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ORIGINAL ARTICLE

A comparative study of groundwater vulnerability methods in a porous aquifer in Greece

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Abstract

Groundwater vulnerability assessment is critical for the effective groundwater management, particularly in areas with significant anthropogenic activities, such as agriculture. In this study, seven different methods, namely, DRASTIC, Pesticide DRASTIC, SINTACS, Nitrate SINTACS, GOD, AVI, and SI, were implemented using Geographical Information System techniques in Nea Moudania aquifer, Chalkidiki, Greece, to evaluate and identify groundwater vulnerability zones. The study area was classified into five categories: very low, low, moderate, high, and very high vulnerability. The southern and south-western parts of the study area had the highest pollution potential; the corresponding potential is lower in the northern part. Furthermore, single-parameter sensitivity analysis has revealed that the vadose zone and the topography were the most influential parameters of the vulnerability indexes, while the hydraulic conductivity exhibited the lowest effective weight. Finally, nitrate concentrations, taken from 23 observation wells, were employed for the validation of the aforementioned seven methods, using the coefficient of determination (R^2). Results showed that Pesticide DRASTIC and Nitrate SINTACS were the most accurate and efficient methods for the present study area, which is characterized by intense agricultural activities.

Keywords DRASTIC, SINTACS, AVI, GOD and SI methods · GIS · Groundwater vulnerability assessment · Nitrate · Porous aquifer · Sensitivity analysis

Introduction

Groundwater is a significant source of fresh water, and it is essential for meeting water demands associated with irrigation, domestic and industrial use (Machiwal et al. 2018). According to Shekhar and Pandey (2014), more than 30% of the global water needs are met with groundwater. Nonetheless, nowadays, the quality and quantity of groundwater are at high risk. Particularly, groundwater is being threatened directly by many human activities, such as overexploitation, intensive agriculture, burgeoning population, rapid urbanization, wastewater leakage, increasing food production, changes in land use, and also indirectly, through seawater intrusion, climate change, and global warming (Gardner and Vogel 2005; Green et al. 2011; Saidi et al. 2011; Haritash et al. 2017; Machiwal et al. 2018; Ncibi et al. 2020; Chaudhari et al. 2021; Nagkoulis and Katsifarakis 2021).

Furthermore, the extensive use of chemical fertilizers contributes to the significant problem of nitrate pollution of aquifers. The United States of America Environmental Protection Agency (EPA) uses nitrate concentration in groundwater as an indicator for groundwater quality deterioration and identification of vulnerable areas (Haritash et al. 2016; Shrestha et al. 2016; Houria et al. 2020). Nitrate pollution has acute effects on public health and the ecosystems (Li et al. 2017). Thus, the prevention of groundwater pollution is of crucial importance for efficient groundwater management.

Groundwater vulnerability mapping is an efficient tool to prevent groundwater pollution significantly (Oke 2020). In order to assess groundwater vulnerability and contamination risk, researchers developed various techniques and

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methodologies, which can be divided into two major categories: objective (physically based and statistical) and subjective rating methods (Wu et al. 2016). Objective methods offer a more detailed approach, but require a lot of data and complex computational structure for their application. However, since data availability is often limited, the use of subjective methods is usually adopted. (Kumar et al. 2015; Jaunat et al. 2019). Among the most commonly used subjective methods in porous aquifers are DRASTIC (Aller et al. 1987), GOD (Foster 1987), AVI (Van Stempvoort et al. 1993), SINTACS (Civita 1994) and SI (Ribeiro 2000).

