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Assessing the natural vulnerability of the recharge area of the Velika Gorica well field

Marin Validžić[1]; Jelena Parlov[2*]; Dario Perković[3]
[1]University of Zagreb Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, Zagreb, Croatia
[2]University of Zagreb Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, Zagreb, Croatia; https://orcid.org/0000-0002-2862-7222
[3]University of Zagreb Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, Zagreb, Croatia; https://orcid.org/0000-0003-2625-6568
Corresponding author: jelena.parlov@rgn.unizg.hr

Abstract

Groundwater is an important natural resource and plays a crucial role in the preservation of ecosystems, providing potable water and the supply of various industries in the Republic of Croatia. Therefore, it represents a major challenge of utmost importance for hydrogeologists dedicated to the protection of its qualitative and quantitative integrity. Thus, one of the most common methods used in groundwater protection projects, namely the assessment of the natural vulnerability of aquifers, is applied in this study. The study focuses on the recharge area of the Velika Gorica well field, located in the Zagreb aquifer, which is composed of alluvial deposits. The natural vulnerability assessment of the Velika Gorica well field recharge area was determined using the parametric SINTACS method. This method includes the assessment of seven parameters and is applied for two different scenarios. The final vulnerability index is determined by multiplying the parameter values by weighting coefficients. The result is a map illustrating the natural vulnerability of the Velika Gorica well field recharge area. This map shows different zones with varying degrees of natural vulnerability. The assessment shows that the entire observed area falls into a groundwater vulnerability class greater than high in both scenarios. This indicates a significant risk of groundwater contamination in the recharge area of the Velika Gorica well field.

Keywords: vulnerability index; SINTACS method; alluvial aquifer; Velika Gorica well field

1. Introduction

Groundwater is a vital natural resource in the Republic of Croatia, playing a crucial role in maintaining ecosystems, supplying drinking water, and supporting various industrial sectors. However, with the increasing population, urbanization, and intensified agricultural activities, there is growing pressure on these waters. Sustainable management and protection of this vital resource are essential, not only to ensure long-term water supply but also to preserve ecological balance and protect human health. In this context, legal frameworks such as the Sustainable Development Strategy of the Republic of Croatia (**URL1**), Water Management Strategy (**URL2**) and the Water Act (**URL3, URL4** and **URL5**) play a crucial role in water management. Furthermore, adherence to European Union guidelines, such as the Water Framework Directive (**URL6**), becomes increasingly important as it promotes sustainable water management and the protection of natural resources.

Assessing aquifer vulnerability is crucial for protecting groundwater. It helps us identify potential sources of contamination, plan land use, and take measures to protect drinking water supplies. Additionally, vulnerability assessment enables us to assess environmental impacts and respond promptly to accidental pollution. In this context, using the SINTACS method to assess groundwater vulnerability in Velika Gorica recharge area is crucial. This method allows for a detailed analysis of vulnerability and the identification of areas with higher or lower vulnerability. The application of geographic information systems (GIS) facilitates the preparation of input data, analysis, and interpretation of results.

In this study focus is on the recharge area of the Velika Gorica well field, which is supplied with water from the Zagreb aquifer composed of alluvial deposits from the Sava River. The aim is to conduct a detailed analysis of groundwater vulnerability in this area to better understand its susceptibility to contamination and contribute to the preservation of water quality for future generations.

The boundaries of the recharge area of the Velika Gorica well field were determined using the particle tracking model (with an assumed pumping rate of Q = 850 l/s) defined for the delineation of the sanitary protection zones of the Velika Gorica well field (**Bačani & Posavec, 2009**). **Figure 1** shows the results of the groundwater flow simulation and particle tracking for high and low water periods and thus defines the study area for natural vulnerability assessment. In addition, the wells of the Velika Gorica well field are shown in relation to the adopted second sanitary protection zone and the selected research domain. The Sava River forms the boundary of the recharge area of the well field on the northern side, while the southern boundary is formed by the Sava-Odra Canal. The study frame on the eastern side fully follows the groundwater flow model, while on the western side it also follows the boundary of the flow model, but up to a certain point where a part of the particle tracking route is excluded to avoid an overly irregular shape of the study frame. Thus, in line with the "European approach", the wells are actually reference sites or points where groundwater contamination should not occur under any circumstances, while the groundwater flow paths are routes that can transport contaminated fluid from the potential pollution source, defined by the well field recharge area, to the destination.

