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Fuzzy Decision-Making Valuation Model for Urban Green Infrastructure Implementation

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Abstract: Urban green infrastructure plays a significant role in sustainable development and requires proper land management during planning. This study develops a valuation model for urban green infrastructure in land management, focusing on Zagreb's 17 city districts. The fuzzy AHP method was used to calculate the weighting coefficients for a suitable set of criteria, and the TOPSIS method was used to select the priority city districts for implementing green infrastructure. The research results are relevant to decision makers, who can utilize them to prioritize areas for the development and implementation of green infrastructure. The green infrastructure index calculated in this study can be compared with other spatial and land data for effective spatial planning.

Keywords: green infrastructure; the city of Zagreb; decision making; fuzzy AHP; TOPSIS

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1. Introduction

Most of the world's population lives in urban areas, and that number is increasing every day. Accelerated urbanization leads to overbuilding, air and environmental pollution, increasing climate change, and increased consumption of energy and natural resources. One of the ways to solve these problems is to plan green infrastructure. Urban green infrastructure is considered an essential structural part of cities. It plays a key role in strengthening the resilience and transformation of urban areas and in the sustainable development of Planet Earth [1,2].

Urban green infrastructure was introduced within the framework of the approach to sustainability and resilience of primarily urban areas. Investing in green infrastructure makes sound economic sense because an area can offer multiple benefits, provided its ecosystems are in a healthy condition. Such healthy ecosystems provide society with many valuable economically, socially, and ecologically important goods and services [3]. In the strategic document on green infrastructure, the European Commission defines green infrastructure as a strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services and preserve biodiversity in urban and rural areas. It means that green infrastructure is not just any green area, but those green areas that realize at least one of the ecosystem services, provisioning, regulating, cultural, and supporting services [4]. Green infrastructure can mitigate the risks of climate change, helping to reduce the urban heat island effect and reduce the risk of flooding [5–8]. It improves air quality, and various scientific studies prove that in this way it affects a higher quality of life, and better physical and mental health [9–13]. It also helps preserve biological diversity through the preservation and restoration of natural habitats [14–16]. Green infrastructure also supports renewable energy. By integrating it with renewable energy, green infrastructure helps build a sustainable and energy-efficient future [17]. Unlike gray infrastructure, which usually has only one goal, green infrastructure is multifunctional and brings many social, ecological, and economic benefits [18,19], both in rural and urban environments. If properly planned, green infrastructure can result in a wide variety of benefits for both people and nature. Individual elements of green infrastructure may not necessarily provide all the desired benefits, but if they are well connected, then the entire network of green infrastructure can provide most of the benefits [20].

To obtain all the benefits from green infrastructure, the World Health Organization recommends that when planning and designing urban green areas, attention should be paid to the fact that green areas need to be located near people and their places of residence. Green infrastructure must be diverse, multifunctional, and adaptable to people's needs. Additionally, it is essential to pay attention to its subsequent maintenance [21]. This is why Cecil Konijnendijk [22,23] proposed the 3–30–300 rule for urban green infrastructure. The goal of this rule is to enable equal access to trees and green areas in such a way that every citizen should see at least 3 trees from his home, that in every neighborhood there should be at least 30% tree canopy coverage, and that everyone within a radius of 300 m has access to at least one green area surface. Applying the 3–30–300 rule will improve and expand urban green infrastructure and thus promote cities' health, well-being, resilience, and sustainable development. Many cities around the world have already adopted the 3–30–300 rule as part of their urban programs [24], and the implementation of the rule is also recommended in the UNECE document, which provides guidelines for green recovery and sustainable, healthy, and resilient cities [25]. The fact that it is included in the 2030 Agenda, which defines 17 global goals of sustainable development, speaks of the importance of green infrastructure for sustainable development. More precisely, one of the seven sub-goals for achieving goal 11, which is aimed at developing inclusive, safe, resilient, and sustainable cities, is providing access to safe and inclusive green and public spaces [26]. Special emphasis on access to green public spaces was brought by the New Urban Agenda emphasizing the importance and multifunctionality of green infrastructure [27]. Green infrastructure is continuously recognized and included in numerous other global and European strategies for sustainable development. The importance of green infrastructure is also recognized in Croatia. Based on the European Recovery Plan, the Government of the Republic of Croatia presented the National Recovery and Resilience Plan, in which the strategy of green urban renewal and development of green infrastructure was included as one of the goals [28]. The importance of green infrastructure in Croatia was highlighted by the adoption of the Program for the Development of Green Infrastructure in Urban Areas for the period from 2021 to 2030. This program outlines goals and measures for the development of green infrastructure in urban areas for the establishment of sustainable, resilient, and safe cities and settlements through increasing the energy efficiency of buildings and construction areas, the development of green infrastructure, and urban transformation and rehabilitation. The program intends to provide all stakeholders with a framework for the implementation of green infrastructure development in urban areas by identifying measures and activities, necessary frameworks and prerequisites for implementation, expected effects of measures, and anticipated sources of funding. The ultimate goal is to increase green infrastructure in urban areas [29].

From the above, green infrastructure plays a significant role in sustainable development and it is necessary to take care of the implementation of green infrastructure during spatial planning.