DRASTIC is the most popular, reliable and widely used empirical rank/score-based index method. It has been developed by the US EPA and uses seven hydrogeological parameters, namely depth to water (*D*), net recharge (*R*), aquifer media (*A*), soil media (*S*), topography (*T*), impact of the vadose zone (*I*) and hydraulic conductivity (*C*), which control the movement of contaminants towards and through an aquifer (Sener and Sener 2015). The significant advantage of DRASTIC is its simplicity and flexibility in different hydrogeological regimes and sources of pollution, such as agricultural, urban and industrial (Ahmed et al. 2015; Allouche et al. 2017). However, despite its popularity, DRASTIC method introduces human subjectivity, errors and uncertainty in the determination of the rating scales and the weighting coefficients (Goyal et al. 2021). Hence, attempts were undertaken to generally modify the method, in order to better evaluate groundwater vulnerability for a specific aquifer, by (1) adjusting factor weights of the original DRASTIC through different techniques (e.g., sensitivity analysis, AHP method, multiple linear regression) or (2) adding extra factors, such as land use or irrigation type (Secunda et al. 1998; Thirumalaivasan et al. 2003; Ncibi et al. 2020; Saranya and Saravanan 2021; Sresto et al. 2021; Lakshminarayanan et al. 2022). Specifically, Awawdeh et al. (2015) developed a modified DRASTIC model by adding two extra parameters, namely lineaments density and land use/land cover. Results of this model showed a more accurate vulnerability map compared with DRASTIC and a strong correlation between lineaments density and nitrate concentration. Another variation of the standard DRASTIC method (DRAMIC) tried to eliminate the subjectivity by replacing two parameters (soil media and topography) with aquifer thickness (*M*) and contaminant impact parameter (*C*) (Wang et al. 2007). In addition, Kazakis and Voudouris (2015) developed DRASTIC-PA and DRASTIC-PAN models for groundwater vulnerability and risk assessment by replacing the qualitative parameters, namely aquifer media, soil media and impact of the vadose zone, with aquifer thickness, nitrogen loss from soil and hydraulic resistance. Furthermore, in order to verify the accuracy of a groundwater vulnerability method for a specific aquifer, the correlation between chemical parameters, such as nitrate concentration (Javadi et al. 2011), TDS (Shakoor et al. 2020), chloride concentration (Krogulec et al. 2019), sulphide concentration (Ahirwar et al. 2020) and manganese concentration (Mogaji 2018) with groundwater vulnerability values is often used. Notably, the most commonly used chemical parameter for validation is nitrate concentration, since nitrate is highly associated with various anthropogenic activities, such as agriculture (Krishna et al. 2015; Khosravi et al. 2018).

A special variant of DRASTIC is Pesticide DRASTIC, which has the ability to evaluate groundwater vulnerability for a specific pollutant. Compared to the original DRASTIC, it uses different parameter weights for the seven factors, while the parameters ratings are identical. According to Saha and Alam (2014) and Saida et al. (2017), between the two methods, Pesticide DRASTIC has a higher correlation coefficient value, which indicates that the method is more suitable in areas with agricultural activities and extensive use of chemical fertilizers. Another study, comparing DRASTIC and GOD methods reveal that DRASTIC is more effective in evaluating groundwater vulnerability zones according to the correlation (69% and 56%, respectively) with nitrate concentrations (Boufekane and Saighi 2017). Moreover, Oroji (2019) employed four different methods (SI, GOD, SINTACS and DRASTIC) for groundwater vulnerability assessment in a porous aquifer in Iran and found out that the DRASTIC model is the most accurate.

SINTACS method was developed as an adaptation of DRASTIC to the particularities of Mediterranean regions, such as Italy, Greece, Algeria and Morocco. In this method, the definition of parameters' weights and rates is more flexible than DRASTIC. A comparative study in Algeria between DRASTIC and SINTACS resulted in a significant concordance between the methods (Kaddour et al. 2014). A modified method of SINTACS has also been developed by incorporating Land Use parameter (SINTACS-LU), improve the accuracy and efficiency of vulnerability assessment (Eftekhari and Akbari 2020; Jesudhas et al. 2021). SI method is another DRASTIC adaptation and can be used in areas with diffuse agricultural pollution with relatively accurate results (Stigter et al. 2006; Ribeiro et al. 2017). Besides, GOD and AVI are two practical and simplified index-based methods that can be employed in areas with data limitations, providing rapid groundwater vulnerability assessment. The application of all these methods is discussed in the Methodology section.

In general, the need for groundwater vulnerability assessment is high, particularly in agricultural areas with significant nitrate pollution and scarcity of hydrochemical data. Nonetheless, the employment of a single groundwater vulnerability method in a specific region may sometimes lead to inaccurate results, due to the method's inherent uncertainty and limited suitability. Our study focuses on the application and validation of an ensemble of models to evaluate and identify groundwater vulnerability zones to pollution, in Nea Moudania aquifer, Chalkidiki, Greece, which is a typical Mediterranean area with intense agricultural activities and extensive nitrate pollution. Specifically, seven different index methods, namely DRASTIC, Pesticide DRASTIC, SINTACS, Nitrate SINTACS, GOD, AVI and SI were implemented alongside with Geographical Information System (GIS) techniques for the sustainable management of groundwater resources. The accuracy of outputs of the seven methods is validated with the correlation between reported nitrate concentration (NO_3^-) in groundwater and vulnerability index. The combined approach for vulnerability assessment used in this study could support policymakers and planners in decision-making aiming to protect the aquifer system of Nea Moudania, from further groundwater deterioration. An additional, more general objective of this study is to assess the performance, suitability, adaptation and limitations of different groundwater vulnerability methods in an agricultural area, through comparison with field data on nitrate pollution.