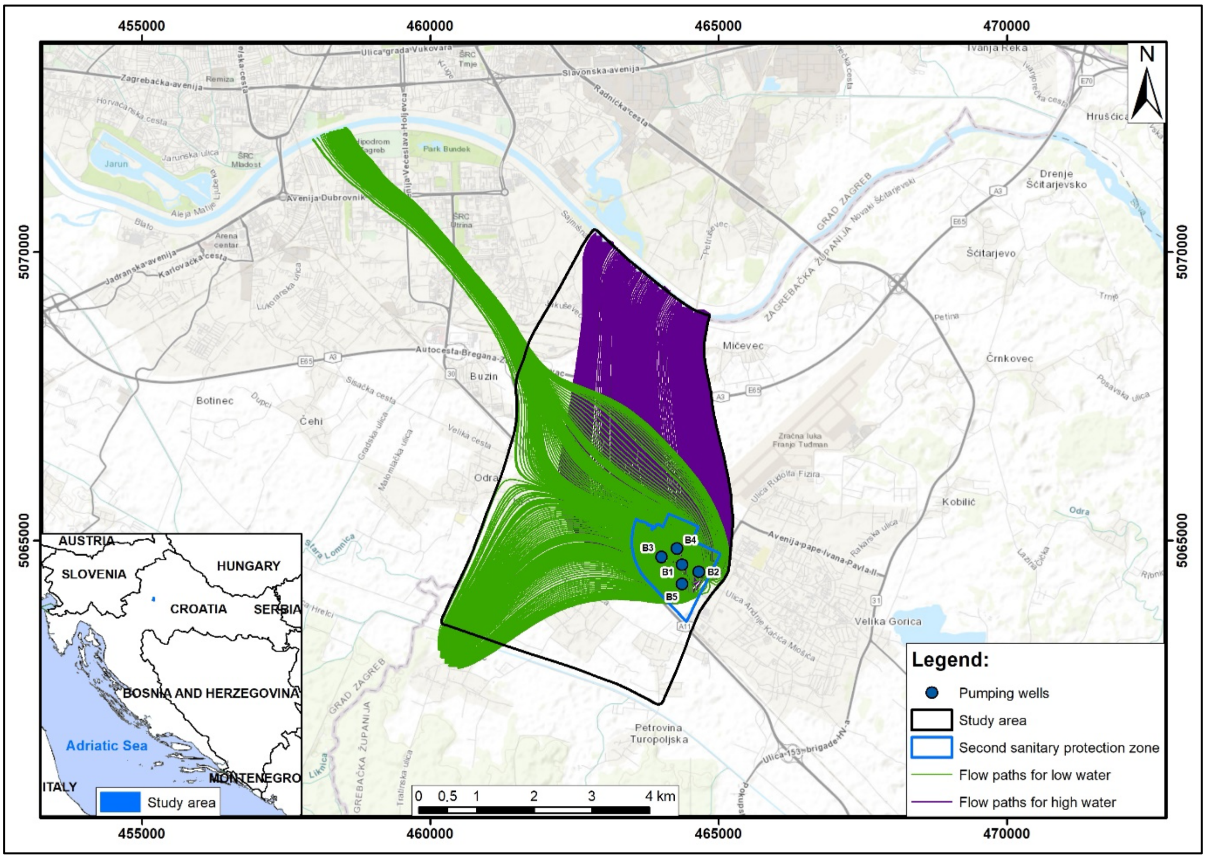
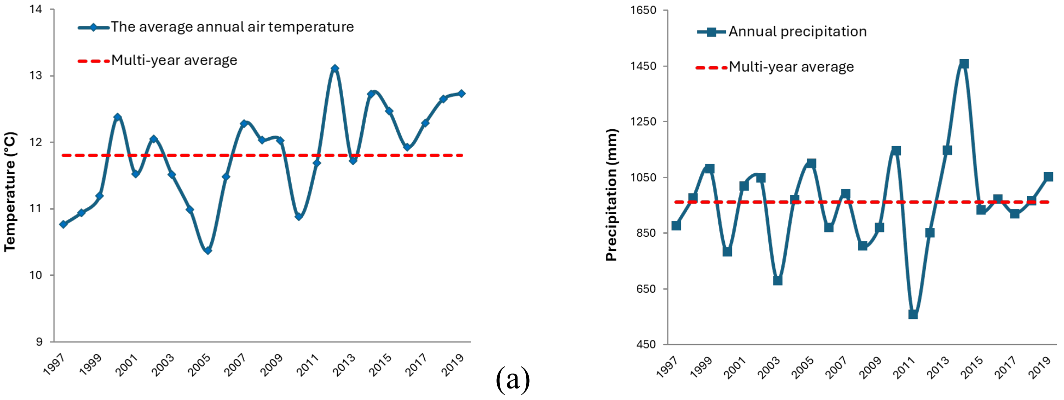


Figure 1. The study area with simulated flow paths for low and high water (according to **Bačani & Posavec, 2009**)

2. Characteristics of the study area

The average annual air temperatures measured at the Zagreb-Pleso meteorological station for the period from 1997 to 2019 are shown in **Figure 2a**. The average annual air temperature for the selected period is 11.8°C, with fluctuations ranging from the lowest value of 10.4°C in 2005 to the highest of 13.1°C in 2012.

Figure 2b shows the distribution of annual precipitation for the Zagreb-Pleso meteorological station from 1997 to 2019. Annual precipitation ranges from 560.3 to 1459.5 mm, with the multi-year average value for the twenty-two-year period being 961.5 mm. On a monthly basis, the highest rainfall occurs in September (108.9 mm), while the lowest occurs in January (59.1 mm).



(a) (b)

Figure 2. The average annual air temperatures (a) and annual precipitation (b) measured at the Zagreb-Pleso meteorological station (from 1997 to 2019)

The study area consists of four pedological units, which are, in order of prevalence: Fluvisoil, Eutric Cambisoil on Holocene deposits, Pseudogley-gley, and water bodies (**Figure 3a**). **Fluvisoil** is a hydromorphic soil type formed by increased moisture due to unrestrained flooding. Such soils occur along watercourses and rivers. It is characteristic of the Zagreb area that they have not been flooded for many years, but are categorised as alluvial soils due to their underdevelopment. **Eutric Cambisoil on Holocene deposits** is classified as an automorphic soil, as it was formed exclusively by precipitation without water stagnation. It is only developed on alluvial clayey deposits in the area of the Zagreb aquifer. The texture of this soil varies from powdery-clayey to, less frequently clayey-loamy. **Pseudogley-gleys** soils are hydromorphic soils characterised by alternating dry and wet periods and thus by reduction and oxidation processes. They contain a horizon where clayey making them impermeable and highly compacted (**Ružičić, 2013**).

Figure 3b illustrates the relationship between the geological deposits of the study area based on the 1:100,000 scale geological base maps, sheet Zagreb (**Šikić et al., 1977**), with the corresponding legend for the geological map of the Zagreb sheet (**Šikić et al., 1979**), and the Ivanić Grad sheet (**Basch, 1981**), with the corresponding legend for the geological map of the Ivanić Grad sheet (**Basch, 1983**). The study area is characterised by a simple geological structure consisting of alluvial deposits of the second Sava terrace – a2 (gravel and sand), floodplain sediments – ap (clayey silts), oxbow alluvium – am (clayey silts and silty clays) and recent alluvial deposits – a (sand and gravel).

