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RESEARCH ARTICLE

Sanitary landfill site selection using GIS-based on a fuzzy multi-criteria evaluation technique: a case study of the City of Kraljevo, Serbia

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Abstract

Adequate disposal of municipal solid waste (MSW) is one of Serbia's most complex environmental challenges. The problem is more serious in urban areas, since large amounts of waste are disposed of in locations that do not comply with environmental, technical, and socio-economic standards. Such is the case for the city of Kraljevo, where about 116,000 inhabitants do not have a sanitary landfill facility. This research includes a multi-criteria analysis, conducted with the help of geographic information systems, to find a suitable landfill site location. After data collection, the first step was to process 15 environmental and socio-economic factors utilizing the fuzzy analytic-hierarchy process method. The second step comprised the visual analysis and selection of the ten most suitable locations from the synthetic convenience map. The third step involved the final ranking of sites by means of the fuzzy multi-objective analysis by ratio, plus the full multiplicative form method, based on four additional beneficial and non-beneficial criteria. The results show that sanitary landfill candidate site A4 is the most suitable location for constructing a sanitary landfill site due to its large area (569 ha) and relatively short distance from the urban zone (8 km). This study is the first to integrate geographic information systems and the fuzzy analytic-hierarchy process, multi-objective analysis by ratio, and the full multiplicative form algorithm for sanitary landfill selection. The results of the research can be used as a reference for safe waste disposal in the city of Kraljevo.

Keywords Analytic-hierarchy process · Multi-objective analysis · Waste management · Landfilling · Municipal solid waste · Waste disposal

Introduction

Municipal waste comprises household and commercial waste collected from a specific territorial unit following legal regulations and environmental standards. With the growth of the world's population and the accelerated processes of urbanization and industrialization, global waste production is increasing (Alam and Qiao 2020; Torkayesh et al. 2021). Globally, it is estimated that about 11.2 billion tons of solid waste is collected annually, and it is foreseen that by 2025, 4.3 billion members of the urban population will be generating 1.42 kg of municipal waste per capita on a daily basis (Mian et al. 2017; Yildirim et al. 2022).

Sustainable municipal waste management (WM) is one of the biggest environmental challenges for spatial planners, and local and city authorities in developing countries (Khan et al. 2018; Filkin et al. 2022; Nanda et al. 2022). Non-sanitary landfills are created due to a lack of planning and organization in WM and, as such, can significantly impact human health, biodiversity, land degradation, and water pollution (Şener et al. 2010; Gorsevski et al. 2012; Asif et al. 2020). Among the methods used in WM, a sanitary landfill is the most common way of disposing of municipal waste for economic, technical, and organizational reasons (Mishra et al. 2020; Yang et al. 2022; Ahire et al. 2022). Although landfill

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is at the bottom of the WM scale (waste reduction, reuse, recycling, composting and landfilling), it is recommended that only waste that has no energy or recycling potential is disposed of in the waste disposal (WD) process (Ajibade et al. 2019; Carević et al. 2021).

Inadequate WM is a major problem in respect of environmental protection in the Republic of Serbia. Due to accelerated industrialization and economic growth, there has been progressive growth in the total amount of all types of solid waste in the last 40 years. In respect of the research area Kraljevo, based on the Local WM Plan (2012), the average resident generates 1.28 kg of waste per day, which is more than the national average of 0.93 kg/day/per capita. In addition to a large number of illegal landfills that are smaller in size, municipal waste in this area is mostly disposed of in the unsanitary landfill known as "Kulagića ada." This landfill is located on alluvial sediments and is 150 m from the West Morava river, which poses a risk to surface water and groundwater quality. This study deals with environmental, social, and economic criteria, in order to select the appropriate location for the construction of a sanitary landfill (Chabuk et al. 2017; Arjwech et al. 2020; Abdelouhed et al. 2022). The researched environmental and socio-economic factors are also covered by the Law on Waste Management in the Republic of Serbia (2018) and are in accordance with the criteria established for determining the location of the sanitary landfill, published in the Official Gazette of the Republic of Serbia no. 54/1992. Furthermore, the Decree on Disposal of Waste was published in the Official Gazette of the Republic of Serbia no. 92/2010.

When analyzing environmental conditions, numerous factors must be taken into consideration in order to make the results more valid. In this study, several natural conditions were considered: geophysical (distance from faults), hydrogeological (groundwater vulnerability, rock types, distance from surface waters), pedological (soil types), geomorphological (aspect and slope), climatological (wind direction and rainfall), and protected areas (natural and cultural). In respect of WM, the analysis and importance of environmental factors require selecting the most suitable location, which has a minor negative influence on the environment.

Socio-economic conditions are equally important in waste disposal, due to the fact that during construction of sanitary landfills, there is concern for the safety and health of the local population. Therefore, in order to prevent any influence on the community as a result of potential accidents (exposure to landfill gas, leachate contamination), the following criteria were applied: land use, distance from urban and rural areas, distance from main roads, distance from industrial areas, and distance from the airport.

Beneficial and non-beneficial criteria fall into economic, technical, and aesthetic categories. The location of a sanitary landfill is based on these criteria. To satisfy all stakeholders (decision makers, investors, and the local community), the following criteria were applied: distance from the waste production center, landfill capacity, road network construction and visibility. Based on those criteria, it is possible to choose an economically acceptable location in terms of construction and maintenance costs that will not significantly damage the environment.

Over the past 10 years, a large number of studies have been published, dealing with landfill site selection using geographic information systems (GIS) and multi-criteria decision analysis (MCDA) (Manyoma-Velásquez et al. 2020; Majid and Mir 2021; Asefa et al. 2021). By assigning weighting factors to the criteria and integrating them into a GIS, relevant results can be obtained to show the most suitable locations (Karakuş et al. 2019; Othman et al. 2021; Rame et al. 2022). Numerous researchers favor GIS and the analytical-hierarchical process (AHP), including Kamdar et al. (2019), who researched municipal solid waste (MSW) disposal sites in the province of Songkhla (Thailand). Alkaradaghi et al. (2019) explored suitable locations for the Sulaimaniyah territory of Iraq. Šušnjar et al. (2021) analyzed the ecological suitability of East Sarajevo (Bosnia and Herzegovina) for selecting a landfill location. In Mersin (Turkey), Bilgilioglu et al. (2022) identified the most suitable sites for MSW disposal. The AHP method provides a means of decomposing a problem into a hierarchy of subproblems that can be more easily comprehended and subjectively evaluated (Şener et al. 2010).

In recent years, authors have increasingly integrated fuzzy sets with the AHP method (FAHP) (Abdulhasan et al. 2019; Zarin et al. 2021). For example, Ali and Ahmad (2020) identified the most suitable landfill sites in Kolkata (India). Moreover, Mohsin et al. (2022) presented a new approach to determining the location of sanitary landfills, which involved combining FAHP with machine learning models (support vector machine (SVM) and random forest-RF)).

In addition to the AHP method, the best–worst method (BWM), the technique for order of preference by similarity to ideal solution (TOPSIS), simple additive weighting (SAW), the decision-making trial and evaluation laboratory (DEMATEL), etc. have been applied in MCDA and waste management (Ali et al. 2021; Sisay et al. 2021; Torkayesh et al. 2022). These models can often be found in combination with fuzzy numbers for WD (Pasalari et al. 2019; Liu et al. 2021).

Multi-objective optimization based on ratio analysis plus the full multiplicative form (MULTIMOORA) is an MCDA technique based on the results of three methods: ratio system, reference point approach, and full multiplicative form (Hafezalkotob et al. 2019a; Lin et al. 2020). In this research, MULTIMOORA can be used to analyze and rank a number of suitable sites for a sanitary landfill and their criteria. Rahimi et al. (2020) used the fuzzy

BWM-MULTIMOORA-GIS hybrid approach for the city of Mahallat in Iran for this purpose. In our study, the fuzzy AHP-MULTIMOORA hybrid algorithm was applied. Therefore, this study was the first to integrate GIS, AHP, and MULTIMOORA approaches with fuzzy logic in terms of site selection for sustainable MSW disposal. The contribution of this article is reflected in the application of an integrated MCDA model that determines and ranks the most suitable landfill sites, based on 19 criteria and high-resolution data.

The main goal of this study was to identify the most suitable location for the construction of a sanitary landfill through geospatial data and quantitative analysis. The applied criteria are aimed at satisfying engineering and technical protocols, as well as social security in terms of alleviating "not-in-my-backyard" syndrome (NIMBY). This syndrome occurs due to the dissatisfaction of social groups regarding the choice of landfill location and its proximity to rural and urban areas (Chiueh et al. 2008; Demesouka et al. 2019).