Study area description

The study area of Nea Moudania (Fig. 1) is an important agricultural land. It is located in the south-western part of Chalkidiki peninsula, in the Region of Central Macedonia, Northern Greece. Administratively it belongs to the municipalities of Nea Propontida and Polygyros and covers an area of approximately 77.86 km^2. Generally, the altitude in the area is low and ground slopes are mild. The climate is semi-arid to humid, while the average annual precipitation is approximately 420 mm (Siarkos and Latinopoulos 2016). The watershed of Nea Moudania is part of the Peonia geological zone and consists of rocky formations (gneiss,

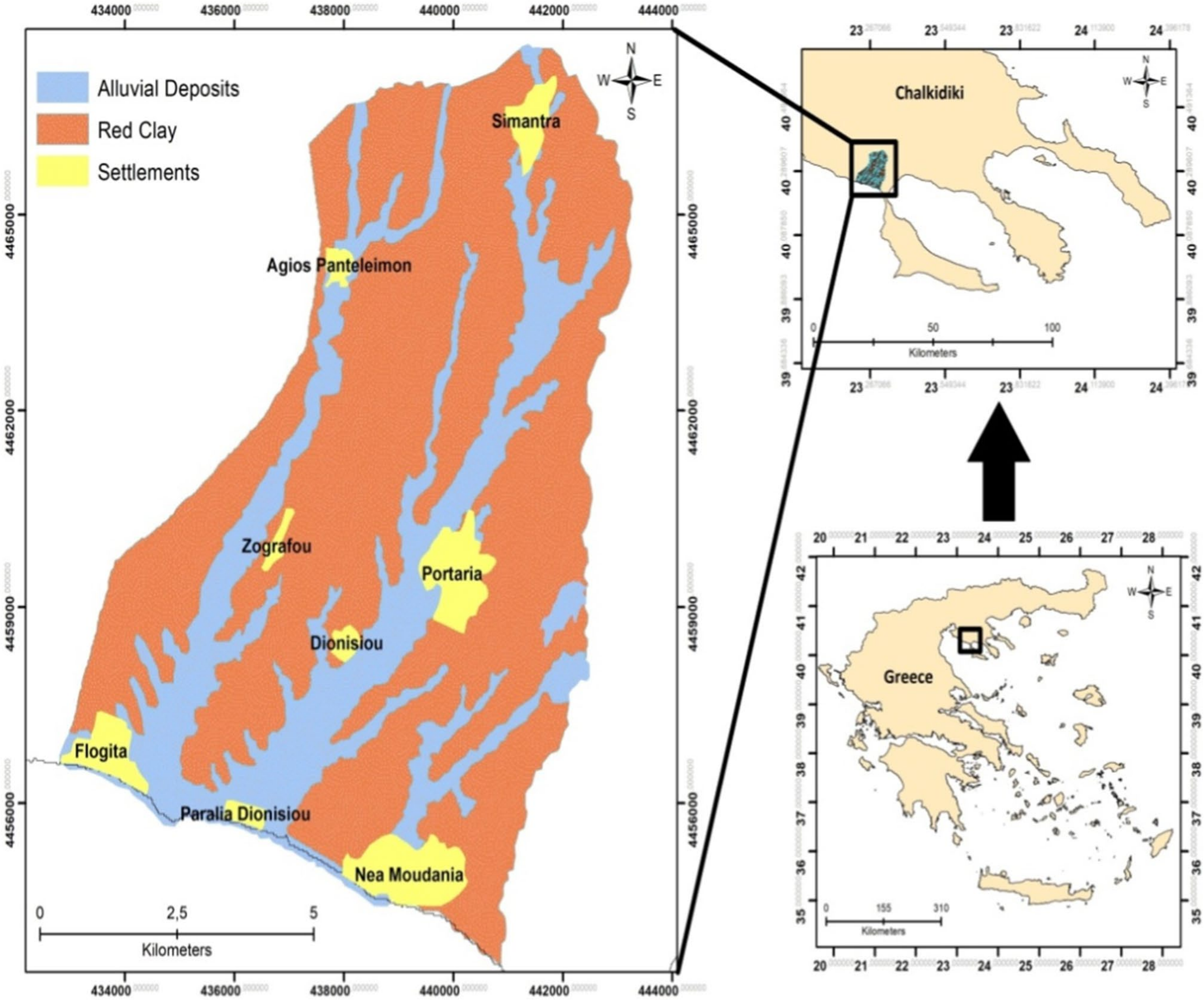

Fig. 1 Location and geological map of the study area

ophiolite and clay schists) in the north, while in the south of Neogene sediments, such as red clay (Moudania formation) and Quaternary alluvial deposits, such as sandstones, conglomerates, clays, gravels and sands (Syridis 1990; Svigkas et al. 2020). Generally, the rocky formations are considered as impermeable, thus hydrogeological interest is primarily focused on the recent deposits (important capacity of water storage and substantial sediment thickness) (Kirlas 2017). The water system shows intense heterogeneity and complexity and consists of successive permeable, semi-permeable and impermeable beds (Siarkos and Latinopoulos 2016). The unsaturated zone has an average thickness of approximately 45 m and it mainly consists of semi-permeable materials (Veranis et al. 2016).