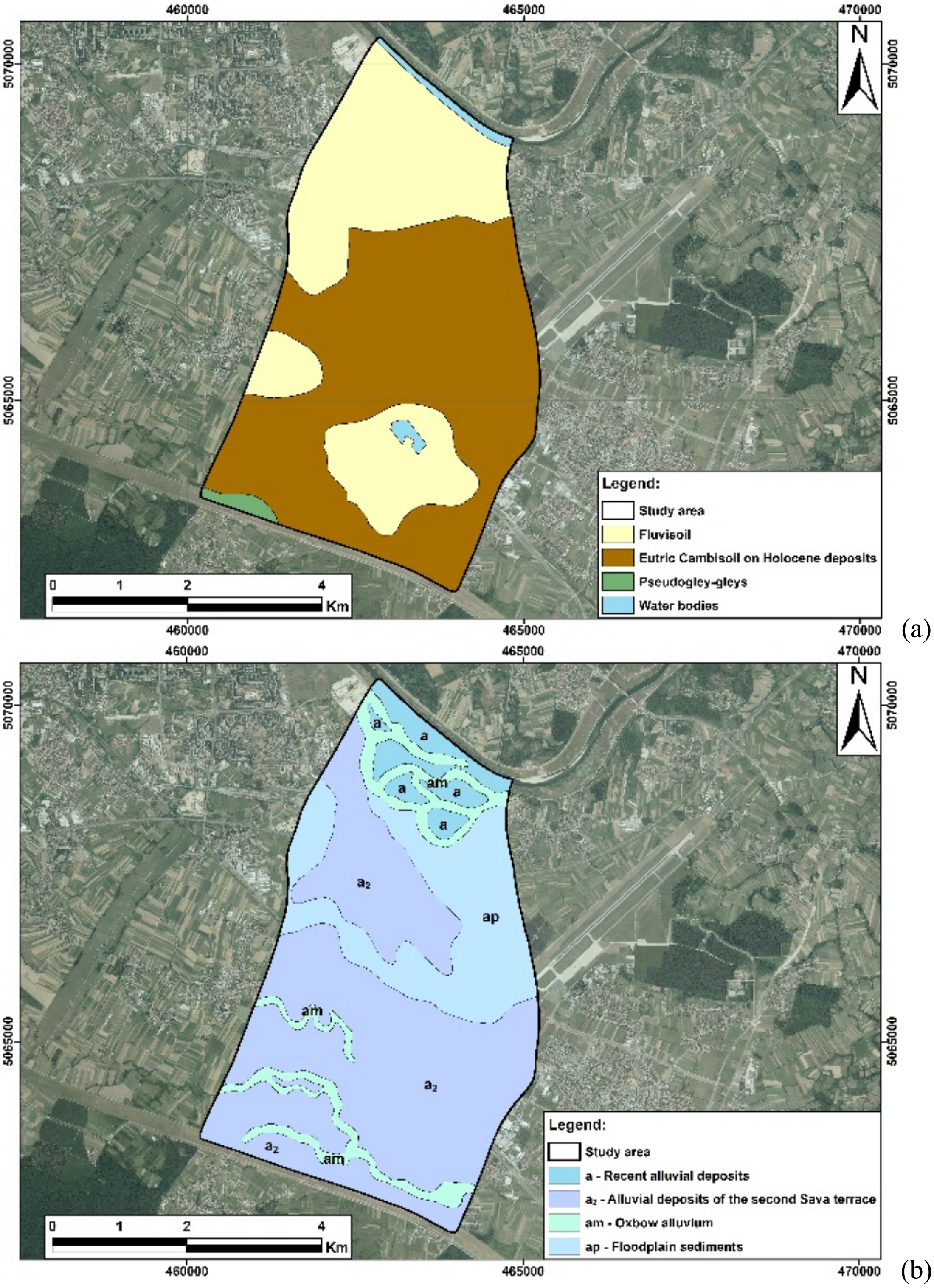


Figure 3. Pedological (a) and geological (b) map

The aquifer is an unconfined type with a regional groundwater flow direction from north-west to south-east (**Bačani & Posavec, 2009**). It consists of two layers, with the first layer consisting mainly of alluvial deposits of the Sava River, mostly consisting of gravels and sands, while the second layer consists mainly of lacustrine-marshy deposits. The layers are hydraulically connected. On the surface there are very thin covers of poorly permeable deposits of clay and silt, which are often absent. The aquifer is recharged mainly by infiltration from the Sava River and by precipitation (**Posavec, 2006**).

3. Method

The SINTACS method (**Civita, 1994**) is classified as a parametric method for assessing aquifer vulnerability. It can be considered as a certain upgrade to the American DRASTIC method (**Aller et al., 1987**), as it was developed with the aim of correcting deficiencies related to the ranges of values of individual parameters and assigning appropriate points. Additionally, the authors aimed to create a new method that would provide greater flexibility and applicability throughout Italy regardless of the aquifer type. Over the years, the original version of the SINTACS method evolved and changed with an increasing number of tests and grounded experiences (over 500 applications in various areas) until the year 2000 when the SINTACS R5 version was proposed (**Civita & De Maio, 2000**). According to this version, vulnerability assessment is based on scoring seven parameters and possesses five weighting systems that depend on the hydrogeological structure of the aquifer and surface conditions due to anthropogenic loading. For the purposes of this study, the SINTACS R5 method will be applied, which assesses vulnerability based on the evaluation of the following seven parameters:

1 Parameter S1 - depth to groundwater,
2 Parameter I - effective infiltration,
3 Parameter N - attenuation capacity in the unsaturated zone,
4 Parameter T - attenuation capacity in soil/cover layers,
5 Parameter A - hydrogeological characteristics of the aquifer,
6 Parameter C - hydraulic conductivity of the aquifer, and
7 Parameter S2 - slope of the terrain.

The assessment parameters in the model are converted into SINTACS parameters using certain tables, diagrams, ranges, and calculations, with each parameter ranging from 1 to 10, where a higher value indicates a greater vulnerability of the aquifer (**Civita & De Maio, 2004**). The final vulnerability is obtained by calculating the vulnerability index according to the **Equation1**:

$$I_{SINTACS} = \sum_{i=1}^{7} P_i \cdot W_i \qquad (1)$$

where are:
- the P_i is the rating of each of the seven parameters that the method considers and
- W_i is the relative weight.

In **Figure 4**, the basic steps and processes of data preparation and processing involved in creating a vulnerability map are shown. GIS technology, specifically ArcMap 10.1, was utilized for preparing and analysing parameters using the SINTACS method to evaluate the natural vulnerability of the Velika Gorica well field recharge area. It is important to emphasise that the entire GIS analysis was performed in the official coordinate system of the Republic of Croatia, HTRS96/TM, while the GIS basemap layers are represented by the digital orthophoto map at a scale of 1:25,000 and the topographic map at a scale of 1:25,000 from the Geoportal of the State Geodetic Administration (**URL7**). Microsoft Excel was used to create a database and calculate certain values required for the preparation of the SINTACS parameters.

The vulnerability index is useful at a regional scale to priorities area of very extreme, extreme, high, moderate, low and very low vulnerability regions.