Materials and methods

Study area

The city of Kraljevo is located in the center of Serbia. Morphological conditions and traffic connectivity are two important factors in terms of WM. The study area can be divided into two morphological units. In the northern part, there is a vast valley formed by the West Morava river, which has a west–east orientation. This part of the city of Kraljevo is the most densely populated and all three urban settlements are located in this valley (Kraljevo, Mataruška Spa, and Ribnica). The southern part of the study area is mostly mountainous and less densely populated. In the central part, the Ibar river is prominent (Milošević et al. 2009). The average altitude of the study area is 615.2 m.

The city of Kraljevo administratively belongs to the Raška district. It is the largest administrative unit by area in the Republic of Serbia, with an area of 1530 km^2 and 92 settlements (Fig. 1). According to the 2011 Census, there were 125,488 inhabitants in the area, 64,175 of whom lived in the urban settlement of Kraljevo. The degree of urbanization grew steadily during the period 1948–2011. In 1953, 22.0% of the total population lived in urban settlements. According to the data from 2011, urbanization was much higher, at 54.8%. The increase in urbanization also affects the increased generation of MSW and its disposal problems. The urban settlement of Kraljevo is one of the most important industrial and service centers in Central Serbia. Accelerated urbanization has created a number of problems in terms of adequate WM, conservation of natural resources and implementation of planning regulations. All maps in the study are presented in the Universal Transverse Mercator – north zone 34 (UTM 34 N) coordinate system.

Data collection

Data sets taken from different sources were used in this study. The open-source program QGIS with GRASS was

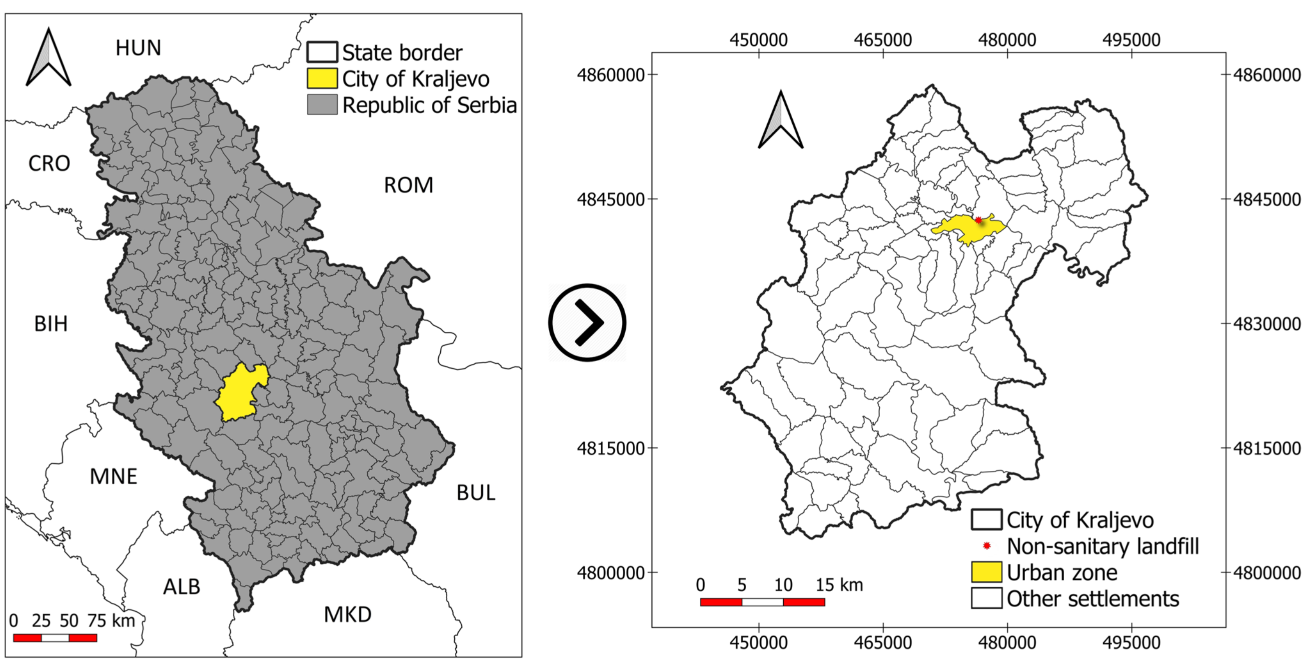


Fig. 1 Geographical position of study area

used for the purpose of GIS data analysis (QGIS Development Team 2019). In respect of the environmental factors, the vulnerability of the city of Kraljevo to groundwater was determined by digitizing the content from the map of groundwater vulnerability in Serbia (Milanović et al. 2010). According to the procedure of vectorization of contents from the geological sheets of the basic geological map of Serbia, on a scale of 1/100.000, data regarding rock types and faults were obtained (Geoliss 2022). Digitization was used to create a pedological map, where maps of soil types on a scale of 1/50.000 were interpreted (Institute for Soil Studies 1963). A digital elevation model (EU-DEM) with a spatial resolution of 25 m was used to create terrain slope, aspect and wind exposition index maps (Copernicus—Land Monitoring Service 2016) (Table 1).

The amount of precipitation from the Kraljevo meteorological station was analyzed for the period 1949–2020 (Republic Hydrometeorological Service of Serbia 2022). In terms of socio-economic factors, sets of data on land use, with a spatial resolution of 10 m, were obtained by digitizing content from the National Spatial Data Infrastructure—GeoSrbija (2022) website. The settlements were marked via Google Earth (2022), while the main roads were obtained by importing vector content from Open Street Map (2022). Industrial plants and the airport were digitized based on Copernicus—Land Monitoring Service (2018) and Google Earth images. Data in respect of protected natural and cultural areas were obtained by downloading data from the geospatial databases of the International Union for Conservation of Nature and United Nations Environment Program (IUCN and UNEP 2022), the Institute for Nature Conservation of Serbia (2022), and GeoSrbija (2022). Topographic maps on a scale of 1/50.000 were used for digitizing permanent and occasional surface watercourses (Military Geographical Institute 1970). All data were rasterized, and the resolution of the final map cell was 25 × 25 m. In respect of distance from the waste production center, there was an available road network database in Open Street Map (2022). Capacity, i.e., the landfill's surface, was calculated in the QGIS program by converting the synthesis map from raster into vector. The analysis of potential road network construction and visibility was performed using the Google Earth (2022) program.

Criteria selection for suitable landfill site

The selection of appropriate criteria and their analysis are complex tasks. For the purpose of this study, environmental and socio-economic criteria were taken into account. Ten sub-criteria were analyzed and singled out in respect of environmental factors, while five were extracted regarding the socio-economic aspect. These 15 criteria were involved in GIS processing and the FAHP process, which aimed to obtain a synthetic benefit map. The criteria were chosen by experts in the following areas: hydrogeology, waste management, geography, GIS, environment, spatial

Table 1 Data collection and sources

Criteria	Format	Source of data
Groundwater vulnerability	Vector to raster	Milanović et al. (2010)
Geology	Vector to raster	Geoliss (2022)
Soil types	Vector to raster	Institute for Soil Studies (1963)
Slope	Raster	Copernicus—Land Monitoring Service (2016)
Aspect	Raster	Copernicus—Land Monitoring Service (2016)
Wind exposition index	Raster	Copernicus—Land Monitoring Service (2016)
Rainfall	Raster	Republic Hydrometeorological Service of Serbia (2022)
Distance from faults	Vector to raster	Geoliss (2022)
Distance from surface waters	Vector to raster	Military Geographical Institute (1970)
Distance from protected and cultural areas	Vector to raster	UCN & UNEP (2022), GeoSrbija (2022), Institute for Nature Conservation of Serbia (2022)
Land use	Vector to raster	GeoSrbija (2022)
Distance from urban and rural areas	Vector to raster	Google Earth (2022)
Distance from main roads	Vector to raster	Open Street Map (2022)
Distance from industrial areas	Vector to raster	CLC (2018), Google Earth (2022)
Distance from the airport	Vector to raster	CLC (2018), Google Earth (2022)
Distance from the waste production center	Vector	Open Street Map (2022)
Landfill capacity	Raster to Vector	QGIS Development Team (2019)
Road network construction	Vector	Google Earth (2022)
Visibility	Vector	QGIS Development Team (2019)

planning, and mathematics. After obtaining more suitable locations, four beneficial and non-beneficial criteria were selected for the fuzzy MULTIMOORA method. Beneficial and non-beneficial criteria were based on their role and significance in the socio-economic and technical overview of the entire procedure (treatment effectiveness, occupational hazards, capital cost, operational cost, maintenance cost, and service life).

Environmental factors

Groundwater vulnerability Based on the existing map of Serbia's threat to groundwater (Milanović et al. 2010), six classes of threats were identified in the territory of the city of Kraljevo: very low, low, medium, medium–high, high, and very high. Areas that are very poorly and poorly endangered by groundwater are considered the most favorable, because the chance of groundwater contamination is minimal.

