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ORIGINAL PAPER

GIS application for landfill site selection: a case study in Pančevo, Serbia

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Abstract Landfill site selection is a complex process because it requires knowledge about a large number of criteria, parameters, and regulations. The aim of this study was to describe a methodology for landfill site selection and relevant criteria from a geological engineering point of view. To determine landfill suitability in the municipality of Pančevo, Serbia, we used the geographic information system (GIS) and analytical hierarchical method (AHP). Seven criteria and eighteen subcriteria are discussed, compared, and evaluated. The final map was obtained by overlaying and is reclassified into four classes: unsuitable, poorly suitable, moderately suitable, and most suitable. The results obtained show that 62.31 % of locations are unsuitable, 13.49 % are poorly suitable, 12.08 % are moderately suitable, and 12.12 % are most suitable. The analysis revealed geological engineering criteria as the most important, followed by hydrogeological and hydrological criteria. Geomorphological criteria were the least important.

Keywords Landfill · Site selection · GIS · AHP · ILWIS · Serbia

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Introduction

Landfill site selection is a difficult process because it requires knowledge about many criteria, parameters, and regulations (Kontos et al. 2005; Alavi et al. 2013). The aim is to find the best location that will minimize hazards to the environment (Kontos et al. 2005). Selection of the disposal site is probably the most important step in the development of solid waste management (Yilmaz and Atamaca 2006).

Modern methodology of landfill site selection involves use of the Geographic Information System (GIS), which enables spatial data display and facilitates the selection process. Employing GIS for choice of site involves finding locations that satisfy a set of criteria (Bonham-Carter 1994). Many authors have already used GIS and multicriteria methods for site selection (Malczewski 1999; Dai et al. 2001; Kolat et al. 2006; Sener et al. 2006, 2011; Simsek et al. 2006; Ersoy and Bulut 2009; Sharifi et al. 2009; Nas et al. 2010; Kara and Doratli 2012; Zelenović et al. 2012; Alavi et al. 2013). The most frequently used multicriteria method is the analytical hierarchical method (AHP). Siddiqui et al. (1996) were among the first to employ GIS with AHP for landfill site selection in Oklahoma and presented the spatial-AHP method. Many examples of this were subsequently described (Dai et al. 2001; Kontos et al. 2003; Kolat et al. 2006; Sener et al. 2006, 2011; Guiqin et al. 2009; Zelenović et al. 2012; Alavi et al. 2013). GIS integrated with AHP is a powerful tool because GIS provides manipulation and presentation of the data and AHP supplies consistent ranking (Sener et al. 2006; Alavi et al. 2013).

The assumption that any site can be engineered for a landfill still commonly prevails, with the consequence that locations unsuitable from a geological/hydrogeological standpoint are often developed on the premise that the landfill liner provides sufficient protection to the environment (Allen et al. 2003). Furthermore, there is uncertainty as to the long-term durability of geomembrane liners, because landfill liners may be subject to severe deterioration over long time-scales due to the corrosive effects of leachate together with elevated temperatures generated by exothermic processes operating within landfills (Allen 2001; Allen et al. 2003). Yildrim (1997) points out that geological engineering studies and applications play a major role in the selection of locations for storage of municipal waste. It is therefore imperative to seek out and develop sites for landfills with natural characteristics, which can provide secondary protection to the environment in the event of failure of the landfill liner (Allen et al. 2003). In site selection, geology plays a determining role (Yilmaz and Atamaca 2006). Particularly high standards are required for long-term functioning of the geological barrier. The geological barrier is the naturally occurring rock immediately below the landfill, extending some distance into the surrounding area, which, due to its properties and extent, can substantially hinder the spread of contaminants (Dorhofer and Siebert 1998). The assessment of geological barriers at disposal sites is essential (Langer 1998).

The most common method of waste management in Serbia is disposal. According to the Waste statistic and management in Republic of Serbia (2008–2010), waste is dumped in unsanitary landfills that are located in inappropriate places (Statistical Office of the Republic of Serbia 2012). Data for waste quantities in Serbia are incomplete. Records exist only in some municipalities for the last few years and only for dumps used by public companies. The average daily amount of municipal solid waste (MSW) per citizen is 0.99 kg, with an average yearly mass of 0.36 t per person (Statistical Office of the Republic of Serbia 2012).

Until recently, landfill sites in Serbia were located on municipal land. Prior geological engineering investigations were usually not carried out, with subsequent deformation of the landfill and the surrounding terrain (Knežević 1984). Site selection was performed recently for a regional landfill in Srem county (Zelenović et al. 2012).

This paper describes GIS methodology for landfill site selection from the geological engineering point of view. Few reports by geologists have dealt with this problem (Yildrim 1997; Dorhofer and Siebert 1998; Simsek et al. 2006; Yilmaz and Atamaca 2006; Ersoy and Bulut 2009). Our aim is to show the importance of geological engineering criteria and their crucial role. As a case study, we have selected the municipality of Pančevo. We used ILWIS 3.7.2 (Integrated Land and Water Information System), a free open-source remote sensing and GIS software.

Materials and methods

To define criteria we used data from geological, hydrogeological, and geological engineering maps (scale 1:100,000). All maps were scanned and then digitized. Digitization and site selection were performed using ILWIS 3.7.2 (with integrated AHP).

A digital elevation model (DEM) was produced from the digitized contour lines of 1:25000 topographic maps (Fig. 3). To compare different maps, standardization was necessary, i.e., transformation of different units (distance, age etc.) in the input map to the same values for all. Standardization was different among maps, where factors are identified and for constraint. Values between 0 (unsuitable) and 1 (suitable) are obtained from standardized maps. We prepared a database with 18 digitized and 18 standardized maps. The standardized maps were used as input for landfill site selection. All maps were converted to raster maps.

All criteria were divided into two main groups: geo criteria and other criteria (Fig. 2). Geo criteria included geomorphological (land slope), hydrogeological and hydrological (groundwater depth, soil permeability, flooding), engineering-geological (lithology, stability, bearing capacity, construction material). Other criteria included environmental (distance from water supply, thermo-mineral spring, rivers and channels, protected areas, gas and oil pipelines), economic (distance from roads and railways), social (distance from settlements, airport, cultural sites), and climate (aspect). All criteria were evaluated by AHP. Each criterion was given a number indicating its importance in comparison to the others. In ILWIS a textual description of each number is used.

Study area

The municipality of Pančevo is situated in northern Serbia (Vojvodina), in the county of South Banat (Fig. 1). The study area is about 755 km^2. The rivers Danube and Tamis form its south and west borders. They are typical lowland rivers with many tributaries, meanders, old streams, and backwaters. The study area is also intersected by the Danube-Tisa-Danube network channel system and belongs to the Danube and Black Sea catchment.

According to the Republic Hydrometeorological Service of Serbia, the examined area has a moderate continental climate with an average annual temperature of 11.3 °C. January, the coldest month, has an average temperature of −1.4 °C, while that for July, the warmest month is

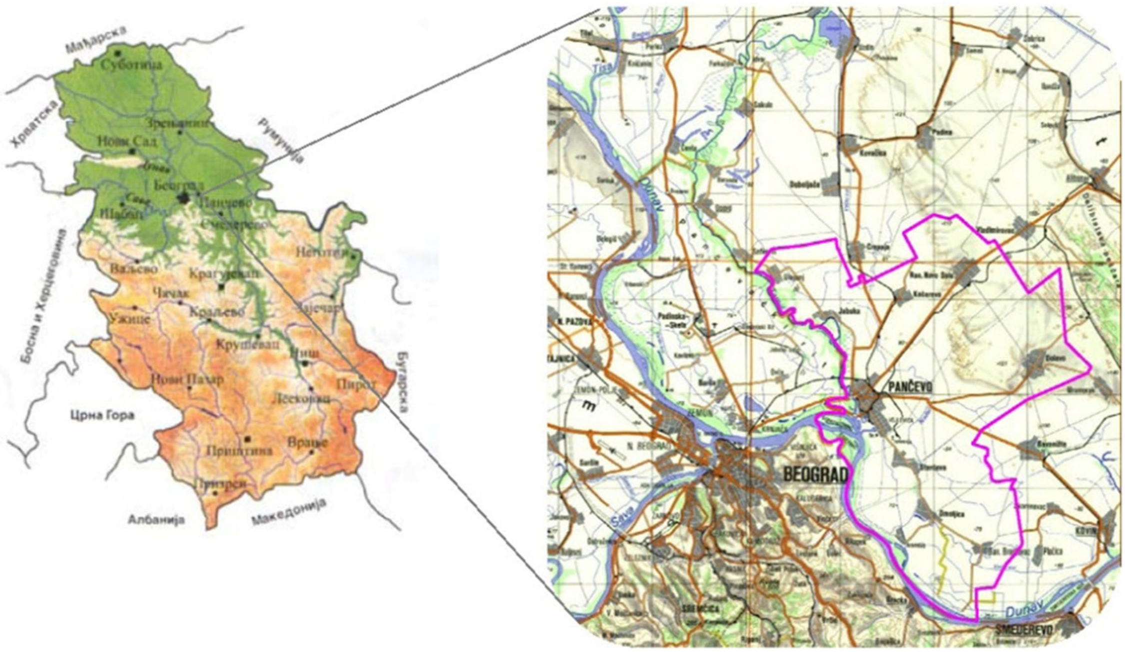


Fig. 1 Location of the study area

20–22 °C. Mean annual rainfall is 643 mm. June is the wettest month with 12–13 % of the total annual rainfall, and October the driest with an average 5–6 % of the total rainfall.

The study area is lowland terrain, geomorphologically distinguished by two types of relief: alluvial and eolian. The alluvial plains of the Danube and Tamis rivers have elevations of 68–75 m. Most of the study area is built from eolian sediments consisting of two units: loess plateau and loess terraces. A large number of shallow depressions characterizes the loess plateau. Loess terraces are flat areas intersected by shallow valleys of surface water. There are two loess sections: lower terraces between 70–80 m and higher ones between 93–98 m. Both sections are about 5 m in height.

Geologically, the study area is covered with Quaternary sediments of the Pleistocene and Holocene age and 25–50 m thickness. Quaternary sediments are alluvial, eolian, diluvial, and swamp. Eolian sediments are directed NW-SE and are represented by loess, loessic clay, and sandy loess. Loess thickness is up to 50 m and loess with intact structure can reach 15 m thickness. Surface loess porosity is up to 40 %. Loess is a sensitive soil deposit. In the dry and undisturbed state, its shear strength is high. With increase in moisture content (due to penetration of leachate), loess is prone to collapse. The neogene sediments underlying the Quaternary sediments have a maximal thickness of about 500 m. The bedrock consists of crystalline schists.

Tectonically, the study area is part of the Banat depression, which is relatively inactive seismically. Based on available seismotectonic information, the geologic fault is considered relatively inactive and there are no active faults in the study area. The assumed fault in the NNW direction coincides with the direction of the Danube.

According to historic data three earthquakes have been registered, which give the basic characteristics of seismic activity. The major epicenters were Svilajnac and Lazarevac in Serbia and Vranca in Bulgaria. Svilajnac (magnitude $M = 6.3$ in 1893) is 82.5 km away and Lazarevac ($M = 6.0$ in 1922) is 55 km away, while Vranca ($M = 7.2$ in 1977) is 520 km from the study area. In addition, there were more than 220 earthquakes of magnitude $M > 3.5$ over a period of 239 years or 183 earthquakes of magnitude $M > 3.5$ over 78 years within a 100-km radius from Pančevo. Seismic risk analysis shows that the study area has a potential seismic intensity of 7° MCS scale for the returning period of 100 years and 8° MCS for 500 years with a 63 % probability of occurrence.

Analytical hierarchy process

Saaty's AHP is a widely accepted multicriteria method (Dai et al. 2001; Kontos et al. 2003; Kara and Doratli 2012; Ersoy et al. 2013). This mathematical procedure

Table 1 Fundamental scale for comparison

Intensity of importance	Description
1	Equal importance
3	Moderate importance of one factor over another
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values
1/2, 1/3, …, 1/9	Reciprocals values

decomposes the complex decision into simpler problems. At the top of the hierarchy are goals, followed by criteria, subcriteria, and alternatives at the lowest level (Sener et al. 2006). The AHP divides problems for decision into understandable parts, each of which is analyzed separately and integrated in a logical manner (Alavi et al. 2013). Determination of criteria/subcriteria weight is achieved using a matrix in which all elements are mutually compared. AHP enables a comparison of criteria and alternatives to evaluate individual elements of the hierarchy and then determine the weight of each criterion, using a matrix in which all elements are compared with each other. Each criterion in comparison with another is assigned a number, which represents an estimate of its worth or how many times that element is more important or dominant over the one with which it is compared.

Derivation of the comparison criteria and subcriteria presented in this report and their calculated weight is shown in Table 1.

To reduce the influence of subjectivity and possibility of inconsistencies, Saaty defined the consistency ratio (CR) as follows:

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI}$$

CI—consistency index, RI—average resulting consistency index, depends on matrix order.

Consistency index CI expressed as:

$$\mathrm{CI} = (\lambda_{\max} - n)/(n - 1)$$

$\lambda_{\max}$—largest or principal eigenvalue of the matrix; n—matrix order.

A $\mathrm{CR} \geq 0.1$ requires revision of the judgments in the matrix, identifies reasons for inconsistencies and repeats the process of comparing (Dai et al. 2001). If the CR is < 0.1, the judgments are deemed trustworthy (Marinoni 2004; Coyle 2004; Saaty 2008).

