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ASSESSMENT AND OPTIMIZATION OF NOISE TOTAL EMISSIONS IN BELGRADE, SERBIA

Road traffic, aircraft, waste trucks, construction equipment, and industrial facilities are just a few important noise sources that pollute the environment and affect human health. Considering that noise pollution is increasing due to continuous urbanization and increased road traffic, solving this problem is necessary. Optimization of total noise emissions in Belgrade, Serbia was done since noise has always been a source of pollution. This paper presents the use of GIS to establish a multi-factor assessment model to divide infected grids and select control sites, along with the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method, IDW (Inverse Distance Weighting) interpolation technique, zonal GIS (Geographic Information System) statistics, and noise optimization in the investigated area. The analysis was based on noise data recorded (L_{den} – the average noise level over a 24--hour period) values in spring and autumn measuring cycles at 34 measuring points in 11 Belgrade municipalities in 2023. The results showed that noise emission in some control sites requires more than a 25% reduction. The improvement of the environment is required to control the background of noise pollution in Belgrade.

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1. INTRODUCTION

Noise is polluting the environment, and it is harmful to human health. The level of environmental noise today is higher than ever before, and it will continue to increase due to population growth, as well as due to urbanization and the increase of mobile sources of noise [1, 2]. An increase in noise levels is also affected by the construction of main roads, the expansion of the air transport network, and the railways, which are still the largest sources of noise [3]. Noise produces direct and negative effects that accumulate after a certain period and endanger human health [4]. In addition, noise affects housing, social, and work environments, causing economic and non-material losses. Noise impedes sleep, concentration, communication, and recreational activities of people [4]. The objective of the competent ministries should be to protect citizens from the harmful effects caused by noise pollution. People have the right to choose the nature of their acoustic environment, and this should not be imposed by others [4, 5].

The existence of noise pollution problems has not yet been fully acknowledged, even though this problem is continuously growing in developing countries. In the paper of Davis and Masten [6], there are three reasons why the problem of environmental pollution caused by noise is not treated as a problem of air and water pollution. These reasons stemmed from the definition and perception of noise as a subjective experience and the difficulty in linking the cause with effects when it comes to health problems caused by noise pollution. The noise level in the city can be examined in three different ways such as noise levels caused by traffic and transport, industrial activities, sports activities, commercials, and entertainment establishments [7]. In comparison with other pollutants, noise control in the environment is hampered by insufficient knowledge of its impact on humans and the deficiencies of the defined criteria. Therefore, noise is a significant environmental problem in many urbanized zones [8].

In Serbia, the problem of noise pollution is widespread. The conducted measurements of noise levels in larger cities confirm that the noise level exceeds the limited values. Noise pollution in Belgrade is similar to that in many urban areas. Belgrade, the capital of Serbia, records an increase in the rate of population growth. The number of inhabitants in the region of Belgrade increased from 1.66 million in 2011 to 1.68 million in 2022 [9]. In recent years, changes have been made in terms of urbanization, industrialization, and the expansion of road networks and infrastructure. During the measurement of noise levels in Belgrade in 2023, the Belgrade City Public Health Institute [10] concluded that the dominant source of noise pollution in Belgrade is road traffic, according to the results of most measuring spots. However, their report [10] pointed out that other sources also have a certain influence on noise pollution, and for this reason, it is necessary during the construction works and reconstructions to perform physical fencing of the noise sources, whereby the fences must meet certain acoustic standards, primarily in terms of noise absorption. In the case of noise originating from catering restaurants, performances, concerts, etc., it is necessary to carry out additional noise level measurements in certain seasonal periods or weekends, in cooperation with the competent inspection if there are complaints. Belgrade City Public Health Institute [10] has concluded that besides the urgent application of control measures for reducing noise pollution caused by road traffic, adequate sound protection of buildings is of primary importance for protecting people's health from the harmful effects of noise and their undisturbed life and work.

This paper aims to (1) compare the measured results with the limited values, (2) show the noise influence on certain municipalities of the city using the IDW (Inverse Distance Weighting) interpolation technique in GIS, (3) rank the municipalities from those with the highest to those with the smallest noise pollution level using TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method and GIS (Geographic Information System) and (4) establish the cut scheme of noise emission using GIS tools.

2. MATERIALS AND METHODS

The monitoring system in Belgrade. Belgrade is the capital of Serbia, consisting of 17 municipalities. According to the *Annual report on the implementation of the environmental noise level measurement program in the territory of Belgrade in 2023*, published by the Belgrade City Public Health Institute, Center for Hygiene and Human Ecology [10], control of noise emissions was done at 34 measuring spots. Those measuring spots were located in 11 municipalities of Belgrade and their choice depended on the density of the population, the proximity of major roads, important institutions, layout of industrial facilities, the location of noise sensitive areas such as schools, hospitals and recreation areas, and the size and purpose of the covered area. Based on average daily, evening, and night values of measured noise pollution for the year 2023, the average noise level over 24 hours (L_{den}) was calculated by the Belgrade City Public Health Institute [10] for every measuring cycle (spring and autumn), every measuring spot and presented in the above-mentioned annual report. In further analysis, data of L_{den} values for both measuring cycles were used to analyze the noise influence in Belgrade. However, it should be emphasized that future measurements should be conducted over the entire year (covering all four seasons) to provide a more realistic picture and better understanding of noise pollution assessment.

Methods. The purpose of this work is to quantitatively divide the investigated area (into grids) of Belgrade to improve the precision of dividing the area and obtain the optimal noise emission amounts of every municipality of Belgrade under the control scenario. Noise emission control is a spatial optimization decision problem that is combined with zonal statistics, that was used to compute the optimization scheme for the noise emission distribution.

Figure 1 shows the hierarchical model of optimization of the total noise emission based on GIS. Combining noise emission data from documented reports with the Google Satellite View map of Belgrade as the base layer and vector data that was manually created on the base map to present measuring spots (by points), municipalities of Belgrade (by polygons) and grids of the investigated area (by polygons) the multifactor evaluation model was established.