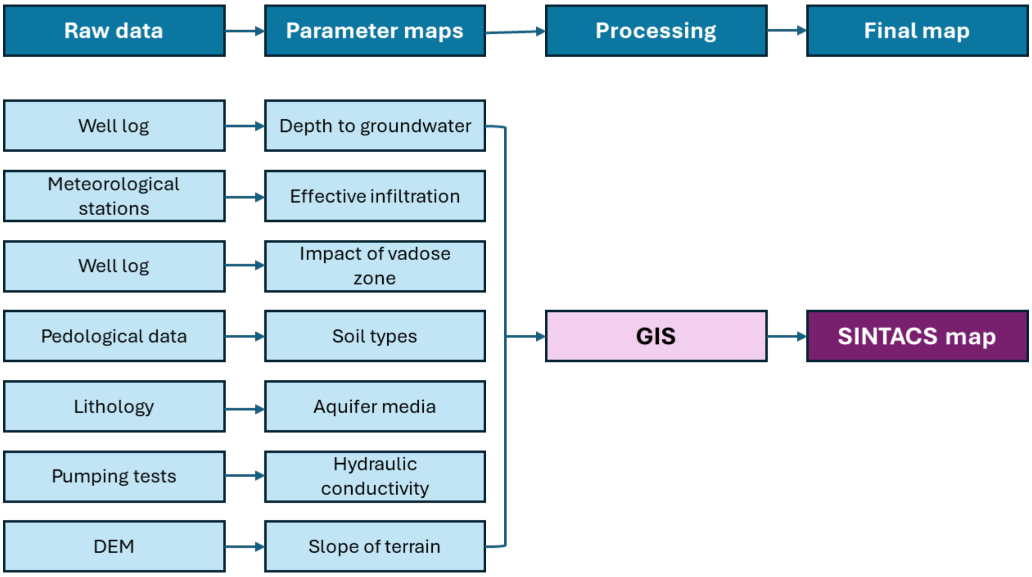


Figure 4. Flow chart of steps and processes in creating a vulnerability map

4. Results

The depth to the groundwater (parameter S1) was determined based on measurements from 18 piezometers during the period from 1997 to 2012. Maps of the highest high groundwater levels and the lowest low groundwater levels were created (**Figure 5a** and **Figure 5b**), and with the use of weighting factors, maps of parameter S1 for scenario 1 (**Figure 5c**) and parameter S1 for scenario 2 (**Figure 5d**) were produced.

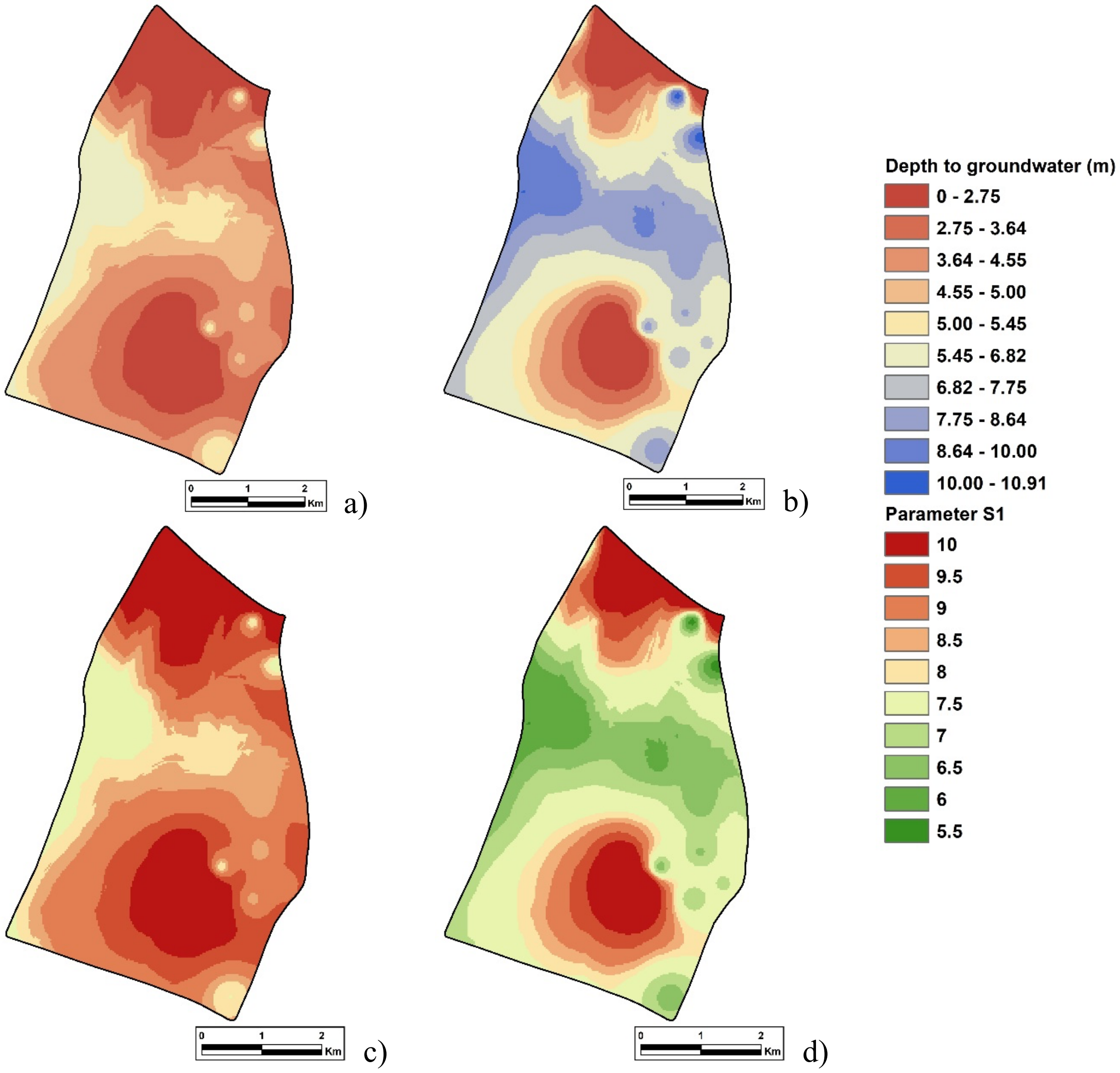


Figure 4. Spatial distribution of the parameter S1 for scenario 1 and scenario 2

The effective infiltration (parameter I) represents the amount of water per unit area that penetrates the soil surface and reaches the groundwater. The role that effective infiltration plays in assessing the vulnerability of aquifers is very significant as contaminants are entrained at the surface but are also diluted, first as they travel through the unsaturated zone and then within the saturated zone. The effective infiltration was analysed for two scenarios for the period from 1997 to 2019. The first case refers to the year with the highest precipitation (2014), in which the calculated actual evapotranspiration was also the highest for the observed period, while the second case considers the year with the lowest precipitation (2011). Table 1 shows the associated values of the parameter x (depending on the texture and hydraulic properties of the soil; for each soil type present in the recharge area) and the calculated values of effective infiltration for two scenarios.