Geology The city of Kraljevo presents a complex geological setting, as it is situated in the Western Vardar Zone, which comprises the remnants of the oceanic lithosphere and parts of the ancient Gondwana margin (Cvetkovic et al. 2016). The oldest rocks are represented by Late Paleozoic low-grade metamorphic rocks (e.g. gneiss, schist, calc-schist, phyllite, marble) that are exposed in the southwestern area (Urošević et al. 1973; Brković et al. 1977, 1978). Lower and Middle Triassic limestones and dolomites have been observed in the central-south area of the city. The ophiolite zone was obducted in the Latest Jurassic, before the suturing between Eurasia and Gondwana. It occurs in the central region, but also to the east. Flysch sedimentation represented by clastic-carbonate turbidites started in the Cretaceous and ended around the Cretaceous-Paleogene boundary (Schmid et al. 2008). After the final closing of the Vardar Ocean, different tectono-magmatic conditions led to magmatism and the formation of continental sedimentary basins (Cvetkovic et al. 2016). Understanding rock types is particularly important in distinguishing the most suitable geological formations for waste disposal; in this case, these are shale and clay. These rocks represent an ideal waterproof layer, which could mitigate the penetration of leachate deep below the surface, in case of an accident.

Soil types The pedological characteristics largely depend on the geological background. The classification of land types into credit rating classes was performed, so the lands with the lowest agricultural productivity were categorized as the most suitable for landfill construction—lithosol, leptosol, and regosol. Due to their great agroecological importance, very fertile soils, such as fluvisol and chernozem, were rated the lowest.

Slope The degree of inclination of the terrain plays an important role immediately before and after the construction of a sanitary landfill. Flat terrains are the most suitable for the construction of sanitary landfills. As the slope of the land increases, the degree of susceptibility of the terrain to natural hazards (torrential floods, forest fires, erosion intensity) and infiltration of leachate increases (Mallick 2021). The 0–4° slope interval was rated as the most suitable for sanitary landfills (Table 2).

Aspect The western and eastern exposures were rated as the most suitable for sanitary landfills. The south sides are exposed to the sun for a very long time, increasing the risk of fire. In addition, soil moisture may increase and result in a higher concentration of surface and groundwater on the north side.

Wind exposition index Territories where the wind speed is high were assessed as unsuitable due to the possibility of spreading unpleasant odours to the surrounding settlements. However, leeward sides with a value < 1 are ideal locations to construct sanitary landfills.

Rainfall A large amount of annual precipitation can make it difficult to maintain a sanitary landfill due to the high concentration of atmospheric sediment in a small area. Terrains with an annual rainfall of < 900 mm were marked as the most suitable.

Distance from surface waters Sufficient distance of the landfill from rivers and springs would minimize the possibility of contamination and reduction of the surface water quality. Terrains with a distance greater than 450 m from watercourses were assigned the highest value.

Distance from protected and cultural areas All protected natural and cultural objects were initially eliminated from the evaluation process to avoid a negative impact on existing ecosystems. A distance of 5 km from cultural sites is sufficient to preserve the historical significance and tourist potential, because the landfill cannot have a harmful effect on the environment.

Distance from faults The subduction zone of the former Vardar Ocean is located in the investigated area, where the African oceanic crust is subducted under the European oceanic crust (Mladenovic et al. 2011). As the distance of the landfill from the risk areas increases, the potential impact of tectonic activities decreases. The locations with the greatest values are more than 1.5 km away from existing faults.

Table 2 Reclassification of environmental and socio-economic values

Factors	Parameter	Rank	Area (km^2)	Percentage (%)
Groundwater vulnerability	Very high	1	18.87	1.23
	High	2	170.98	11.18
	Medium–high	3	657.12	42.95
	Medium	4	487.78	31.88
	Very low, low	5	195.11	12.75
Geology	Alluvial deposits, pyroclastic rocks, low-grade metamorphic rocks, limestones, and dolomites	2	1074.44	70.24
	Lake deposits, clastic series, dacitoandesite, and granodiorite	3	198.11	12.95
	Flysch	4	139.94	9.15
	Shale and clay	5	117.27	7.67
Soil types	Fluvisol, chernozem	1	691.97	45.23
	Vertisol, eutric cambisol	2	209.78	13.71
	Dystric cambisol, kalkokambisol	3	7.81	0.51
	Planosol, leptic calcisol	4	272.66	17.82
	Lithosol, leptosol, regosol	5	347.65	22.72
Slope	> 25°	1	182.11	11.90
	15–25	2	469.48	30.69
	8–15	3	386.03	25.23
	4–8	4	201.87	13.20
	0–4	5	290.36	18.98
Aspect	S	1	188.05	12.29
	N	2	205.14	13.41
	SE, SW	3	379.22	24.79
	NE, NW	4	390.08	25.50
	E, W, unexposed	5	367.38	24.01
Wind exposition index	> 1.196	1	63.27	4.14
	1.09–1.196	2	252.81	16.53
	0.984–1.09	3	510.77	33.39
	0.878–0.984	4	530.61	34.68
	0.772–0.878	5	172.40	11.27
Rainfall	> 1350 mm	1	25.36	1.66
	1200–1350	2	170.91	11.17
	1050–1200	3	268.19	17.53
	900–1050	4	384.00	25.10
	736–900	5	681.40	44.54
Distance from faults	0–250 m	1	361.82	23.65
	250–500	2	234.96	15.36
	500–1000	3	297.64	19.46
	1000–1500	4	170.78	11.16
	> 1500	5	464.66	30.37
Distance from surface waters	0–150 m	1	915.73	59.86
	150–250	2	324.31	21.20
	250–350	3	146.41	9.57
	350–450	4	69.38	4.53
	> 450	5	74.04	4.84
Distance from protected and cultural areas	0–2000 m	1	447.22	29.23
	2000–3000	2	228.32	14.92
	3000–4000	3	228.56	14.94
	4000–5000	4	219.72	14.36
	> 5000	5	406.04	26.54
Land use	Forest, water surface	1	880.02	57.54
	Built area, agricultural land	2	255.04	16.68
	Humid soil	3	52.66	3.44
	Shrub	4	185.58	12.13
	Grassland, bare soil	5	156.12	10.21

Table 2 (continued)

Factors	Parameter	Rank	Area (km^2)	Percentage (%)
Distance from urban and rural areas	0–500 m	1	890.67	58.22
	500–1000	2	274.17	17.92
	1000–1500	3	147.80	9.66
	1500–2500	4	150.19	9.82
	> 2500	5	67.03	4.38
Distance from main roads	0–200 & > 3500 m	1	499.25	32.63
	2000–3500	2	269.74	17.63
	1500–2000	3	146.51	9.58
	800–1500	4	270.04	17.65
	200–800	5	344.33	22.51
Distance from industrial area	0–400 m	1	14.97	0.98
	400–800	2	18.77	1.23
	800–1500	3	42.92	2.81
	1500–2000	4	29.13	1.90
	> 2000	5	1424.08	93.09
Distance from the airport	0–800 m	1	7.55	0.49
	800–1500	2	7.28	0.48
	1500–2500	3	13.08	0.85
	2500–4000	4	25.12	1.64
	> 4000	5	1476.84	96.53

Socio-economic factors

Land use Categorization of land use was performed by processing satellite images. For the construction and maintenance of the landfill, it is important to determine the purpose of the land and avoid agricultural complexes. Water areas and forest ecosystems were marked as very unsuitable, while the greatest value was given to bare land and grasslands.

Distance from urban and rural areas It is recommended that the landfill distance from residential areas should be greater than 2.5 km in order not to endanger the population and the environment. However, waste transport costs will be significantly increased if the landfill is too far from the settlement.

Distance from main roads Asphalt roads and railways, by which adequate waste transport is possible, were taken into account. The sufficient distance of the landfill from roads and railways is 200–800 m because of passenger safety, and it is important that the landfill is not too far away, due to transport costs and the need for construction of new roads.

Distance from industrial areas A greater distance of the landfill from industrial facilities reduces the risk of accidents. Grade 5 was assigned to the territories that are more than 2 km away from industrial sites.

Distance from the airport Air traffic occurs in the study area's north-western region. A potential landfill should not be located near the airport, as this would endanger passenger safety and affect landfill maintenance (López et al. 2022; Paul and Ghosh 2022). The best rated areas are located more than 4 km from the airport.

The values of all 15 criteria were reclassified by processing the data in a GIS. Thematic maps with unclassified values were obtained first. Then, classification and assignment of the grades for every interval were performed. Assigned values and guidelines for landfill site selection were processed in accordance with previous research and similar MCDA models (Rahimi et al. 2020; Torkayesh et al. 2021; Ahire et al. 2022). Depending on the study area's size, the interval values in different studies may vary.

Layers were reclassified into five classes based on the value and degree of convenience: limited (1), unsuitable (2), poorly suitable (3), suitable (4), and the most suitable (5). Limited values are extremely unfavorable for the environment and socio-economic development of the community, while the most suitable values are ideal for constructing a sanitary landfill (Fig. 2).