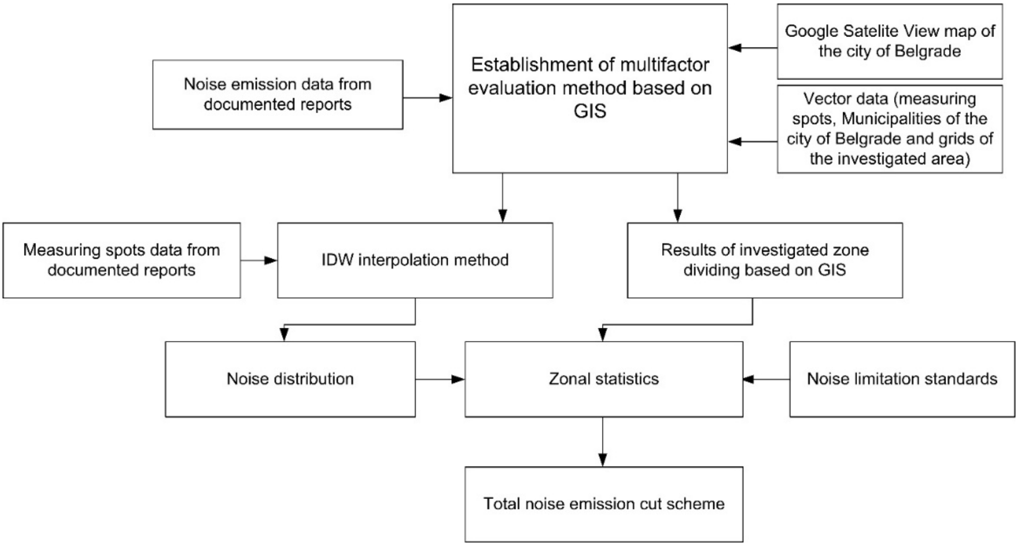

Fig. 1. Hierarchical model of optimization of total noise emission based on GIS

The maximum allowed values of noise indicators in the open space according to acoustic zones defined by the regulation on noise indicators, limit values, methods for assessing noise indicators, disturbance, and harmful effects of noise in the environment were published by the Official Gazette of the Republic of Serbia, No. 75/2010 [11]. This regulation has defined only the maximum allowed values of noise indicators L_{day}, L_{evening}, and L_{night} (Table 1). Considering that the research presented in the paper used calculated L_{den} values, the maximum allowable noise emission amounts according to adjusted national standards with Directive 2002/49/EC [12] (Table 1) were used to optimize noise total emission. There is no national standard for the limit value of L_{den}, so the value of 55 dB was used in the research. Since traffic noise has the biggest influence on the population in all 11 municipalities, the threshold value for L_{den} for road traffic was considered. Although WHO [13] recommended reducing exposure to road traffic noise below 53 dB, in the research, the limit value of 55 dB was used for all zones (Table 1) to conduct a harmonized analysis for all grids. However, it should be noted that the Republic of Serbia is in the process of joining the European Union and that national regulations are still being harmonized with EU directives regarding the permitted level of environmental noise, as well as Belgrade's noise management policies are being harmonized with the best European practices.

Table 1

Maximum allowed values of noise indicators in the open space according to acoustic zones; adjusted national standards with Directive 2002/49/EC [12] [dB]

Zone	Space purpose	Level of noise		
		L_{day} and $L_{evening}$	L_{night}	L_{den}
1	areas for rest and creation, hospital zones and rehabilitation centers, cultural and historical sites, great parks	50	40	55
2	tourist areas, camps, and school zones	50	45	55
3	strictly residential areas	55	45	55
4	business and residential areas, commercial and residential areas, and children's playgrounds	60	50	55
5	city center, craft, trade, administrative zone with apartments, zones along highways, main, and city roads	65	55	55
6	industrial, warehouse, and service areas and transport terminals without residential buildings	at the border of this zone, noise must not exceed; the limit value in the neighboring zone		

Integrated evaluation. 24-hour noise emissions (L_{den}) for both measuring cycles (spring and autumn) were calculated by the Belgrade City Public Health Institute [10] for all 34 measuring spots, using the following formula:

$$L_{den} = 10\lg\frac{1}{24}\left(12\times10^{(L_{day})/10} + 4\times10^{(L_{evening}+5)/10} + 8\times10^{(L_{night}+10)/10}\right) \quad (1)$$

where: L_{day}, $L_{evening}$, L_{night} are the A-weighted long-term average sound levels determined over all day, evening, and night periods of the year, respectively, dB [14].

Regulations of the Republic of Serbia in terms of closer definition and use of established indicators of noise in the environment predict that the period of 24 hours is divided into three referent time intervals:

1) day, lasting 12 hours (from 6 a.m. to 6 p.m.),
2) evening, lasting 4 hours (from 6 p.m. to 10 p.m.),
3) night, lasting 8 hours (from 10 p.m. to 6 a.m.).

Ranking the most affected municipalities of Belgrade by the noise emission was done with the TOPSIS method, one of the methods of MCDM (multi-criteria decision-making).

The TOPSIS method selects alternatives that are closest to the ideal solution and at the same time furthest from the worst alternative. The classical TOPSIS method is based on information about attributes defined by the decision-maker, expressed in numerical data, while the only subjective inputs are weighting factors. The procedure of the classical TOPSIS method is explained through several steps [15, 16]:

Step 1. Construct a decision matrix and determine weighting factors for the criteria. Let $X = (x_{ij})$ be the decision matrix, and $W = [w_1, w_2, ..., w_n]$ the weight vector, where x_{ij} belongs to the set R, w_j belongs to the set R and $w_1 + w_2 + ... + w_n = 1$. The criterion function can be maximum or minimum.

Step 2. Calculate the normalized decision matrix. Value normalization can be performed using one of several standardized formulas. The most used method is to calculate normalized values as follows:

$$n_{ij} = \frac{x_{ij}}{\left(\sum_{i=1}^{m} x_{ij}^2\right)^{1/2}} \tag{2}$$

Step 3. Calculate the weight-normalized decision matrix. The weight-normalized values of v_{ij} are calculated as follows:

$$v_{ij} = w_j n_{ij}, \text{ for } i = 1, ..., m; \ j = 1, ..., n \tag{3}$$

where w_j is the weight of the jth criterion, $\sum_{j=1}^{n} w_j = 1$.