Analysis of previous research has established that there is a lot of research on green infrastructure, such as combating climate change [5,8,30], reducing flooding [31,32], improving air quality [33,34], improving water and soil quality [35], preserving biodiversity [16,36], and promoting physical and mental health [11,37,38]. However, there is significantly less research focused on the evaluation of green infrastructure in land management [39]. The analysis indicates that most research emphasizes the ecological and social benefits of green infrastructure, with less emphasis on the economic benefits. The same conclusion was reached by several other authors in their systematic literature reviews of green infrastructure [40–42]. The lack of appropriate spatial data infrastructure is considered the main challenge in evaluating green infrastructure in land management.

Some of the authors specifically used the fuzzy AHP (Analytic Hierarchy Process) multi-criteria evaluation method in their research on green infrastructure [43–47], as well as the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method of multi-criteria evaluation [36,48,49].

The structure of this article is organized as follows: Section 2 discusses the materials and methods of this research. It shows the spatial data required for the development of a valuation model of urban green infrastructure. It also explains the criteria for determining the green infrastructure index and the method of calculating the green infrastructure index using the fuzzy AHP and TOPSIS methods in detail. Section 3 discusses the Croatian (city of Zagreb) case study, which demonstrates the implementation of the proposed model. In Section 4, the results were summarized and the advantages of the developed model are presented. Finally, Section 5 provides conclusions and highlights potential directions for future research in this area.

2. Materials and Methods

To more easily evaluate green infrastructure and to examine which areas are more prioritized for its implementation, a model for the evaluation of urban green infrastructure in land management was developed. The developed model was implemented in the area of the city of Zagreb. The area of the city of Zagreb was chosen because it is the capital of Croatia, it has problems with construction at the expense of green areas, and because of the availability of spatial data.

Several different types of spatial data were collected from the city of Zagreb, which were used to conduct this research. The City Office for Economy, Environmental Sustainability, and Strategic Planning in the city of Zagreb has provided data on the planned purpose and actual use of the city of Zagreb's areas for the year 2020. From the City Office for Renovation, Construction, Spatial Planning, Construction, Communal Affairs, and Traffic in the city of Zagreb, data from the Green Cadastre on elements of green infrastructure were taken. All data are stored in the official projection coordinate reference system of the Republic of Croatia, that is, in the Croatian Terrestrial Reference System for the epoch 1995.55–HTRS96. All the above data can be viewed through the geoportal of the Zagreb Spatial Data Infrastructure (ZG Geoportal). ZG Geoportal is the access point of the Zagreb spatial data infrastructure and contains spatial data of the city's administrative bodies, companies, and institutions [50]. Via ZG Geoportal, it is only possible to view the data that the city of Zagreb has, but it is not possible to download and manage the data.

To develop a valuation model for urban green infrastructure in land management, all analyses were carried out for residential and mixed-use zones. From the data on actual land use, only those lands whose purpose is residential and mixed were filtered, and for the area of the city of Zagreb, there are 16,251 residential and mixed-use zones located in the area of 17 city districts (Brezovica, Črnomerec, Donja Dubrava, Donji Grad, Gornja Dubrava, Gornji Grad–Medveščak, Maksimir, Novi Zagreb–istok, Novi Zagreb–zapad, Peščenica–Žitnjak, Podsljeme, Podsused–Vrapče, Sesvete, Stenjevec, Trešnjevka–jug, Trešnjevka–sjever, and Trnje). In this research, an analysis was made for each city district.

Several different analyses of the availability of green infrastructure were carried out, namely, an analysis of the availability of trees, an analysis of the availability of recreational facilities, an analysis of the availability of public green areas, an analysis of the availability of water surfaces, and an analysis of the land surface temperature, and an analysis of brownfield areas were also carried out. These analyses were chosen because they can be conducted using available spatial data and compared with other spatial and land information, making them applicable to land management. Additionally, all analyses can be performed within a specific time interval, allowing for the monitoring of changes over time. They were automated and performed in QGIS using a combination of spatial and attribute queries. At the end, a cross-section analysis was made, and an index of green infrastructure was determined using fuzzy AHP and TOPSIS multi-criteria methods.

Due to the unavailability of data, only green infrastructure located in public areas was analyzed, that is, private green areas were not included in the analysis. Also, the final data should be able to be used in land management systems; therefore, all analyses should be feasible based on existing official data. That is, by using the proposed analyses, the data can be calculated in certain time intervals, and in this way, it is possible to determine the current and desired states.

2.1. Analysis of the Availability of Green Infrastructure

According to the World Health Organization, residents in urban areas should have access to green infrastructure and public green areas of at least 0.5–1 hectare within 300 m of air distance from their homes [21,51]. Therefore, in this paper, analyses of the availability of green infrastructure were carried out within a radius of 300 m from individual residential and mixed-use zones, and an average value was determined for each city district. For each residential and mixed-use zone, it was determined how many trees, recreational facilities, and public green areas larger than 0.5 hectares are within 300 m of air distance from that residential and mixed-use zone, and whether it is within 300 m of air distance from some residential and mixed-use zones and some water surface. Due to the multi-functionality and connectivity of green infrastructure, individual analyses inevitably overlap with each other, but concerning the available data, the previously mentioned accessibility analyses were defined and the valuation model for urban green infrastructure was defined.