Beneficial and non-beneficial criteria

Distance from the waste production center Waste transport costs increase with the distance from the center for waste production, in this case from the urban zone of Kraljevo. By applying GIS analysis, it is possible to determine starting and destination points in order to identify the most cost-effective location.

Landfill capacity The area of potential sanitary landfills is an important factor in sustainable WD. Economically speaking,

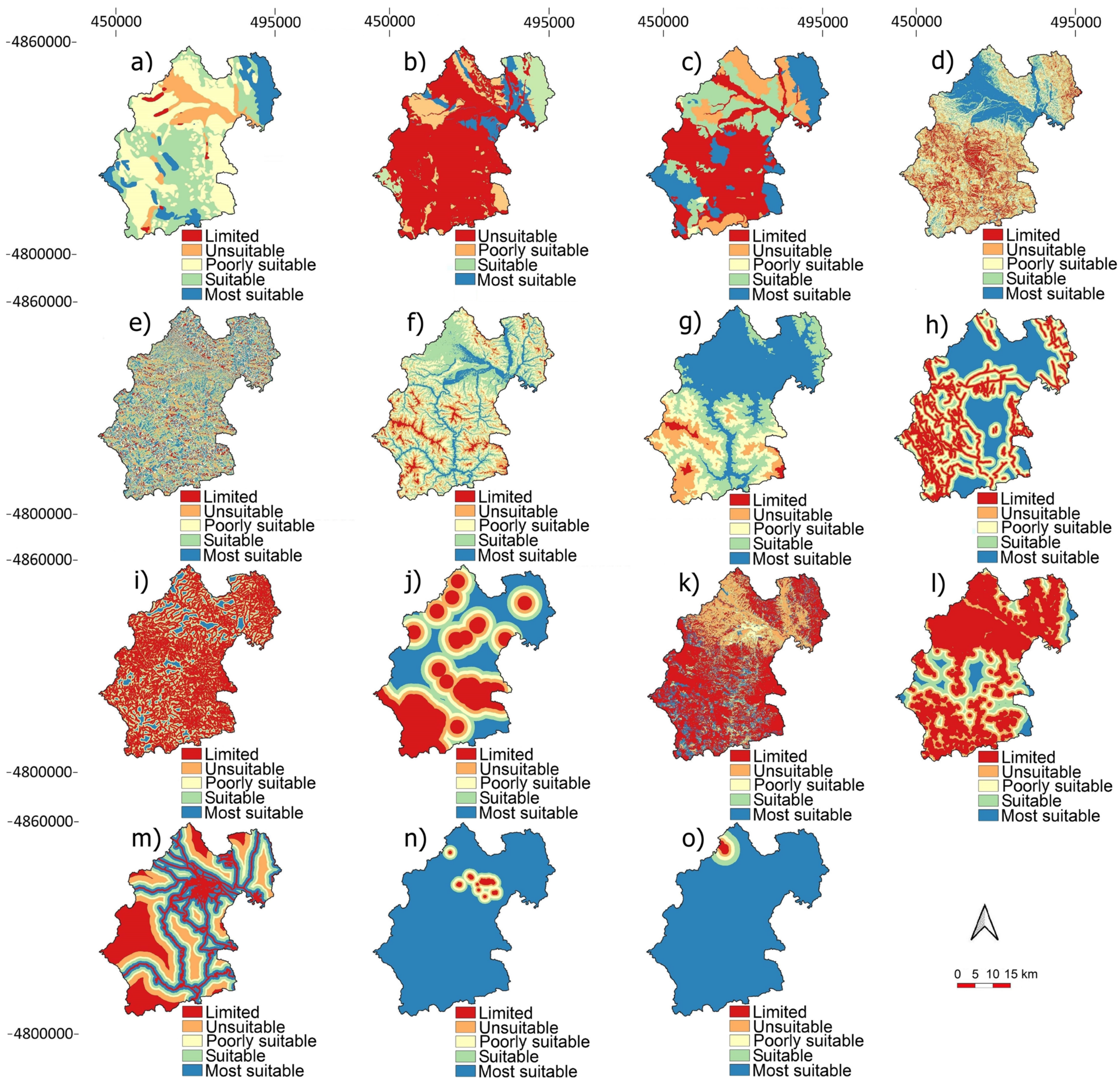


Fig. 2 Suitability reclassified maps: (**a**) groundwater vulnerability; (**b**) geology; (**c**) soil types; (**d**) slope; (**e**) aspect; (**f**) wind exposition index; (**g**) rainfall; (**h**) distance from faults; (**i**) distance from surface waters; (**j**) distance from protected and cultural areas; (**k**) land use; (**l**) distance from urban and rural areas; (**m**) distance from main roads; (**n**) distance from industrial area; (**o**) distance from the airport

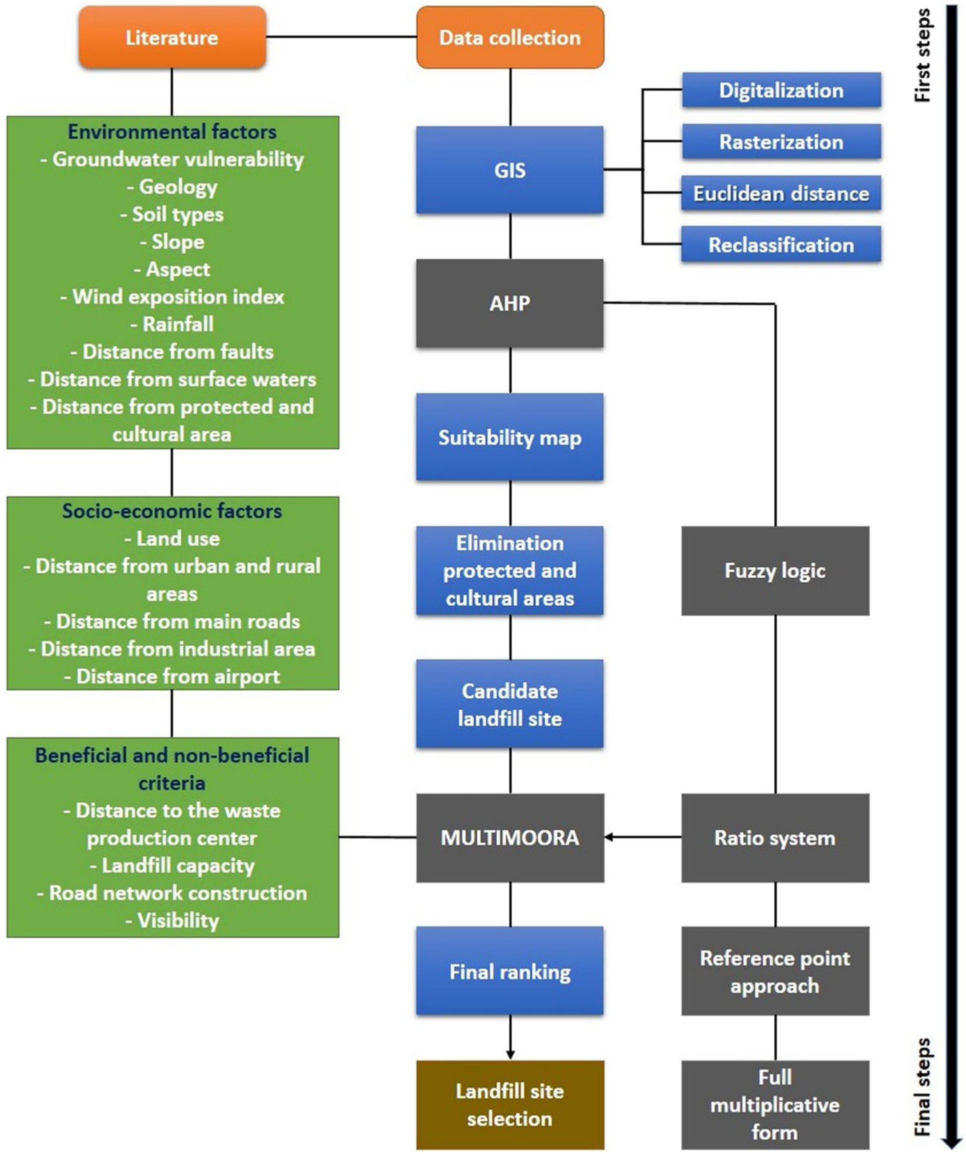
the larger the suitable location, the longer the WD process would be, and there would be no need to find new locations over a longer period of time.

Road network construction A factor that indicates the distance of the asphalt road or railway from suitable locations. The accessibility of the location depends on the existence of roads. Therefore, the closer the landfill is to the roads, the lower the costs of building new roads will be.

Visibility The degree of visibility of the location has aesthetic and environmental significance. If the potential landfill is surrounded by vegetation (trees or hedges), observers passing near the landfill will not notice anthropogenic changes within the landscape. The degree of visibility is determined by field research and satellite observation.