Step 4. Determining the ideal positive and negative solutions. The positive ideal solution A^+ has the following form:

$$A^+ = \left(v_1^+, v_2^+, ..., v_n^+\right) = \left(\left(\max_i v_{ij} \mid j \in I\right), \ \left(\min_i v_{ij} \mid j \in J\right)\right) \tag{4}$$

The negative ideal solution A^- has the following form:

$$A^- = \left(v_1^-, v_2^-, ..., v_n^-\right) = \left(\left(\min_i v_{ij} \mid j \in I\right), \ \left(\max_i v_{ij} \mid j \in J\right)\right) \tag{5}$$

where I is related to the max function and J to the min function of the criterion.

Step 5. Calculate the separation measures from the positive and negative ideal solutions. The separation of each alternative from the ideal positive solution is calculated by the following equation:

$$d_i^+ = \left(\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^p\right)^{1/p}, \quad i = 1, 2, ..., m; \quad p \geq 1 \tag{6}$$

The separation of each alternative from the negative ideal solution is calculated by the following formula:

$$d_i^- = \left(\sum_{j=1}^{n} \left(v_{ij} - v_j^- \right)^p \right)^{1/p}, \quad i = 1,\ 2,\ ...,\ m; \quad p \geq 1 \tag{7}$$

In the study, computing the Euclidean distance from each alternative to positive and negative ideal solutions was done using a traditional n-dimensional Euclidean metric, i.e., $p = 2$.

Step 6. Calculate values relatively close to the positive ideal solution. The relative closeness of the ith alternative A_j to A^+ is calculated as follows:

$$R_i = \frac{d_i^-}{d_i^- + d_i^+} \tag{8}$$

where $0 \leq R_i \leq 1$, $i = 1, 2, ..., m$; d_i^- is the separation of each alternative from the negative ideal solution; d_i^+ is the separation of each alternative from the positive ideal solution.

Step 7. Ranking preferences or selecting alternatives closest to 1. The set of alternatives is ranked in descending order according to the values of R_i.

GIS is a computer-based information system that can be used to analyze spatially referenced data. GIS uses display tools and enables the creation of a decision support system that can be used in the decision-making process. GIS is commonly used in planning, managing, and making decisions in the field of engineering and environmental protection. In recent years, the rapid development of GIS and software tools has expanded its application in many other areas of research [16, 17].

Spatial and spatial-temporal distributions of physical and socio-economic phenomena can be predicted by functions depending on the location in the multidimensional space, as a multivariate scalar or vector. Typical examples are elevations (altitudes), climatic phenomena, population density, etc. Many methods of interpolation and approximation have been developed to predict the values of spatial events in unforeseen locations. In GIS applications, these methods are designed to support transformations between different discrete and continuous representations of spatial and spatial-temporal fields. The point selection method used to calculate the interpolation function varies depending on the method used and its specific implementation.

IDW interpolation was used in this study to show the distribution of noise emission. This is one of the simplest methods based on the assumption that the value at an uncompressed point can be approximated as a weighted average of values within points within certain distances or from a given number of the nearest points (usually 10 to 30) [18, 19]. The weights are usually inversely proportional to the distance [20, 21], which leads to estimation in an unspecified location. Therefore, the interpolation is calculated as follows:

$$F(r)=\sum_{i=1}^{m} w_i z(r_i)=\frac{\sum_{i=1}^{m} z(r_i)\left|r-r_i\right|^p}{\sum_{j=1}^{m}\frac{1}{\left|r-r_j\right|^p}} \tag{9}$$

where m represents the number of the nearest points, r location, and p represents the parameter.

Grid analysis in GIS. The spatial analysis technique was used to divide the investigated area into grids. Based on the raster and vector layers and attribute database in GIS, each grid was treated as an evaluation unit. The QGIS package (version 2.18.15) was used to create a layer containing all of the embedded operational information for topological grids segmented based on the boundaries of the study area. In the attribute table of this layer, each grid is a basic data set, and the weighting factor is stored in the data set field [17]. The area of investigation consisted of 13×8 grids, covering the total area of research of 805.48 km^2. To generate grid emission data, average values of 24-hour noise emission (L_{den}) measured at each 34 measuring spots were used in zonal statistics of GIS. The distribution of noise emission during the spring and autumn measuring cycles was calculated using the interpolation technique IDW and previously entered L_{den} values for all measuring spots.

Selecting control sites by GIS. Spatial optimization in GIS enabled the selection of control sites using the following steps:

1. The algorithm for creating a vector grid in QGIS was used to mark the area of investigation, consisting of 13×8 grids.
2. Zonal statistics of QGIS enabled calculating average, minimum, and maximum values of noise pollution for every grid.
3. The deviation of the average noise emissions in each grid was calculated concerning the maximum permitted noise level (55 dB), and the noise emission cut ratio scheme was created.
4. Finally, the grids were ranked by the previously calculated total cut ratio.

3. RESULTS AND DISCUSSION

3.1. RANKING MUNICIPALITIES BY TOPSIS METHOD

The TOPSIS method was used, bearing in mind that the research aims to reach the results of the ranking of the municipalities with the highest noise influence, with the overall analysis based on the results of noise level measurements at 34 measuring spots in Belgrade. Table 1 shows limited values of noise indicators, according to acoustic zones. These data are important for comparing them with measured results.

The entire process of this analysis consisted of three levels: (1) the collection of information and the compilation of spatial data in GIS, (2) the ranking of the municipalities using the TOPSIS method, and (3) mapping the municipalities on the thematic map, based on the ranking results of the applied TOPSIS methodology.

Considering that the TOPSIS method was used for ranking municipalities of Belgrade with the highest noise emission, 11 alternatives, i.e., municipalities (A_1 – Stari Grad, A_2 – Savski venac, A_3 – Vračar, A_4 – Zvezdara, A_5 – Voždovac, A_6 – New Belgrade, A_7 – Zemun, A_8 – Palilula, A_9 – Surčin, A_{10} – Čukarica, and A_{11} – Rakovica) were selected for ranking. The alternatives are ranked according to three criteria: C_1 – maximum 24-hour noise emissions in the spring period ($L_{\text{den\_spring}}$), C_2 – maximum 24-hour noise emissions in the autumn period ($L_{\text{den\_autumn}}$), and C_3 – population density. The first two criteria were assumed to be equal, i.e., 0.35 (35%), and the third criterion was assumed to be 0.30 (30%). The sum of all weights was equal to 1.0 (100%, Table 2). Subsequently, the other steps of the TOPSIS method were carried out.