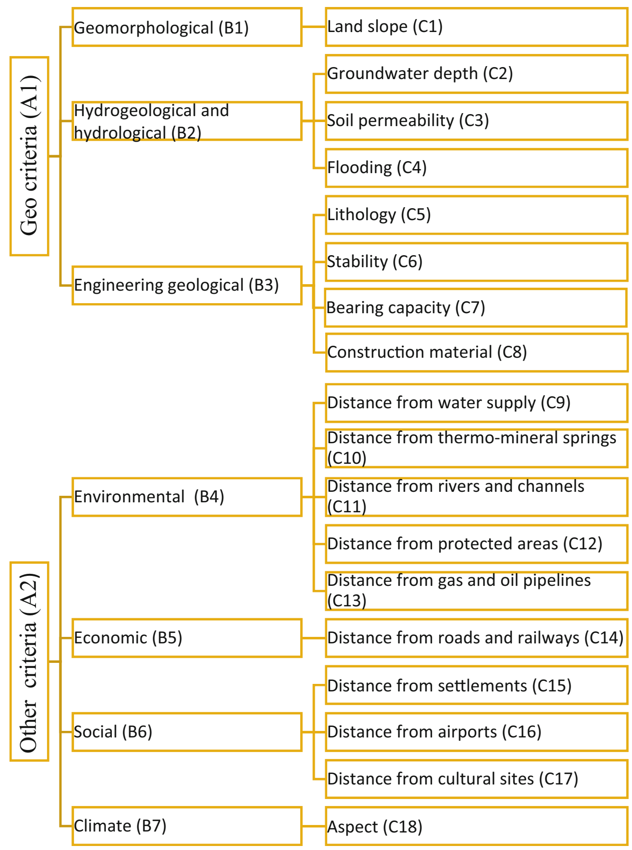


Fig. 2 Hierarchy model for landfill suitability

Criteria description

The main criteria for our study area were divided into two groups: geo and other criteria. Geomorphological, hydrogeological and hydrological and geological engineering criteria fell within the geo group, while environmental, economic, social, and climatic criteria belonged to the other group (Fig. 2).

Standardized maps were evaluated by AHP. Criteria defined as constraints were omitted from the evaluation because they are considered as unacceptable for landfill. Scores are given in Table 2 and weights in Tables 3, 4, 5, 6, 7, 8, 9, and 10.

Land slope

Slope is important because it affects the ease of engineering construction and susceptibility to land sliding (Dai et al. 2001; Kolat et al. 2006; Sumathi et al. 2008). Our slope map (%) was obtained from the digital elevation model (DEM) generated from digitized contour lines. The DEM was in the Transverse Mercator projection system,

Table 2 Standardization criteria and buffer zones

Subcriteria	Buffer zones	Values
Land slope (C1)	0–2	0
	2–10	1
	>10 %	0.5
Groundwater depth (C2)	<3	0
	3–7	0.25
	7–10	0.5
	>10 m	1.0
Soil permeability (C3)	High permeability	0
	Medium permeability	1
Flooding (C4)	Floodplain	0
	Non-floodplain	1
Lithology (C5)	Pa; (P,PG)a; PRPa; PGb	0
	l, lp, PGd	0.5
	PRGld	1
Stability (C6)	l, lp	0
	PGd	0.5
	Pa; (P,PG)a; PGb; PRPap; PRGld	1
Bearing capacity (C7)	PGb	0
	l, lp, PRGld, PGd	0.5
	Pa, (P,PG)a, PRPap	1
Construction material (C8)	PRPap; Pa; (P,PG)a	0
	l, lp	0.5
	PRGld, PGb, PGd	1
Distance from water supply (C9)	<500	0
	>2000 m	1
Distance from thermo-mineral springs (C10)	<500	0
	>2000 m	1
Distance from rivers and channels (C11)	<500	0
	>500 m	1
Distance from protected areas (C12)	<500	0
	>500 m	1
Distance from gas and oil pipelines (C13)	<500	0
	>500 m	1
Distance from roads and railways (C14)	<100	0
	>100 m	1
Distance from settlements (C15)	<500	0
	>2000 m	1
Distance from airports (C16)	<1500 m	0
	>1500 m	1
Distance from cultural sites (C17)	<500	0
	>500 m	1
Aspect (C18)	Flat areas	0
	SE, NW	0.25
	N, W, E, S, SW	0.5
	NE	1

Pa sand, alluvial; *(P,PG)a* sand and sandy clay, alluvial; *PRPap* silty sand, facies inundations; *PGb* sandy clay, swamp; *PGd* sandy clay, diluvial; *l* loess; *lp* sandy loess; *PRGld* loessic clay

Table 3 Pairwise comparison matrix (A1–A2)

Landfill suitability	A1	A2	W
A1	1	3	0.750
A2	1/3	1	0.250

CR = 0; *A1* GEO criteria; *A2* other criteria

Table 4 Pairwise comparison matrix (B1–B3)

A1	B1	B2	B3	W
B1	1	1/7	1/9	0.055
B2	7	1	1/3	0.290
B3	9	3	1	0.655

CR = 0.067; *A1* GEO criteria; *B1* geomorphological; *B2* hydrogeological and hydrological; *B3* engineering geological

Table 5 Pairwise comparison matrix (B4–B7)

A2	B4	B5	B6	B7	W
B4	1	7	3	5	0.565
B5	1/7	1	1/5	1/3	0.055
B6	1/3	5	1	3	0.262
B7	1/5	3	1/3	1	0.118

CR = 0.041, *A2* other criteria, *B4* environmental, *B5* economic, *B6* social, *B7* climate

Table 6 Pairwise comparison matrix (C2–C4)

B2	C2	C3	C4	W
C2	1	5	7	0.731
C3	1/5	1	3	0.188
C4	1/7	1/3	1	0.081

CR = 0.05; *B1* hydrogeological and hydrological, *C2* groundwater depth, *C3* soil permeability, *C4* flooding

Table 7 Pairwise comparison matrix (C5–C8)

B3	C5	C6	C7	C8	W
C5	1	3	5	7	0.551
C6	1/3	1	3	7	0.274
C7	1/5	1/3	1	5	0.131
C8	1/7	1/7	1/5	1	0.044

CR = 0.086; *B3* engineering-geological, *C5* lithology, *C6* stability, *C7* bearing capacity, *C8* construction material

Table 8 Pairwise comparison matrix (C9–C12)

B4	C9	C10	C12	W
C9	1	3	5	0.714
C10	1/3	1	1	0.143
C12	1/5	1	1	0.143

CR = 0; *B4* environmental, *C9* distance from water supply, *C10* distance from thermo-mineral springs, *C12* distance from protected areas

Table 9 Pairwise comparison matrix (C15–C17)

B6	C15	C17	W
C15	1	5	0.833
C17	1/5	1	0.167

CR = 0; *B6* social, *C15* distance from settlements, *C17* distance from cultural sites

ellipsoid Bessel 1941, datum Hermannskogel, and georeferenced with pixel size 25 × 25 m (Fig. 3).

Flat relief and small height differences characterize the study area. Therefore, three classes were allocated (Fig. 4). The highest grade (1) was assigned to the areas with 2–10 % slope. Areas steeper than 10 % were assigned a grade of 0.5, while areas with <2 % slope were given the smallest grade (0).

Groundwater depth

The depth to the groundwater table is important because it minimizes the risk of contamination (Simsek et al. 2006). According to Serbian regulations, the landfill site must have a depth of more than 2 m to the groundwater table to prevent the possibility of contamination. The hydro isobaths map was used for this criterion. The study area is characterized by high groundwater except in the northeast

Table 10 Criteria group, criteria, subcriteria, and their weight

Criteria group	Criteria	Subcriteria	Weight
GEO criteria (A1)			0.750
	Geomorphological (B1)		0.055
		Land slope (C1)	1.0
	Hydrogeological and hydrological (B2)		0.290
		Groundwater depth (C2)	0.731
		Soil permeability (C3)	0.188
		Flooding (C4)	0.081
	Engineering-geological (B3)		0.655
		Lithology (C5)	0.551
		Stability (C6)	0.274
		Bearing capacity (C7)	0.131
		Construction material (C8)	0.044
Other criteria (A2)			0.250
	Environmental (B4)		0.565
		Distance from water supply (C9)	0.714
		Distance from thermo-mineral springs (C10)	0.143
		Distance from rivers and channels (C11)	Constraint
		Distance from protected areas (C12)	0.143
		Distance from gas and oil pipelines (C13)	Constraint
	Economic (B5)		0.055
		Distance from roads and railways (C14)	1.0
	Social (B6)		0.262
		Distance from settlements (C15)	0.833
		Distance from airports (C16)	Constraint
		Distance from cultural sites (C17)	0.167
	Climate (B7)		0.118
		Aspect (C18)	1.0

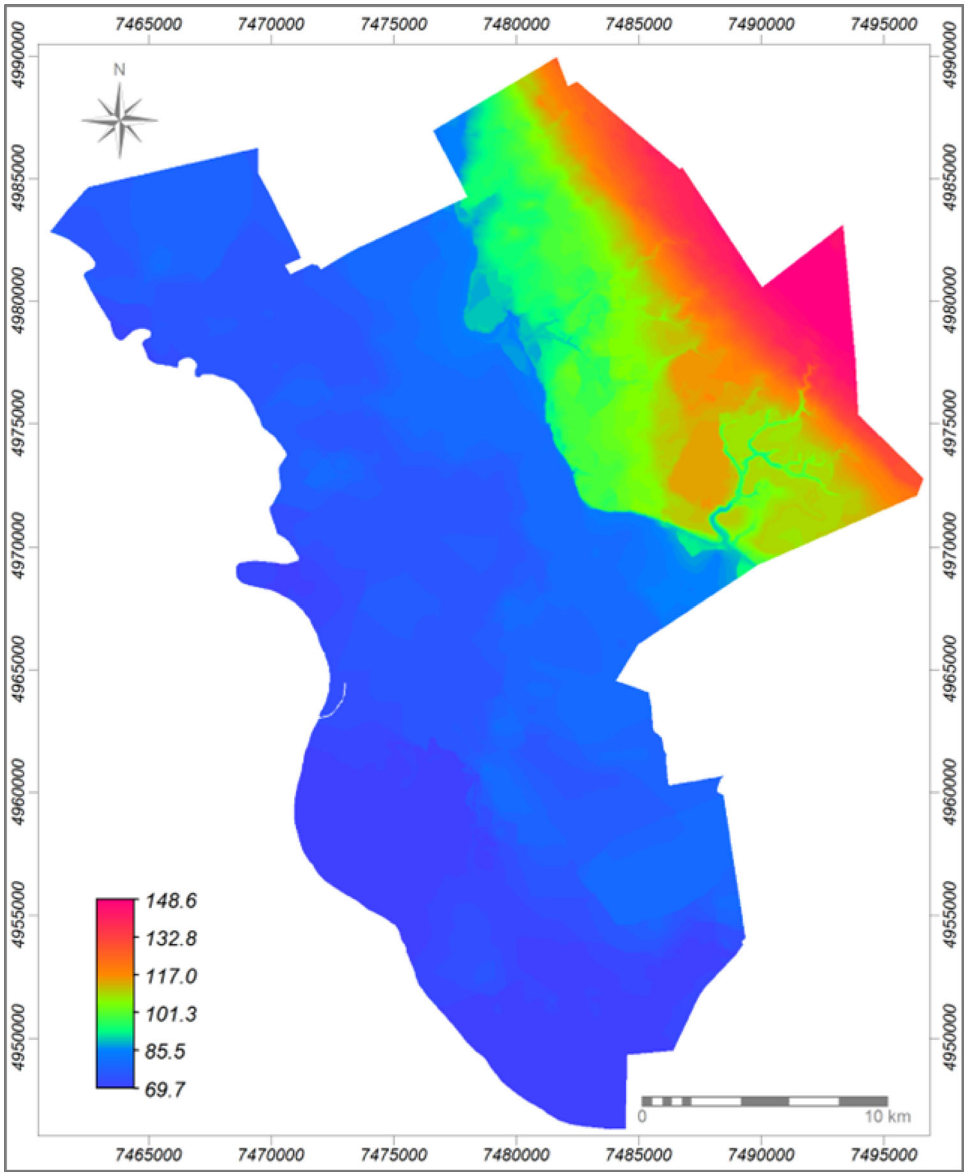


Fig. 3 Digital elevation model of study area

where depths are over 7 or 10 m. Groundwater depth in the study area was divided into four classes (Fig. 5). Depths <3 m were given the score of 0. Those from 3 to 7 m were scored 0.25, between 7–10 m scored 0.5, and 1.0 was given to depths >10 m.

Soil permeability

The landfill site should be in impermeable soil so that in the case of liner failure the possibility of contamination will be minimal (Kontos et al. 2003, 2005; Simsek et al. 2006). The classification parameter was the coefficient of permeability. Geological units with permeability $k_f < 1 \times 10^{-7}$ m/s are considered impermeable (Kontos et al. 2005, Simsek et al. 2006). These units (layers) almost prevent any downward movement of pollutants and their infiltration into groundwater (Simsek et al. 2006). In our case, two classes were allocated according to soil permeability: permeable, with a coefficient of permeability k_f $<10^{-5}$ m/sec and moderately impermeable where $k_f = 10^{-5}–10^{-7}$ m/sec (Fig. 6). Impermeable layers were scored as 0, while moderately impermeable ones were scored as 1.

