nairobi.

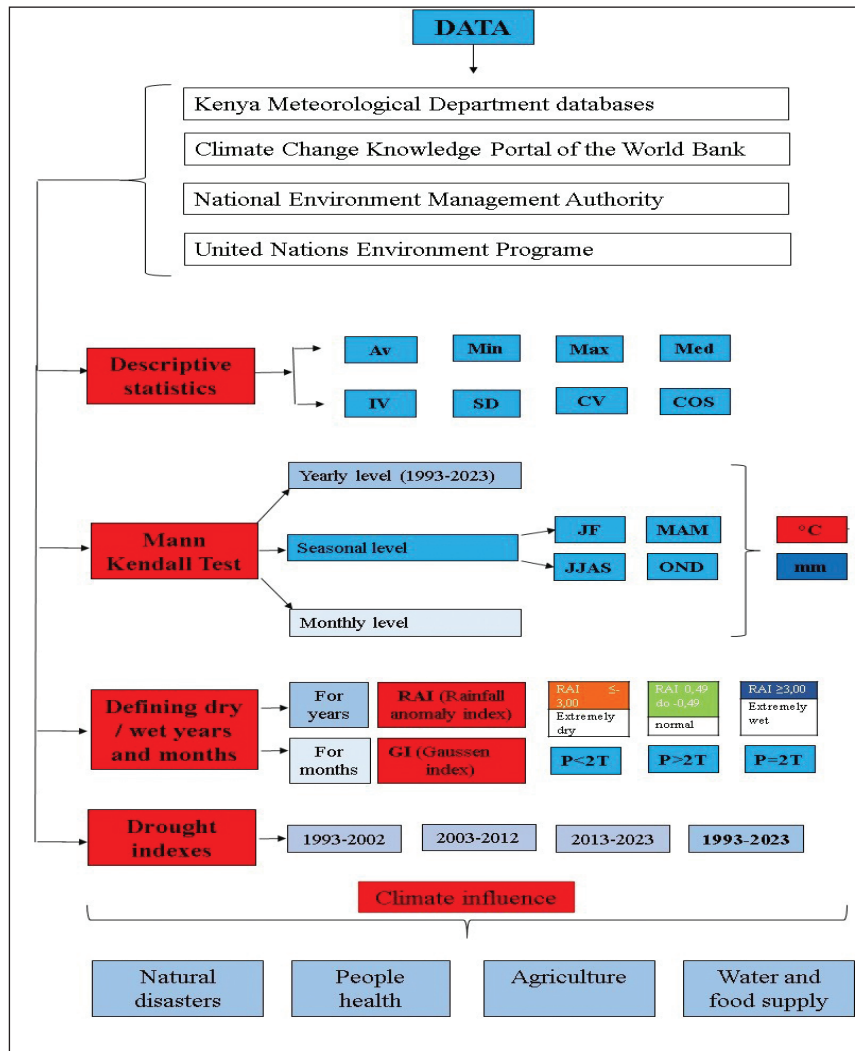


Figure 2. Conceptual model of paper

Statistical methods

Descriptive statistics includes 8 parameters in this paper:

- Average values (*Av*) were used to identify mean values of temperature and precipitation for the entire period (1993–2023). They are an important indicator of changes in temperature and precipitation.
- Minimum values (*Min*) are calculated for temperatures and precipitation on an annual, monthly and seasonal level with the aim of observing regularities in the occurrence of the lowest temperatures.

- Maximum values (*Max*) were analyzed for temperatures and precipitation on an annual, seasonal and monthly level with the aim of establishing in which period they are most prevalent.
- Median values (*Med*) were used in this paper because this value is less susceptible to extreme values of these indicators. Considering the climatic characteristics of Nairobi, this value is more important for rainfall where the variations are more pronounced.
- The interval of variations (*IV*) was used in this paper with the aim of observing the amplitudes between the lowest and highest values of temperature and precipitation in Nairobi.
- Standard deviation (*SD*) and Coefficient of variation (*CV*) are used to indicate the deviation of values from the arithmetic mean. A higher value of the standard deviation indicates a higher variability in relation to the average values and vice versa.
- The coefficient of skewness (*COS*) was used to establish the symmetry of the data distribution. The values generally range from 2 to -2. If $COS > 0$, right asymmetry is present, which indicates the expression of higher values. If $COS < 0$, left asymmetry is present and indicates the existence of smaller values in the data series.

Mann Kendall test

The non-parametric Mann-Kendall test was used for the analysis, determination and decomposition of air temperature time series. This test was originally proposed by Mann (1945) and later improved by Kendall (1975) and has been widely used in climatological and hydrological time series (Atilgan et al, 2017; Bajat et al, 2015; Dragičević et al, 2015; Langović, 2019; Manojlović et al, 2022; Milentijević et al, 2022; Sedlak, Srejić & Manojlović, 2025), but also in medical geographical research (Kričković et al., 2024; Kričković, E. et al., 2025a; Kričković, E. et al., 2025b; Kričković, E. et al., 2025c).

$$S = \sum_{i=2}^n \sum_{j=1}^{i-1} \text{sign}(x_i - x_j)$$

Where the function of the sign is defined as:

$$\text{sign}(x) = \begin{cases} 1, & \text{for } x_i - x_j > 0 \\ 0, & \text{for } x_i - x_j = 0 \\ -1, & \text{for } x_i - x_j < 0 \end{cases}$$

If there are equal values in the data series:

$$V(S) = 1/18 \left[n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5) \right]$$

Where is:

n – number of observations,

g – number of groups of equal values,

t_p – number of elements in the p -th group of equal values.

The standardised test statistic Z is given by

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0, \\ 0 & \text{if } S = 0, \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0, \end{cases}$$

The following two hypotheses were tested using the Mann-Kendall test. The null hypothesis states that there is no trend in the selected data series. The alternative hypothesis indicates a statistically significant trend in the selected data series. A positive trend value (Z) indicates an upward trend and a negative value indicates a downward trend. If the Z value is greater than 1.96, this is an indicator of the statistical significance of the trend (Alhaji et al., 2018; Nyamtseren, Feng & Deo, 2018; Khand et al., 2020; Manojlović et al., 2021).