2.1.1. Analysis of the Availability of Trees

The analysis of the availability of trees is based on data from the Green Cadastre managed by Zagreb holding–Zrinjevac, which includes green infrastructure elements transferred from the City Office for Renovation, Construction, Spatial Planning, Construction, Communal Affairs, and Traffic. However, these data do not cover green infrastructure elements in areas managed by other institutions. To address this gap, the average number of trees per square meter was calculated for parks, forest parks, and forests using available data. Additionally, data on land use from the City Office for Economy, Environmental Sustainability, and Strategic Planning were used to determine the number of trees in parks, forest parks, and forests not under the jurisdiction of Zrinjevac. After identifying the trees included in the analysis, we determined the total number of trees within 300 m of each residential and mixed-use zone in the city of Zagreb.

2.1.2. Analysis of the Availability of Recreational Facilities

The analysis of the availability of recreational facilities is limited to green infrastructure elements that were obtained from the City Office for Renovation, Construction, Spatial Planning, Construction, Communal Affairs, and Traffic. These data are from the Green Cadastre under the jurisdiction of the Zagreb holding–Zrinjevac, which means that they do not contain data of green infrastructure elements located in areas under the jurisdiction of other institutions or private owners. Among the available elements of green infrastructure, recreational facilities include playgrounds and paths, and the analysis was carried out based on these elements and on the areas for which data are available.

2.1.3. Analysis of the Availability of Public Green Areas

In its document on urban green areas, the World Health Organization emphasizes that people living in urban and rural areas should have access to public green areas larger than 0.5 hectares within 300 m of their homes [21]. Therefore, only green areas larger than 0.5 hectares are considered in the analysis of the availability of public green areas. In the city of Zagreb, 1660 such areas have been identified, including botanical gardens, zoos, parks, forest parks, or forests. City gardens are not included in this analysis, because they are given for the use of individual citizens or households and therefore are not accessible to the general public [52]. After identifying the public green areas included in the analysis, the availability of public green areas larger than 0.5 hectares within a 300 m radius of each residential and mixed-use zone was determined.

2.1.4. Analysis of the Availability of Water Surfaces

Water surfaces are an important part of the urban green infrastructure, also known as blue infrastructure. Blue infrastructure includes natural or artificial, permanent or temporary water surfaces found in urban areas. These can be rivers, lakes, banks, wetlands, coastal waters like estuaries, deltas, coastal tidal areas, and other water bodies [53]. To analyze the availability of water surfaces in the city of Zagreb, water and water assets in the form of polygons were included. These were filtered from the vector layer "land use" obtained from the City Office for Economy, Environmental Sustainability, and Strategic Planning. The analysis determined whether there is at least one water surface within a 300 m radius of each residential and mixed-use zone or none.

2.2. Analysis of Land Surface Temperature

Due to increasing urbanization and significant changes in land use, there are global climate changes and an increase in the land surface temperature, which leads to the formation of urban heat islands [54]. Many studies have confirmed that urban green infrastructure plays an important role in mitigating the effect of urban heat islands and reducing the land surface temperature [55], which is especially important in the summer months. Part of the urban green infrastructure creates a shadow and thus limits the heating of the soil and absorbs part of the solar radiation, and evapotranspiration increases the air humidity and thus reduces the temperature in the city [56]. Therefore, it is necessary to recognize the urban green infrastructure as one of the important tools for the fight against climate change and temperature increase. The land surface temperature can be determined in different ways, and in the framework of this research, it was determined by semi-automatic classification in QGIS.

Using a raster containing data on the land surface temperature, we determined the land surface temperature of individual residential and mixed-use zones, in such a way that each residential and mixed-use zone was assigned to the value of the raster cell that covers that specific area. After the analysis of land surface temperature by residential and mixed-use zones, these data were grouped, and by using them, we determined the average land surface temperature for each city district.

2.3. Analysis of Brownfield Areas

Brownfield areas are areas that were influenced by the previous use of that location and the surrounding land abandoned and underutilized areas, areas that may have real or possible problems with contamination and are mostly located in developed urban areas and require intervention to return them to beneficial use [57]. From the data on actual land use in the city of Zagreb, 146 brownfield areas were identified in the city of Zagreb, and it was determined how many brownfield areas are located within each city district and what their total area is.

2.4. Green Infrastructure Index

The previously explained analyses are defined as criteria for determining the green infrastructure index. To calculate the final green infrastructure index, it is necessary to use the fuzzy AHP method to determine the weights of all criteria and then to calculate the green infrastructure index using the TOPSIS method.

2.4.1. The Fuzzy AHP Method

Fuzzy sets, introduced by Zadeh [58], are an extended form of the classical sets where sets are binary determined, while fuzzy sets have a degree of membership. The mathematical expression of the fuzzy set can be described as presented in Equation (1) [59].

A fuzzy number $\widetilde{A}$ on $\mathbb{R}$ is triangular fuzzy number if it has membership function $\mu_{\widetilde{A}}(x) : \mathbb{R} \rightarrow [0,1]$ equal to the following:

$$\mu_{\widetilde{A}}(x) = \begin{cases} \frac{x-l}{m-l}, & l \leq x \leq m \\ \frac{u-x}{u-m}, & m \leq x \leq u \\ 0, & otherwise \end{cases} \tag{1}$$

where l and u are upper and lower bounds of the fuzzy number $\widetilde{A}$, and m is the middle value. Thus, triangular fuzzy number can be marked as $\widetilde{A} = (l, m, u)$.