Flooding

Flooding is determined in relation to surface water (Fig. 7). The absolute maximum recorded for the Danube in

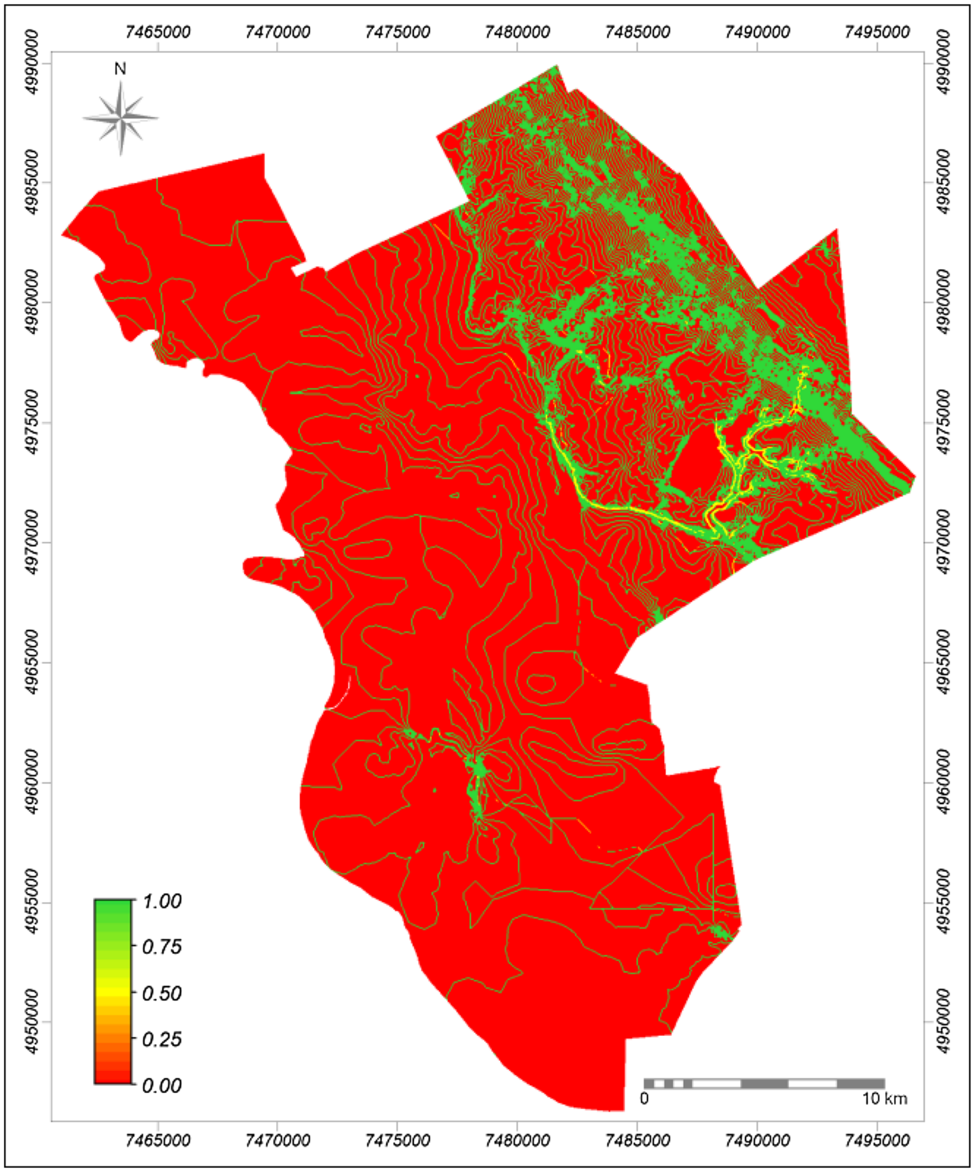


Fig. 4 Standardized map of land slope

Pančevo was 754 cm (altitude 74.87 m). The absolute minimum altitude was 66.03 m. Along the Danube banks artificial levees about 76 m in height protect the surrounding area from flooding but this is possible near the banks by the artificial levees. Flooding of the river Tamis area can occur at the maximum water level of the Danube. In our study area, two classes were allocated: the flooding area around the rivers Danube and Tamis were scored as 0 and the others were scored as 1.

Lithology

Lithology, stratification, and their spatial relationships are important for predicting the movement of leachate. Suitable locations should have relatively simple lithology so that the possibility of contamination can be measured reliably (Čanak 1990). Only cohesive, argillaceous rocks have favorable properties as a geological barrier, while sand, gravel, and heavily fractured sandstone or limestone cannot regarded as barrier rocks (Dorhofer and Siebert 1998). The engineering geological map was used for defining these criteria. The study area is built of Quaternary sediments: alluvial, eolian, diluvial, and swamp. Lithologically, sand of different varieties (silty, clayey) and silt (sandy) predominate with small amounts of clay sediments. The eight lithological units in the study area were divided into three classes (Fig. 8). The score 0 was given to sand (Pa), sand and sandy clay (P,PGa), silty sand (PRPap) and

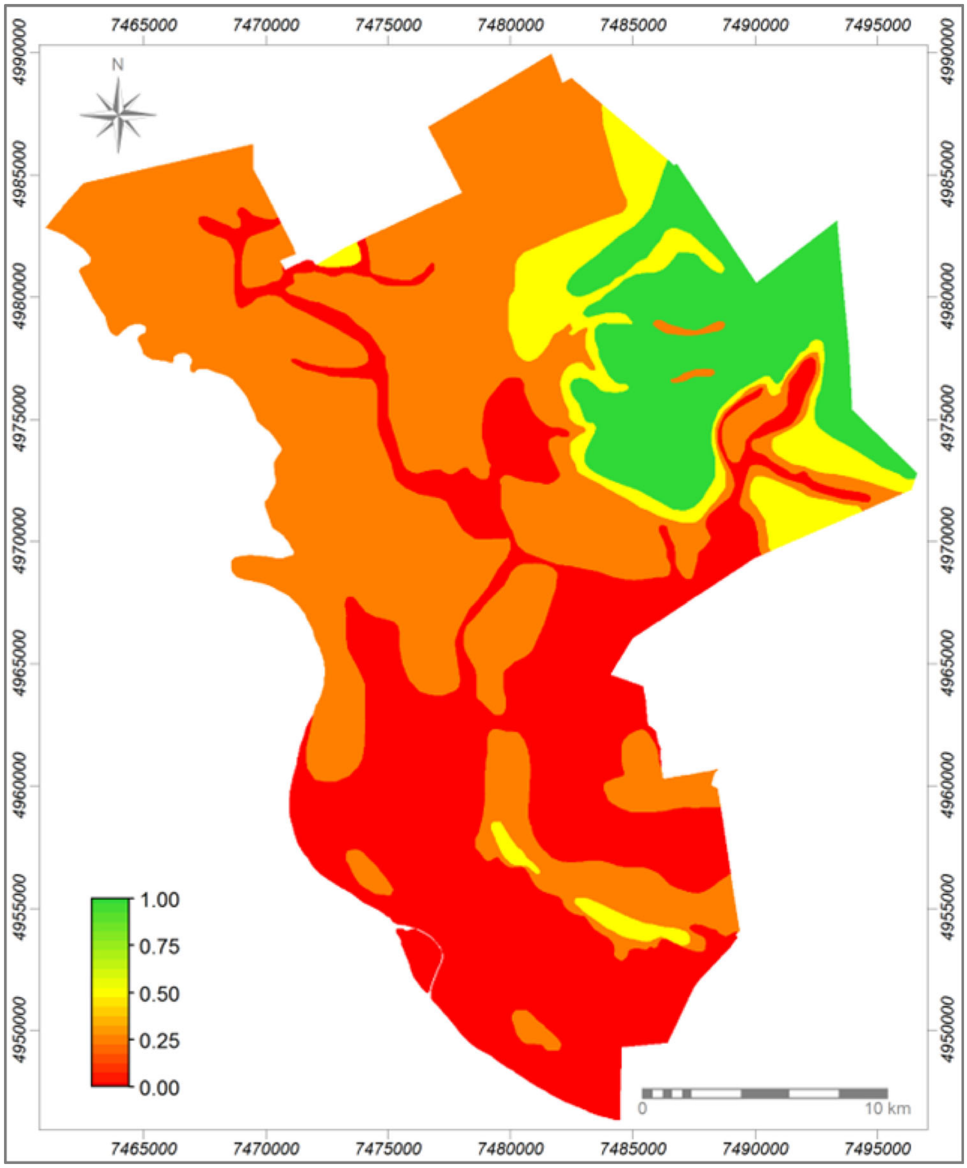


Fig. 5 Standardized map of groundwater depth

swamp, and sandy clay (PGb). Loess (l), sandy loess (lp), and sandy clay (PGd) was scored 0.5. The highest score was assigned to loessic clay (PRGld).

Stability

For a landfill, a critical concern is long-term soil stability. Site location in a stable area is imperative for preventing the failure of landfill liners and protecting surface and groundwater from contamination (Dai et al. 2001). Landfills are required to remain stable over long periods without constant repair (Dorhofer and Siebert 1998). No landslides have been registered in the study area. However, part of it is built from loess, so an interesting aspect is declining stability due to increasing moisture content. Three classes were allocated according soil stability (Fig. 9). Loess (l) is unstable and was graded as 0. Sandy clay diluvial (PGd) was given a score of 0.5. Sand (Pa), sand and sandy clay (P,PGa), sandy clay (PGb), silty sand (PRPap), and loessic clay (PRGld) received the highest score (1).

Bearing capacity

Landfills are particularly sensitive in terms of soil parameters. The soil should have the necessary bearing capacity, which should be known (Ersoy et al. 2013). Langer (1998) and Bagchi (2004) considered it within

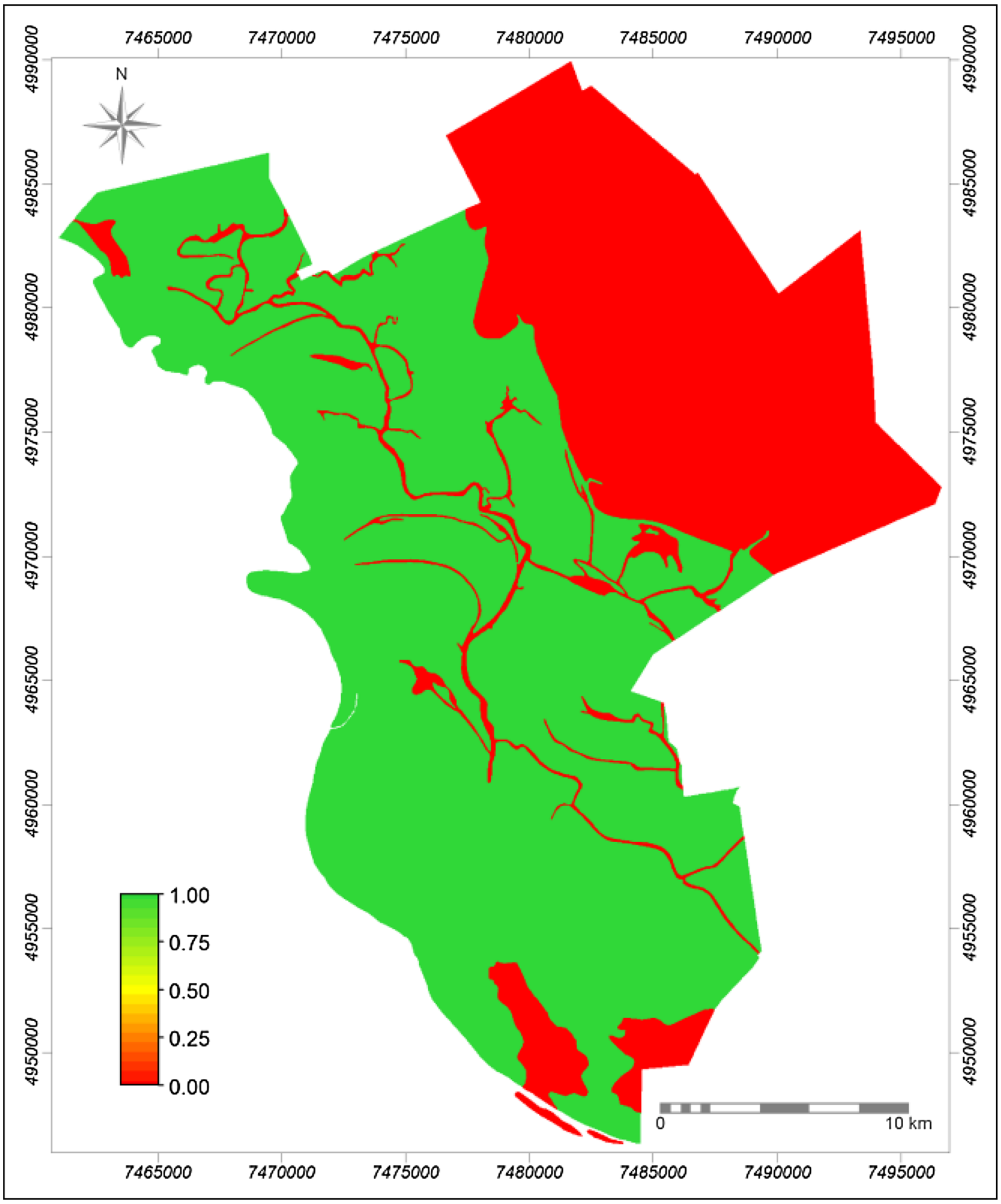


Fig. 6 Standardized map of soil permeability

stability. However, this criterion is usually omitted from the site selection because it is considered that the burden of waste is much less than the object. Landfill construction involves making liners, drainage layers, supporting facilities, roads, etc. Therefore, it is a very important criterion from the geological engineering point of view. Three classes were formed according to bearing capacity (Fig. 10). Sandy clay (PGb) was given a score of 0. Sandy loess (lp), loess (l), loessic clay (PRGld) and sandy clay, diluvial, (PGd) received a score of 0.5. Sand (Pa), sand and sandy clay (P, PGa), and silty sand (PRPap) were graded as 1.