Defining years on dry / wet

The Rainfall Anomaly Index (RAI) indicator was used to rank years according to dryness. Based on precipitation data, it estimates the intensity and duration of drought and has practical applications in water resources management and agriculture. Lower values indicate greater drought intensity and vice versa (Table 2). It is calculated according to the formula (Rajić & Zemunac, 2017):

$$RAI = 3 * \frac{P_Y - P_{av}}{P_{max} - P_{av}}$$

Where: P_Y - the amount of precipitation in a given year (mm), P_{av} - the mean value of the sum of precipitation for the entire observed period (for this study 1993-2023), P_{max} - the mean value of the 10 maximum recorded sums of annual precipitation within the observed period (1993-2023).

Table 2. Value scale for RAI

Value	$\leq -3,00$	-2,99 to -2,00	-1,99 to -1,00	-0,50 to -0,99	0,49 to -0,49	0,50 to 0,99	1,00 to 1,99	2,00 to 2,99	$\geq 3,00$
Description	Extremely dry	Very dry	moderate dry	slightly dry	normal	slightly wet	Moderate wet	Very wet	Extremely wet

Source: Rajić & Zemunac, 2017

To determine the dry months, the Gausse index (GI) was applied according to which $P < 2T$, where P is the monthly amount of precipitation, and T is the temperature. This means that for each individual month, the amount of precipitation is compared with twice the value of the average monthly air temperature. The situations are as follows (Toigo et al., 2006):

- if $P < 2T \rightarrow$ the month is dry
- if $P > 2T \rightarrow$ the month is not dry
- if $P = 2T \rightarrow$ near the threshold for being classified as dry

Drought indexes

In this paper are used three different drought indexes:

Lang's rain factor (LRF) represents the relationship between the amount of precipitation and the average annual air temperature. It is calculated according to the formula:

$$LRF = \frac{P}{T}$$

The Emmanuel de Marton Drought Index (DMI) is one of the oldest drought indices and is used to identify drought on an annual, seasonal and monthly scale (Brđanin & Sedlak, 2021). For the purposes of this study, the analysis was done only on an annual basis. It is calculated according to the formula:

$$DMI = \frac{P}{T + 10}$$

The Pina Combined Drought Index (PCI) is an important index for identifying drought regions (Luković et al., 2024). In this index, terms related to precipitation for the driest month (P_{dry}) and temperature for the driest month (T_{dry}) have been introduced. It is calculated according to the formula:

$$PCI = \frac{1}{2} + \left(\frac{P}{T + 10} + \frac{12P_{dry}}{T_{dry} + 10} \right)$$

These three different indices indicate the severity of drought in Nairobi (Table 3). Their values were calculated for each individual year, but also for several periods:

1993-2023, 1993-2002, 2003-2012, 2013-2023. Based on the established extreme values, the driest and wettest years were identified. The values of these indices reflect the characteristics of the climate, but also of other natural conditions (type of vegetation, runoff, water resources).

Table 3. Drought indexes with scales

LRF		DMI		PCI	
Values	Type	Values	Type	Values	Type
< 20	Very dry	< 10	Dry	PCI < 10	Dry
20 ≤ LRF < 40	Dry	10 ≤ DMI < 20	Semi-dry	10 ≤ PCI ≤ 20	Semi-dry
40 ≤ LRF < 60	Semi-dry	20 ≤ DMI < 24	Mediterranean	20 ≤ PCI ≤ 30	Moderate dry
60 ≤ LRF < 100	Semi-humid	24 ≤ DMI < 28	Semi-humid	30 ≤ PCI ≤ 40	Moderate wet
100 ≤ LRF < 160	Humid	28 ≤ DMI < 35	Humid	PCI > 40	Wet
LRF > 160	Perhumid	35 ≤ DMI ≤ 55	Very humid		
		DMI > 55	Excessively humid		

Source: Andrade, Contente & Santos, 2021; Ioannis Charalampopoulos & Droulia, 2025; Živanović et al., 2024.

Results

The main characteristics of climate in Nairobi

In Table 4. average values of air temperature and precipitation in Nairobi are shown. The highest annual temperature was measured in 2009 and 2023, while the lowest was in 1993. The highest amount of precipitation was in 2019, while the lowest was in 2000. Amplitudes of annual air temperatures in Nairobi are not expressed (IV indicates this). The difference between the wettest and driest years is significantly greater. The median indicates that half of the total number of years has an air temperature lower than 20.63°C, that is, less than 682.47 mm of precipitation. The stated values are higher in relation to the average values (A_v), but the differences are greater in precipitation (by 7.2% in relation to A_v) in relation to temperatures (by 0.2% higher in relation to A_v). In terms of precipitation, there are also larger deviations from the mean value, as indicated by the SD values. The COS values are negative, which indicates that the average values are more influenced by years with lower temperatures, i.e. smaller amounts of precipitation.

In the case of average values of temperature and precipitation at the seasonal level, there are greater differences in terms of precipitation. Only in the *OND* season are average temperatures higher compared to the annual level for the period 1993-2023. A total of 16.4% of the average annual precipitation is discharged in *JF*, 44% in *MAM*, 10.2% in *JJAS* and 29.7% in *OND*. The lowest temperature and the lowest amount of precipitation is in the *JJAS* season. *JF* has the maximum temperature, and

MAM has the amount of precipitation. Median values for temperatures are higher compared to average temperatures during the dry seasons of *JF* and *OND*. In the case of precipitation, the ratio of the median to the average value has a different pattern. Only in *JF* is the median higher than the average value (by 1.1%). The differences between maximum and minimum air temperature values are most pronounced in *JF*. In terms of precipitation, the differences between maximum and minimum values are more pronounced in the rainy seasons (*OND*, *MAM* seasons) compared to the dry seasons. *JF* season has the highest *SD* values for temperatures, while *MAM* season for precipitation. *JF* and *OND* seasons have negative *COS* values for temperatures, indicating that these values are more influenced by lower temperatures. *COS* values for precipitation are positive in three seasons (*MAM*, *JJAS*, *OND*), which indicates that their mean values are more influenced by the values of years with higher amounts of precipitation.