Furthermore, fuzzy AHP will be briefly explained in few steps [59].

Step 1. Matrices pairwise comparison of all criteria by assigning them linguistic terms with belonging fuzzy sets as follows:

$$\widetilde{A} = \begin{bmatrix} 1 & \widetilde{a}_{12} & \cdots & \widetilde{a}_{1n} \\ \widetilde{a}_{21} & 1 & \cdots & \widetilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{a}_{n1} & \widetilde{a}_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \widetilde{a}_{12} & \cdots & \widetilde{a}_{1n} \\ 1/\widetilde{a}_{12} & 1 & \cdots & \widetilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\widetilde{a}_{1n} & 1/\widetilde{a}_{2n} & \cdots & 1 \end{bmatrix} \tag{2}$$

Step 2. Defining geometric mean using geometric mean operator. This way, experts' compromised fuzzy weights are denoted by geometric mean of lower, middle, and upper values of triangular fuzzy set [60].

$$\widetilde{G}_i = (l_i, m_i, u_i) = [(l_{i1} \otimes l_{i2} \otimes \ldots \otimes l_{ik})^{\frac{1}{k}}, (m_{i1} \otimes m_{i2} \otimes \ldots \otimes m_{ik})^{\frac{1}{k}}, (u_{i1} \otimes u_{i2} \otimes \ldots \otimes u_{ik})^{\frac{1}{k}}] \tag{3}$$

where $i = 1, 2, \ldots n$ and $j = 1, 2, \ldots, k$, n is the number of criteria and k is the number of experts.

Then, to normalize fuzzy criteria weights, following expression is used:

$$\widetilde{w}_j = \frac{(l_i, m_i, u_i)}{(\sum_{i=1}^{n} u_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} l_i)} = \left[\frac{l_i}{\sum_{i=1}^{n} u_i}, \frac{m_i}{\sum_{i=1}^{n} m_i}, \frac{u_i}{\sum_{i=1}^{n} l_i}\right] \tag{4}$$

Step 3. The defuzzyfied and normalized crisp criteria weights are obtained as follows:

$$w'_j = \frac{\frac{l_i}{\sum\limits_{i=1}^{n} u_i} + \frac{m_i}{\sum\limits_{i=1}^{n} m_i} + \frac{u_i}{\sum\limits_{i=1}^{n} l_i}}{3} \tag{5}$$

$$w_j = \frac{w'_j}{\sum_{j=1}^{n} w'_j} \tag{6}$$

The linguistic values of fuzzy numbers and their fuzzy sets are shown in Table 1 and are used in mutual comparison of criteria weights.

Table 1. Linguistic value and belonging numerical value of membership functions [60].

Linguistic Value	Numerical Value
Equal importance	(1,1,1)
Low importance	(1,2,3)
Moderate importance	(2,3,4)
Moderate to strong importance	(3,4,5)
Strong importance	(4,5,6)
Strong to very strong importance	(5,6,7)
Very strong importance	(6,7,8)
Very strong to extreme importance	(7,8,9)
Extreme importance	(8,9,9)

2.4.2. The TOPSIS Method

The TOPSIS method was proposed by Hwang and Yoon [61], and further developed by Chen and Hwang [62], and Hwang, Lai, and Liu [63]. It is a technique for order of preference by similarity to ideal solution. It is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution and the largest geometric distance from the negative ideal solution [61]. The TOPSIS method assumes that each criterion has a monotonically increasing or decreasing utility, making it easier to locate positive ideal and negative ideal solutions. The positive ideal solution is formed as the combination of the best criteria values, and the negative ideal solution is the combination of the worst criteria values. Euclidean distances are used to measure the distance of each alternative from the positive ideal solution and negative ideal solution, and the order of preferences of alternatives is achieved by comparing Euclidean distances [64].

To determine the order of alternatives using the TOPSIS method, it is first necessary to calculate the normalized decision matrix, and the value of r_{ij} is normalized according to the following expression [61,62]:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n. \quad (7)$$

The next step is to determine the weighted normalized decision matrix. Weighted normalized value v_{ij} is calculated according to the following expression [61,62]:

$$v_{ij} = w_j \times r_{ij},\ i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n \quad (8)$$

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

Then, it is necessary to determine the positive and negative ideal solution. For benefit criteria, the best values are maximum, and for cost criteria, the best values are minimum [64]. Accordingly, the positive and negative ideal solution will be as follows [62]:

$$A^* = \{v_1^*, \ldots, v_n^*\} = \left\{ \left(max_i v_{ij} \,\middle|\, j \in J \right),\ \left(min_i v_{ij} \middle| j \in J' \right) \right\} \quad (9)$$

$$A^- = \left\{v_1^-, \ldots, v_n^-\right\} = \left\{ \left(min_i v_{ij} \,\middle|\, j \in J \right),\ \left(max_i v_{ij} \middle| j \in J' \right) \right\} \quad (10)$$

where J is the set of benefit criteria, and J' is the set of cost criteria.