The study area is intensively cultivated and irrigated, while touristic and urban development along its coast is extensive (Panteli and Theodossiou 2016). The permanent population is approximately 16,000 people, while maximum population during the summer (low rain) period exceeds 40,000 people (Kirlas 2017). Therefore, water demand for irrigation and domestic use is high, particularly during the summer months. Additionally, the area is characterized by scarcity of surface water combined with low annual precipitation and thus groundwater is the only viable water source (Kirlas and Katsifarakis 2020). Generally, a basic network of private and municipal wells can partially satisfy the total water demand (Latinopoulos et al. 2003). Over the years water deficit has become a significant problem, as water demand exceeds the aquifer's recharge and consequently, due to overexploitation, considerable groundwater level lowering has occurred (Kirlas 2021). In addition to the quantitative degradation of groundwater, the improvident use of fertilizers and pesticides has resulted in the qualitative deterioration of the aquifer system. Hence, an integrated management of this system, including protection of groundwater quality, is of pivotal importance.

Methodology

In this paper, seven different methods were applied in GIS environment to delineate contamination vulnerability zones of Nea Moudania aquifer in Northern Greece. Specifically, the groundwater intrinsic and specific vulnerability evaluation includes the implementation of following methods: DRASTIC, Pesticide DRASTIC, SINTACS, Nitrate SINTACS, GOD, AVI and SI. GIS techniques are proper tools for handling and analyzing large data sets in order to produce easily comprehensible vulnerability maps. The output maps were created using the inverse distance weighted (IDW) method (Chakraborty et al. 2022). The methodology employed in this study has the following steps: (1) raw data sets collection, (2) GIS map construction for every parameter for the different methods, (3) preparation of vulnerability maps for each method, (4) sensitivity analysis to compare the effective with the theoretical parameters weight, (5) validation of vulnerability maps with nitrate concentration using determination coefficient (R^2).

DRASTIC and pesticide DRASTIC methods

The most widely used method for groundwater vulnerability evaluation (intrinsic and specific) is DRASTIC. It is an overlay index method initially developed in 1987 by the US EPA and the American Water Works Association (AWWA). According to Barzegar et al. (2018) it is supposed to be the most popular, reliable, economical, efficient and easy to use method for assessing groundwater vulnerability.

DRASTIC is an acronym for the seven most significant hydrogeological parameters, which predominantly control groundwater flow and pollution, namely, depth to water (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I) and hydraulic conductivity (C). The method is based on the following four assumptions: (1) pollution occurs at the ground surface, (2) pollutants seep into the water table by precipitation, (3) pollutants have the same mobility as water, (4) the study area must be at least 0.4 km^2 (Hamza et al. 2014). According to its importance, each parameter is assigned with a weight between 1 and 5. The least important parameter has a weight equal to 1, while 5 is allocated to the most important one (Salih and Al-Manmi 2021). The weights and the ratings are based on the Delphi technique (Gogu and Dassargues 2000). Standard DRASTIC is used for normal conditions, whereas pesticide DRASTIC is adopted in agricultural areas with extensive use of pesticides and fertilizers and for this reason the respective weight classification is different (Aller et al. 1987). Moreover, the rating of each parameter depends on its relative significance on pollution potential and ranges from 1 to 10 (Table 1). The final DRASTIC Index (DI) is a weighted linear combination of the aforementioned parameters and is calculated using Eq. (1).

$$\mathrm{DI} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_W + C_r C_w \tag{1}$$

where D, R, A, S, T, I and C indicate the seven parameters of the method, while indices w and r represent the weight of each parameter and the corresponding rating, respectively.

Standard DRASTIC Index varies from 23 to 230, while the Pesticide DRASTIC Index varies from 26 to 256. In general, higher values of DRASTIC Index are equivalent to greater aquifer vulnerability. Commonly, DRASTIC Index above 200 indicates very high vulnerability (Ncibi et al. 2020). Aller et al. (1987) did not suggest any specific classification for Pesticide DRASTIC index results and thus