All approaches and procedures used for the purpose of this research are presented in the flowchart given in Fig. 3.

Fig. 3 Flowchart of the proposed methodology



GIS analysis

Geospatial technologies based on the use of GIS are highly applicable in the field of environmental science (Durlević et al. 2021; Novkovic et al. 2021; Valjarević et al. 2021; Jangre et al. 2022). Moreover, GIS and geospatial data provide appropriate presentation of results for research in the fields of geography and geochemistry (Gulan et al. 2022). In this study, all input and output data were integrated with GIS software. Digitization of a number of topographic and geological maps, as well as those from Google Earth and Open Street Map, was mandatory for obtaining raster data. Determination of the Euclidean distance and reclassifying criteria into five suitability classes (1—the least suitable, 5—the most suitable) were performed in the QGIS program. After 15 thematic maps were produced in the frame of QGIS via a raster calculator by multiplying weighting coefficients with reclassified layers, a synthesis map of suitability was obtained, eliminating the protected areas. According to the synthesis map, ten sites were distinguished in the GIS. They were converted into vector data with the aim of a better final calculation.

Fuzzy set theory

Fuzzy set theory can solve practical environmental problems and was proposed in 1965 by Zadeh (1965). It offers a simple way to draw precise conclusions from uncertainty, vagueness and inaccuracy. For example, when making the decision to categorize a spatial object on a map as a member, fuzzy logic is included for spatial planning. In classical set theory, an entity is either a part of a set or it is not. Since a feature object can be used with membership values between 0 and 1 by fuzzy set theory, this represents the degree of the membership function.

In this study, fuzzy triangular numbers are used and transformed into crisp numbers that can be used in decision-making. A fuzzy set $\overline{a}$ is defined as a pair (U, m) where U is a set and m is a membership function with a value in the range zero (no full membership) to one (full membership).

A fuzzy number $\overline{a}$ on $\mathbb{R}$ (set of real numbers) is defined as a triangular fuzzy number (TFN) if its membership function $\mu_{\overline{a}}(x) : \mathbb{R} \rightarrow [0, 1]$ is as shown by Eq. (1):

$$\mu_{\overline{a}}(x) = \begin{cases} 0 & x < a, x > c \\ \frac{x-a}{b-a} & a \le x < b \\ \frac{c-x}{c-b}, & b \le x \le c \end{cases}, \quad (1)$$

where a, b, c represent the lower, modal, and upper limit, respectively (Guo and Zhao 2017). The triplet (a, b, c) then represents the TFN. The basic mathematical operators and distance between two TFNs are given by Rahimi et al. (2020). For landfill site mapping, fuzzy set theory makes the definition of a partial location membership considered for multi-class mapping. The fuzzy membership function was used to study spatial variance, and its trend resulted in the creation of fuzzy boundaries for each potential zone.

According to the research conditions and the type of data used, it is necessary that the output of the fuzzy process is converted to crisp numbers that can be used in decision-making. The methods used for this purpose are called defuzzification methods. Equation (2) shows the method of defuzzification used in this study, i.e., the centroid (geometric center) method. The geometric center of the surface below the fuzzy membership function diagram is determined as the definite value of the fuzzy number, as shown by Eq. (2):

$$\overline{A} = \frac{(c-a)+(b-a)}{3} + a \quad (2)$$

where $\overline{A}$ is the final definite number, a is the lower limit, b has the highest membership value and c is the upper limit.

The distance between two triangular fuzzy numbers $\overline{A} = (a, b, c)$ and $\overline{B} = (a', b', c')$ is given by Eq. (3):

$$d\left(\overline{A}, \overline{B}\right) = \sqrt{\frac{1}{3}\left[(a-a')^2 + (b-b')^2 + (c-c')^2\right]} \quad (3)$$

Analytic hierarchy process

The analytic hierarchy process (AHP) is an MCDA method developed to complete a problem by identifying the solution problems, grouping them, and then arranging them into a hierarchical structure (Putra et al. 2018; Kabak et al. 2018; Liang and Yang 2021; Durlević et al. 2022). It can be used to determine criteria weights or priorities and support other MCDA techniques. First of all, there is a need to define the problem and determine the kind of knowledge sought. After that, the decision hierarchy is structured from the top (goal of the decision), through the intermediate (criteria on which subsequent elements depend) and the lowest level (set of the alternatives) (Saaty 1994). The comparison matrices are constructed for each element in the upper level with respect to the level immediately below. The priorities obtained from the comparisons are used to weight the priorities in the level immediately below. This is performed for each element. For each decision variant (for example, for each location), weights along with the criterion values are used to form a single scalar value, which represents the relative strength of the variable. When creating each matrix, the consistency ratio (CR), which determines if the degree of departure is acceptable (<0.1) or not (>0.1), is taken into account. The consistency ratio represents the ratio between the consistency index and the random consistency index. The AHP aims to consider expert knowledge. The AHP can be combined with fuzzy logic approaches to address ambiguity and provide a basis for additional study that relies on the merits of fuzzy membership. Fuzzy upgrading of the AHP was developed to deal with fuzzy hierarchical issues.

The FAHP method is used similarly to the AHP method. The difference is that the FAHP method sets the AHP scale into the fuzzy triangle scale to be accessed primarily. Firstly, all parameters are used to create pairwise comparison matrices. In each case, depending on whichever of the two parameters is more important, linguistic concepts are applied to the pairwise evaluations. The pairwise comparison matrices are of the form given in Eq. (4):

$$\widetilde{A} = \begin{bmatrix} \widetilde{1} & \widetilde{a}_{12} & \dots & \widetilde{a}_{1n} \\ \widetilde{a}_{21} & \widetilde{1} & & \widetilde{a}_{2n} \\ \vdots & & \ddots & \vdots \\ \widetilde{a}_{n1} & \widetilde{a}_{n2} & \dots & \widetilde{1} \end{bmatrix} = \begin{bmatrix} \widetilde{1} & \widetilde{a}_{12} & \dots & \widetilde{a}_{1n} \\ \widetilde{a}_{21}^{-1} & \widetilde{1} & & \widetilde{a}_{2n} \\ \vdots & & \ddots & \vdots \\ \widetilde{a}_{n1}^{-1} & \widetilde{a}_{n2}^{-1} & \dots & \widetilde{1} \end{bmatrix} \quad (4)$$

where $\widetilde{a}_{ij}$ denotes the measure, and if $i = j$ we have $\widetilde{1} = (1, 1, 1)$, while $\widetilde{1}, \widetilde{2}, \widetilde{3}, \widetilde{4}, \widetilde{5}, \widetilde{6}, \widetilde{7}, \widetilde{8}, \widetilde{9}$ measure the importance of criterion i relative to that of criterion j and $\widetilde{1}^{-1}, \widetilde{2}^{-1}, \widetilde{3}^{-1}, \widetilde{4}^{-1}, \widetilde{5}^{-1}, \widetilde{6}^{-1}, \widetilde{7}^{-1}, \widetilde{8}^{-1}, \widetilde{9}^{-1}$ measure the importance of criterion j relative to that of criterion i. The fuzzy conversion scale is described in Mallick et al. (2018): "Stage I Buckley's geometric mean method was used to determine the criterion's fuzzy geometric mean and fuzzy weighting." The value $\widetilde{a_{in}}$ is the fuzzy comparison value of criterion i to criterion n; therefore, $\widetilde{r_i}$ is the geometric mean of the fuzzy comparison value of criterion i to each criterion, $\widetilde{w_i}$ i is the fuzzy weight of the i th criterion, which a TFN can show, and $\widetilde{w}_i = (aw_i, bw_i, cw_i)$. Here aw_i, bw_i, cw_i denote the lower, middle, and upper values of the fuzzy weight of the i th criterion, respectively.

The FAHP is promising as it fixes important limitations on the traditional AHP. In this study, the FAHP was applied to determine the criteria weightings and, based on the GIS, a high-reliability map was generated for the landfill site suitability area.

MULTIMOORA method

The result of the intellectual effort to extend and upgrade the MOORA method, is a three-part MULTIMOORA, which includes the ratio system method, the reference point method and the full multiplicative form method (Hafezalkotob et al. 2019a; Rahimi et al. 2020). The MOORA method aims to simultaneously optimize two or more overlapping qualities or objectives under constraints. MULTIMOORA is not a different algorithm, but it includes three or more methods that control each other and orders the alternatives depending on their performance values.