The distance between each alternative can be measured by the n-dimensional Euclidean distance. The distance of each alternative from the positive ideal solution is given as follows [62]:

$$S_i^* = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^* \right)^2}, i = 1, 2, \ldots, m. \quad (11)$$

Respectively, the distance of each alternative from the negative ideal solution is given as follows [62]:

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^- \right)^2}, i = 1, 2, \ldots, m. \quad (12)$$

Then, it is necessary to calculate the relative coefficient of closeness of each alternative to the positive ideal solution. The relative closeness coefficient of the alternative A_i with respect to A^* is defined as follows [62]:

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-},\ 0 < C_i^* < 1, i = 1, 2, \ldots, m. \quad (13)$$

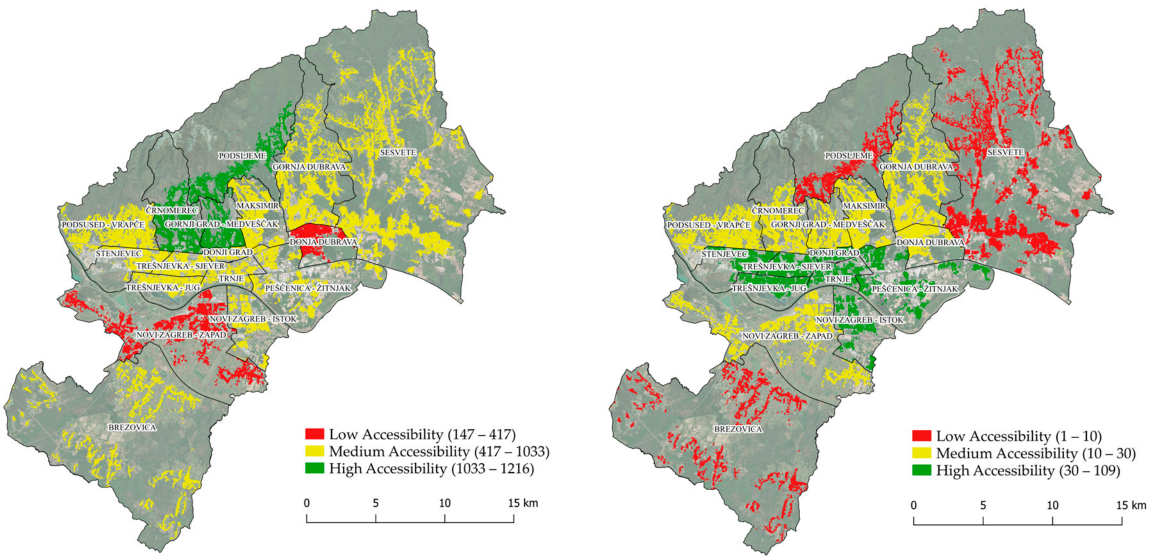
The last step is to order the alternatives according to the relative closeness coefficient in such a way that the best option is the alternative that has the highest relative closeness coefficient, and the worst is one with the smallest relative closeness coefficient [61].

3. Results

This section presents the results obtained by implementing the proposed model in the area of the city of Zagreb. At the beginning, six valuation criteria were defined according to which the green infrastructure index was determined using multi-criteria methods. The criteria weights are obtained by the fuzzy AHP method, and the final green infrastructure index was determined using the TOPSIS method. The result of the proposed methodology is the determination of the priority areas for the implementation of green infrastructure. In this way, the proposed model can help final decision makers to more easily decide about future activities related to urban green renewal.

3.1. Valuation Criteria

Six valuation criteria are defined: (C1) analysis of the availability of trees, (C2) analysis of the availability of recreational facilities, (C3) analysis of the availability of public green areas, (C4) analysis of the availability of water surfaces, (C5) analysis of the land surface temperature, and (C6) analysis of brownfield areas. As mentioned in the previous section, all analyses were performed in QGIS 3.28.15 "Firenze" software using a combination of spatial and attribute queries. Given that we are interested in green infrastructure near the place of residence, an analysis was made for each residential and mixed-use zone, and at the end, an average value was determined for each city district in the area of the city of Zagreb. Figure 1 shows all the criteria analyzed at the city district level. Figure 1a shows an analysis of the availability of trees and the average availability of trees for each city district within a radius of 300 m from residential and mixed-use zones located within the same city district. Figure 1b,c show the same, only for recreational facilities and for public green areas larger than 0.5 hectares. Figure 1d shows whether, on average for all residential and mixed-use zones in a particular city district, there is an accessible or inaccessible water surface within a radius of 300 m. Figure 1e shows the average land surface temperature of all residential and mixed-use zones within the same city district, and Figure 1f shows brownfield areas by city districts.