Table 1 Weight, ranges and ratings of DRASTIC and Pesticide DRASTIC parameters

DRASTIC parameter	Range/type	Rating	Standard weight	Pesticide weight
D: depth to water (m)	0–10	10	5	5
	10–20	7		
	20–30	5		
	30–40	3		
	> 40	1		
R: net recharge	3–5	1	4	4
	5–7	3		
	7–9	5		
	9–11	8		
	11–13	10		
A: aquifer media	Massive shale	2	3	3
	Metamorphic/igneous	3		
	Weather metamorphic/igneous, clay with sand	4		
	Glacial till, clay with gravel	5		
	Bedded sandstone, shale sequences, massive sandstone, massive limestone	6		
	Sand	7		
	Sand and gravel	8		
	Basalt	9		
	Karst limestone	10		
S: soil media	No shrinking clay	1	2	5
	Muck	2		
	Clay loam	3		
	Silty loam	4		
	Loam	5		
	Sandy loam	6		
	Shrinking clay	7		
	Peat	8		
	Sand	9		
	Gravel	10		
	Thin or absent	10		
T: topography (%)	0–2	10	1	3
	2–6	9		
	6–12	5		
	12–18	3		
	> 18	1		
I: impact of vadose zone	Confining layer	1	5	4
	Silt/clay	3		
	Shale	3		
	Limestone	3		
	Sandy clay	4		
	Sandstone	6		
	Sand, gravel and silt	7		
	Sand and gravel	8		
	Basalt	9		
	Karst limestone	10		
C: hydraulic conductivity (m/day)	0.04074–4.074	1	3	2
	4.074–12.222	2		

Table 1 (continued)

DRASTIC parameter	Range/type	Rating	Standard weight	Pesticide weight
	12.222–28.518	4		
	28.518–40.74	6		
	40.74–81.48	8		
	> 81.48	10		

most scientists define the boundary of each according to their own judgment.

SINTACS method

SINTACS method was proposed by Civita (1994) for the particularities of Mediterranean regions and is composed of the same parameters as the DRASTIC method, namely it includes the following parameters (their names are given in Italian, as well, to explain the name of the method): depth to water (Soggiacenza), effective infiltration (Infiltrazione), unsaturated zone (Nonsaturo), soil media (Tipologia della copertura), aquifer media (Acquifero), hydraulic conductivity (Conducibilità idraulica) and topographic slope (Superficie topografica) (Gogu et al. 1996; Ikenna et al. 2021). Although SINTACS uses the same parameters as DRASTIC, the assigned ratings of each parameter are different as shown in Table 2. Notably, due to the fact that the weights in SINTACS are given in a more inclusive manner for the consideration of all possible environmental conditions, this method can be applied in different hydrogeological zones (Kumar et al. 2013). The string of weights is given in Table 3. The vulnerability classes and the corresponding ranges are given in Table 4. The SINTACS index ranges from 26 to 260 and is calculated as the weighted sums of the seven parameters, using Eq. 2.

$$\text{SINTACS} = S_r S_w + I_r I_w + N_r N_w + T_r T_w + A_r A_w + C_r C_w + S_r S_w \tag{2}$$

GOD method

GOD method is a commonly used parametric vulnerability method developed in United Kingdom (Foster 1987). It consists of three parameters only, namely, the type of groundwater confinement (G), overall lithological character of the vadose zone (O) and depth to groundwater table (D); thus the method is useful when data availability is small (Boufekane and Saighi 2017; Mfonka et al. 2018; Duarte et al. 2019). The ranges and ratings of the GOD parameters are given in Table 5, while the vulnerability ranges are shown in Table 6. The GOD index is calculated according to the following Eq. 3, and it ranges from 0 (negligible vulnerability) to a maximum of 1 (extreme vulnerability).

$$\text{GOD} = G \times O \times D \tag{3}$$

AVI method

AVI method (Van Stempvoort et al. 1993) is based on two primal physical parameters: (1) thickness of every sedimentary layer deposit above the uppermost saturated aquifer surface d, and (2) its estimated hydraulic conductivity K (Table 7). Using these two parameters AVI method calculates the theoretical factor, namely, hydraulic resistance c, as given below (Eq. 4):

$$c = \sum_{i=1}^{n} \frac{d_i}{K_i} \tag{4}$$

This factor represents the approximate time for water to move by advection downward through the porous media above the aquifer surface. However, it does not indicate the actual duration of water or contaminants flow, since diffusion and sorption are not considered (Wachniew et al. 2016). The relationship of the hydraulic resistance c to the aquifer vulnerability is shown in Table 8. A limitation of this method is that it does not consider many significant parameters, such as climatic conditions, hydraulic gradient and porosity. Moreover, it is not suitable for karst aquifers (Kumar et al. 2015).

SI method

The Susceptibility Index (SI) is an adaption of the DRASTIC method and was developed by Ribeiro (2000) to assess diffuse agricultural pollution in hydrogeological settings mainly found in Portugal. The method is based on four DRASTIC parameters, namely depth to water (D), net recharge (R), aquifer media (A) and topography (T) and one additional parameter which defines the land use (LU) (Noori et al. 2019). The rest of the DRASTIC parameters (S, I, C) were not included, because the original quality characteristics of natural soils often change during cultivation of land due to ploughing, tillage and other techniques (Stigter et al. 2006). The SI is calculated by Eq. 5.