Availability of construction material

To provide material for the liner, daily, and final cover it is necessary to for borrow from pits near the landfill site (Čanak 1990; Kayabali 1996). The role of the landfill cover is twofold. It prevents penetration of surface water and thus reduces the amount of leachate generated at the landfill. It also controls the movement of leachate and gas in the landfill (Sener 2004). Three classes were allocated according to availability of construction material (Fig. 11). Loessic clay (PRGld) and sandy clay, diluvial, and swamp (PGd, PGb) received a score of 1. Silty sand (PRPap), sand

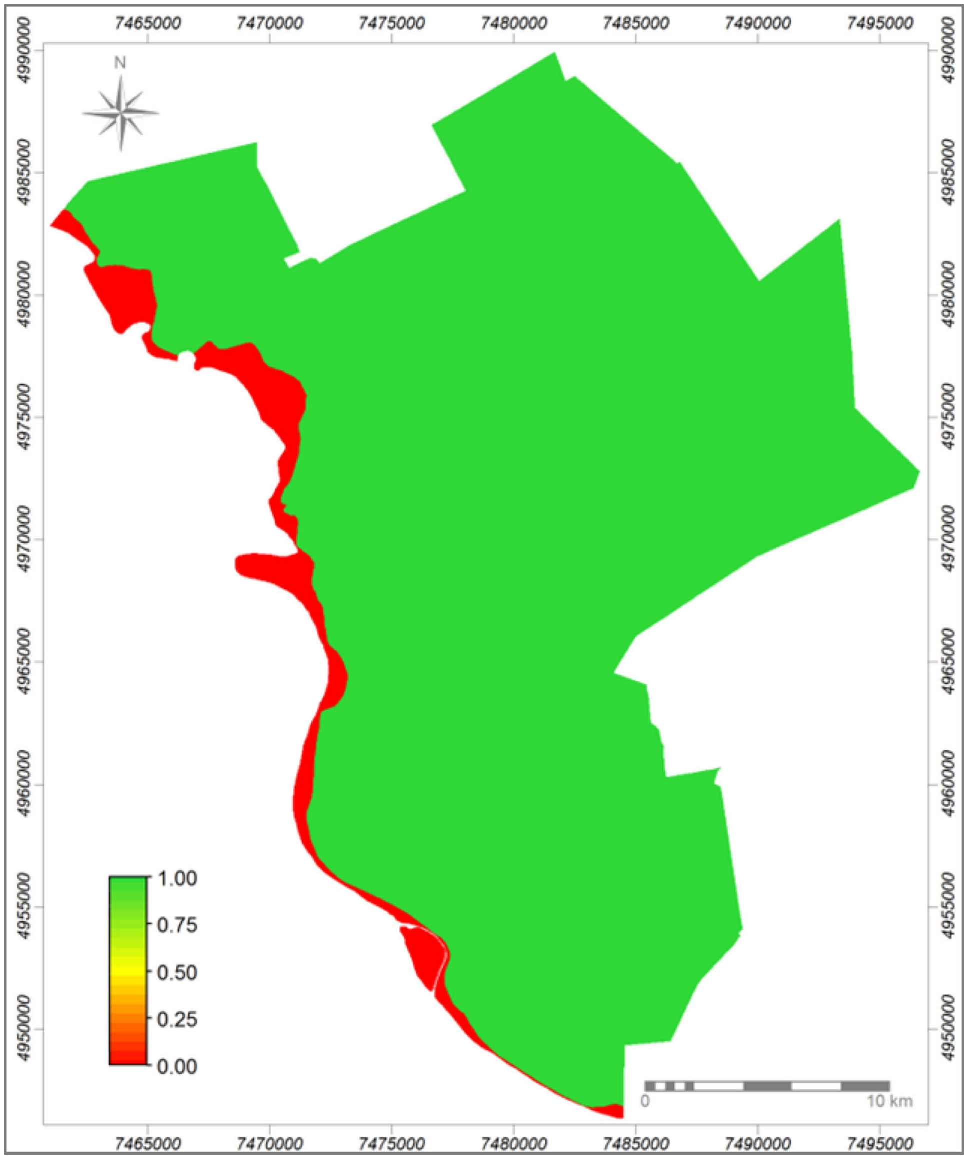


Fig. 7 Standardized map of flooding

(Pa), and sand and sandy clay (P,PGa) were assigned a score of 0. Loess (l) and sandy loess (lp) were graded as 0.5.

Distance from water supply

According to Serbian regulations a landfill cannot be located in a water supply protected area. For Pančevo's water supply, these zones have immediate, narrower, wider, and belt protection (Matić et al. 2005). A distance of 500 m from the external borders of the protection zone is taken as the minimum. Three classes were allocated in the study area according to distance from the water supply zone (Fig. 12). A distance <500 m was given the score of 0. A distance >2000 m was scored as 1. Distances between 500–2000 m received an intermediate grade.

Distance from thermo-mineral springs

There is a thermo-mineral spring in the study area (Omoljica) that is not subject to organized exploitation. The local population uses the water as a small spa. According to Serbian regulations, a landfill cannot be located in the protected area around a spring of thermo-

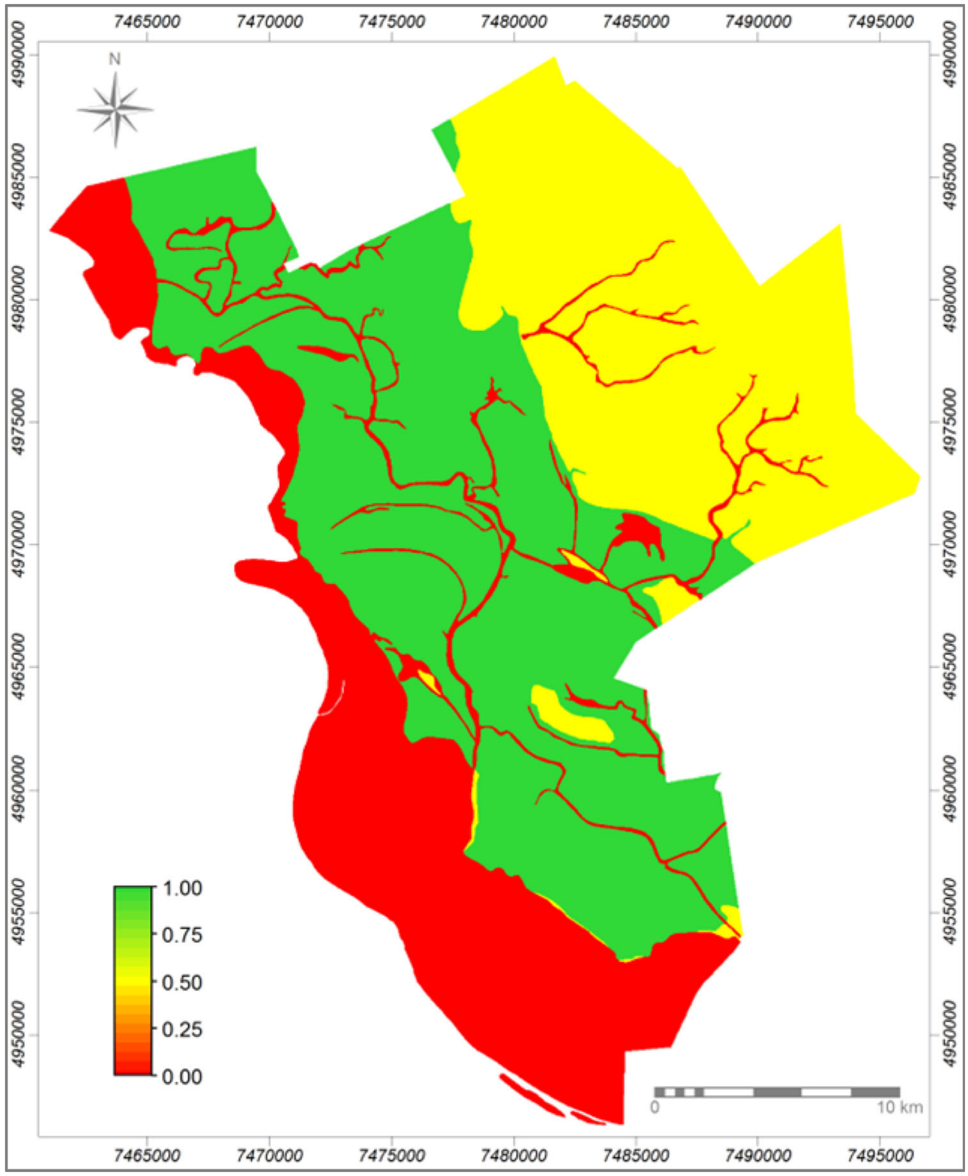


Fig. 8 Standardized map of lithology

mineral water. No protection zone for Omoljica thermo-mineral spring has been defined but the distance of 500 m from the spring is taken as the minimum (Fig. 13).

Distance from rivers and channels

Landfills cannot be located on river or channel banks. The effect of this criterion greatly depends on the lithology. Thus, for example, in very cracked limestone with numerous and interconnected splits the width of this zone is crucial in preventing pollution. The distance of 500 m from river or channel banks is taken as the minimum (Kontos et al. 2005; Sharifi et al. 2009; Zelenović et al. 2012; Yildrim 2012). Two classes were formed in the study area (Fig. 14). Distances <500 m were scored as 0 and those >500 m were given a score of 1.

Distance from protected areas

The Nature Park Ponjavica, placed in the third class of protected areas by local regulations or fifth category-protected land/sea landscapes (www.pancevo.rs) is situated within the study area. Taking the distance of 500 m from the protected area as the minimum (Kontos et al. 2005;

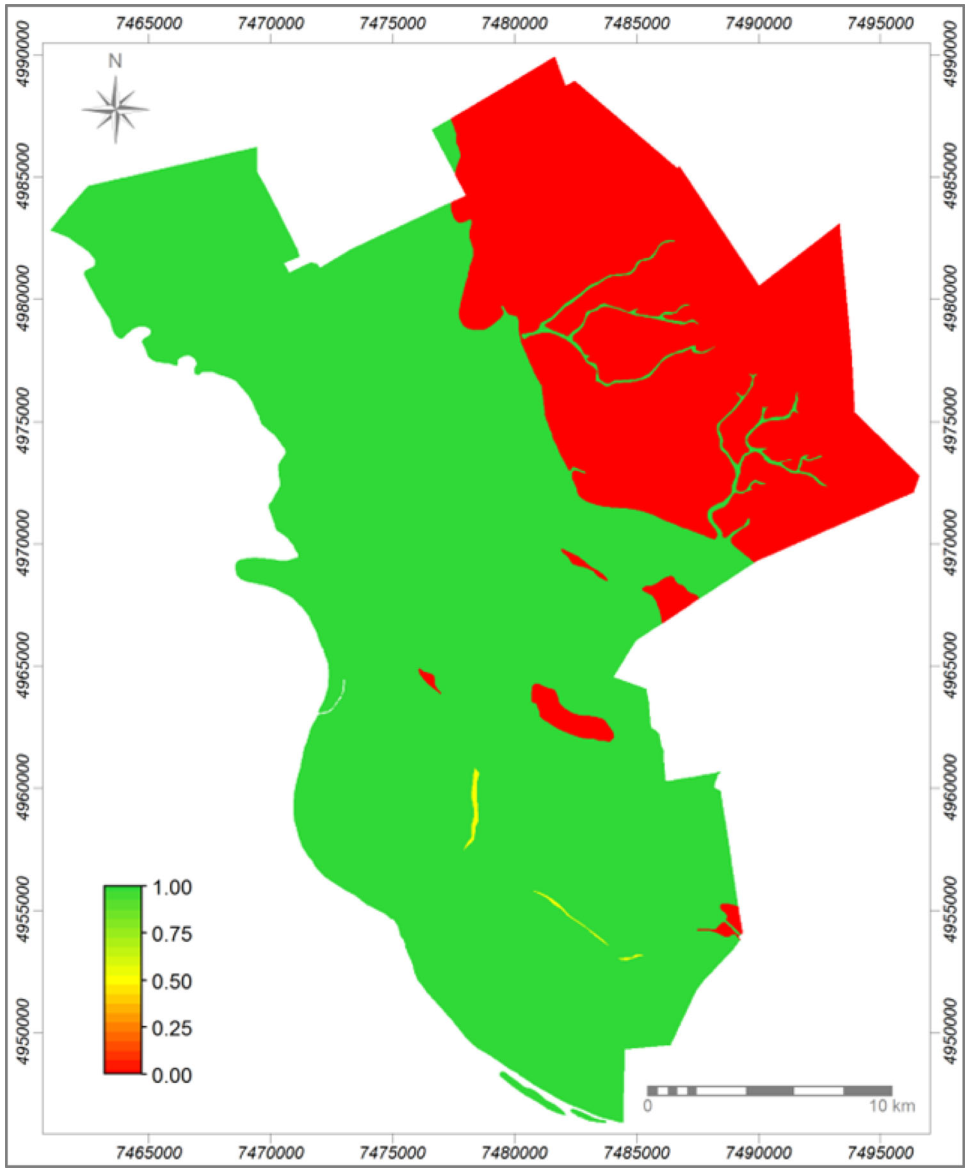


Fig. 9 Standardized map of stability

Zelenović et al. 2012; Yildrim 2012), two classes were allocated to the study area (Fig. 15). Distances <500 m were assigned a score of 0 and those >500 m were scored as 1.