Table 1. The effective infiltration (I) for scenario 1 and scenario 2

		Scenario 1 (Year 2014)			**Scenario 2 (Year 2011)**		
Soil type	**X**	**(P-Et)**	**I (mm/year)**	**Parameter *I***	**(P - Et)**	**I (mm/year)**	**Parameter *I***
Eutric Cambisoil on Holocene deposits	0.2	806	161	6.5	117	23	1.0
Fluvisol	0.3	806	242	9.0	117	35	1.5
Pseudogley-gley	0.1	806	81	4.0	117	12	0.0
Water body	1.0	806	806	10.0	117	1	10.0

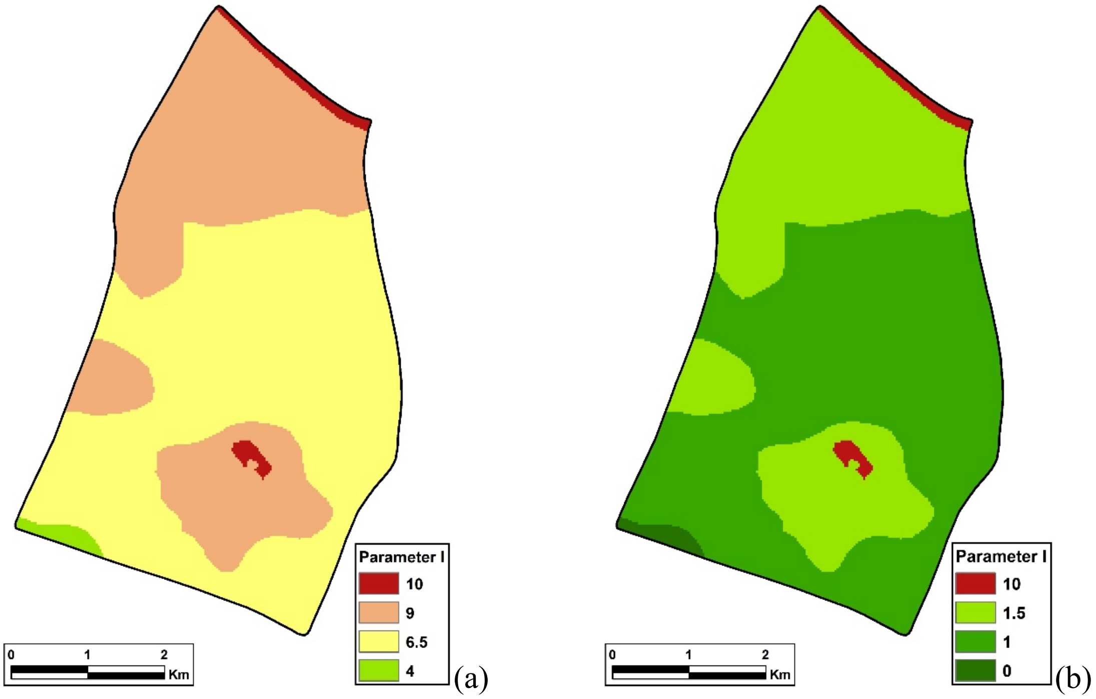


Figure 5. *Spatial distribution of the parameter I for scenario 1 (a) and scenario 2 (b)*

The unsaturated zone is described as the zone below the typical soil horizon and above the water table, which is unsaturated or discontinuously saturated. The unsaturated zone is the “second line” of defence" of the hydrogeological system against fluids or water-borne contaminants. Therefore, the **attenuation capacity of the unsaturated zone (parameter N)** is crucial. The thickness of the unsaturated zone at high (**Figure 6a**) and low (**Figure 6b**) groundwater levels led to a spatial distribution of the associated parameter N for scenario 1 (**Figure 6c**) and scenario 2 (**Figure 6d**).