(**a**) (**b**)

Figure 1. *Cont.*

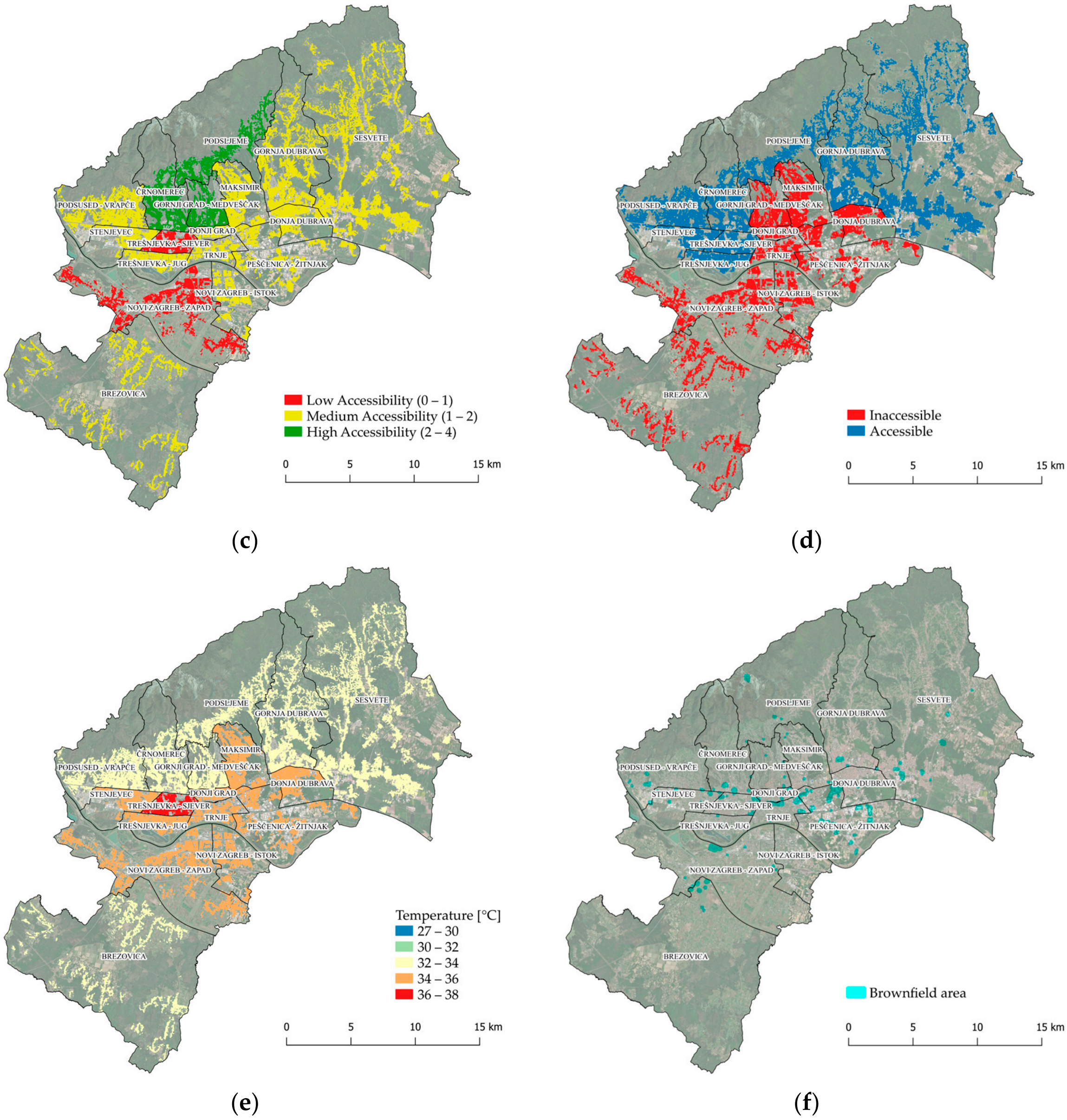


Figure 1. Valuation criteria: (**a**) analysis of the availability of trees; (**b**) analysis of the availability of recreational facilities; (**c**) analysis of the availability of public green areas; (**d**) analysis of the availability of water surfaces; (**e**) analysis of the land surface temperature; (**f**) analysis of brownfield areas.

3.2. Green Infrastructure Index

To determine the index of green infrastructure, we utilized previously explained valuation criteria, and the multi-criteria methods fuzzy AHP and TOPSIS. First, it is necessary to determine the weights of the criteria using the fuzzy AHP method. A team of experts compared the valuation criteria using Saaty's scale of relative importance. The team of experts consisted of an urban planner, landscape architect, surveyor, civil engineer, and a representative from the city of Zagreb administration. Along with the team of experts, interviews were also conducted with the end users, citizens of the city of Zagreb. Based on the assessments of experts and users, and the application of the arithmetic mean, the final assessments of the relative importance of the criteria were determined using triangular fuzzy numbers (Table 2).

Table 2. Pairwise comparison matrix, triangular fuzzy numbers.

Criteria	C1	C2	C3	C4	C5	C6
C1	1,1,1	1/3,1/2,1	1/5,1/4,1/3	1/4,1/3,1/2	1,1,1	4,5,6
C2	1,2,3	1,1,1	1/4,1/3,1/2	2,3,4	1,1,1	5,6,7
C3	3,4,5	2,3,4	1,1,1	2,3,4	1,1,1	5,6,7
C4	2,3,4	1/4,1/3,1/2	1/4,1/3,1/2	1,1,1	1,1,1	5,6,7
C5	1,1,1	1,1,1	1,1,1	1,1,1	1,1,1	4,5,6
C6	1/6,1/5,1/4	1/7,1/6,1/5	1/7,1/6,1/5	1/7,1/6,1/5	1/6,1/5,1/4	1,1,1

After the final assessments of the relative importance of the criteria have been made, it is possible to determine the weights of the criteria. First, the fuzzy weights of the criteria were calculated (see Table 3), based on which we obtained the normalized and final weight of each valuation criterion (see Table 4).