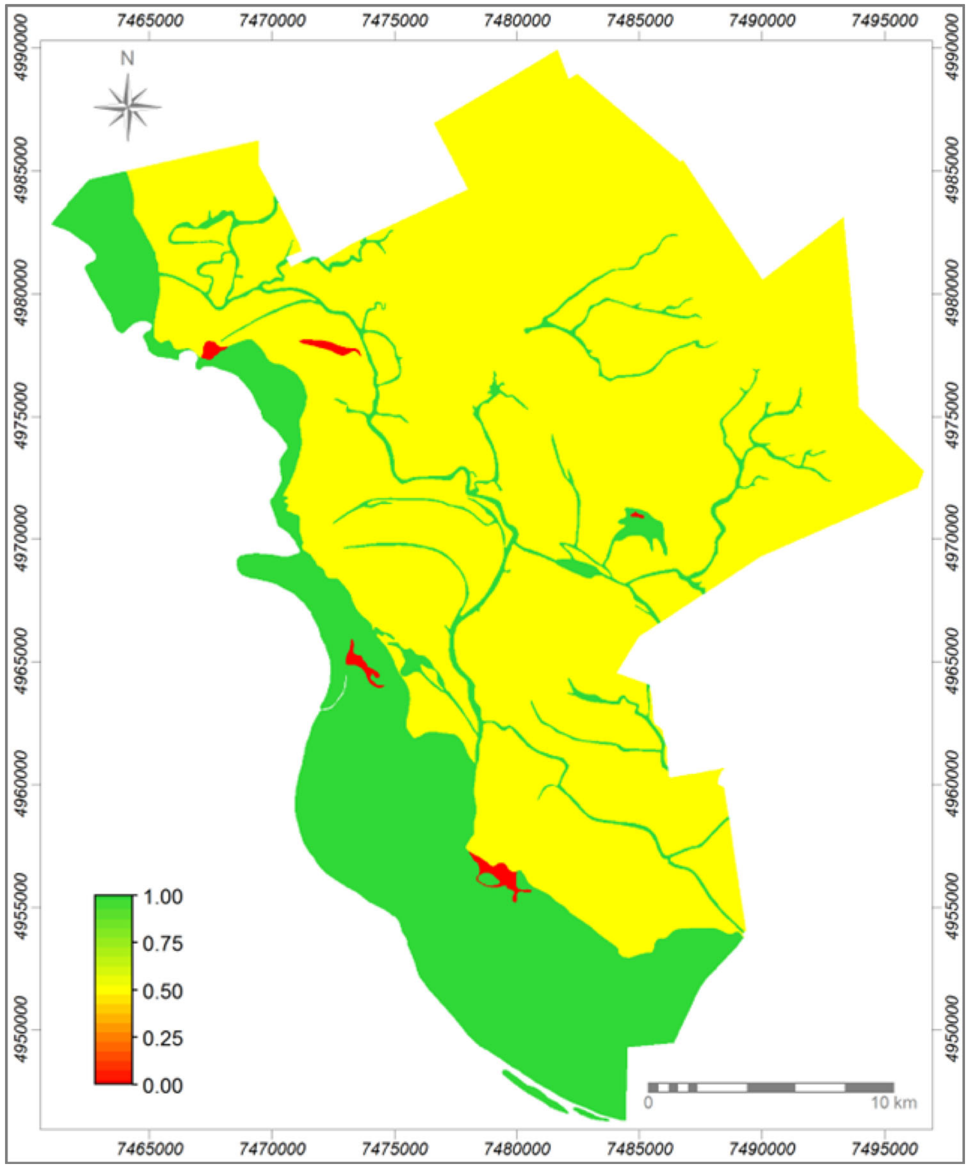
Distance from gas and oil pipelines

Landfills should not be located on gas and oil pipeline routes. In the event of damage, pipeline explosions may be carried to methane generated at the landfill from decomposition of garbage (Jahić 1980). The recent case of a gas pipeline explosion (March 2013) during construction of a highway embankment near Belgrade shows the importance of this criterion. Two classes were formed in the study area (Fig. 16). Distances <500 m were graded as 0 and those >500 m received a score of 1.

Distance from roads and railways

According to Serbian regulations, landfills cannot be located in protective zones around roads, the width of which depends on the road category. The distance of 100 m was adopted as the minimum (Čanak 1990; Sener 2004; Sener et al. 2011). Two classes according to the distance

Fig. 10 Standardized map of bearing capacity



from roads and railways were formed for our study area (Fig. 17). Distances <100 m were scored as 0 while those >100 m were given the score of 1.

Distance from settlements

According to the regulations of the Republic of Serbia the distance between the outer border of the landfill and the nearest object-populated areas must not be less than 500 m. The accepted minimum distance from the outer border of settlements is 500 m, so three classes were allocated (Fig. 18). Distances <500 m were given the score of 0 while those >2000 m were scored as 1. Distances between 500–2000 m received an intermediate score.

Distance from airports

Among landfill phenomena are flocks of birds that pose a risk to aviation safety. Therefore, landfills must be located an appropriate distance from airports. Near Pančevo city there is an airport used for sporting and commercial purposes (Fig. 19). A radius of 1500 m from airports is accepted as the zone in which landfills cannot be located (Čanak 1990; Siddiqui et al. 1996). Two classes were

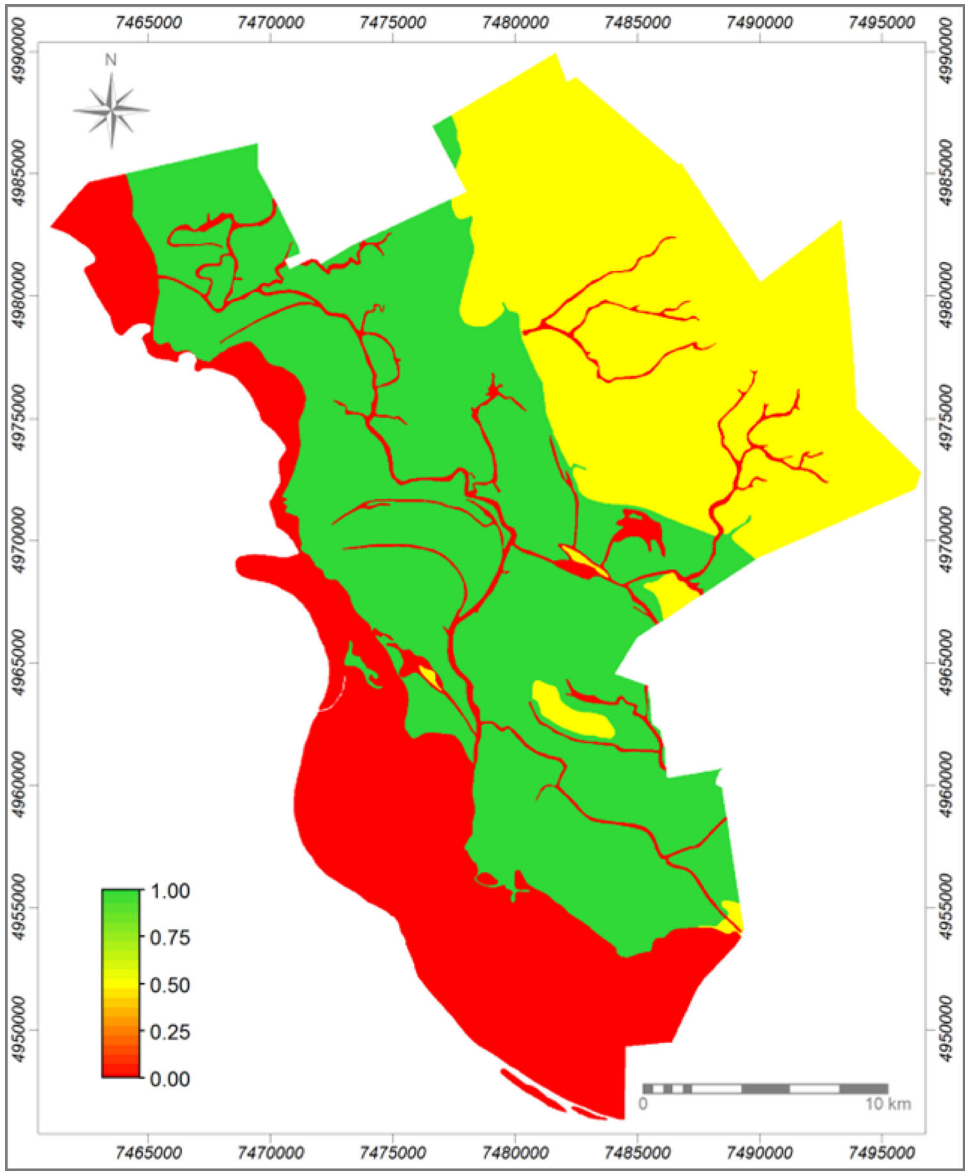


Fig. 11 Standardized map of construction material

formed according to distance from the airport. Distances <1500 m were given the score of 0, while those >1500 m received the score of 1.

Distance from cultural sites

In addition to archaeological sites in the municipality (Starčevo, Ivanovo), there are many monuments, buildings, and churches under protection in the study area. Serbian regulations define that landfills cannot be located within 500 m from cultural sites. Two classes were allocated according to distance from such sites (Fig. 20). Distances <500 m were graded 0 and those >500 m were scored 1.

Aspect

Landfills should not be exposed to wind or if this is not possible, it should be placed in the opposite direction to the most frequent wind. Four classes were allocated in the study area, according to wind frequency (Fig. 21). The most frequent winds are southeasterly and northwesterly and they were given the score of 0.25. The lowest frequency northeast wind was given the highest rating. Northern, western, southern, and southwestern winds have slightly lower frequencies and were scored 0.5. Flat areas are exposed to winds from all sides and they were given the lowest score zero.

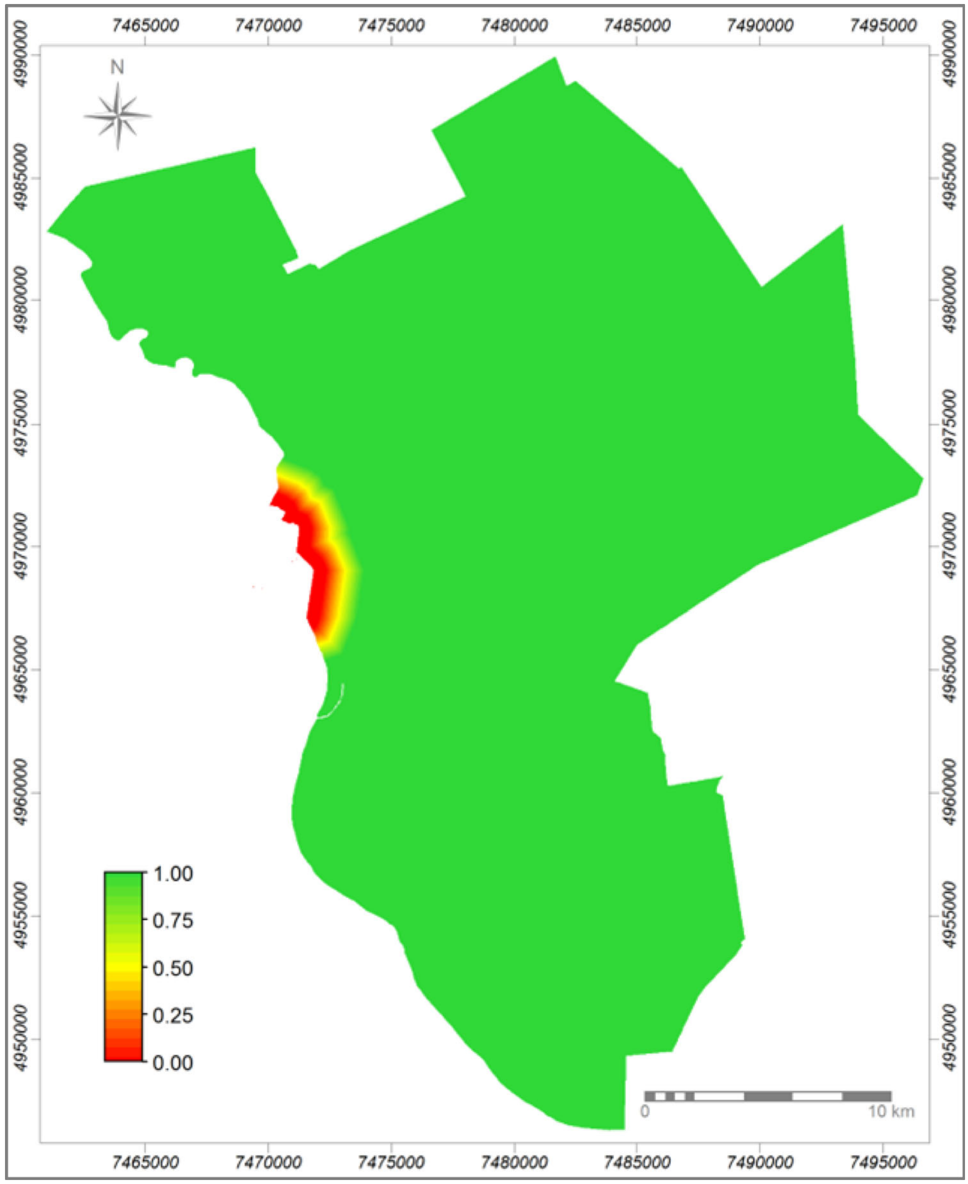


Fig. 12 Standardized map of distance from water supply

Standardized maps evaluated by AHP. Criteria defined as constraints omitted from the evaluation. Pairwise comparison matrixes, weight (W), and consistency index (CR) presented in Tables 3, 4, 5, 6, 7, 8, 9, and 10.

Results and discussion

The final suitability map was obtained using GIS and AHP and reclassified the study area into four classes: unsuitable, poorly suitable, moderately suitable, and most suitable (Fig. 22).