Table 4. Seasonal and yearly temperatures and rainfall in Nairobi for period 1993-2023.

Season	<i>JF</i>		<i>MAM</i>		<i>JJAS</i>		<i>OND</i>		yearly	
	°C	mm	°C	mm	°C	mm	°C	mm	°C	mm
<i>Av</i>	21.47	104.11	21.34	280.21	19.33	65.03	20.88	189.29	20.58	636.75
<i>Min</i>	19.68	1.51	20.43	98.67	18.55	29.79	20.04	69.98	19.97	283.79
<i>Max</i>	22.35	301.99	22.33	569.6	20.28	147.62	21.53	552.36	21.11	932.19
<i>Med</i>	21.58	105.26	21.31	259.41	19.32	60.47	20.94	151.16	20.63	682.47
<i>IV</i>	2.67	300.48	1.90	470.93	1.73	117.83	1.49	482.38	1.13	648.4
<i>SD</i>	0.53	76.03	0.43	116.43	0.37	27.61	0.34	111.91	0.31	178.58
<i>CV</i>	0.29	5779.84	0.18	13556.95	0.14	762.08	0.12	12524.78	0.10	31889.64
<i>COS</i>	-0.59	-0.05	0.24	0.54	0.13	0.50	-0.51	1.02	-0.45	-0.77

There are no large deviations between the average monthly temperatures in Nairobi (Table 5). In a 10 months, the lowest average temperatures were recorded in the 20th century. The only exception being April with the lowest monthly temperature in 2018 and June with the lowest monthly temperature in 2001. January, February and March had the lowest temperatures in 1993. July, August and September had the lowest monthly temperatures in 1998. In 1999, the lowest monthly temperatures were measured for October, November and December. Conversely, the highest monthly temperatures have been recorded for all months in the 21st century, beginning in 2005. In the first decade of the 21st century (until 2010), the highest monthly temperatures were recorded in February, December and June. In the third decade of the 21st century (2020–2023), as many as five months recorded the highest temperatures for the period 1993–2023, these were; November in 2021, May in 2022 and August, September and October in 2023. Between the amplitudes of the highest and lowest monthly temperatures, the differences are greater in the period December - April, compared to the months from May to November (with the exception of August).

A greater deviation from the mean values is present in the period January – April, which is indicated by higher values of the *SD*. In 8 months, a negative asymmetry was expressed ($COS < 0$), which indicates that the values are influenced by a smaller number of lower monthly temperature values. This is especially pronounced for October, May and January, which indicates that there is no regularity in the seasonal distribution.

Table 5. Temperature in Nairobi (1993-2023)

Months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
<i>Av</i>	21.18	21.76	22.03	21.44	20.55	19.37	18.65	19.12	20.19	21.01	20.78	20.86
<i>Min</i>	19.64	19.72	20.74	20.37	19.65	18.82	17.73	18.03	19.37	20.22	20.03	19.88
<i>Max</i>	21.87	22.91	23.29	23.06	21.15	20.28	19.49	20.23	21.33	22.12	21.82	22.15
<i>Med</i>	21.27	21.84	21.99	21.42	20.63	19.29	18.67	19.16	20.18	21.11	20.82	20.89
<i>IV</i>	2.23	3.19	2.55	2.69	1.5	1.46	1.76	2.2	1.96	1.9	1.79	2.27
<i>SD</i>	0.52	0.61	0.60	0.57	0.37	0.41	0.43	0.43	0.44	0.40	0.40	0.44
<i>CV</i>	0.27	0.37	0.37	0.32	0.14	0.17	0.19	0.19	0.19	0.16	0.16	0.19
<i>COS</i>	-0.52	-0.39	0.19	0.10	-0.62	0.61	-0.17	-0.29	0.05	-0.73	-0.34	-0.23

The lowest average monthly rainfall in Nairobi is from June to September (table 6). The rainiest months are April, November, and May. In comparison with the temperature distribution of the year with the lowest and highest amounts of precipitation by month for the period 1993-2023 in Nairobi is not properly distributed in time. Mostly, the months with the lowest amounts of precipitation were registered in the 20th century while the highest amounts of precipitation per month were registered in the 21st century. Seven months recorded the highest amount of precipitation in the period 2013-2023. December, January, April and May have the biggest differences between the minimum and maximum values of precipitation on a monthly basis. This is indicated by *SD* values, which are the highest in those months, while they are the lowest during June – September. Compared to the monthly values for temperature, negative asymmetry ($COS < 0$) is expressed here only in two months: February and August.

Table 6. Precipitation in Nairobi (1993-2023)

Months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
<i>Av</i>	58.23	50.25	78.40	115.39	80.57	23.74	11.62	14.79	14.54	36.00	89.24	63.98
<i>Min</i>	1.45	0.06	10.77	13.21	14.77	5	1.79	4.76	0.05	1.03	26.84	6.96
<i>Max</i>	230.64	161	204.42	251.69	225.41	90.83	35.01	33.71	33.65	145.6	225.63	245.63
<i>Med</i>	42.35	50.47	60	102.21	71.69	19.06	9.94	14.81	12.45	28.5	73.08	41.9
<i>IV</i>	229.19	160.94	193.65	238.48	210.64	85.83	33.22	28.95	33.6	144.57	198.79	238.67
<i>SD</i>	58.77	38.23	58.15	68.49	49.87	19.63	8.29	7.27	8.79	30.50	56.82	57.13
<i>CV</i>	3454.06	1461.74	3381.58	4690.20	2487.38	385.36	68.71	52.83	77.23	930.13	3229.05	3263.29
<i>COS</i>	0.81	-0.02	0.95	0.58	0.53	0.71	0.61	-0.01	0.71	0.74	0.85	1.16

Annual temperature and rainfall trend in Nairobi

In the period 1993-2023, a statistically significant increase in air temperature was identified in Nairobi at the level of significance $\alpha = 0.001$ (0.1%). The value of Test Z ($Z = 3.54$) indicates its significance. In the mentioned period, the average annual temperature increase is 0.025°C . The mentioned data indicates pronounced processes of air temperature increase (Figure 1). In the period 1993–2023, no statistical significance was identified in changes in the amount of precipitation in Nairobi, although a decrease was recorded ($Z = -0.20$). The average guided decrease in precipitation amounts to 0.69 mm per year (Figure 2). Rising temperatures in Nairobi have increased heat stress, dehydration and discomfort, particularly among outdoor workers and vulnerable populations in the informal settlements. Global warming will be a particular challenge in the future if rising temperature trends continue.