Table 2

Defined model used in the TOPSIS method

Alternative	C_1	C_2	C_3	Alternative	C_1	C_2	C_3
A_1	72.6	72.7	8996	A_7	68.5	71.6	1184
A_2	70.6	70.9	2635	A_8	78.6	76.2	406
A_3	72.1	70.9	18 492	A_9	69.0	68.1	158
A_4	61.7	60.3	5572	A_{10}	61.4	68.1	1124
A_5	66.6	68.4	1183	A_{11}	67.2	66.4	3495
A_6	72.6	67.4	5127	Weight	0.35	0.35	0.30

Based on Eq. (2), the normalized decision matrix was calculated, which is shown in Table 3. The max function of the criteria was used in the analysis, i.e., all alternatives (municipalities) were ranked by the highest noise emission during both measuring cycles (spring and autumn), as well as by the highest population density.

Table 3

Normalized decision matrix

Alternative	C_1	C_2	C_3	Alternative	C_1	C_2	C_3
A_1	0.31570	0.31635	0.40086	A_7	0.29787	0.31156	0.05276
A_2	0.30700	0.30851	0.11742	A_8	0.34179	0.33158	0.01809
A_3	0.31353	0.30851	0.82400	A_9	0.30005	0.29633	0.00704
A_4	0.26830	0.26239	0.24829	A_{10}	0.26700	0.29633	0.05009
A_5	0.28961	0.29763	0.05271	A_{11}	0.29222	0.28893	0.15574
A_6	0.31570	0.29328	0.22846				

Based on Eq. (3), the weight matrix of the criteria was calculated, and the results are shown in Table 4.

Table 4

Weighting decision matrix

Alternative	C_1	C_2	C_3	Alternative	C_1	C_2	C_3
A_1	0.11050	0.11072	0.12026	A_7	0.10426	0.10905	0.01583
A_2	0.10745	0.10798	0.03522	A_8	0.11963	0.11605	0.00543
A_3	0.10973	0.10798	0.24720	A_9	0.10502	0.10372	0.00211
A_4	0.09391	0.09184	0.07449	A_{10}	0.09345	0.10372	0.01503
A_5	0.10136	0.10417	0.01581	A_{11}	0.10228	0.10113	0.04672
A_6	0.11050	0.10265	0.06854				

Using formulas (4)–(8), the final results of the ranking of alternatives were obtained, which are shown in Table 5. As seen in the last column, the most critical municipalities of Belgrade are: A_3 – Vračar, A_1 – Stari Grad, A_4 – Zvezdara, A_6 – New Belgrade, and A_{11} – Rakovica, and the least critical are: A_9 – Surčin, A_{10} – Čukarica, and A_5 – Voždovac.

Table 5

Ranking alternatives

Alternative	d_i^+	d_i^-	R_i	Results of the TOPSIS analysis [%]	Rank
A_1	0.12738	0.12085	0.48685	17.46	2
A_2	0.21248	0.03941	0.15646	5.61	6
A_3	0.01277	0.24616	0.95069	34.09	1
A_4	0.17629	0.07238	0.29106	10.44	3
A_5	0.23241	0.02006	0.07947	2.85	9
A_6	0.17940	0.06943	0.27901	10.01	4
A_7	0.23199	0.02452	0.09558	3.43	8
A_8	0.24177	0.03581	0.12902	4.63	7
A_9	0.24583	0.01658	0.06318	2.27	11
A_{10}	0.23397	0.01755	0.06976	2.50	10
A_{11}	0.20178	0.04641	0.18700	6.71	5

A weighted sensitivity analysis was applied to determine the optimal influence of each criterion. First of all, it has to be emphasized that the change in the weight of one criterion affected the weight of other criteria because the total of all weights must be equal to 1. Second, the final score of almost all alternatives has changed after the change of weights. The change in the final score of alternatives was calculated by Eqs. (4)–(8), and the ranking results are presented in Table 6. The ranks of alternatives A_3 – Vračar and A_1 – Stari Grad are constant, but the ranking of other alternatives has changed due to changes in weights.

Table 6

Ranking alternatives as the result of a sensitive analysis

Alternative	w_1, w_2, w_3				
	0.45, 0.45, 0.10	0.4, 0.4, 0.2	0.35, 0.35, 0.30	0.30, 0.30, 0.40	0.25, 0.25, 0.50
A_1	2	2	2	2	2
A_2	5	7	6	6	6
A_3	1	1	1	1	1
A_4	7	4	3	3	3
A_5	10	9	9	9	8
A_6	4	3	4	4	4
A_7	6	8	8	8	7
A_8	3	5	7	7	9
A_9	9	10	11	11	11
A_{10}	11	11	10	10	10
A_{11}	8	6	5	5	5

3.2. DATA COLLECTION AND PREPARATION OF SPATIAL DATA IN THE GEOGRAPHIC INFORMATION SYSTEM (GIS)

The collection of information and the preparation of spatial data has been done through several phases. First, the measuring points were located using the Google Earth software tool and then downloaded, converted from .kml to .shp files, and thus digitized and georeferenced as points using the QGIS software tool. The Google Satellite View map was used as the base layer. The measuring spots are shown in Fig. 2. The measuring spots are presented in five different colours, considering the defined zones of noise pollution (Table 1). The fact is that measuring spots: M1, M4, M5, M17, M18, M23, M26, M27, and M30 are located in the residential zone (where the levels during day and evening should not exceed 55 dB, and 45 dB during the night). Measuring spots: M6, M9, M11, M12, M13, M14, M15, M19, M20, M21, M22, M31, M32, M33, and M34 are next to very busy roads (where the levels during day and evening should not exceed 65 dB and 55 dB during the night). Measuring spots: M2, M3, M8, M10, and M16 are in the urban zone of the city center (where the limited values for day and evening are 65 dB and 55 dB during the night). Measuring spots M7 and M29 are in the industrial zone, and measuring spot M24 is in the school zone (where the limited values for day and evening are 50 dB and 45 dB during the night). Measuring spot M25 is in the hospital area (where limited levels for day and evening are 50 dB and 40 dB during the night), and measuring spot M28 is in the recreation zone (where the limited levels for day and evening are 50 dB and 40 dB during the night period). Although it is possible to compare the obtained relevant levels with the limited values of noise indicators, it must be emphasized that no measuring spot belongs to the fourth zone (business and residential areas, commercial and residential areas, and children's playgrounds), as can also be seen in Fig. 2.