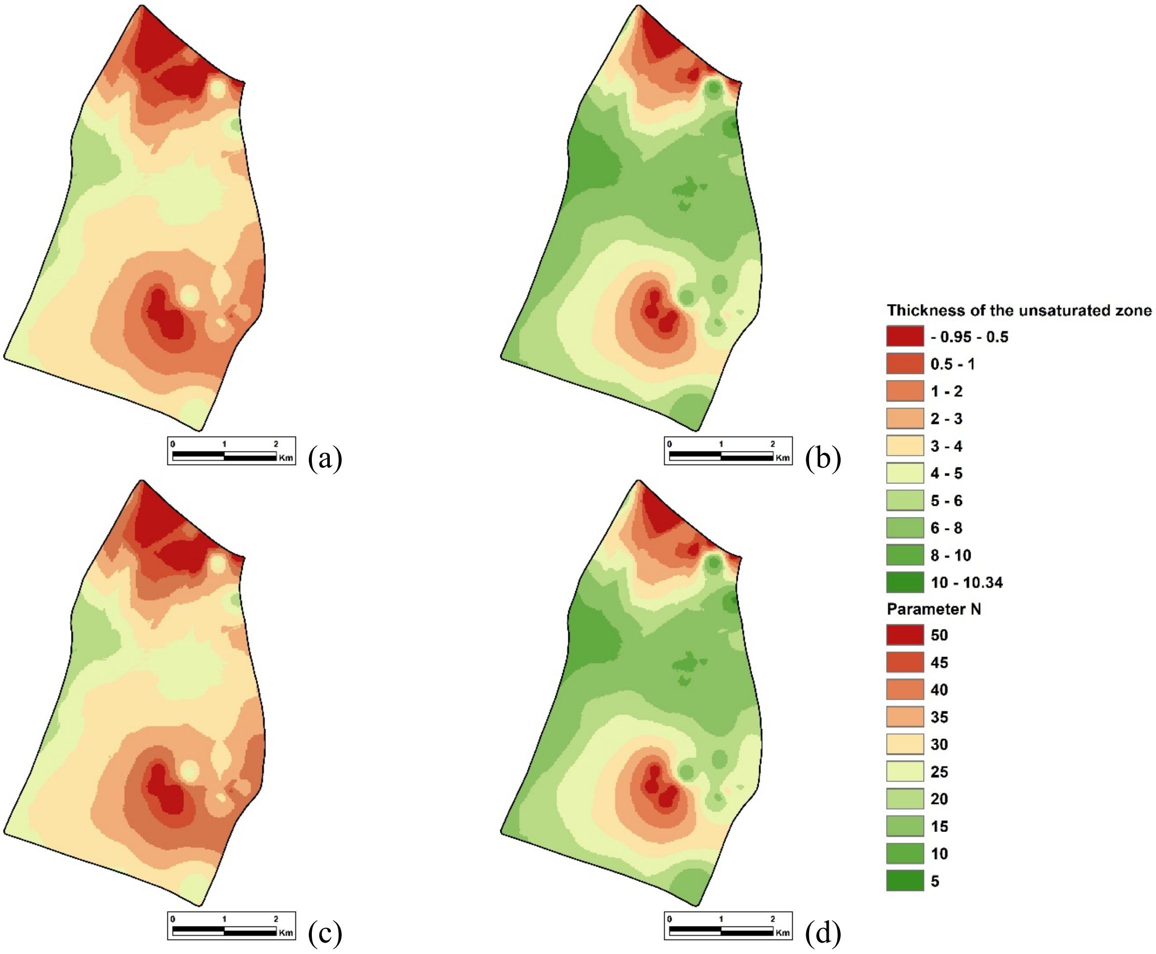
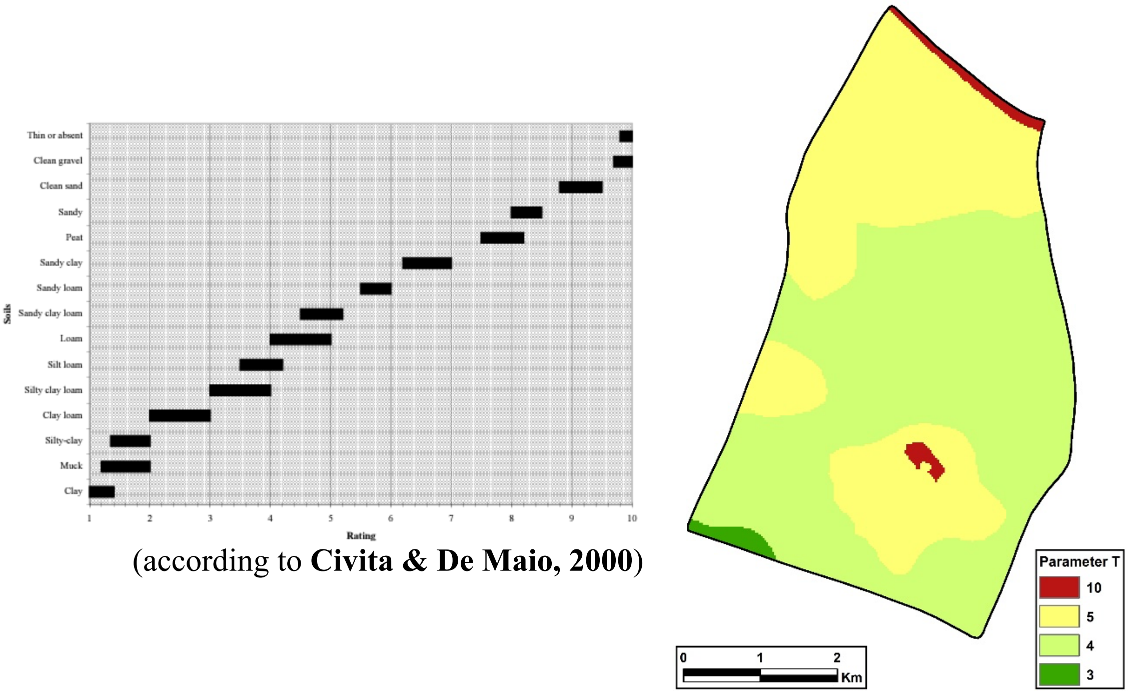


Figure 6. Thickness of the unsaturated zone at high (a) and low (b) groundwater levels and spatial distribution of the parameter N for scenario 1 (c) and scenario 2 (d)

The parameter T represents the attenuation capacity of the soil/cover layers to retain contaminants. When assessing the vulnerability of the aquifer, the soil is considered separately from the unsaturated zone and independently as the first line of defence of the aquifer against potential contamination, as it is able to slow down or retain the movement of the contaminated fluid through the hydrogeological system. **Figure 7** shows all possible values of the parameter T assigned to the different soils based on their granulometric composition, as well as the spatial distribution of the parameter T within the recharge area of the Velika Gorica well field.



(according to **Civita & De Maio, 2000**)

Figure 7. Spatial distribution of the parameter T

The hydrogeological characteristics of the aquifer (parameter A) depend on the properties of the rocks of which it is composed. The Zagreb aquifer consists of medium to coarse-grained alluvial deposits, i.e. gravel and sand particles predominate in its lithological composition, with small amounts of fines. For the purposes of the SINTACS classification, the aquifer is generally categorised as consisting of coarse-grained alluvial deposits, and the entire thematic layer is given a score of 8 according to **Civita & De Maio (2000)**.

The hydraulic conductivity range of the aquifer (parameter C) represents the ability of the groundwater to move within the aquifer. To create this thematic layer, data on the hydraulic conductivity of the aquifer was collected from pumping tests of 11 different wells. The values are between 0.01 and 0.05 m/s (**Figure 8**), and the entire study area was assigned a value of 10 according to **Civita & De Maio (2000)**.