The results showed that 62.31 % are unsuitable locations, 13.49 % are poorly suitable, 12.08 % are moderately suitable, while 12.12 % of the location are most suitable. We found that the significance of geo criteria is far larger than that of the other criteria. Namely, geo criteria play a decisive role in site selection.

Among geological engineering criteria, lithology was of the greatest importance in site selection. Although no landslide had been registered in the study area, stability was also critical due to sensitivity of the loess sediments. Bearing capacity was somewhat less important than

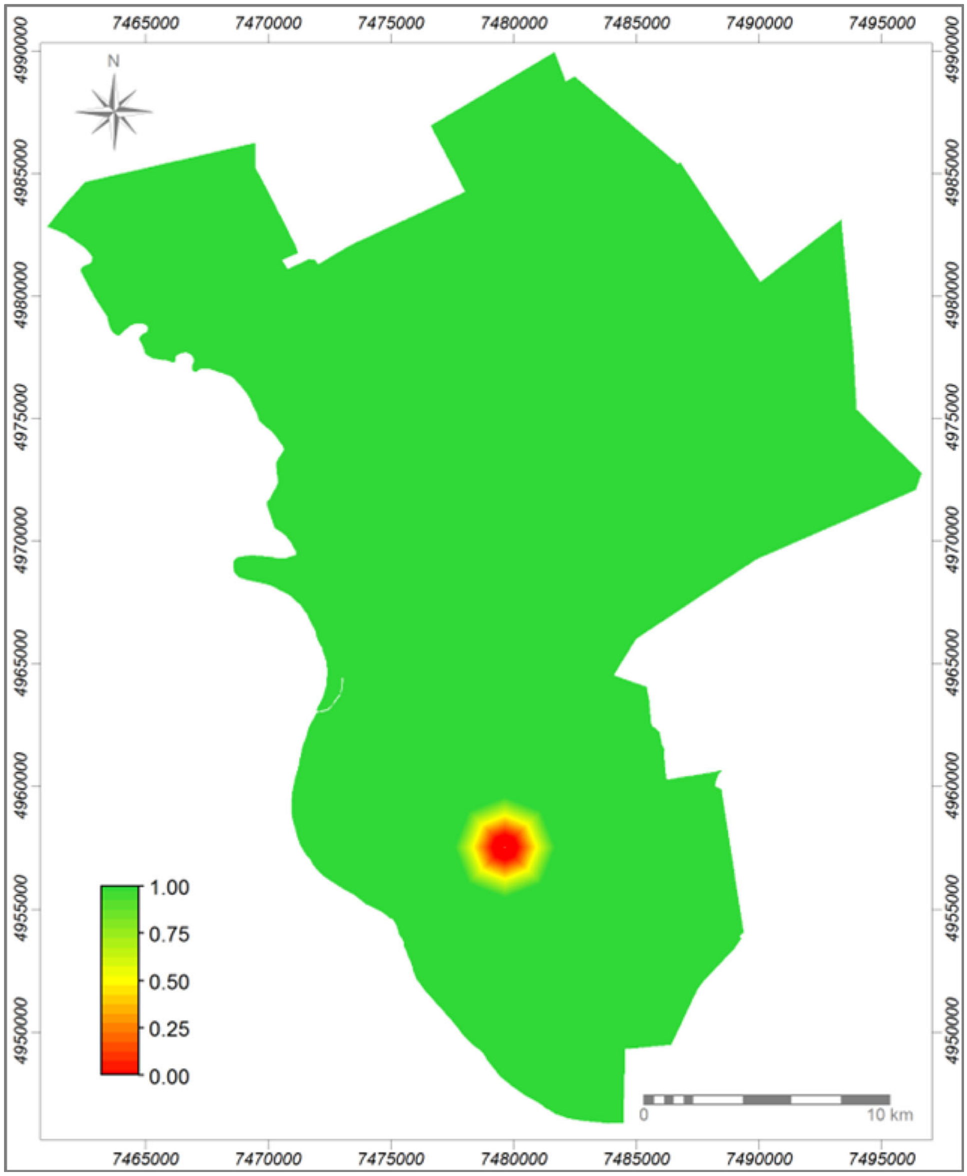


Fig. 13 Standardized map of distance from thermo-mineral springs

stability, while availability of construction material was least important.

Among hydrogeological and hydrological criteria, the depth to groundwater was most important. Permeability was less so, while flooding was the least significant factor.

Low slopes, high groundwater level, instability, and permeability characterize the study area, about 82.9 % of which is flat. Slopes rated as favorable (2–10 %) accounted for only 0.51 % of the examined area. Flat surfaces are also unfavorable from the aspect of wind direction. About 33.29 % of the study area has a high groundwater level (<3 m), about 47.3 % between 3–7 m, while levels deeper than 10 m were found in only 12 %. Permeability depends on lithology and about two-thirds (64.19 %) have medium permeability. Flooding probability had little significance and was determined to be 4.79 %.

To define lithology, stability, and construction material as the base we used the geological engineering map. In our case a geological map would not be useful because the exploration area is built from Quaternary sediments only. Similar lithology (silty-sandy-clay) impedes standardization but there were still three classes, among which 27.12 % were unfavorable locations and 64.05 % favorable investigative areas. Concerning

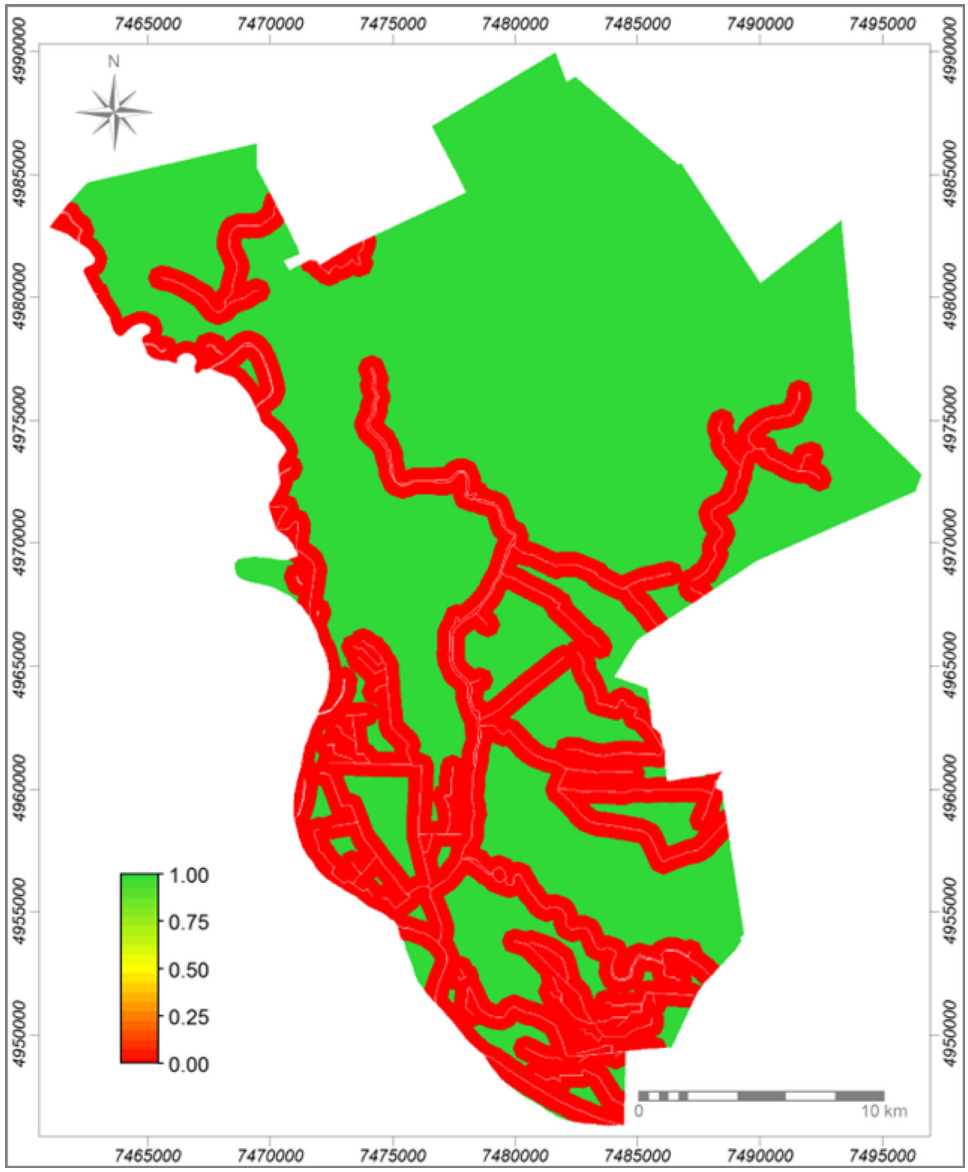


Fig. 14 Standardized map of distance from rivers and channels

stability, 70.15 % were considered stable, while 29.73 % were unstable.

The characteristics of the examined area (small slope angle, high groundwater, considerable soil permeability, similar lithology, etc.) made standardization and evaluation difficult. In most cases, only two or three classes were allocated. All criteria were classified into two main groups, which were further divided into seven criteria and 18 subcriteria. For each subcriterion (C1–C18) a corresponding map was drawn. Distances from rivers and channels (C11), gas and oil pipelines (C13), and the airport (C16) were defined as constraints. These constraints were considered as areas unacceptable for landfills and they were not valued. It was not possible to make a constraint map in ILWIS.

The objective of this study was to present a methodology for landfill site selection from the geological engineering point of view. This investigation is the first in Serbia to be carried out by engineering geologists (geotechnical). Due to the lack of digital maps, it was necessary to scan and digitize all maps. That required a considerable investment of time, which can be frustrating. Therefore, the existence of a digital database is of great importance for site selection.

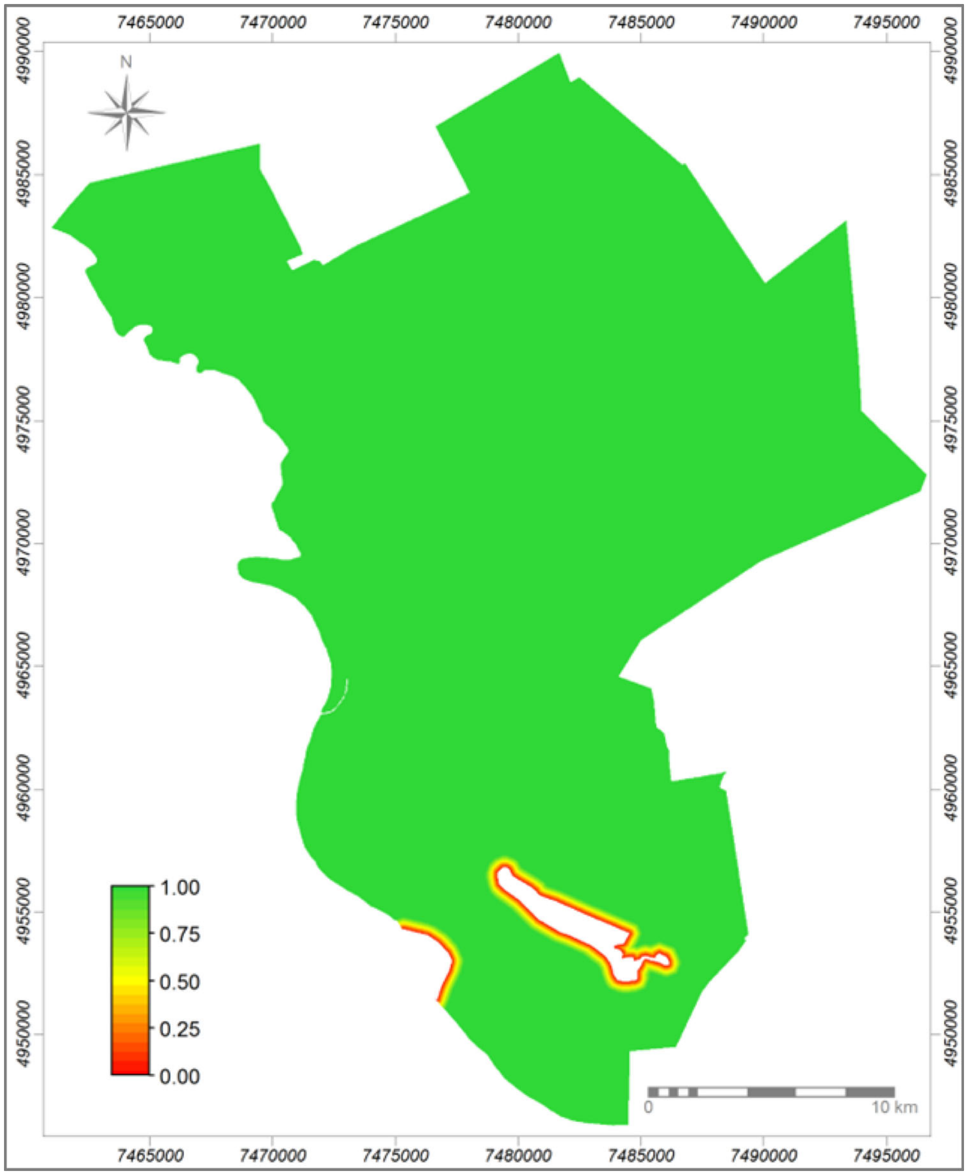


Fig. 15 Standardized map of distance from protected areas

Some advantages of this methodology are spatial data presentation, quick and facile manipulation of the maps, easier and faster evaluation, and low cost (important for developing countries). Disadvantages are the possibility of errors due to pixel size, the availability and accuracy of data, primarily geologic (landslides), and mistakes in data updating, while the number of criteria requires many comparisons. However, the advantages of the presented methodology are far greater than the disadvantages and it can be applied in geotechnical zoning, landslide studies and all spatial and urban planning.