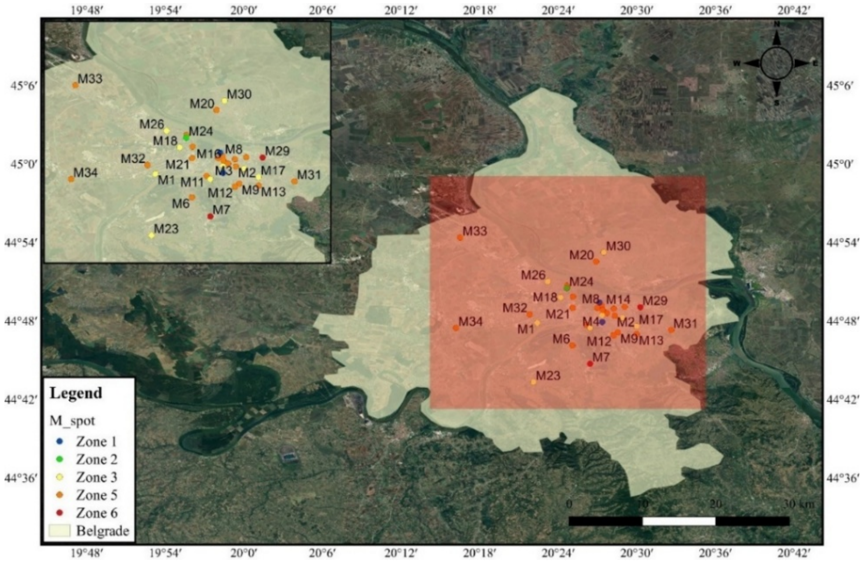

Fig. 2. Map of Belgrade with measuring spots

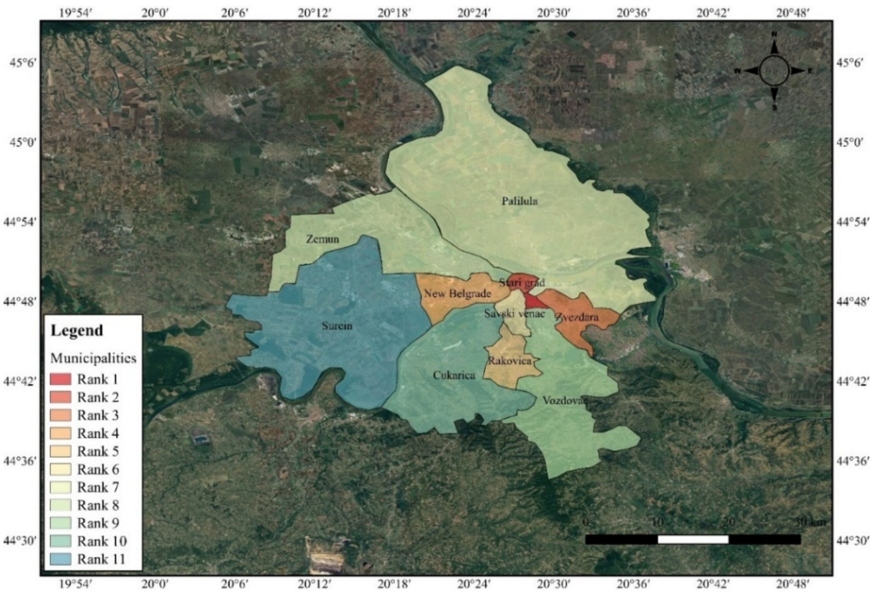

Fig. 3. Ranking of municipalities of Belgrade

GIS was used for the preparation of spatial data and the determination of the area with the highest noise pollution in Belgrade on the thematic map. The ranking of municipalities was based on the results of the ranking obtained using the TOPSIS method. Figure 3 shows the ranking of municipalities from those with the highest noise pollution level to those with the lowest. The municipalities with the highest noise pollution level were A_3 – Vračar, A_1 – Stari Grad, A_4 – Zvezdara, A_6 – New Belgrade, and A_{11} – Rakovica, whilst the municipalities with the lowest noise pollution level were A_9 – Surčin, A_{10} – Čukarica, and A_5 – Voždovac. The municipality Surčin was ranked as the least noise-polluted, although the airport Nikola Tesla is located in that municipality. However, the noise was measured at only one measuring spot, and the population density was the lowest in that municipality. Introducing more measuring spots in the municipality of Surčin would probably change the ranking results. In any case, a larger number of measuring spots may improve the accuracy of the results, enabling one to capture the full complexity of noise pollution in a densely populated urban environment. Thus, future research and analyses should include additional measuring spots to provide a more balanced data set.

3.3. APPLICATION OF THE INTERPOLATION METHOD (IDW) TO SHOW THE SPATIAL NOISE INFLUENCE

Data for 24-hour noise emissions (L_{den}) were calculated by the Belgrade City Public Health Institute [10] using Eq. (1) and published in their annual report.

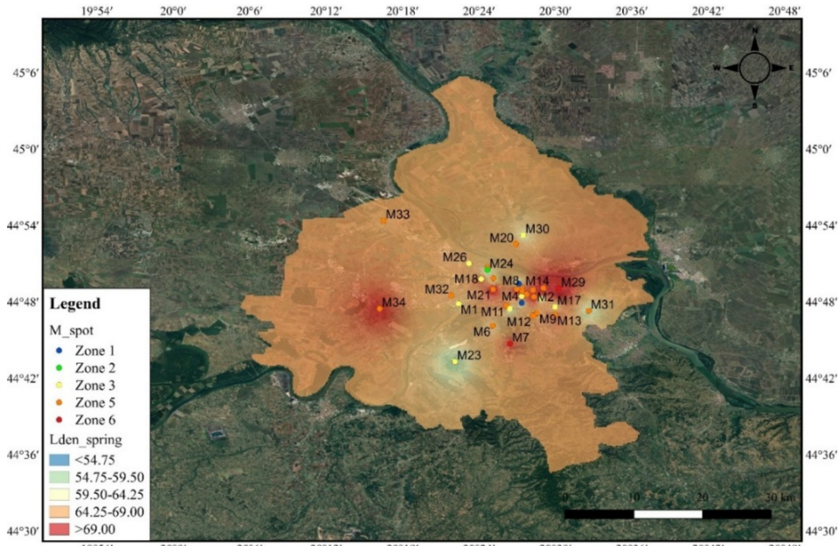

Fig. 4. Noise distribution map according to L_{den} values recorded in the spring period