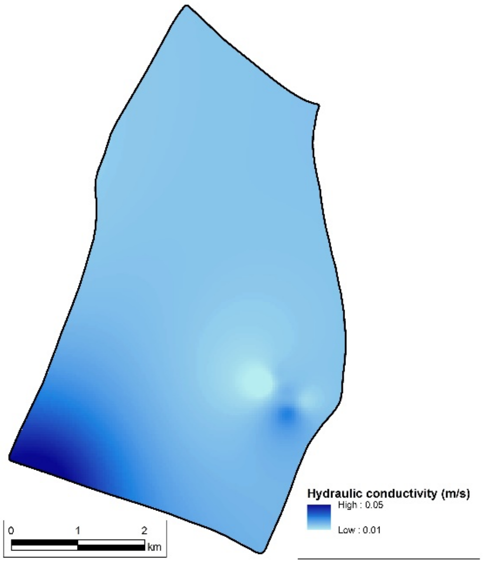


Figure 8. Spatial distribution of the hydraulic conductivity

The hydrological role of the topographic slope (parameter S2) is an important factor in vulnerability assessment, as it determines the amount of surface runoff that is generated. A digital elevation model (DEM) with a resolution of 25 metres was used to determine this parameter. Since the entire study area is located in the alluvial plain of the Sava River, a lowland relief with terrain slopes of less than 1% predominates. Accordingly, the slope map was reclassified into a single class (0-2%) with a parameter S2 value of 10 according to **Civita & De Maio (2000)**. After defining the values of all parameters, the vulnerability index was calculated using the following **Equation 2**:

$$I_{SINTACS} = 5S1 + 5I + 4N + 5T + 3A + 2C + 2S2 \tag{2}$$

Since the study area is almost entirely covered by agricultural and urbanized surfaces, i.e., intensive land use, the "Severe impact" group of weighting coefficients was selected (**Civita, 1994**). The parameter maps extracted above were overlaid in the GIS environment, and the vulnerability index maps of the study area was derived by using **Equations 1** and **2**. From the obtained vulnerability map of the recharge area of the Velika Gorica wellfield for scenario 1 (**Figure 9a**), it is evident that the study area is divided into two classes: extreme and very extreme aquifer vulnerability. The largest area of the study area is occupied by the class of very extreme vulnerability (21.2 km^2), while almost five times smaller area (4.3 km^2) belongs to the class of extreme vulnerability. Furthermore, in the case of low water levels (Scenario 2), the vulnerability index values in the considered area range from 144 to 364. From the obtained vulnerability map of the recharge area of the Velika Gorica wellfield for Scenario 2, as shown in **Figure 9b**, it is visible that the study area is divided into four classes: high, very high, extreme, and very extreme aquifer vulnerability. It can be observed that the classes are fairly evenly distributed within the study area, with the high vulnerability class covering an area of 7.3 km^2, the very high vulnerability class 5.7 km^2, the extreme vulnerability class 7.06 km^2, while the very extreme vulnerability class occupies the smallest area of 5.4 km^2.

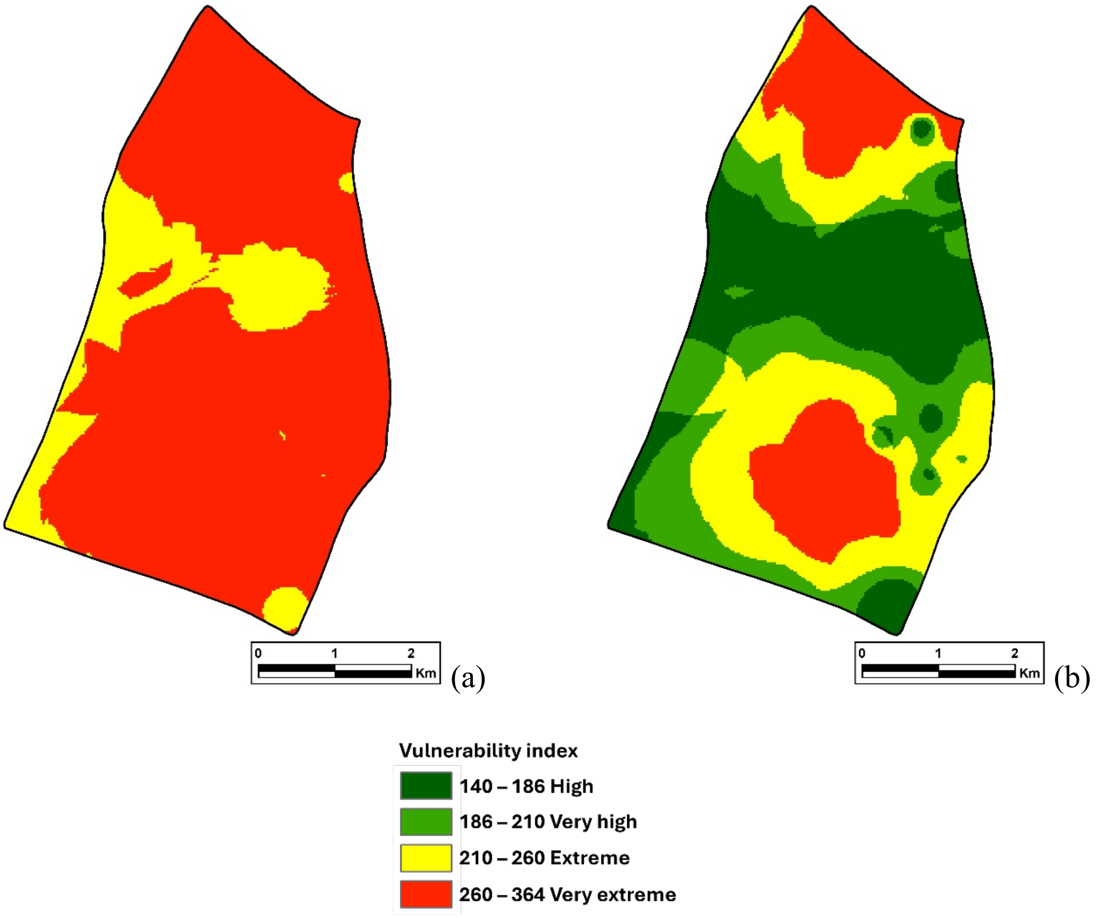


Figure 9. Spatial distribution of the vulnerability index in case of scenario 1 (a) and scenario 2 (b)

5. Discussion and conclusions

The determination of the aquifer vulnerability using the SINTACS method for scenario 1 resulted in values exceeding the extreme vulnerability threshold for the entire investigated area, which emphasises that the recharge area of the Velika Gorica well field is significantly vulnerable to contamination in case of a high groundwater level. These results were also to be expected, as the studied area is located in the alluvial valley of the Sava River. It is therefore a lowland area with gentle slopes and relatively shallow depth to groundwater, while the subsurface consists of alluvial deposits of medium to coarse texture with high hydraulic conductivity. In addition, the Zagreb aquifer is an unconfined aquifer with a weakly developed overburden that is exclusively associated with floodplains and thus directly linked to surface activities. Numerous factors have a negative impact on the vulnerability of the aquifer. Almost every parameter of the SINTACS method was evaluated with values above 5 in scenario 1, which leads to high vulnerability index values.