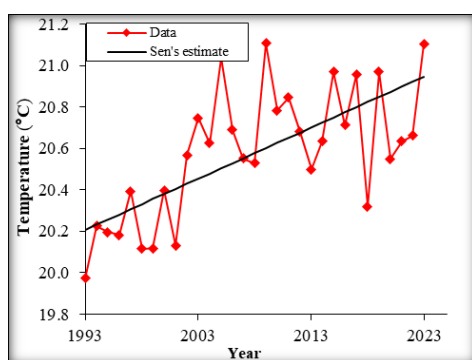


Figure 3. Temperature trend in Nairobi

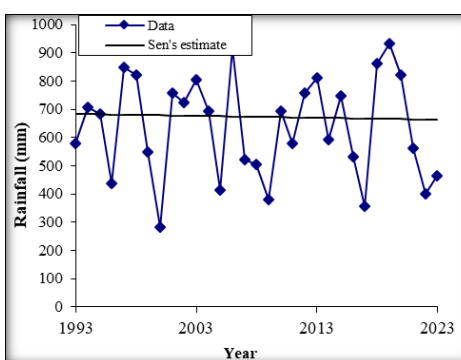
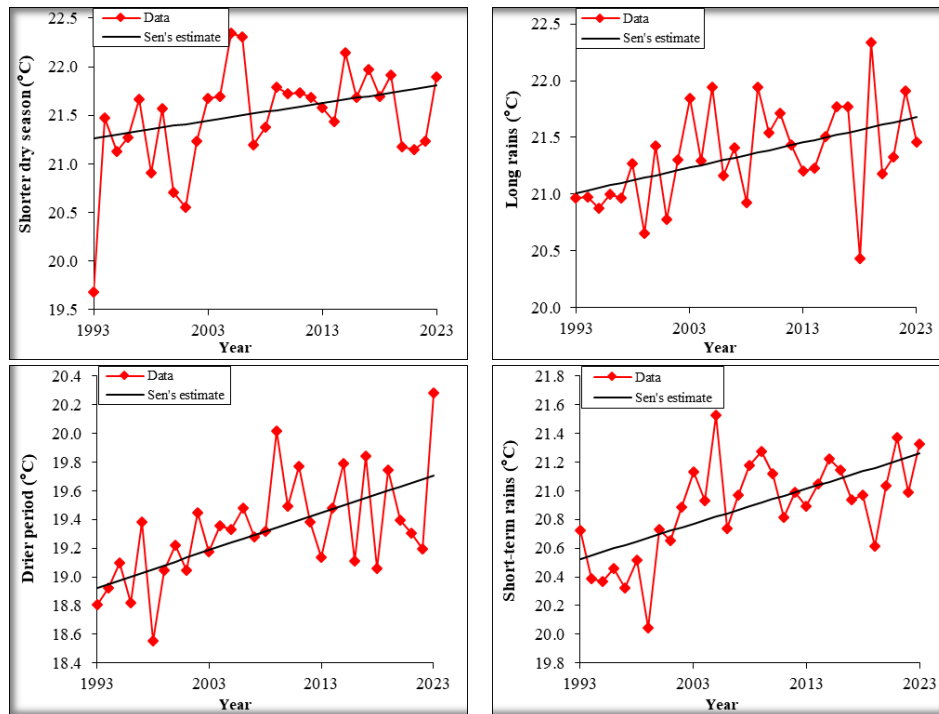


Figure 4. Precipitation trend in Nairobi

Seasonal temperature trend in Nairobi

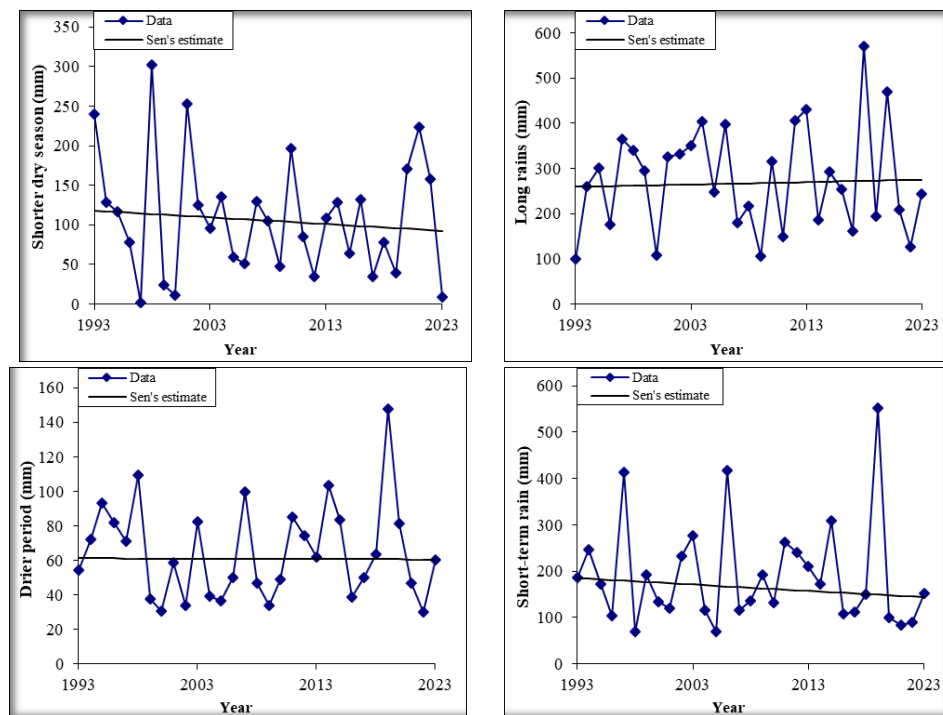
Different seasonal trends of air temperature change were identified in Nairobi (Figures 3-6). A statistically significant increase in air temperature was recorded in all four seasons ($Z > 1.96$). In the *JF* season, a statistically significant increase in air temperature was recorded at the level of significance $\alpha = 0.001$ (0.1%) with a value of $Z = 3.71$ and an average annual temperature increase of 0.024°C . *JJAS* and *MAM* season have a statistically significant increase in temperature at the level of significance $\alpha = 0.01$ (1%). For *JJAS* season, the value $Z = 3.16$ was registered with an average annual increase in air temperature by 0.026°C . For *MAM* season, the value $Z = 2.58$ was registered with an average annual increase in air temperature of 0.022°C . For *OND* season, a statistically significant increase in air temperature was recorded at the $\alpha = 0.05$ (5%) significance level with a value of $Z = 2.09$ and an average annual increase in air temperature of 0.018°C . If an increase in air temperature in