The L_{den} data were entered into a spatial database in GIS separately for the spring and autumn periods, and Eq. (9) was used for calculating interpolation so the spatial influence of 24-hour noise emissions for both periods could be defined (Figs. 4, 5). As can be seen in Fig. 4, the average noise level during 24-hour periods in spring cycle ranged from 50.0 to 75.6 dB, with the highest level at the measuring spots: M_{14} (75.6 dB), M_{29} (74.8 dB), M_{19} (72.6 dB), M_{21} (72.6 dB), M_2 (72.1 dB), M_{16} (70.6 dB), and M_{34} (69.00 dB), and this is the area marked with red colour. The lowest noise level was at the measuring spots: M_{28} (50.0 dB), M_{24} (52.0 dB), M_{23} (55.0 dB), M_{27} (55.3 dB), M_{31} (58.00 dB), M_{25} (59.10 dB), M_5 (59.10 dB), and M_{30} (59.20 dB) and this is the area marked with blue and light green colour. As can be seen in Fig. 5, the average noise level during 24-hour periods in the autumn cycle ranged from 47.9 to 76.2 dB. The highest noise level (the area marked with red colour) was at the following measuring spots: M_{14} (76.2 dB), M_{19} (72.7 dB), M_{29} (72.4 dB), M_{15} (71.6 dB), M_2 (70.9 dB), M_{16} (70.9 dB), M_{11} (70.8 dB), M_{33} (68.5 dB), M_8 (68.4 dB), M_{13} (68.4 dB), M_{23} (68.1 dB), M_{34} (68.1 dB), and M_3 (68.0 dB) while the lowest noise level (the area marked with blue and light green colour) was at the measuring spots: M_{28} (47.9 dB), M_{30} (53.2 dB), M_{17} (56.7 dB), and M_{31} (57.2 dB).

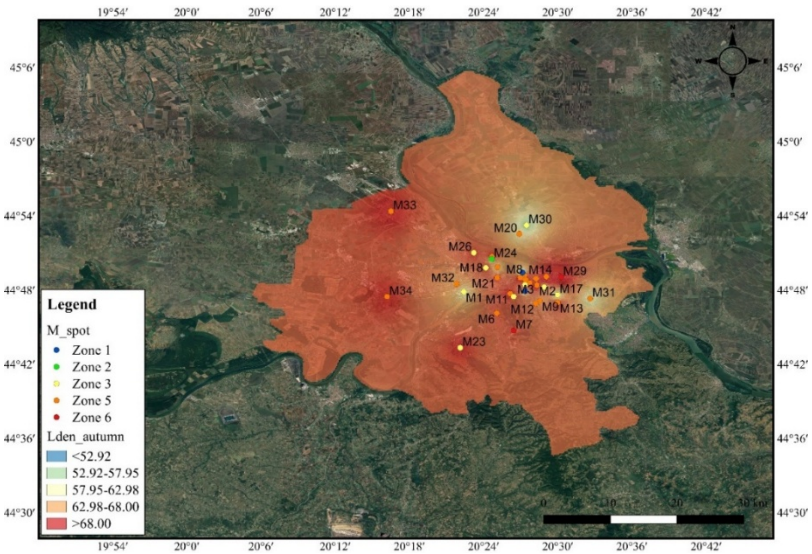

Fig. 5. Noise distribution map according to L_{den} values recorded in the autumn period

3.4. DETERMINING NOISE-POLLUTED GRIDS AND ESTABLISHING A NOISE EMISSION CUT RATIO SCHEME

Zonal statistics in GIS enabled the calculation of the cut scheme of noise-polluted grids. From the results presented in Table 7, it can be seen that the noise emission in most grids needs to be cut from 15% to 20%. Also, some grids have even higher levels of noise emission, which is mainly caused by the busy road traffic in Belgrade.

Table 7

Total noise control cut scheme

Grid No.	Average L_{den} by grid	Total cut [%]	Grid No.	Average L_{den} by grid	Total cut [%]	Grid No.	Average L_{den} by grid	Total cut [%]
101	65.21	–18.55	310	64.23	–16.78	606	64.93	–18.05
102	65.00	–18.18	311	65.33	–18.77	607	64.45	–17.17
103	64.58	–17.41	312	63.25	–15.00	608	64.05	–16.45
104	63.98	–16.32	313	60.74	–10.43	609	64.70	–17.63
105	62.86	–14.29	401	67.23	–22.23	610	65.79	–19.62
106	62.45	–13.54	402	67.68	–23.05	611	66.53	–20.96
107	59.14	–7.53	403	65.63	–19.33	612	66.06	–20.11
108	65.04	–18.25	404	64.32	–16.95	613	65.29	–18.71
109	65.26	–18.65	405	63.44	–15.34	701	65.53	–19.15
110	64.86	–17.92	406	62.25	–13.18	702	65.55	–19.17
111	64.72	–17.67	407	64.84	–17.89	703	65.16	–18.46
112	64.55	–17.36	408	66.10	–20.18	704	64.77	–17.76
113	64.41	–17.11	409	62.54	–13.71	705	64.62	–17.49
201	65.83	–19.69	410	65.02	–18.22	706	64.62	–17.48
202	65.67	–19.39	411	64.63	–17.50	707	64.35	–17.00
203	64.93	–18.05	412	64.05	–16.45	708	63.51	–15.46
204	64.22	–16.75	413	61.30	–11.45	709	61.32	–11.49
205	63.69	–15.79	501	66.09	–20.15	710	62.80	–14.18
206	63.72	–15.85	502	65.98	–19.96	711	64.85	–17.90
207	64.33	–16.96	503	65.16	–18.46	712	65.25	–18.64
208	65.13	–18.42	504	64.45	–17.18	713	65.14	–18.44
209	65.51	–19.10	505	64.05	–16.45	801	65.82	–19.66
210	64.74	–17.71	506	64.29	–16.88	802	66.17	–20.30
211	64.73	–17.68	507	65.33	–18.77	803	65.51	–19.10
212	64.31	–16.93	508	64.68	–17.59	804	64.88	–17.96
213	64.10	–16.54	509	66.15	–20.27	805	64.62	–17.49
301	67.00	–21.81	510	68.76	–25.02	806	64.44	–17.15
302	67.29	–22.34	511	69.97	–27.21	807	64.09	–16.53
303	65.53	–19.14	512	66.74	–21.35	808	63.14	–14.79
304	64.34	–16.97	513	64.74	–17.71	809	60.47	–9.95
305	63.65	–15.73	601	65.52	–19.12	810	61.82	–12.39
306	63.40	–15.27	602	65.37	–18.85	811	64.04	–16.43
307	64.29	–16.88	603	64.99	–18.16	812	64.72	–17.67
308	64.39	–17.06	604	64.63	–17.51	813	64.89	–17.98
309	63.81	–16.01	605	64.53	–17.32			