Table 3. Fuzzy weights.

Criteria	Fuzzy Weights		
C1	0.103	0.104	0.114
C2	0.189	0.204	0.213
C3	0.321	0.331	0.328
C4	0.150	0.152	0.158
C5	0.204	0.177	0.154
C6	0.034	0.032	0.032

Table 4. Normalized weights.

Criteria	Weights of Criteria
C1	0.107
C2	0.202
C3	0.327
C4	0.153
C5	0.178
C6	0.033

After defining the weights of the criteria using the TOPSIS method, the relative closeness coefficient was calculated. In this research, it represents the final green infrastructure index. The green infrastructure index ranges from zero to one. The higher in rank position of the green infrastructure index the better value of green infrastructure in that area compared to other investigated areas. In other words, a smaller green infrastructure index means there is less green infrastructure in that area compared to others. Therefore, these are the areas where the development and implementation of green infrastructure should be started first.

According to the formulas explained in Section 2.4.2 and using the criteria weights determined by the fuzzy AHP method (Table 4), the green infrastructure index was calculated for each city district in the area of the city of Zagreb using the TOPSIS method. The green infrastructure index of city districts was determined based on analyses carried out for each city district. The area of the city of Zagreb is divided into 17 city districts, and for each, the average value of an individual criterion was calculated based on residential and mixed-use zones (Figure 1). Positive and negative ideal solutions were determined using the TOPSIS method, to calculate the distance from the positive and negative ideal solutions and finally calculate the green infrastructure index. Table 5 shows the green infrastructure index for all city districts, and along with the green infrastructure index, the table also shows the values of positive and negative ideal solutions. The presentation of the index of green infrastructure by city districts is also given in Figure 2, where the index of green infrastructure is divided into five classes according to the given scale.

Table 5. Green infrastructure index for city districts.

City District	S_i^*	S_i^-	GI Index	Rank
Brezovica	0.158	0.055	0.258	14
Črnomerec	0.097	0.165	0.630	1
Donja Dubrava	0.174	0.032	0.155	16
Donji Grad	0.097	0.114	0.540	5
Gornja Dubrava	0.112	0.104	0.482	6
Gornji Grad–Medveščak	0.097	0.149	0.605	2
Maksimir	0.124	0.086	0.410	9
Novi Zagreb–istok	0.158	0.063	0.286	13
Novi Zagreb–zapad	0.186	0.025	0.118	17
Peščenica–Žitnjak	0.159	0.054	0.253	15
Podsljeme	0.111	0.134	0.547	4
Podsused–Vrapče	0.124	0.091	0.424	7
Sesvete	0.129	0.094	0.420	8
Stenjevec	0.145	0.083	0.364	11
Trešnjevka–jug	0.106	0.131	0.553	3
Trešnjevka–sjever	0.155	0.079	0.338	12
Trnje	0.135	0.090	0.401	10

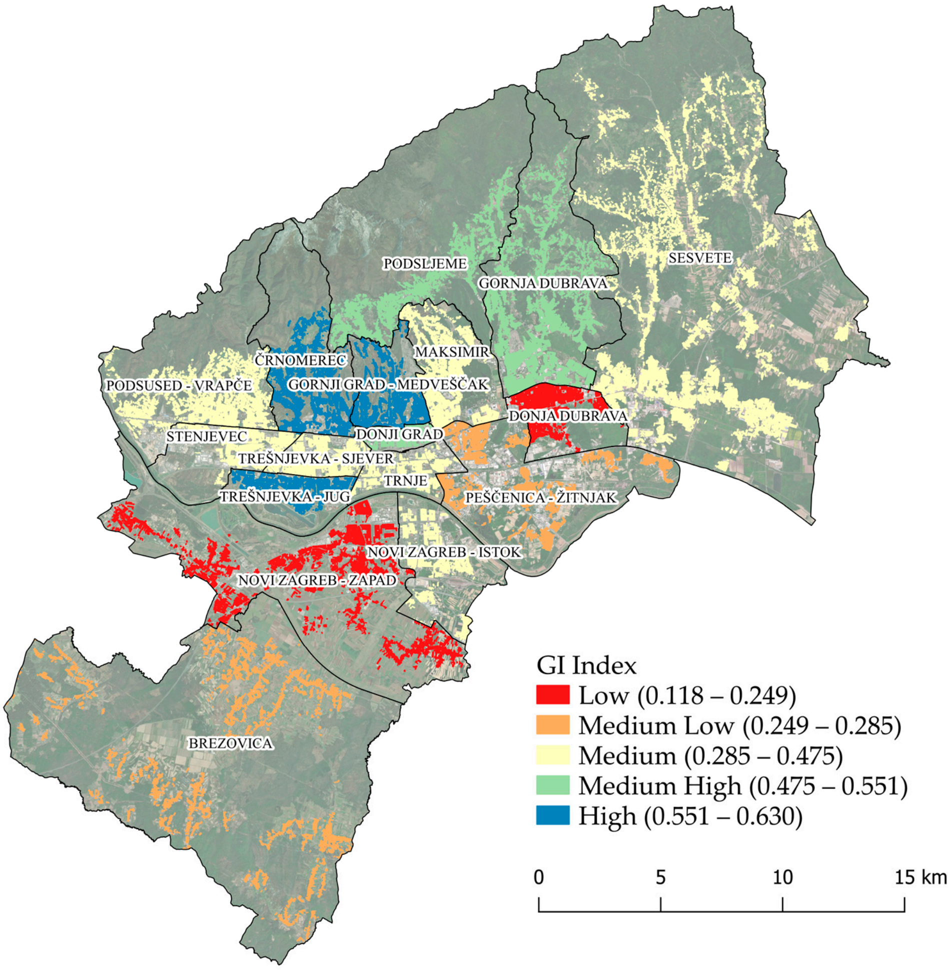


Figure 2. Green infrastructure index for city districts.