First, we define a set of alternatives $A = \{a_1, a_2, a_3, \ldots a_m\}$ which we intend to compare with respect to a set of criteria $C = \{c_1, c_2, c_3, \ldots c_n\}$. The first step involves constructing a decision matrix and a weight vector. Thus, for MULTIMOORA, decision matrix $V = (v_{ij})_{m \times n}$ and is composed of the ratings v_{ij} which represent the evaluation value of the i th alternative under the j th criterion for $i = 1,2,\ldots,m$, $j = 1.2,\ldots, n$, and $W = [w_1, \ldots, w_j, \ldots, w_n]$. Since the ratings of alternatives on the multiple criteria of the problem may have different dimensions, the ratings should be normalized before utilization. Normalization is the most robust choice for application in MULTIMOORA. Let $V = (v_{ij})_{m \times n}$ be the decision matrix and v_{ij} be the evaluation value of the ith alternative under the jth criterion for $i = 1,2,\ldots,m$, $j = 1.2,\ldots, n$. Let $V^* = (v^*_{ij})_{m \times n}$ be the standardized decision matrix where v^*_{ij} represents a standardized form of v_{ij}. Therefore, Eq. (5):

$$v^*_{ij} = \frac{v_{ij}}{\sqrt{\sum_{i=1}^{m} v_{ij}^2}} \tag{5}$$

As a fully compensatory model, the ratio system model is useful when "independent" criteria exist in the problem. For cases with the existence of "dependent" criteria, full multiplicative form, as an incompletely compensatory model, is a beneficial tool. As a non-compensatory model, the reference point approach is a "conservative" method compared with the ratio system and full multiplicative form models. Ratio system and full multiplicative form both provide the opportunity to compensate for the poor performance of an alternative in respect of one criterion by the performances in respect of other criteria (the degree of compensation related to the two techniques is not equal). However, the reference point approach does not allow such an opportunity. As "dependent" and "independent" criteria may exist simultaneously in the problem, and for the sake of obtaining a "conservative" result, MULTIMOORA integrates the three methods to exploit the advantages of each of them and reach a final outcome that is more robust than the individual results.

The fuzzy ratio system method Ratio system, which uses the arithmetic weighted aggregation operator, is a fully compensatory model. This means that small normalized values of an alternative could be completely compensated by the same degree of large values. In other words, an alternative with poor performance with respect to some criteria and fine performance with respect to the remaining criteria can be substituted by an alternative with moderate performance for all criteria. To every alternative a_i we assign evaluation value y_i according to the following Eq. (6):

$$y_i = \sum_{j=1}^{g} w_j v^*_{ij} - \sum_{j=g+1}^{n} w_j v^*_{ij} \tag{6}$$

where g and n-g represent the numbers of beneficial and non-beneficial criteria, respectively. Alternatives are then sorted in descending order, where the best alternative is the one with the highest value of y_i, according to Eq. (7):

$$a^*_{RSM} = \{a_i | \max_i y_i\} \tag{7}$$

The fuzzy reference point method In the reference point approach, the best alternative is the one whose worst value in respect of all criteria is not very bad. As a non-compensatory model, this approach first involves finding the alternative ratings with the worst performance with respect to each criterion and then selecting the overall best value (i.e., the minimum value) from the worst ratings. Firstly, the maximal attribute reference point r_j is calculated as defined in Eq. (8):

$$r_j = \begin{cases} \max_i v^*_{ij}, j \le g \\ \min_i v^*_{ij}, j > g. \end{cases} \tag{8}$$

Then, the final rank is determined as follow in Eq. (9):

$$a^*_{RPM} = \left\{a_i | \min_i z_i\right\} \tag{9}$$

where z_i represents the maximal deviation of v^*_{ij} from referece point r_j. Hence, Eq. (10) gives:

$$z_i = \max_j |r_j - v^*_{ij}| \tag{10}$$

The best alternative based on the reference point approach has the minimum utility z_i and the ranking of the approach is produced in ascending order.

The fuzzy full multiplicative form method Full multiplicative form, which uses the geometric weighted aggregation operator, is an incompletely compensatory model. In this technique, small normalized values of an alternative cannot be completely compensated by the same degree of large values. Thus, the issue leads to the conclusion that an alternative with moderate performance may be superior to an alternative with both good and bad performances concerning different criteria. The evaluation value U_i is defined as in Eq. (11):

$$U_i = \frac{\prod_{j=1}^{g} (v_{ij}^*)^{w_j}}{\prod_{j=g+1}^{n} (v_{ij}^*)^{w_j}} \tag{11}$$

where the numerator represents the product of all beneficial values and the denominator represents the product of all non-beneficial values of v_{ij}^*. The best alternative based on full multiplicative form has the maximum utility U_i and the ranking of this technique is generated in descending order, or more formally as in Eq. (12):

$$a_{FMFM}^* = \left\{ a_i | \max_i U_i \right\} \tag{12}$$

After obtaining the subordinate rankings, we need to fuse them in order to obtain the final ranking of alternatives. The most suitable method introduced in literature is the dominance theory method. Using dominance theory and dominance-directed graphs, the outcomes of the three subordinate techniques, i.e., fuzzy ratio system, fuzzy reference point, and fuzzy full multiplicative form, are integrated into the final ranking. The details of the dominance theory are fully discussed in the study of Hafezalkotob et al. (2019b). Dominance-directed graphs, also called tournaments, consider each of three subordinate rankings of MULTIMOORA as a tournament. Each alternative can also be considered a team. In this theory, team a can dominate team b or vice versa, but not both. Vertex matrix M is produced, which shows the relation of dominance among the alternatives for each tournament. In matrix $M = [m_{PQ}]$ of each tournament, if team a dominates team b, m_{PQ} equals 1, or 0. Afterwards, M^2 is computed and then $A = M + M^2$. The row summation of A represents relative preference. The highest value of the row summation shows the best alternative and the lowest value indicates the worst alternative.

Here, the general principle of the MULTIMOORA method has been presented, and has been adapted to a set of triangular fuzzy numbers for the purpose of this paper.

Results

By investigating the importance of 15 criteria and their integration with a GIS and the FAHP method, weighting coefficients were assigned to each factor. Groundwater vulnerability is the most significant condition in this study, while the lowest value was assigned to WEI (Table 3). The daily need for water (drinking water, irrigation of agricultural plots), for a certain percentage of the world's population, is based on the use of underground water. Thus, to minimize the chances of contamination of groundwater, a sanitary landfill needs to be located where the groundwater level is far below the surface.

According to Saaty (1994), the consistency ratio should be less than or equal to 0.1. In this matrix, the consistency ratio (CR) is 0.04, which means that the degree of departure is acceptable. By multiplying the coefficients with the convenience classes, synthetic maps for the potential location of the sanitary landfill were obtained (Fig. 4). The evaluation of the suitability of the territory is given on the first map. In contrast, the territories that were further considered from the perspectives of economic validity and ecological acceptability are shown on the second map. Due to their great ecological importance, protected natural and cultural areas, covering an area of 149.33 km^2, were eliminated from the evaluation. Therefore, the unsuitable category is mostly

Table 3 FAHP and normalized weighting coefficients of the investigated criteria

Data layer	Fuzzy weights	Normalized weights
Groundwater vulnerability	1, 1, 1	0.1127
Distance from urban and rural areas	0.38, 0.63, 1.67	0.1057
Land use	0.37, 0.59, 1.43	0.0994
Geology	0.36, 0.56, 1.25	0.0969
Distance from surface waters	0.33, 0.5, 1	0.0918
Distance from main roads	0.31, 0.45, 0.83	0.0846
Distance from protected and cultural areas	0.29, 0.4, 0.67	0.0771
Soil types	0.29, 0.4, 0.67	0.0688
Slope	0.28, 0.38, 0.63	0.0625
Distance from faults	0.27, 0.36, 0.57	0.0557
Distance from industrial areas	0.25, 0.33, 0.5	0.0475
Distance from the airport	0.24, 0.31, 0.44	0.0388
Aspect	0.22, 0.29, 0.4	0.0299
Rainfall	0.2, 0.25, 0.33	0.0198
Wind Exposition Index (WEI)	0.19, 0.24, 0.31	0.0087
CR = 0.04		

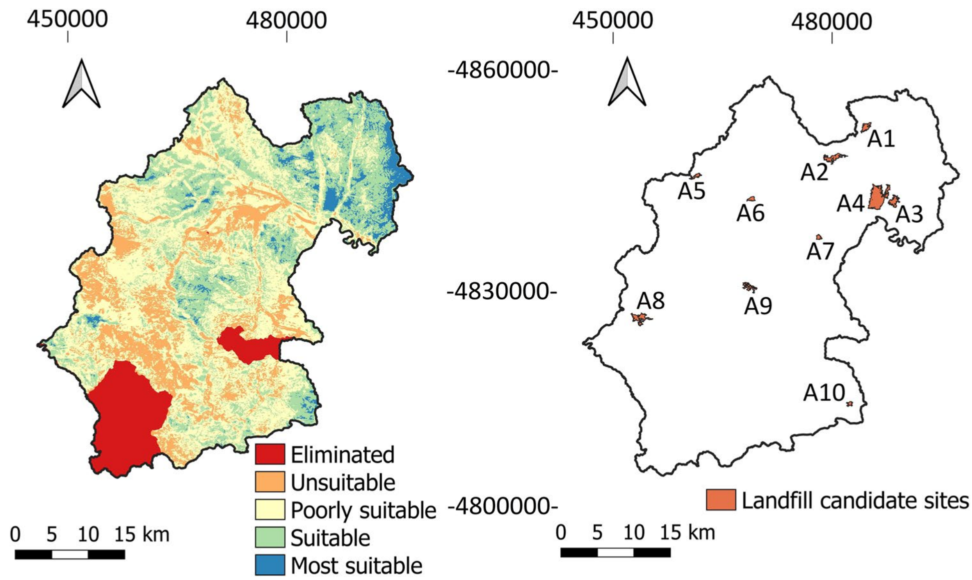


Fig. 4 Synthetic map of suitability and location selection

represented by the central, southern and western parts of the city, covering a total area of 256.33 km^2.