Conclusions

Landfill site selection in the Pančevo municipality was performed using GIS and AHP. Eighteen maps were prepared that first had to be standardized and then evaluated. The large number of criteria were a laborious factor in the analysis, which showed that 12.12 % of our study area is suitable for landfills. These places are located in the central part of the study area.

Geological, hydrogeological, and geological engineering maps with a 1:100,000 scale were used as the basis for analysis. They were first scanned, digitized, and rasterized.

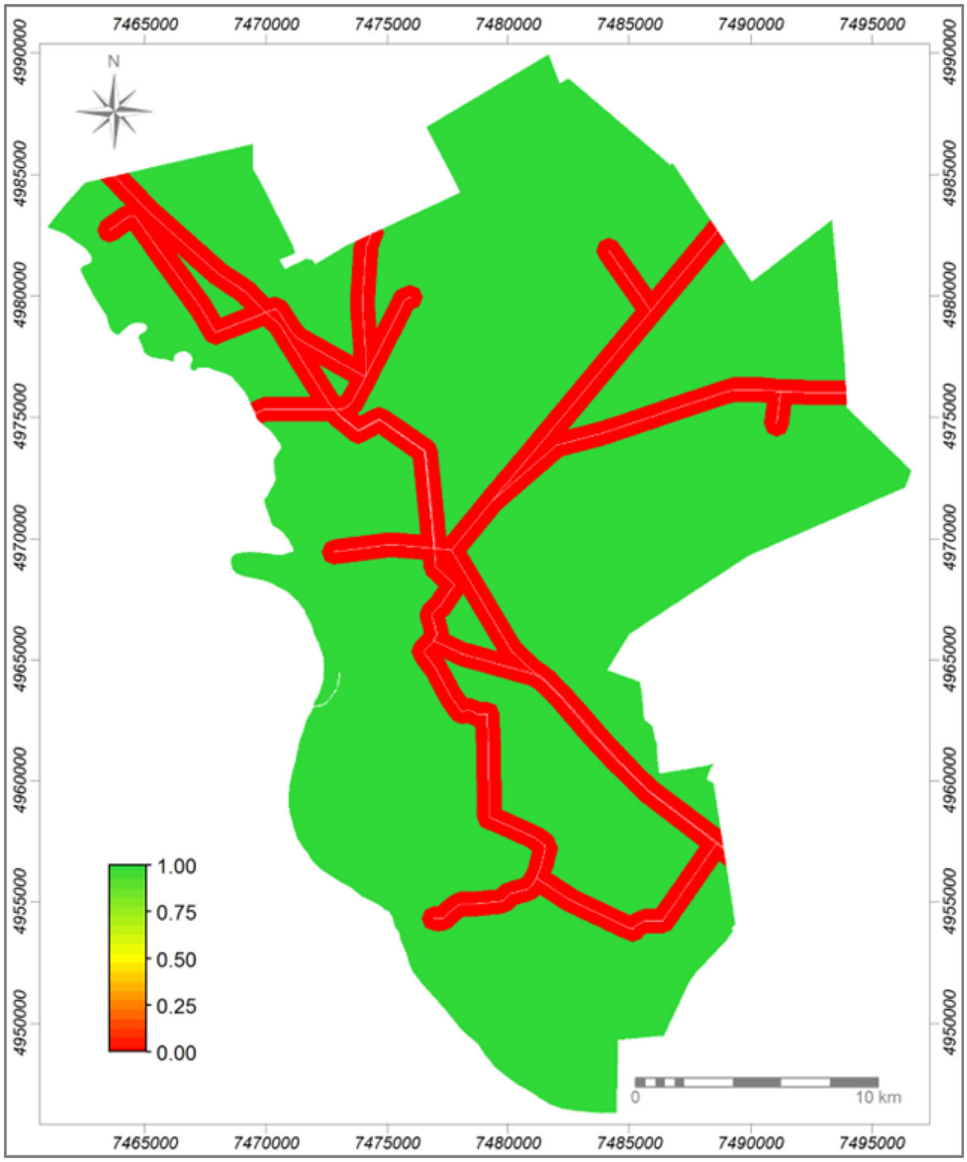


Fig. 16 Standardized map of distance from oil and gas pipelines

The presented methodology points to the role and importance of engineering criteria even in terrain where landslides are not dominant processes, as in the area of the Pannonian Basin. Our analysis showed that geo criteria are the most important in the site selection process. After geo criteria, the most crucial were geological engineering criteria, while less importance was given to hydrogeological and hydrological criteria. Geomorphological criteria were the least important.

GIS makes site selection easier and speeds up the procedure. Manipulation of maps is easy and fast. The most sensitive part in the application of AHP is the evaluation of criteria. This is a subjective process, which depends on the experience of the evaluator. Therefore, the consistency index (CR), obtained when comparing for indicating errors in judgment, is of benefit.

Locations defined as suitable need to be checked in the field because the results depend on data updates, so field