the *JJAS* season is accompanied by a lower amount of precipitation, this has serious consequences for the population's nutrition. Declining yields are leading to rising food prices in Nairobi, which is a major problem for the poor population. During the *MAM* season, rising air temperatures in Nairobi lead to increased evaporation. This increases the frequency of heavy rainfall in a short period of time, which leads to flooding and soil erosion.



Figures 5-8. Seasonal temperature trends in Nairobi

In Nairobi, at the seasonal level, there are no statistically significant trends in changes in the amount of precipitation ($Z < 1.96$) in the period 1993-2023 (Figures 7-10). A decrease in precipitation was recorded for *OND* season ($Z = -0.82$), *JF* season ($Z = -0.34$) and *JJAS* season ($Z = -0.10$). The average decrease in precipitation amounts to 1.38 mm per year for *OND* season, 0.84 mm per year for *JF* season and 0.02 mm per year for *JJAS* season. In the *MAM* season, an increase in the amount of precipitation was registered in the period 1993-2023, which is not statistically significant ($Z = 0.10$). In that season, the average annual increase in precipitation amounts to 0.54 mm per year.



Figures 9-12. Seasonal precipitation trends in Nairobi

In the period 1993-2023, the highest statistically significant increase in temperature at the level of significance $\alpha = 0.001$ (0.1%) was identified for the months of October and July (Table 7). For the months of March and August, a statistically significant trend of temperature increase was identified at the level of significance $\alpha = 0.01$ (1%). The increasing number of months in Nairobi has a trend of increasing air temperature at the $\alpha = 0.05$ (5%) significance level. These are: May, June, September, November, and December. For February, an increase in air temperature was identified at the level of significance $\alpha = 0.1$ (10%). January and April are the only months in which no statistically significant trend of air temperature increase was identified ($Z = 1.56$ for January; $Z = 1.09$ for April).

Changes in rainfall patterns in Nairobi are less pronounced by month over the period 1993-2023 years. For the month of September, a statistically significant increase in precipitation was identified at the level of significance $\alpha = 0.05$ (5%). For the month of November, a statistically significant decrease in precipitation was identified at the level of significance $\alpha = 0.1$ (10%). There are no statistically significant trends for other months ($Z < 1.96$). The decrease in the amount of precipitation in the period 1993-2023 was registered for the months of January, March, May, June, July, August and October.

Table 7. Monthly temperature and precipitation trends in Nairobi

Month	Temperature trends			Rainfall trends		
	Test Z	Significant	Q	Test Z	Significant	Q
January	1.56	/	0.018	-0.44	/	-0.445
February	1.77	+	0.021	0.03	/	0.016
March	2.72	**	0.032	-0.48	/	-0.496
April	1.09	/	0.013	0.95	/	1.440
May	2.18	*	0.018	-0.75	/	-0.808
June	2.31	*	0.017	-0.54	/	-0.144
July	3.84	***	0.031	-0.83	/	-0.114
August	3.03	**	0.025	-0.80	/	-0.105
September	2.14	*	0.019	2.48	*	0.465
October	3.93	***	0.027	-0.44	/	-0.288
November	2.30	*	0.020	-1.68	+	-1.203
December	2.53	*	0.019	0.58	/	0.587
Year	3.54	***	0.025	-0.20	/	-0.688

Note: α significance level, + $\alpha = 0.1$, * $\alpha = 0.05$, ** $\alpha = 0.01$, *** $\alpha = 0.001$, / no significance; Q Sen's slope

Dry and wet years and months in Nairobi

RAI indicates the different varieties of dry and wet years in Nairobi compared to the average value for the period 1993-2023 (Figure 11). Approximately one third of the total number of individual years had extreme values of this indicator ($RAI \leq -3$, $RAI \geq 3$), of which six were extremely dry and four were extremely wet. Extreme values are especially pronounced in the last years of this period. This is indicated by the fact that in the last seven years of the research period (2017-2023), four years had these extreme values (two extremely dry and two extremely wet years each). In the time series of data, their arrangement is such that dry and wet years often occur one after the other. This is the case with the years 1996 and 1997 ($RAI = -3.04$; $RAI = 3.24$), 2005 and 2006 ($RAI = -3.42$, $RAI = 4.27$), 2017 compared to the following two years ($RAI = -4.27$ in 2017, $RAI = 3.43$ in 2018, $RAI = 4.51$ in 2019).

Extremely wet years have negative impact on people in Nairobi. Frequent floods particularly affected people living in informal settlements such as Kibera and Mukuru, where houses are often located in low-lying areas with inadequate drainage. Floodwater damage or sweep away houses and household property, destroy urban crops, contaminate water sources and worsen already poor sanitation conditions. They disrupted health systems, sanitation, roads, bridges, schools, places of worship, public transport, food systems and livelihoods. The impacts fell hardest on women, children, persons with disabilities and low-income households, many of whom faced displacement, livelihood losses, exclusion from relief systems, increased exposure to violence and difficulty accessing safe shelters and services.