These are the major target areas to cut noise emissions. Noise pollution grid numbers 301, 302, 401, 402, 408, 501, 509, 510, 511, 512, 611, 612, and 802 are the most polluted, and the noise emission in those grids needs to be cut for about 21.81, 22.34, 22.23, 23.05, 20.18, 20.15, 20.27, 25.02, 27.21, 21.35, 20.96, 20.11, and 20.30%, respectively.

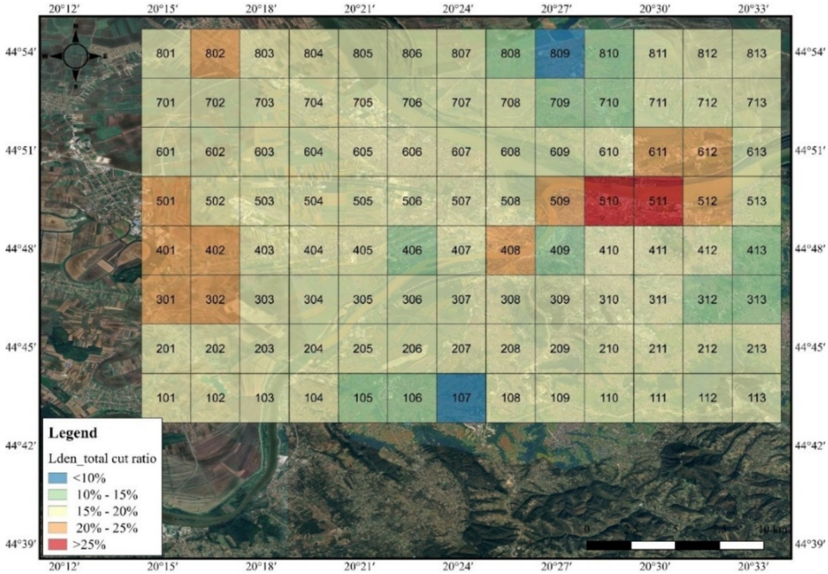

Fig. 6. Total noise control cut scheme

Figure 6 shows the total noise control cut scheme. The most polluted grids 510 and 511, where noise emissions should be cut by 25.02% and 27.21% are in the area of Stari Grad and Palilula. Stari Grad is the second municipality, and Palilula is the seventh-ranked using the TOPSIS method. Therefore, it is evident that the results of the total noise control cut scheme do not match the results of the TOPSIS method. The total noise control cut scheme was calculated based on zonal statistics that enabled calculating average L_{den} noise emissions by grids, and those values were compared to the limited value of 55 dB to calculate the cut ratio for every grid. On the other hand, the TOPSIS method was done based on three criteria: maximum L_{den} noise emissions measured in spring, maximum L_{den} noise emissions measured in autumn, and population density in every municipality. If the TOPSIS method was based only on L_{den} noise emissions in spring and autumn measuring cycles, the results of ranking would match the total noise control cut scheme presented in Fig. 6. Introduction of the third criterion (population density) in the TOPSIS method has changed the ranking of municipalities. However, the third criterion needed to be introduced because noise has a great effect on human health, so population density is an important criterion for decision-making. This fact confirms the correctness of the multifactor decision-making method used in the research.

Optimization of total noise emission means that according to obtained results, the main pollutant source, in this case, road traffic, must be managed to accomplish better life quality for the people living in Belgrade and maintain noise emissions within the national and EU limitations according to Directive 2002/49/EC [12]. One of the ways to reduce noise caused by road traffic is to plant trees alongside roads (cf. [22]).

4. CONCLUSIONS

Noise pollution in Belgrade is mainly driven by traffic, while industry, small businesses, construction, and other activities have minor importance. Municipal noise levels recorded during 2023 are still high at most of the measuring spots, and the highest overruns of allowed levels are recorded in residential zones (zone 3) and zones along traffic roads (zone 5).

Noise emissions in the autumn measuring cycle were slightly higher compared to noise emissions in spring. The choice of the measuring cycle (spring or autumn) has a minor effect on noise pollution in Belgrade.

The results of an analysis by the TOPSIS method have shown that in Belgrade, a major city in Serbia, noise pollution, mostly caused by traffic, is above the limited values prescribed by Directive 2002/49/EC, which seriously endangers human health. The highest noise pollution level during 2023 was in Vračar, Stari Grad, Zvezdara, New Belgrade, and Rakovica, while the lowest noise pollution level was at Surčin, Čukarica, and Voždovac. Considering that GIS is a powerful tool for the visual presentation of data, the ranking results obtained from the application of the TOPSIS method were entered into the spatial database, and the thematic map in GIS was created.

The main advantages of the suggested model of noise pollution control are the usage of the spatial analysis of GIS for control grids selection, calculating the noise emission distribution by integrating GIS with zonal statistics, and calculating the emission distribution optimization scheme by using control grids also created in GIS.