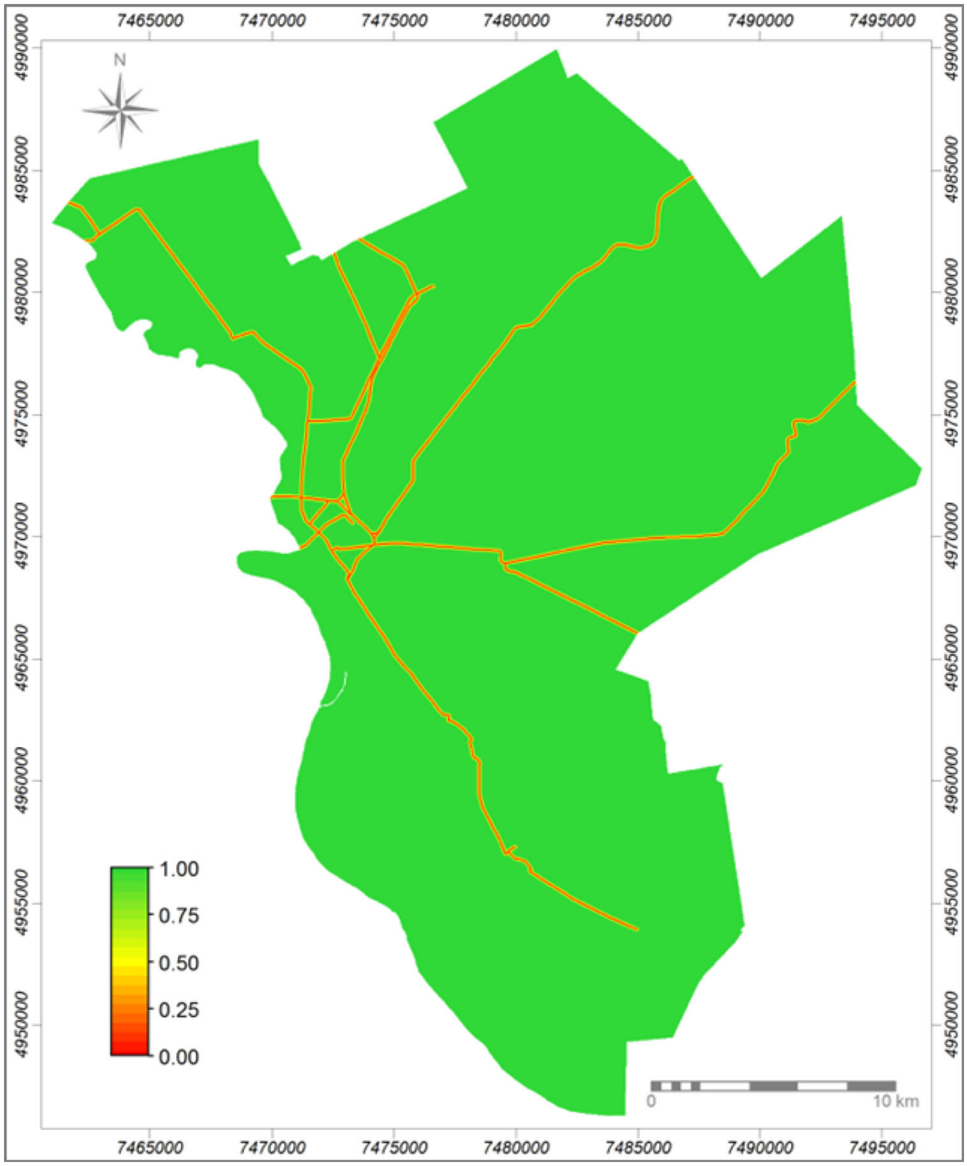


Fig. 17 Standardized map of distance from roads and railways

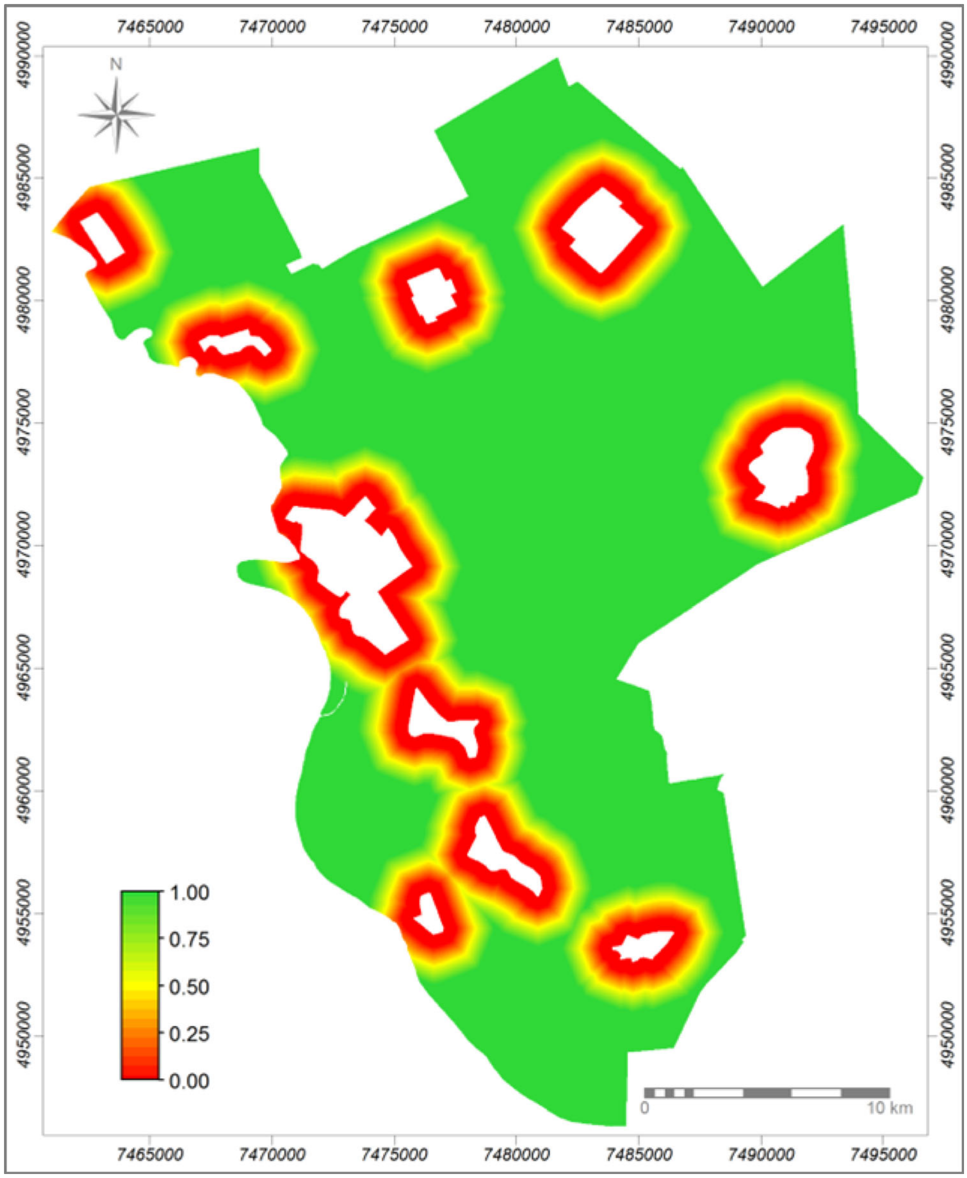


Fig. 18 Standardized map of distance from settlements

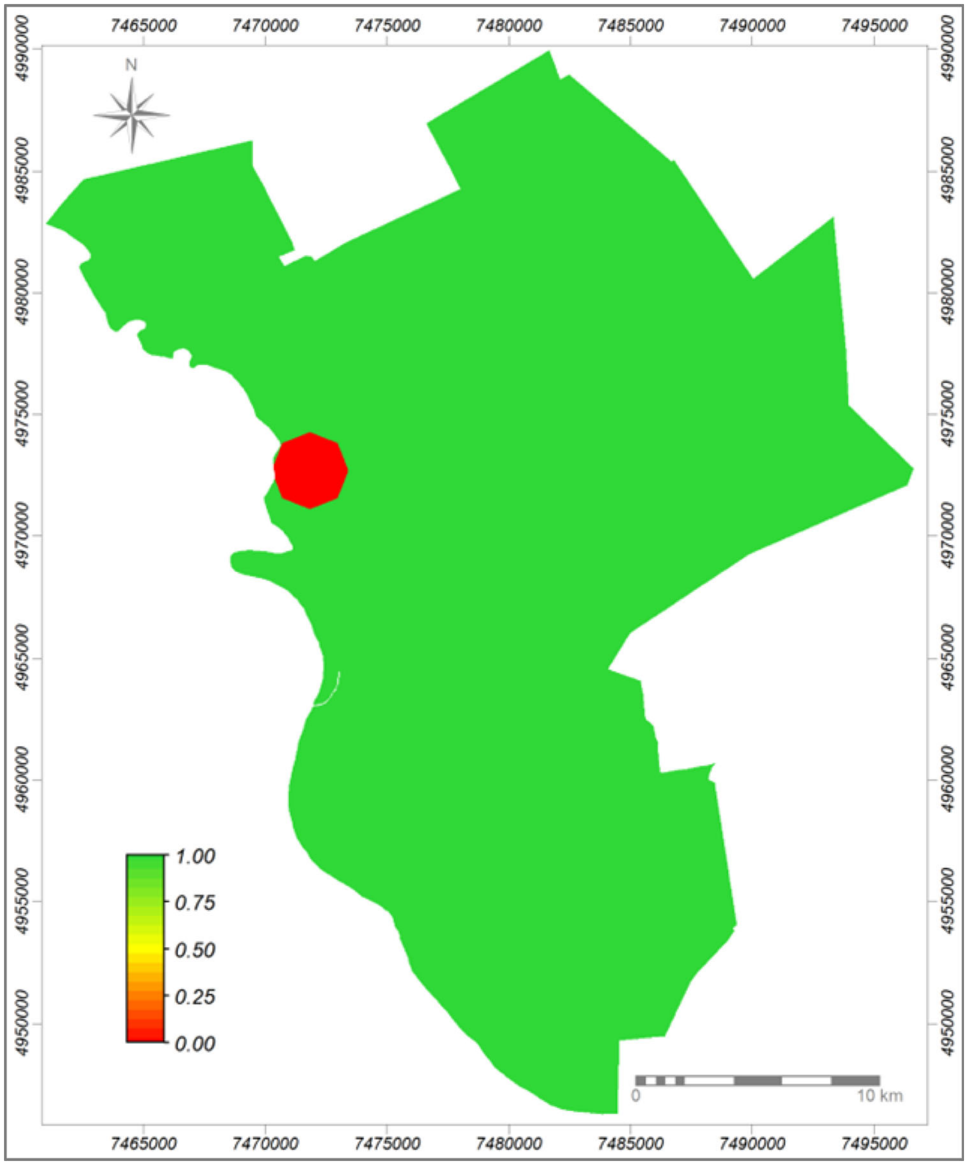


Fig. 19 Standardized map of distance from airports

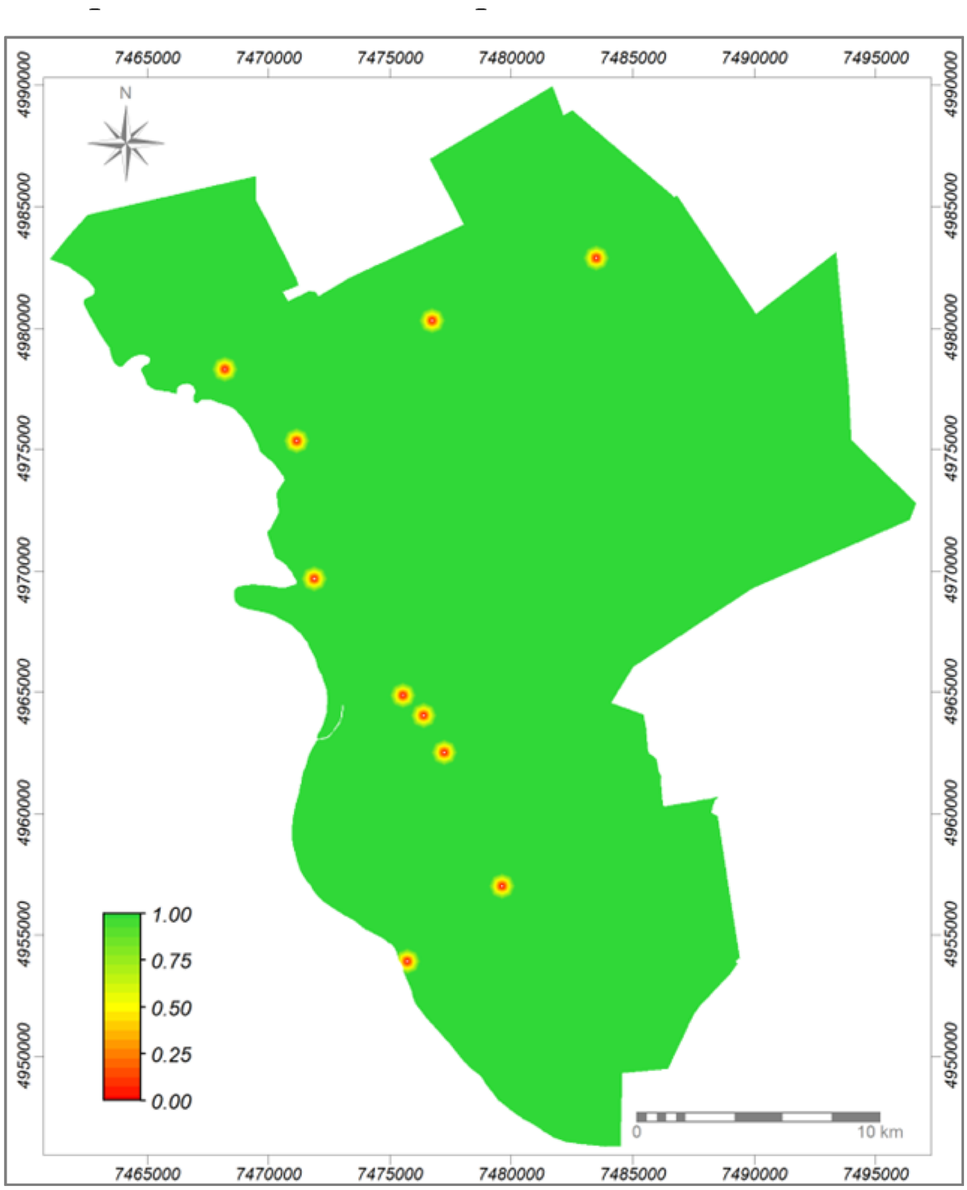


Fig. 20 Standardized map of distance from cultural sites

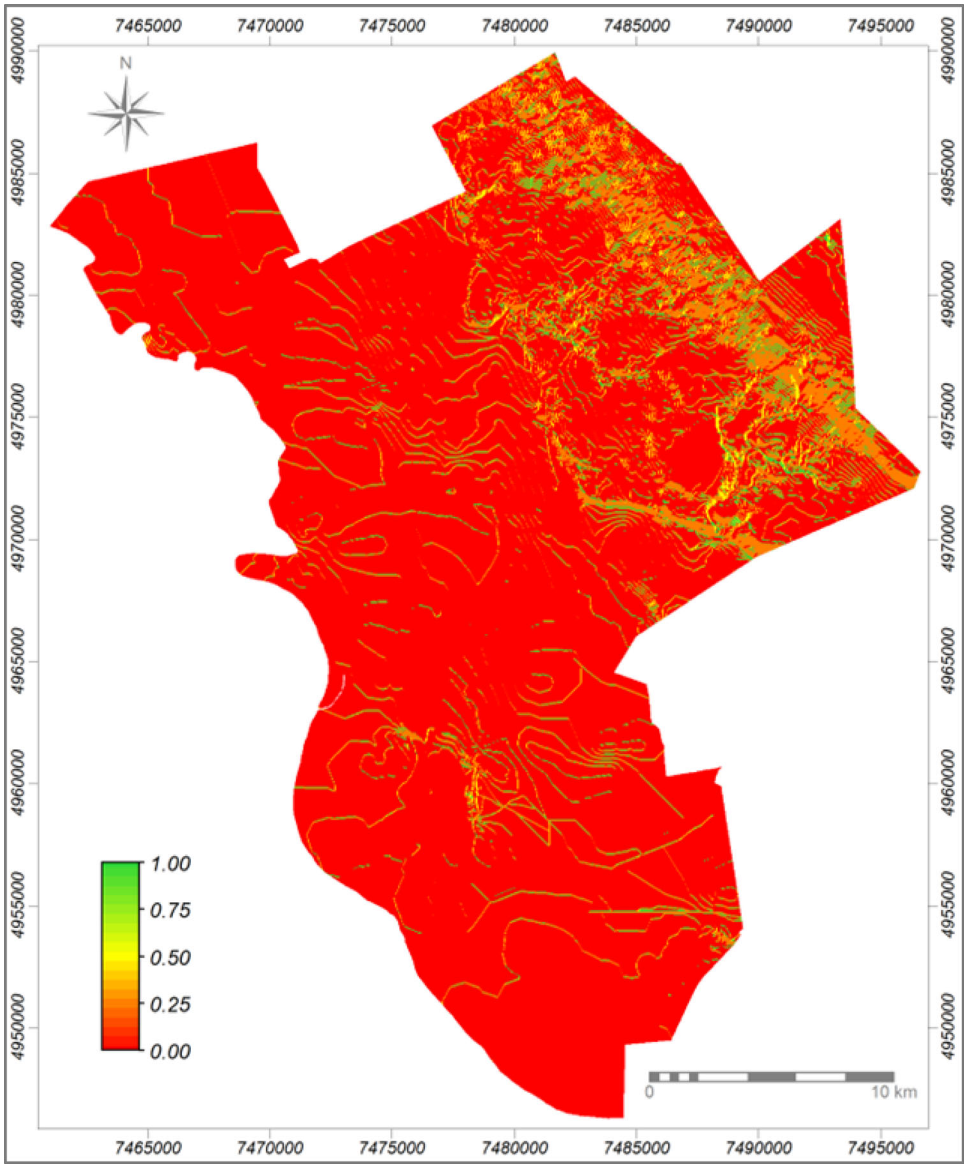


Fig. 21 Standardized map of aspect

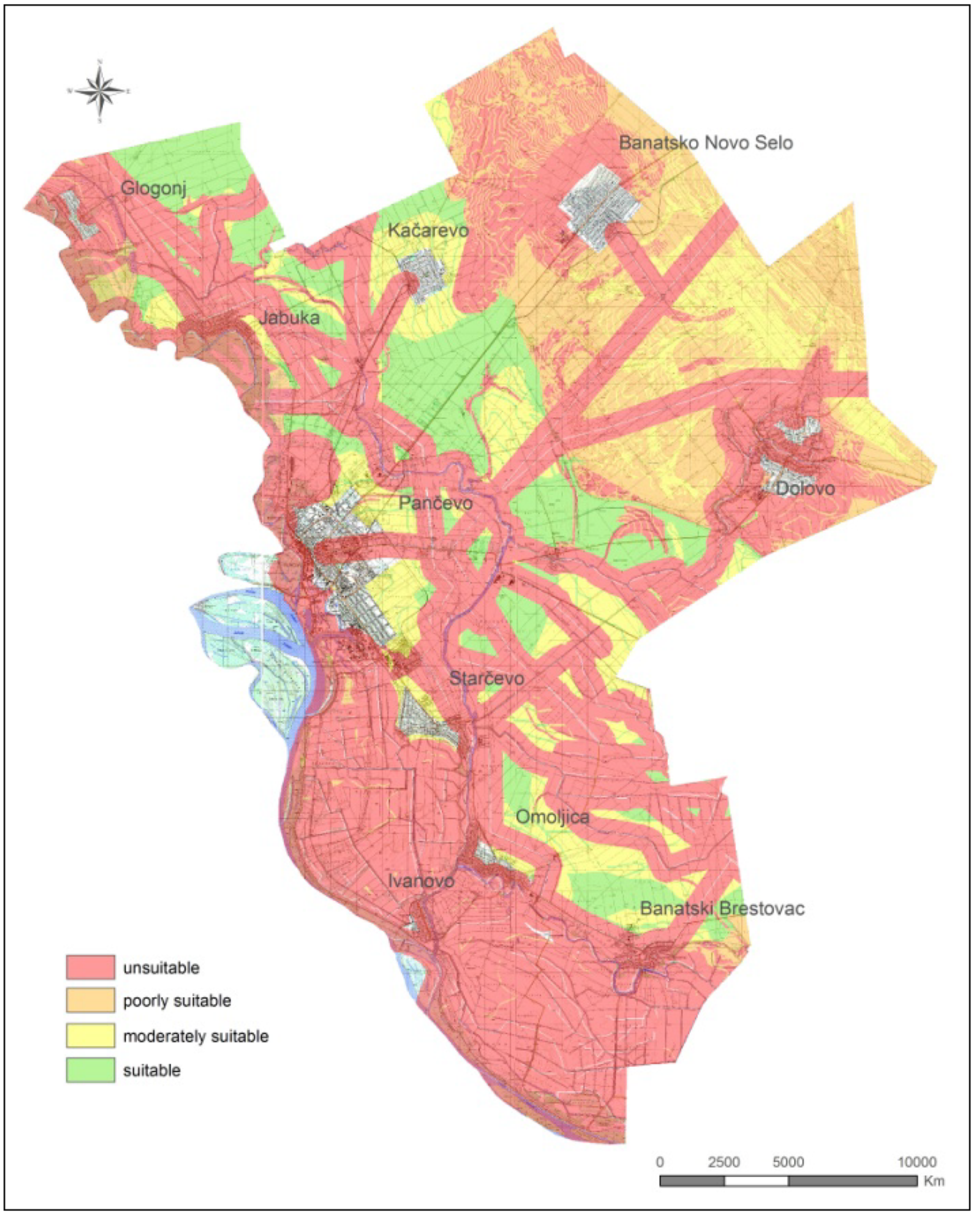


Fig. 22 Landfill suitability map of study area

research at the chosen location is necessary. The presented methodology is not a substitute for field research.

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