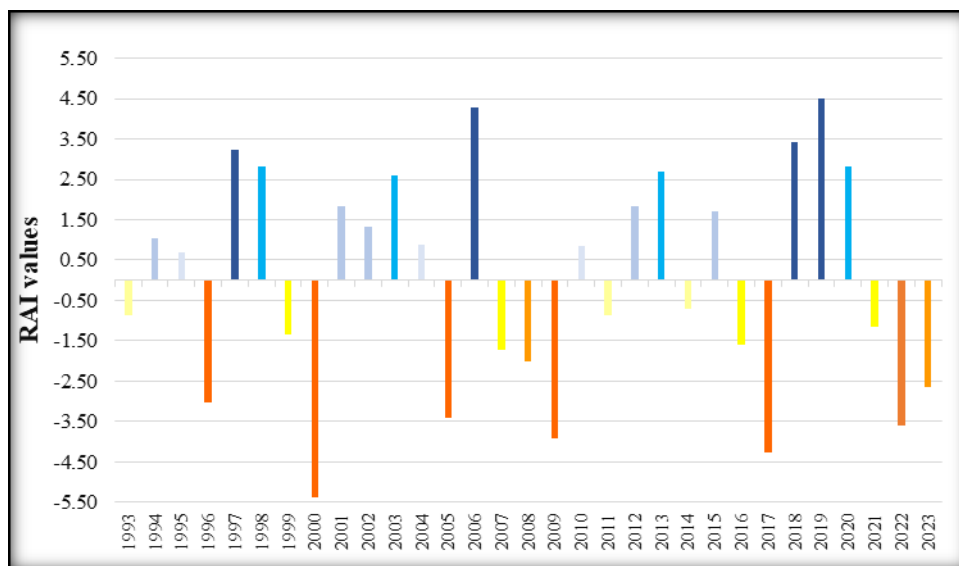


Figure 13. RAI values for Nairobi for period 1993-2023

According to the results of the Gaussen index (GI) for the Nairobi (Table 8), it was found that in the period 1993-2023, there were a total of 5 dry months ($GI < 0$). These are the months from June to October. The reason for this is that in that period the precipitation is the least, although the period June-September is the coldest part of the year (although the average temperatures are less than 2°C lower than the average annual temperature). September and July have the highest values of GI for entire period. In sub-periods 1993-2002, and 2003-2012 the September had the highest values of GI , while in sub-period 2013-2023 it was July. This period largely coincides with the Dryer season, which lasts from June to October. By dividing it into three sub-periods, it was established that in the period 1993-2002 February was the dry month, while in the period 2003-2012 it was January. They belong to the JF season, in which there is a pronounced decrease in monthly rainfall, and at the same time February and January are the second and third hottest months in Nairobi.

Table 8. Values of the Gaussen index for Nairobi

Periods	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1993 - 2002	44.53	-0.79	34.13	54.20	45.45	-10.00	-24.68	-22.71	-30.59	-6.92	62.62	8.23
2003 - 2012	-2.72	9.67	35.23	64.91	47.92	-22.18	-24.31	-23.75	-25.83	-3.28	48.66	24.05
2013 - 2023	6.72	10.90	33.73	96.06	26.35	-13.05	-27.80	-23.85	-21.51	-7.71	33.24	33.41
1993 - 2023	15.87	6.73	34.34	72.51	39.47	-15.01	-25.67	-23.45	-25.83	-6.03	47.69	22.27

Note: According to the GI dry months are marked with yellow color

Dry periods increased pressure on water supplies and urban agriculture in Nairobi. These impacts are particularly severe among low-income households because they have fewer resources to recover from climate-related events. The last sub-period of the study (2012-2023) indicates a slight increase in *GI* for the JF season, which predicts the possibility of a slight increase in humidity for that season.

Results of drought indexes in Nairobi and socio-economic consequences

Based on the three drought indices for the entire period (1993-2023), Nairobi belongs to dry type according to the *LRF*, between semi-dry and Mediterranean type according to the *DMI*, and semi-dry according to the *PCI* (Table 9). Differences are present by periods with the aim to identify change patterns. In the period 1993-2002, the values of the selected drought indices had the highest values compared to the period 2003-2012, 2013-2023, as well as compared to the entire period 1993-2023. This indicates the process of ariditization at this meteorological station. When we compare the data between 2003-2012 and 2013-2023, it is observed that the drought index values for *LRF* and *DMI* are increased, while *PCI* is lower. Such results are a consequence of the increase in extreme years with a higher amount of precipitation in recent years.

Table 9. Drought index values for the period 1993-2023. and sub-periods

Period	<i>LRF</i>	<i>DMI</i>	<i>PCI</i>
1993-2002	31.59	21.14	13.09
2003-2012	30.18	20.37	12.93
2013-2023	31.07	20.96	12.55
1993-2023	30.94	20.82	12.85

According to *LRF* (Figure 12) in Nairobi in the period 1993-2023 were identified 5 extra-arid years ($LRF < 20$), 21 dry years (LRF 20-40), and 5 semi-dry years (LRF 40-60). According to *DMI* (Figure 13), 1 dry year ($DMI < 10$), 14 semi-dry years (DMI 10-20), 5 Mediterranean type years (DMI 20-24), 8 semi-humid years (DMI 24-28) and 3 humid years (DMI 28-35) were registered in Nairobi. According to the *PCI* (Figure 14), 7 dry years, 23 semi-dry years, and 1 moderate dry year were registered in Nairobi. According to *PCI* and *DMI*, semi-dry years are dominant, while dry years are dominant according to *LRF*.

For all three drought indices, the lowest value was recorded in 2000 ($LRF = 13.9$; $DMI = 9.3$; $PCI = 5.8$). Based on the similarity in extreme values, the years in which droughts were more pronounced were established. These are 2000, 2005, 2009, 2017, and 2022. Conversely, wet years were 1997, 1998, 2003, 2006, 2018, and 2019. The highest drought index values were identified for 2019 according to *LRF* and *DMI*, while according to *PCI* it was 2003. The above data indicate that

extreme climatic phenomena are increasingly present in the most recent years of the period 1993-2023. For all three drought indices, a decrease in value was noted for the period 1993-2023, which is not statistically significant: for *LRF* ($Z = -0.37$), for *DMI* ($Z = -0.31$), for *PCI* ($Z = -0.75$).