The poorly suitable category is most common in the city of Kraljevo, with coverage of 650.69 km^2. Suitable sites for the construction of the landfill have an area of 398.51 km^2 and mostly include central and north-eastern areas. The most suitable locations comprise an area of 73.04 km^2 and are segmented in different parts of Kraljevo, with an emphasis on the northeastern part.

Based on the visual analysis, ten potential territories on which a sanitary landfill could be built were selected. All relevant locations were subjected to final ranking using the fuzzy MULTIMOORA method. For this purpose, beneficial and non-beneficial criteria were used to select the most suitable space from economic and ecological perspectives. The priority criterion was on-site evaluation. In order to meet the criteria for WD, the landfill's capacity plays an important role. The constancy of the road network will greatly facilitate the work of building and maintaining the landfill. Visibility is of ecological and aesthetic significance, and is much less than the previous criteria. The values of weighting coefficients are as follows: distance from the waste production center, 0.45; landfill capacity, 0.32; road network construction, 0.15; visibility, 0.08. The assignment of numerical values in the scale is based on expert opinion and relevant previous studies related to MCDA for landfill site selection.

The scale for the fuzzy MULTIMOORA method is set in a manner for which increasing the landfill capacity represents a positive process in the procedure, i.e., the larger the area, the better the rating. With other criteria, the situation is the opposite. For example, a longer distance from the waste production center result in more intense road network construction, making it difficult to fit the landfill into the landscape (visibility), and reducing the final place in the ranking (Table 4).

Out of ten existing candidate locations, based on the fuzzy MULTIMOORA ranking, the alternative A4 was rated the most suitable for the sanitary landfill (Table 4).

The threat to groundwater is of a medium degree, which is in this case marked as suitable. Groundwater vulnerability is important in terms of the effects on environmental components, such as soil, surface and groundwater pollution. For these reasons, groundwater results represent the point on which spatial planning should be based at the local and regional level. Geologically, this area lies on shale and clay, and it was assessed as the most suitable area from a geological perspective. Clay minerals can absorb all or parts of the hazardous materials present in leaked leachate. This ability restricts the migration of contaminants into groundwater (Harun et al. 2013; Negahdar and Nikghalbpour 2020). These sediments are more effective at filtering out contaminants, not only because they are impermeable, but because chemicals can bind to their particle surfaces and thus allow partial renovation of leachate through various processes. Clays in these deposits have a large cationic-exchange capacity and low permeability, since they can block the filtering of leachate that could contaminate the aquifer system. In addition, clay traps and captures heavy metals that are otherwise difficult to neutralize (Israde-Alcantara et al. 2005). These lithological properties make them generally the most suitable areas for landfill. The remains of the waste can be used for agricultural purposes. In addition, the land-use predisposition can improve relations between waste and agricultural lands (Tsangas et al. 2020). Balkan countries typically share similarities in culture and history. However, this specific region has received little academic attention and produced fewer scholarly deals in respect of the green

Table 4 Fuzzy MULTIMOORA matrix and ranking

PLL	Beneficial and non-beneficial criteria values with fuzzy algorithm				MULTIMOORA Ranking			
	DWPC (km) (-)	LC (ha) (+)	RNC (m) (-)	V (-)	FRS	FRPA	FFMF	FRFM
A1	18, 18, 18	89, 89, 89	4, 5, 6	3, 4, 5	8	9	7	8
A2	17, 17, 17	147, 147, 147	3, 4, 5	1, 2, 3	5	3	5	5
A3	11, 11, 11	116, 116, 116	3, 4, 5	2, 3, 4	4	4	4	4
A4	8, 8, 8	569, 569, 569	3, 4, 5	3, 4, 5	1	1	1	1
A5	13, 13, 13	47, 47, 47	4, 5, 6	4, 5, 6	7	6	8	7
A6	4, 4, 4	40, 40, 40	3, 4, 5	3, 4, 5	2	7	2	2
A7	4, 4, 4	33, 33, 33	3, 4, 5	4, 5, 6	3	8	3	3
A8	46, 46, 46	162, 162, 162	5, 6, 7	1, 2, 3	9	2	9	9
A9	13, 13, 13	86, 86, 86	5, 6, 7	1, 2, 3	6	5	6	6
A10	66, 66, 66	30, 30, 30	4, 5, 6	1, 2, 3	10	10	10	10

PLL - potential landfill location, *DWPC* - distance from the waste production center, *LC* - landfill capacity, *RNC* - road network construction, *V* - visibility, *FRS* - fuzzy ratio system, *FRPA* - fuzzy reference point approach, *FFMF* - fuzzy full multiplicative form, *FRFM* - final ranking of fuzzy MULTIMOORA

economy. The green economy, especially in countries such as Serbia, Bosnia and Herzegovina and North Macedonia, is strongly connected to the new strategy of waste management (Licastro and Sergi 2021). When it comes to soil types, the location is dominated by leptosol and vertisol. Vertisol is not suitable for the construction of a sanitary landfill due to its significant agroecological potential. Agricultural crops such as sunflower, sugar beet, cotton, etc. thrive on this type of land. In this case, preference is given to soil of the leptosol type, because atmospheric precipitation cannot seep into the depth through the impermeable horizon, which includes clay. Due to this structure and texture, agricultural productivity is very low. The slope of the terrain in most of the A4 territory is less than 8°, which can be defined as convenient. This result is important for environmental and technical reasons. In the context of ecology, flat terrains are characterized by a lower intensity of erosion; thus, the process of soil erosion will be significantly milder compared to steep terrains. From the technical–technological aspect, due to the increase in the slope of the terrain, there is an increase in the cost of excavation of the landfill and construction of access roads.

As for the level of insolation of the terrain, all classes of exposure are represented. Although the level of insolation is not essential for the construction and sustainability of a sanitary landfill, it is recommended that the landfill should be built on land facing east and west in order to minimize the risk of potential fires or accumulation of drain water. From the climatological aspect, alternative A4 is located on the leeward side (values < 1), which means that entry of harmful gases in the city can be avoided. At the same time, the annual amount of precipitation is less than 900 mm. The very weak influence of wind provides an advantage to the location, because unpleasant odors will not spread to the surrounding settlements. A smaller amount of precipitation will not cause contamination of the surface of the land. More than 80% of the territory is far enough from the fault (> 1 km), thus reducing the impact of geophysical factors to the minimum. In addition, most of the location is more than 450 m away from surface watercourses, providing a safe zone between the landfill and nearby rivers and streams. This area meets the requirements in terms of distance from protected natural and cultural sites. The location of A4 is more than 4 km away from the nearest protected natural asset (Stari Hrast in the Godačica settlement). It is about 3.5 km away from the nearest cultural monument (Church of St. Nicholas in Vrba).

The purpose of the land in this area is diverse, with alternating forests, agricultural land, grass and shrubby vegetation. Areas with low vegetation are considered suitable areas, but neglected agricultural plots can also be taken into account. To build a landfill, the least valuable land is favored.

Due to the very large area of the location (569 ha), the value of the distance from the settlement varies. In the location itself there are hamlets comprising several houses and cottages. The distance from the center of A4 to the nearest rural settlements (Vitanovac and Čukojevac) is about 2 km. Within this area, it is important to find a territory that would meet the requirements of the social community and avoid harmful effects on the population. The distance between A4 and the main road that connects the surrounding settlements with the urban zone is 753 m. There are paved roads inside the site, so the cost of building new, access roads would be very low. The distance between the nearest industrial zone and the landfill location is 8.42 km; this is a safe zone that reduces the risk of accidents. In addition, any impact of the landfill on air traffic will be eliminated, since the site's distance from the airport is about 20 km.

In addition to environmental criteria and socio-economic factors, site A4 meets the needs of the cost–benefit analysis. Due to the large favorable area, field research can determine the micro-location that will serve as a sanitary landfill. For example, the regional sanitary landfill "Duboko" in western Serbia covers an area of about 15 ha and receives municipal waste produced by 370,000 inhabitants. Given that the city of Kraljevo has about 125,000 inhabitants, there are infrastructural conditions for several neighboring municipalities to dispose of their MSW in this area, which would obtain regional significance. In terms of urban centers, the potential location is ideal, since it is 8 km away from the urban zone of Kraljevo, and about 16 km from the center of the neighboring municipality of Vrnjačka Banja. There are already paved roads in this area, so the connection of the road network is at a satisfactory level. Regarding the visibility and integration of the location into the landscape, the area around the landfill is accessible and susceptible to forming a forest "buffer zone" that would aesthetically mitigate the changes that would occur during the construction of the landfill.