In the case of the second scenario, there was greater diversity in vulnerability degrees. The maximum vulnerability indices remained the same in both scenarios, while the minimum indices varied significantly. This is primarily due to significant differences in parameter I, as effective infiltration due to large precipitation amounts increased the aquifer vulnerability level for the same type of surface deposits. Furthermore, differences arose due to greater depths to groundwater (parameter S1) and thickness of the unsaturated zone (parameter N), while parameters T, A, C, and S2 remained unchanged in both scenarios. Therefore, in conditions of low water levels, areas with very extreme aquifer vulnerability are located near surface waters – the Sava River and Lake

Lomnica southwest of the Velika Gorica well field, while the area with high vulnerability, representing the class with the lowest vulnerability index values in these conditions, is around Velika Mlaka, where the greatest depths to groundwater were actually measured, further indicating the importance of unsaturated zone thickness in assessing aquifer vulnerability.

Although there are no previously published works on vulnerability assessment for such a narrow research area, the vulnerability analysis of the Velika Gorica well field recharge area can be considered reliable, as vulnerability analyses have been conducted at the national level, covering the entire Zagreb aquifer, where similarly high vulnerability (extreme and very high) characteristic of alluvial aquifers with very good hydraulic properties, relatively shallow depth to groundwater, and weak protective function of the unsaturated zone and soil were also observed (**URL8**).

For future research, the use of a digital elevation model (DEM) with higher resolution compared to that applied in this study, at least 5 meters for this large research scale, is recommended. Among other things, a denser network of structural-piezometric boreholes is desirable, since the boreholes used to determine soil thickness are unevenly distributed; they are more densely positioned in the northern part of the research area, while almost absent in the southwest, and a similar situation applies to piezometers, which certainly affects the accuracy of determining some parameters of the SINTACS method. Furthermore, it is recommended to have at least one pedological profile for each soil type, as this will enable safer determination of soil characteristics crucial for parameter assessment, especially through granulometric analysis.

In conclusion, this study conducted a natural vulnerability assessment of the Velika Gorica well field recharge area as part of the Zagreb aquifer. The Zagreb aquifer is an alluvial aquifer composed of gravel and sand of Quaternary age, divided into upper and lower aquifer layers, with relatively weakly developed cover layers in the upper aquifer layer, in certain areas. Therefore, due to its geological structure and intensive land use, the risk of aquifer contamination is significantly increased, which is why vulnerability analysis was conducted in this area. For the purpose of aquifer vulnerability assessment, the parameter SINTACS method was selected, which considers seven parameters: depth to groundwater (S1), effective infiltration action (I), dilution capacity in the unsaturated zone (N), dilution capacity in soil/cover layers (T), hydrogeological characteristics of the aquifer (A), hydraulic conductivity of the aquifer (C), and hydrological role of slope (S2). To determine and analyse each of these parameters, it was necessary to collect quality input data and manipulate them skilfully within the ESRI ArcGIS software package. Since a larger amount of spatial input data was not available for some parameters, e.g., soil data, decisions about values had to be made based on theoretical values, and as interpolation method was applied for point data, the reliability of applying the SINTACS method in some segments may be considered low. However, ultimately, there are weighting factors that improve the analytical process and provide an additional dimension of adaptation to the prevailing conditions in the research area. In addition to the above, the SINTACS method includes seven parameters in its evaluation, which presents a challenge in situations with a lack of sufficient input data. To precisely assess the parameters, it is necessary to have high-quality input data, which is not always easy to collect. After collecting input data, it is essential to carefully analyse their relevance, and for quality analysis and precise approximation, it is important to have a detailed knowledge of the hydrogeological and environmental characteristics of the researched area.

From the obtained maps of natural vulnerability of the Velika Gorica well field recharge area, it is visible that the entire observed area in both scenarios is characterized by aquifer vulnerability index greater than large, highlighting the vulnerability to groundwater contamination in this area. Finally, it is clear that the right approach to the management and protection of groundwater resources can minimise the risk of aquifer contamination in such a sensitive area. The large number of consumers and the resulting high demand for groundwater from the Zagreb aquifer emphasise the importance of protecting the recharge area of the Velika Gorica well field and all other well fields within the Zagreb aquifer.

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SAŽETAK

Procjena prirodne ranjivosti priljevnog područja crpilišta Velika Gorica

Podzemna voda je važan prirodni resurs i igra ključnu ulogu u očuvanju ekosustava, osiguravanju pitke vode te opskrbi različitih industrija u Republici Hrvatskoj. Stoga predstavlja veliki izazov od iznimne važnosti za hidrogeologe posvećene zaštiti njihove kvalitativne i kvantitativne cjelovitosti. U ovom se radu primjenjuje jedna od najčešćih metoda korištenih u projektima zaštite podzemnih voda, a to je procjena prirodne ranjivosti vodonosnika. Fokus je na priljevnom području crpilišta Velika Gorica, koje se nalazi u zagrebačkom vodonosniku građenom od aluvijalnih naslaga. Procjena prirodne ranjivosti priljevnog područja crpilišta Velika Gorica provedena je korištenjem parametarske metode SINTACS. Ova metoda uključuje procjenu sedam parametara i primijenjena je za dva različita scenarija. Konačni indeks ranjivosti određen je množenjem vrijednosti parametara s težinskim koeficijentima. Rezultat je karta koja ilustrira prirodnu ranjivost priljevnog područja crpilišta Velika Gorica. Ova karta prikazuje različite zone s različitim stupnjevima prirodne ranjivosti. Procjena pokazuje da cijelo promatrano područje spada u klasu ranjivosti podzemnih voda veću od visoke u oba scenarija. To ukazuje na značajan rizik od onečišćenja podzemnih voda u priljevnom području crpilišta Velika Gorica.

Ključne riječi: indeks ranjivosti; SINTACS metoda; aluvijalni vodonosnik; crpilište Velika Gorica

Author’s contribution

Marin Validžić (1) (mag. ing. geol.) made data analysis and vulnerability analysis. **Jelena Parlov (2)** (full professor) participated in the evaluation of the input data and vulnerability analysis. **Dario Perković (3)** (associated professor) contributed to data processing and interpretation of the spatial analysis.