Table 2 Ranges and ratings of SINTACS parameters (Civita and De Maio 1997)

SINTACS parameters	Range	Rating
S (m)	0–1	10
	1–4	9
	4–6	8
	6–8	7
	8–10	6
	10–20	5
	> 20	4
I (mm)	< 50	1
	50–60	2
	60–75	3
	75–100	4
	100–125	5
	125–150	6
	150–175	7
	175–250	8
	250–325	9
N	Coarse alluvial deposits	6–9
	Karstified limestone	8–10
	Fractured limestone	4–8
	Fissured dolomite	2–5
	Medium fine alluvial deposits	3–6
	Sand complex	4–7
	Sandstone, conglomerate	5–8
	Turbiditic sequences	2–5
	Fissured volcanic rocks	5–10
	Marl, clay stone	1–3
	Clay, silt, peat	1–2
	Pyro-clastic rock	2–5
	Fissured metamorphic rocks	2–6
T	Clay	1–1.5
	Silty-clay	1.5–2
	Clay loam	2–3
	Silty clay loam	3–4
	Silt loam	3.5–4
	Loam	4–5
	Sandy clay loam	4.5–5
	Sandy loam	5.5–6
	Sandy clay	6.3–7
	Peat	7.5–8
	Sandy	8–8.5
	Clean sand	9–9.5
	Clean gravel	9.5–10
	Thin or absent	10
A	Coarse alluvial deposits	8–9
	Karstified limestone	9–10
	Fractured limestone	6–9
	Fissured dolomite	4–7
	Medium fine alluvial deposits	6–8
	Sand complex	7–9
	Sandstone, conglomerate	4–9
	Turbiditic sequences	5–8
	Fissured volcanic rocks	8–10
	Marl, clay stone	1–3
	Clay, silt, peat	1–3
	Pyro-clastic rock	4–8
	Fissured metamorphic rocks	2–5
C (m/day)	< 0.1	1
	0.1–0.43	2
	0.43–0.86	4
	0.86–4.32	5
	4.32–8.64	6
	8.64–43.2	7
	43.2–86.4	8
	86.4–432	9
	432–864	10
S (%)	0–2	10
	3–4	9
	5–6	8
	7–9	7
	10–12	6
	13–15	5
	16–18	4
	19–21	3
	22–25	2
	> 26	1

$$\text{Susceptibility Index (SI)} = D_r D_w + R_r R_w + A_r A_w + T_r T_w + LU_r LU_w \quad (5)$$

where *D*, *R*, *A*, *T* and *LU* indicate the initials of the parameters, while indices *w* and *r* represent the weight of each parameter and the corresponding rating, respectively. The assigned weights for each SI parameter are shown in Table 9. The rating for land use parameter, derived from Corine Land Cover, ranges between 0 and 100 and is shown in Table 10. Vulnerability ranges and classes are shown in Table 11.

Sensitivity analysis

In general, sensitivity analysis measures the uncertainty and the robustness of the output results obtained from various methods. In this study, the single-parameter sensitivity analysis is implemented to assess the effect of each parameter on the vulnerability index, by comparing its assigned (theoretical) weight with the real (effective) weight (Napolitano and Fabbri 1996; Brindha and Elango 2015; Oke 2020). This technique helps the researcher to evaluate the importance

Table 3 String of weights in SINTACS method (Civita and De Maio 1997)

Parameter	*S*	*I*	*N*	*T*	*A*	*C*	*S*
Normal	5	4	5	3	3	3	3
Severe	5	5	4	5	3	2	2
Seepage	4	4	4	2	5	5	2
Karst	2	5	1	3	5	5	5
Fissured	3	3	3	4	4	5	4
Nitrates	5	5	4	5	2	2	3

Table 4 Vulnerability index rating classes for SINTACS method (Civita and De Maio 1997)

Vulnerability classes	Ranges
Very low	26–80
Low	80–105
Medium	105–140
High	140–186
Very high	186–210
Extremely high	210–260

Table 6 Vulnerability ranges corresponding to the GOD index

Vulnerability	Ranges
Negligible	0–0.1
Low	0.1–0.3
Moderate	0.3–0.5
High	0.5–0.7
Extreme	> 0.7