Discussion

The importance of the AHP method in the selection of a location for municipal waste disposal has been recognized in the last century. By application of the GIS and AHP methods, Siddiqui et al. (1996) determined hydrogeological criteria and the purpose of the land in Cleveland County, Oklahoma, appointing the highest significance to terrain slope. In Greece, Kontos et al. (2003) used the AHP and ten criteria, ascribing equal importance to environmental and socio-economic factors. Land cover was indicated as the most important sub-criterion in this case. Taking into consideration other models of spatial distribution, Delgado et al. (2008) investigated siting a potential landfill in Mexico by application of three models: Boolean logic, binary evidence and overlapping index. The soil thickness (depth) and geological fractures deserve the highest importance. Within the last decade, there has been an increase in research that integrates MCDA models to enable suitable waste disposal sites to be selected. Gorsevski et al. (2012) combined AHP and ordered weighted average (OWA) techniques in North Macedonia. According to the evaluation of 12 criteria, the highest importance was given to hydrogeological conditions. In Vietnam, Wang et al. (2018) included the fuzzy analysis network process (FANP) and the technique for order of preference by similarity to ideal solution (TOPSIS) for solid waste to energy plant location selection, considering the influence on the ecological environment as the most important criterion. The ANP, similarly to the AHP, uses complex interrelationships among decision levels. ANP evaluates all the relationships by considering all interactions, interdependences and feedback in a decision-making problem. Although the application of TOPSIS methods allows the most suitable alternative location to be selected, the problem of evaluating weighting criteria remains.

Within the last few years, in addition to integrated approaches in location selection, attention has been given to describing and evaluating distinct and selected sites. Implementing the fuzzy group BWM-MULTIMOORA-GIS methods, Rahimi et al. (2020) evaluated and identified 11 selected locations. The environmental factor displayed a significantly higher coefficient than the social and economic factors. The benefit of the BWM application is the increasing consistency and uniformity using multi-objective mathematical programming (Yazdi et al. 2020). There are several reasons why the MULTIMOORA method is increasingly implemented in studies: simple mathematics, low computational time, using three different methods for determining subordinate rankings, straightforwardness for decision-makers and employing ranking aggregation tools for integrating the subordinate rankings (Hafezalkotob et al. 2019a). Torkayesh et al. (2021) developed a hybrid model combining BWM and measurement of alternatives and ranking according to compromise solution (MARCOS) in landfill location selection for healthcare waste. Defining the relationship between alternative and reference values (ideal and anti-ideal alternatives) was made possible by applying the MARCOS method. Based on clearly defined relationships, the utility functions of alternatives were determined, and a compromise ranking was made in relation to ideal and anti-ideal solutions (Stević and Brković 2020). In their study, eight alternatives were ranked, based on 16 sub-criteria.

In the case of the city of Kraljevo, the FAHP-MULTIMOORA method was used in analyzing complex decision-making processes. AHP is an efficient and flexible model for quantifying many criteria and alternatives. Conversely, the MULTIMOORA method handles the integrative outcome by combining three utility values, employing a ranking aggregation tool. Using these methods, fuzzy logic achieves diminished subjectivity, i.e., it excludes classic binary logic during construction of the decision matrix.

The results of this research are consistent with previous studies dealing with identifying suitable locations for sanitary landfills. In the case of the city of Kraljevo, a total of 19 criteria were used, which are considered to play a significant role in the selection of the location from ecological, socio-economic and technical perspectives. The study of an adequate site for a sanitary landfill based on the FAHP-MULTIMOORA method has theoretical and practical advantages:

1) A simple mathematical calculation enables obtaining and analyzing results in a brief period.

2) Many criteria have been applied, which have been proven to play a role in evaluating the most suitable location. The final map with a spatial resolution of 25 m obtained by processing high-resolution data provides a realistic representation of appropriate sites for a sanitary landfill.
3) Unlike many MCDA models, the MULTIMOORA method generates an integrative outcome by combining the results of the three ranking methods.
4) According to the results, the FAHP-MULTIMOORA approach provides an opportunity for decision-makers to solve the problems of waste disposal in the local community based on scientific methods.
5) The applied integrated FAHP-MULTIMOORA model can be used for many other environmental activities and challenges (analysis of suitable locations for agricultural production and convenient locations for the installation of renewable energy sources) in territories with similar geographical and socio-economic conditions.

The latest research on finding a suitable location for sanitary waste disposal sites includes the application of artificial intelligence, i.e., machine learning. Mohsin et al. (2022) combined the FAHP with machine learning models and concluded that FAHP-RF is more accurate than FAHP-SVM. Future research in respect of sanitary landfills in Serbia, as well as in the rest of the world, should combine MCDA with fuzzy logic and machine learning models, especially random forest.

There are other methods for waste disposal next to a landfill site, and the best option for waste reduction is to utilize a combination of several methods, such as incineration, waste compaction, biogas generation, composting and vermicomposting. Incineration is a controlled waste burning process, with the potential to use the heat produced for generating electric power. However, due to greenhouse gas emissions, some experts believe that this process is not ecologically applicable. Waste compaction is applied for materials such as cans and plastic bottles, whereas biodegradation is applied for animal and organic industrial waste. Organic domestic waste could be treated by composting and vermicomposting processes. The latter method is, due to the use of worms to decompose organic matter, more efficient than traditional composting. Sanitary disposal should be used only for storage of waste that contains materials or tools that should not be reused or recycled.

Conclusion

Sustainable municipal WM represents a complex challenge for modern society and requires an organized and coordinated set of different activities. Thus, identifying adequate locations for sanitary landfill construction is one of the most important factors in terms of the sustainable development of the area. Because the current location of the sanitary landfill has a negative influence on the environment, it was necessary to perform a scientific investigation of new locations. The construction of sanitary landfills is a safe way to deal with municipal waste. Thus, this study was based on the application of MCDA and a GIS to obtain the optimal view of suitable locations in the territory of the city of Kraljevo. Due to population growth and urbanization processes, the amount of solid waste is increasing every day. According to expert opinion, available literature and data, for the assessment of suitability, 15 environmental and socio-economic criteria were considered and evaluated. Weighting coefficients and synthesis maps were evaluated using the FAHP method, and 73 km^2 of surface area was determined to be very suitable for sanitary landfill construction. Through visual analysis, 10 locations were marked as suitable. Following the Saaty scale, when forming matrices, a consistency ratio lower than 0.1 was acceptable. By applying the fuzzy MULTIMOORA method, four criteria with technical, economic and aesthetic significance were considered. Unlike many approaches in MCDA that have one assessment index, fuzzy MULTIMOORA generates an integrative outcome, by combining the results of three ranking methods with fuzzy logic (Rahimi et al. 2020). According to the estimated data and the obtained results, location A4 was rated as the most appropriate for a potential landfill due to its large area (569 ha), vicinity of the urban zone (8 km), and satisfactory distance from settlements, natural and cultural areas. It is important to emphasize that this location is only about 16 km from Vrnjačka Banja. Thus, the problem of municipal WM in this region can be solved. Before building a landfill, it is necessary to perform detailed field research and prepare an environmental impact assessment study. The proposed methodology may be useful to environmental scientists, urban institutes, and emergency management officers. The results obtained in this study may serve as an effective solution for decision-makers and the local community for sustainable WM. The given results could serve as a reference for future experts, to confirm the validity of data obtained by GIS, utilizing field research. Limitations of the current study relate to the methodological framework. Although experts made decisions regarding selection criteria and locations in respect of waste management and the environment, assigning weighting coefficients for the AHP and MULTIMOORA is subjective. This research can be applied to all other locations in Serbia and regions where the problem of WD is present, because all the essential criteria were analyzed. Furthermore, an integrated method such as FAHP-MULTIMOORA based on a GIS is very precise in determining the most suitable locations. The results of the study contribute to the local community and can serve as guidelines for all other local governments that dispose of municipal waste inadequately. This research could be useful for the government of the Republic of Serbia in establishing a new strategy for better waste management.

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Author contribution Uroš Durlević contributed to the conception, design of the study, and the first draft of the manuscript. Material preparation, data collection, and analysis were performed by Ivan Novković, Ivana Carević, and Luka Stojanović. The methodology in the study was performed by Dragana Valjarević and Aleksa Marjanović. Visualization of the study was performed by Natalija Batoćanin and Filip Krstić. Review and editing was performed by Aleksandar Valjarević. All authors read and approved the final manuscript.

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Declarations

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