The noise pollution control of Belgrade is a comprehensive project. To radically solve this problem, adequate measures must be taken into consideration, and they consist of the following activities:

- Control of the noise sources. In the case of road traffic and traffic in general as the dominant source of noise at most measuring spots, control can be performed by improving traffic management, primarily by automatic traffic regulation and synchronization of traffic lights, replacement of standard roundabouts, construction of road bypasses, relocation of initial and final stops of public transport, by increasing the number of zones with traffic restrictions, road maintenance, etc.

• Development of projects for residential, residential-business, investment, and industrial facilities, small businesses, and urban infrastructure with adequate noise protection and control of their condition during technical acceptance.

• Planning and installation of sound barriers.

• Acoustic zoning of the city territory. This activity is still in progress for Belgrade, and acoustic zoning of the city is of great importance in terms of adequate protection of people and noise environments, because it allows the selection of permits to perform certain activities in some areas of the city.

The results obtained by this analysis may not be the same by introducing an additional number of measuring points, as well as additional criteria according to which the ranking of municipalities would be performed. Certainly, the insufficient number of measuring spots, lack of statistical validation, and limited temporal scope reduce the effectiveness of the paper, and those issues will be addressed in future research to enhance the study's impact. In any case, this paper aimed to show that by combining these methods and techniques, data on noise emission reduction can be obtained.

REFERENCES

[1] HADZI-NIKOLOVA M., MIRAKOVSKI D., DELIPETROV T., ARSOV P., *Noise dispersion modeling in small urban areas with CUSTIC 3.2 software*, Int. J. Emerg. Technol. Adv. Eng., 2012, 2 (12), 84–88.

[2] BOCHER E., GUILLAUME G., PICAUT J., PETIT G., FORTIN N., *Noise modeling: An Open source GIS--based tool to produce environmental noise maps*, Int. J. Geo-Inform., 2019, 8 (3), 130. DOI: 10.3390/ijgi8030130.

[3] KOVAČEVIĆ M., POVIĆ D., KESER T., MESARIĆ D., *Dynamic monitoring and displaying noise levels in populated areas*, Int. J. Electr. Comp. Eng. Syst., 2013, 4 (2), 63–71.

[4] GOINES L., HAGLER L., *Noise Pollution: A Modern Plague*, Southern Med. J., 2007, 100, 287–294.

[5] OYEDEPO S.O., SAADU A.A., *Comparative analysis of noise descriptors in some selected areas in Ilorin Metropolis, Nigeria*, Noise Contr. Eng. J., 2010, 58 (6), 646–657. DOI: 10.3397/1.3532917.

[6] DAVIS M.L., MASTEN S.J., *Principle of Environmental Engineering and Science*, McGraw-Hill, New York 2004.

[7] DURSUN S., OZDEMIR C., KARABORK H., KOCAK S., *Noise pollution and map of Konya city in Turkey*, J. Int. Environ. Appl. Sci., 2006, 1 (1–2), 63–72.

[8] OYEDEPO S.O., *Environmental noise pollution in Ilorin Metropolis, Nigeria*, Nature Environ. Pollut. Technol., 2012, 11 (4), 553–567.

[9] *Statistical Yearbook of the Republic of Serbia*, Belgrade 2023.

[10] Belgrade City Public Health Institute, Center for Hygiene and Human Ecology, *Annual report on the implementation of the environmental noise level measurement program in the territory of Belgrade*, Belgrade 2023 (in Serbian).

[11] Gazette of the Republic of Serbia, no. 75/2010, *Regualtion on noise indicators, limit values, methods for assessing noise indicators, disturbance and harmful effects of noise in the environment*, 2010, available online: https://www.paragraf.rs/propisi/uredba-indikatorima-buke-granicnim-vrednostima-metodama-ocenjivanje-indikatora-buke.html (in Serbian) [accessed on 2nd March 2025].

[12] Directive 2002/49/EC, *Directive of the European Parlament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise*, 2002, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32002L0049&from=EN [accessed on 22 November 2024].

[13] WHO, *Environmental noise guidelines for the European Region*, 2018, available online: https://www.who.int/europe/publications/i/item/9789289053563 [accessed on 22 November 2024].
[14] HARDY A.E.J., JONES R.R.K., TURNER S., *The influence of real-world rail head roughness on railway noise prediction*, J. Sound Vib., 2006, 293 (3–5), 965–974. DOI: 10.1016/j.jsv.2005.12.019.
[15] CHEN S.J., HWANG C.L., *Fuzzy multiple attribute decision making: methods and applications*, Springer--Verlag, Berlin 1992.
[16] JAHANSHAHLOO G.R., LOFTI F.H., IZADIKHAH M., *An algorithmic method to extend TOPSIS for decision making problems with interval data*, Appl. Mathem. Comp., 2006a, 175, 1375–1384. DOI: 10.1016/j.amc.2005.08.048.
[17] ILIĆ I., ŽIVKOVIĆ D., VUŠOVIĆ N., BOGDANOVIĆ D., *Optimizing SO_2 total emission control strategy: case study – Bor (Serbia)*, Environ. Monit. Assess., 2010, 169 (1–4), 587–596. DOI: 10.1016/j.atmosres. 2011.04.002.
[18] TAGHIZADAH R., ZARE M., ZARE S., *Mapping of noise pollution by different interpolation methods in recovery section of Ghandi telecommunication Cables Company*, J. Occup. Health Epidem., 2013, 2 (1–2), 1–11. DOI: johe.rums.ac.ir/article-1-65-en.pdf.
[19] IKECHKWU M.N., EBINNE E., IDORENYIN U., RAPHEL N.I., *Accuracy assessment and comparative analysis of IDW, spline and kriging in spatial interpolation of landform (topography): An experimental study*, J. Geogr. Inf.. Syst., 2017, 9, 354–371. DOI: 10.4236/jgis.2017.93022.
[20] BURROUGH P.A., *Principles of geographical information systems for land resources assessment*, Clarendon Press, Oxford 1986.
[21] WATSON D.F., *Contouring: A guide to the analysis and display of spatial data*, Pergamon, Oxford 1992.
[22] SULTAN T., SHAHID S., RASHEED J., ALSUBAI S., *Investigation of tree characteristics for traffic noise abatement*, Environ. Prot. Eng., 2024, 50 (1), 43–70. DOI: 1010.37190/epe240103.