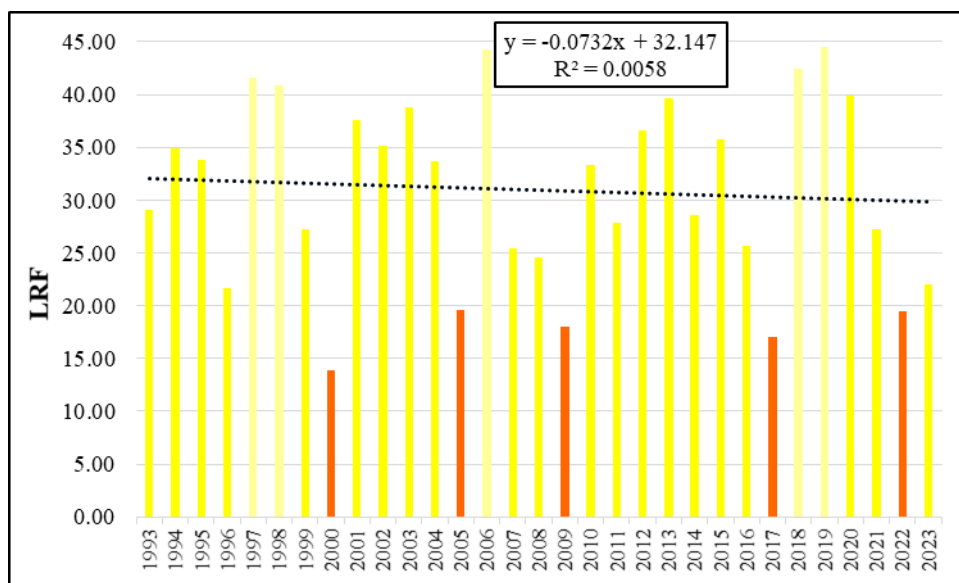


Figure 14. Lang's rain factor for Nairobi (1993-2023)

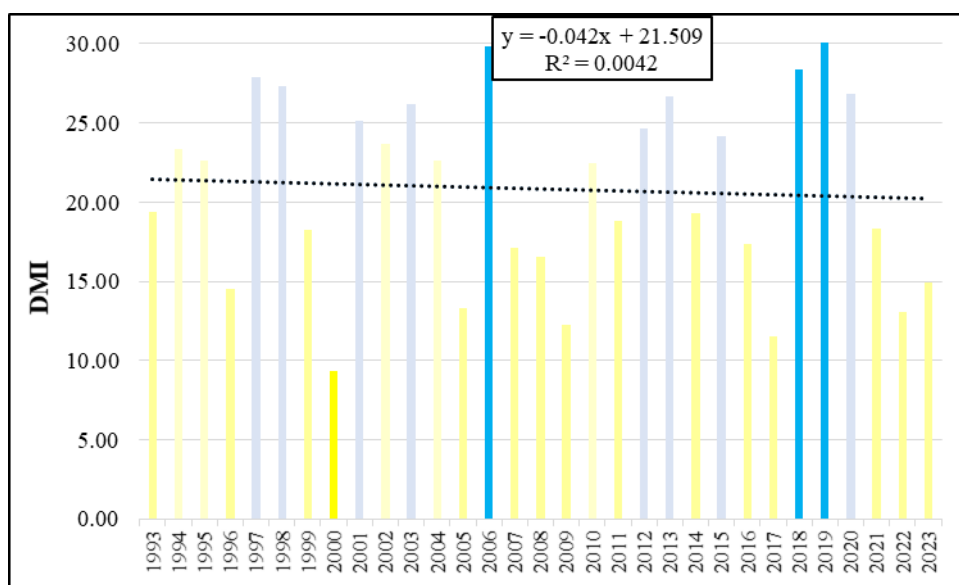


Figure 15. Emmanuel de Marton Drought Index for Nairobi (1993-2023)

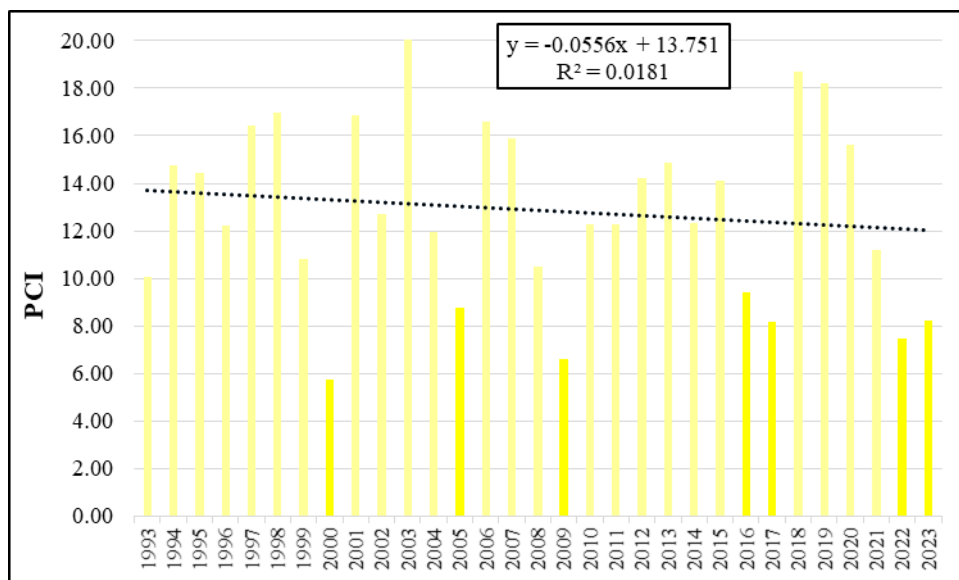


Figure 16. Pina Combined Drought Index for Nairobi (1993-2023)

The decline in drought index in Nairobi is a significant data for future climate projections. This highlights the growing problem of aridification, which is expected to have significant long-term implications for the livelihoods and living conditions in this city and whole region. Increasing drought will affect the population's water supply (lack of water and poor plumbing system), and food supply problems (problem with food quality and price), which will be further exacerbated by population growth. The aforementioned climate trends suggest an increasing risk of poverty, particularly given the population's continued reliance on the primary sector (food production) and the prevalence of inadequate housing conditions among a substantial proportion of residents.