Table 5 Ratings of GOD parameters

GOD parameters	Rating	Range
G: groundwater occurrence	0	None
	0	Overflowing
	0.2	Confined
	0.4	Semi-confined
	0.6	Uncovered (confined)
	0.7–1.0	Unconfined
O: lithology of the vadose zone	0.4	Residual soils
	0.5	Alluvial silt, loess, glacial till
	0.5	Mudstones
	0.5	Shales
	0.6	Aeolian sands
	0.6	Siltstones
	0.6	Igneous/metamorphic formations
	0.6–0.7	Volcanic tuffs
	0.7	Alluvial and fluvio-glacial sands
	0.8	Alluvial fan gravels
	0.7–0.8	Sandstones
	0.8	Recent volcanic lavas
	0.9	Chalky limestone calcarenites
	0.9–1.0	Calcretes + karst limestones
D: depth to groundwater table	0.9	All depths (karst limestones)
	0.9	< 5 m
	0.8	5–20 m
	0.7	20–50 m
	0.5	50–100 m
	0.4	> 100 m

of subjectivity elements in the vulnerability methods (Gogu et al. 2003; Djémin et al. 2016; Noori et al. 2019). The effective weights for all parameters were calculated using the following Eq. 6.

$$W = \left(\frac{P_r P_w}{V}\right) \times 100 \tag{6}$$

where W is the effective weight of each parameter, P_r and P_w are the rating value and the weight of each parameter, and V denotes the overall vulnerability index (Ouedraogo et al. 2016). All thematic maps that were used in the single-parameter sensitivity analysis were prepared in the GIS environment. When a parameter has an effective weight greater than the theoretical one, it has a higher significance on the results of the groundwater vulnerability model.

Vulnerability assessment parameters—data preparation

Depth to water

This parameter is supposed to be of great importance for groundwater quality degradation. It represents the actual depth from ground surface to the water table and its thickness works as a resistive force for the pollutant until it reaches the saturated aquifer. Higher values of depth to groundwater indicate smaller chance of pollution, thus less vulnerability, because of the higher potential for natural attenuation. In this study the groundwater level of 42 observation wells were used during spring period and they were interpolated using the inverse distance weighted (IDW) technique of ArcGIS spatial analyst software to the data (Tirkey et al. 2013; Shahab

Table 7 Rating values of the hydraulic conductivity *K* parameter for the AVI method

K	Lithology	Gravel	Sands	Marls	Loams	Clays
	K (m/d)	10^3	10^{-2}–10^2	10^{-3}–10^{-1}	10^{-4}–10^{-1}	10^{-7}–10^{-5}

Table 8 Relationship of aquifer vulnerability index to hydraulic resistance (Van Stempvoort et al. 1993)

Hydraulic resistance (*c*) [years]	Log *c*	Aquifer vulnerability index (AVI)
0–10	< 1	Very high
10–100	1–2	High
100–1000	2–3	Moderate
1000–10,000	3–4	Low
< 10,000	> 4	Very low

Table 9 Weights for each parameter in SI method

Parameter	Weight
D: depth to water	0.186
R: net recharge	0.212
A: aquifer media	0.259
T: topography	0.121
LU: land use	0.222

Table 10 Ratings for land use parameter according to SI method

Land use	Rating
Industrial discharge, landfill, mines	100
Irrigated perimeters, paddy fields, irrigated and non-irrigated annual culture	90
Quarries, shipyards	80
Artificial covered zones, green zones, continuous urban zones	75
Permanent cultures (vines, orchards, olive trees, etc.)	70
Discontinuous urban zones	70
Pastures and agro-forest zones	50
Aquatic milieu (swamps, saline, etc.)	50
Forest and semi-natural zones	0

Table 11 Vulnerability classes for SI method

Vulnerability classes	Ranges
Extremely low	< 30
Very low	30–40
Low	40–50
Moderate to low	50–60
Moderate to high	60–70
High	70–80
Very high	80–90

et al. 2018; Yankey et al. 2020; Bera et al. 2021; Chakraborty et al. 2022). The rating varies from 1 (for D > 40 m) to 10 (for 0–10 m) and the classification of D values for DRASTIC and Pesticide DRASTIC was made according to Sener et al. (2009) and Khan and Jhariya (2019). Alongside the coastline, in the southern part of the study area the aquifer is generally shallow (depth to water varied from 8 to 20 m) and thus it is more vulnerable to pollution, since the reduced percolation time allows the pollutants to mix up with the groundwater (Bera et al. 2021). On the other hand, the least effect of the depth to water on groundwater vulnerability occurred in the central and northern part of the area, where the aquifer is deeper (> 40 m).