In Table 5 and Figure 2, we see that the city districts of Črnomerec and Gornji Grad–Medveščak have the highest green infrastructure index, which is quite expected considering their location next to Medvednica and the large parks located near the residential and mixed-use zones in these city districts. Also, the city district Trešnjevka–jug, situated along the river Sava and within which the Jarun Recreational Sports Center is located, also has a high green infrastructure index. Meanwhile, the city districts of Donja Dubrava and Novi Zagreb–zapad have the lowest green infrastructure index, which stands out significantly with a small green infrastructure index compared to other city districts. The city district of Donji Grad, as the narrowest center of the city, has a relatively high green infrastructure index, which is more than satisfactory considering the construction of that part of the city. Such a high green infrastructure index is mainly due to the large number of public green areas located near residential and mixed-use zones in that area.

4. Discussion

By applying the proposed valuation model for urban green infrastructure in land management, it is possible to valuate green infrastructure in an area with mathematical formulas and measurable parameters. However, to apply the model, spatial data on planned purpose and actual use, as well as data from the Green Cadastre on green infrastructure, should be available for that area.

As part of this research, the valuation model for urban green infrastructure in land management was examined and implemented in the area of the city of Zagreb. Based on the analyses, the analysis of the availability of trees, the analysis of the availability of recreational facilities, the analysis of the availability of public green areas larger than 0.5 hectares, the analysis of the availability of water surfaces, the analysis of land surface temperature, and the analysis of brownfield areas, the green infrastructure index was calculated. The green infrastructure index was calculated for city districts in the city of Zagreb using the fuzzy AHP and TOPSIS methods. The green infrastructure index calculates the value of green infrastructure in a particular area. A higher green infrastructure index indicates a better value of the green infrastructure in that area compared to other areas.

This study found that the city districts of Črnomerec, Gornji Grad–Medveščak, and Trešnjevka–jug have the highest index of green infrastructure. Črnomerec performed excellently in most criteria, except for the availability of recreational facilities, which resulted in the highest index of green infrastructure for this city district. Gornji Grad–Medveščak followed with a slightly lower index of green infrastructure due to the unavailability of water surfaces. Trešnjevka–jug did not excel in all criteria but had the largest number of recreational facilities and water surfaces, resulting in one of the highest indexes of green infrastructure. On the other hand, Novi Zagreb–zapad has the worst results for most criteria and therefore the lowest index of green infrastructure compared to other city districts.

All the proposed methods involve computer processing, and it is possible to evaluate the green infrastructure consecutively in a relatively short time and at the required time intervals to determine the trend of the green infrastructure index. The ultimate goal is to have the same services everywhere and to have the same density of green infrastructure in all areas. The model developed in this way provides support in land management because it is possible to determine the green infrastructure index and evaluate the current state, plan the ideal future state, and see how the implementation of green infrastructure progresses in a certain time interval. In this way, it is possible for the ultimate decision makers to more easily decide which areas are more prioritized for the development and implementation of green infrastructure. The green infrastructure index determined in this way can be compared with other spatial and land data during spatial planning.

5. Conclusions

Green infrastructure is gaining more and more importance today, especially after the adoption of the 2030 Agenda for Sustainable Development. There is a large body of research highlighting its benefits. However, there is a lack of research studies on green infrastructure for land management purposes. While green infrastructure is important for achieving sustainable development goals, it is also important to pay attention to sustainable land management [39]. When planning green infrastructure, it is necessary to pay more attention to land management to achieve a greater benefit and value of the land and potentially to standardize all available services in the areas where green infrastructure is planned. Therefore, in this research, the valuation model of urban green infrastructure in land management was developed, which can be used to determine the index of green infrastructure and thus enable planners and final decision makers to better plan green infrastructure and decide which areas are more prioritized for its implementation.

The test model evaluated the elements of green infrastructure that are available in the Green Cadastre. However, as we can see in the example of the city of Zagreb, these are not all publicly available elements of green infrastructure that exist in the city of Zagreb. Thus, the unavailability of some spatial data may prevent the full implementation of the developed model. This problem can be solved by additional field collection of data that are not available to us within the existing databases.

In future research, we will compare the green infrastructure index and land value and demonstrate the influence of green infrastructure on total land value. It is recommended that in future research, the number of the population be included in the development of the model and that the obtained data be compared with the population density to provide a more detailed representation of the percentage of green infrastructure relative to the number of inhabitants in a specific area. Also, it is possible to introduce additional criteria that could also affect the final green infrastructure index of the examined area.

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