Discussion

The problems of regional differences, uneven territorial distribution of household income, and economic development opportunities are important theoretical and practical issues in all countries of the world (Vujadinović & Šabić, 2017). Contemporary conceptualizations of the region can contribute to spatial interpretation oriented towards sustainability, territorial governance, long-term regional development, and the assessment of possible future regional transformations in the face of growing socio-spatial complexity and global change (Šabić et al., 2026). The above concept is particularly significant for less developed areas of

the world, such as much of Africa. They are particularly dependent on natural conditions, processes and resources on which the lives of the population often depend. Kenya, with its capital Nairobi, is a good example because climate change and the aridification process will further complicate development.

Existing climate change research in Kenya has mainly focused on the general country record or the rural setting, but the urban setting needs to be included. For instance, documents like the USAID, Climate Risk Profiles and Kenya State of Environment Reports (NEMA 2019-2021) have been informative about climate change effects, though most targeted impact assessments have focused on rural settings and the general country situation, creating a research niche for looking into climate change and its effects in the urbanized atmosphere, especially in the rapidly growing areas such as Nairobi.

The IPCC (2023) and UNEP Adaptation Gap Report (2023) both warn that cities like Nairobi will experience intensifying rainfall variability, more frequent floods, and heat stress events unless adaptation is scaled up. The World Bank's Country Climate and Development Report for Kenya (2023) stresses that the city's growth must integrate climate resilience to safeguard human health, water security, and economic productivity. Assessing Nairobi's environment in terms of climate change is relevant to illustrate the environmental problems modern growing cities face and to inform climate-resilient planning.

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Predictions indicate that continued global warming is likely to bring a further increase in extreme precipitation (Davenport, Burke, & Diffenbaugh, 2021). One of the topics discussed in relation to the effects of climate change is the question of whether rainfall has become more frequent over the last decade. This aspect is crucial, as an increase in the intensity and frequency of rainfall could result in a dramatic increase in flooding, leading to loss of life and economic consequences (Treppiedi, et al., 2021). This statement is consistent with the results obtained in Nairobi, which indicate an intensification of extreme weather conditions.

Contemporary approaches to regional development increasingly deal with issues of well-being as a final outcome (Vujadinović et al., 2023). There has been scant work on the relationship between climate change and urbanization, population density, and environmental problems in Nairobi, including pollution, flooding, and soil erosion (Fekete, 2023). Poverty is also a problem in Nairobi. According to official statistical data, the overall poverty rate in Nairobi was 21% in 2005 and 2006, while in

2021 and 2022 decreased to 16,5% (Kenya National Bureau of Statistics). Although the percentage of the poor is declining, the process of unplanned urbanization and the population growth in Nairobi's informal settlements will further increase the risk for a large part of the population from future climate events and extreme weather conditions, both directly and indirectly.

Therefore, realizing climate change mitigation in the city requires a more nuanced approach given the town's unique environmental, social, and economic systems (Ochola et al., 2020). Due to the above multifaceted issues, new research is required to evaluate the effectiveness of existing adaptation strategies and to design context-appropriate adaptation policies for Nairobi. This knowledge will help us learn how to make urban areas more sustainable when facing climate change challenges.

It is therefore evident that successful and sustainable urbanization/post-disaster rebuilding must respond to these issues and aim to create robust physical structures that can withstand intense climatic conditions and design and build frameworks that support strong social structures, good health provision, and good governance (Ahern 2011). According to the Urban Climate Resilience Theory, urban regions can endure, rebound from, or adapt to climate stresses while sustaining their functions (Meerow, Newell, & Stults, 2016). Given the existence of a large number of informal settlements, the indirect impact of the climate (through droughts, floods) will have a greater impact on Nairobi compared to more developed cities.

Some approaches to urban development have prioritised economic growth and physical expansion, sometimes overlooking the potential environmental and climate-related consequences of rapid urbanisation (Wu, 2019). In the case study of the city of Nairobi, the implementation of planning measures would be necessary to regulate residential areas first, and only then consider potential solutions for climate risks.

An effective way of mitigating of climate change is the use of renewable energy sources (Kim et al., 2022), implementation of the concept of circular economy for reducing greenhouse gas emissions (Ogunmakinde et al., 2022), achieving sustainable development goals (Wilkinson et al., 2022). The existence of numerous basic problems across a large part of the territory of the city of Nairobi would make the implementation of these concepts significantly more difficult. For using renewable energy sources (such as solar power plants), initial capital is necessary. For the concept of a circular economy, it would first be necessary to establish an adequate economic framework and long-term development directions for the city. The Sustainable Development Goals could greatly improve the development of the city of Nairobi. SDG 13 relates to climate action. However, before tackling the problem of climate change, the primary focus would be on addressing the Sustainable Development Goals related to poverty reduction (SDG 1) and the eradication of hunger (SDG 2).

Conclusion

In this paper, the most significant results indicate a statistically significant trend of increasing air temperature with a simultaneous decrease in precipitation that is not statistically significant. At the seasonal level, the highest statistical significance of the temperature increases is for *OND* season. *JF*, *JJAS*, and *OND* seasons with exception of *MAM* season has decreasing trend of precipitation which is not statistically significant. At the monthly level, the highest statistical significance is in the temperature increase for July and October. Monthly precipitation trends indicate the greatest statistical significance of the increase in precipitation for September, as well as the decrease in precipitation for November. *RAI* indices that extreme values are especially pronounced in the last years of this period, while *GI* indices drought months from June to October. Three used indices of drought (*LRF*, *DMI*, *PCI*) indices Nairobi belongs to dry type according to the *LRF*, between semi-dry and Mediterranean type according to the *DMI*, and semi-dry according to the *PCI*.

This study highlights the current problem of climate change using the case study of the city of Nairobi, which belongs of the underdeveloped part of the world. Limitation of this study is impossibility of making relationship between climate data with socio-economic indicators, due to the lack of data or the existence of the same for a shorter period of time that often does not have continuity. This work has practical value because it highlights the pressing problem of global warming and aridification, but due to numerous other basic problems (poverty, inadequate infrastructure, uncontrolled urbanization), it is not a priority. Future research will focus on extreme values of climatic elements, their changes, as well as the impact on the population, their health and the entire economy.

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ISBN 978-86-7714-507-5



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