Net recharge

This parameter represents the amount of surface water that infiltrates through soil into the ground surface and reaches the aquifer system. Infiltration plays a vital role for the movement of surface pollutants into groundwater and within aquifer media. Hence, higher infiltration values lead to increased pollution potential, because the downward movement of pollutants is promoted (Aller et al. 1987). In this study net recharge was estimated using Piscopo method that integrates the slope, rainfall and soil permeability maps as follows (Piscopo 2001; Awawdeh et al. 2015; Muhammad et al. 2015; Baghapour et al. 2016; Khan and Jhariya, 2019; Yankey et al. 2020).

$$\text{Recharge value} = \text{Slope} + \text{Rainfall} + \text{Soil permeability} \tag{7}$$

The slope map was prepared by using the Advanced Space borne Thermal Emission and Reflection Radiometer Digital Elevation Model (ASTER-DEM) data in raster file format with 30 m spatial resolution. Rainfall was calculated in a previous research in the study area, and it was estimated approximately 420 mm/year (Siarkos and Latinopoulos 2016). Soil permeability was calculated based on the results of a soil survey (0–30 cm of soil samples) that was carried out in the study area (Misopolinos et al. 2015). The soil mainly consists of clay loam in the northern part (very low permeability), clay to silty loam in the central (low permeability) and loam to sandy loam in the southern part (moderate to mod-high permeability). The weighed grids of the above three maps have been integrated to give the net recharge index values (Eq. 7). The respective ratings according to this method are given in Table 12. Recharge for the southern part was assigned with 5, whereas the rest of the study area had 3 (Fig. 2).

Table 12 Net recharge ratings according to Piscopo method

Slope		Rainfall		Soil permeability		Recharge value	
Range (%)	Factor	Range (mm/year)	Factor	Range	Factor	Range	Rating
< 2	4	> 850	4	High	5	11–13	10
2–10	3	700–850	3	Mod-high	4	9–11	8
10–33	2	500–700	2	Moderate	3	7–9	5
> 33	1	< 500	1	Slow	2	5–7	3
				Very slow	1	3–5	1

Aquifer media

It represents the characteristics of the saturated zone, which controls the process of the pollutant attenuation. The aquifer media depends on the porosity and the particle size of its constituent materials. Generally, larger grain size results in higher vulnerability. When pollutants reach the water table they get dispersed in groundwater and thus they get diluted (Jesudhas et al. 2021). The rankings of aquifer media were assigned based on the lithological profile of 16 wells. The major constituents of the aquifer media were clay, sand and gravels.

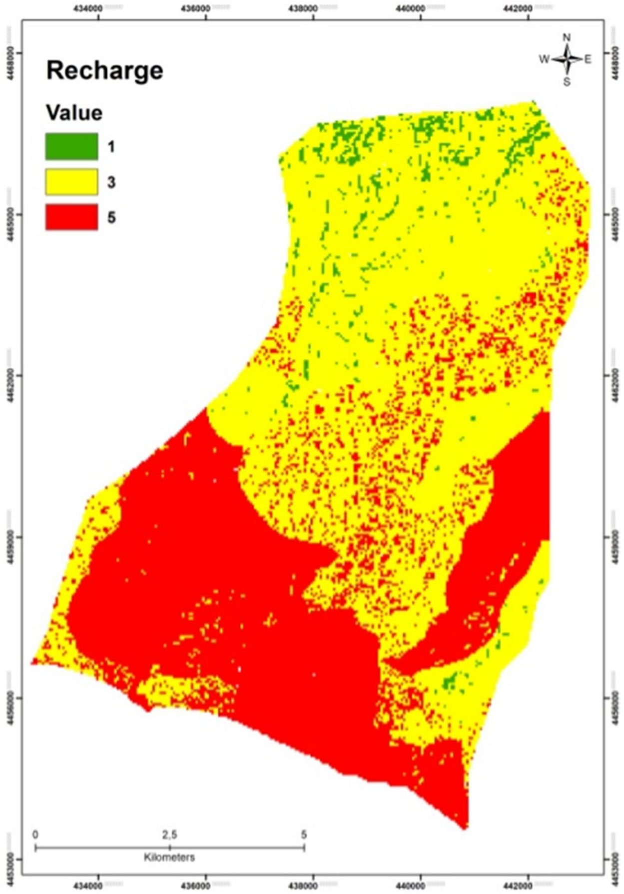

Fig. 2 Recharge of the study area

Soil media

Soil media refers to the uppermost weathered layer of the unsaturated zone, which controls the amount of recharge that can infiltrate downward, depending on soil porosity and permeability (Babiker et al. 2005). This layer can play a significant role in the movement of possible pollutants (Ifediegwu and Chibuike 2021). Coarse texture soils lead to higher vulnerability, compared to fine texture soils, because of the fact that the pollutants can move faster into the aquifer system. Soil map was obtained from a recent research about soil geographic data and delineation of agricultural zones, funded by the Greek Ministry of Agricultural Development and Food (Misopolinos et al. 2015). The type of soil found in the study area was mostly clay loam and silty loam in the northern and central part, which was assigned with 3 and 4, respectively; silty loam, loam and sandy loam in the southern part, which was assigned with 4, 5 and 6, respectively (Fig. 3).

Topography

Topography represents the slope variability of the land surface. In general, low slope areas exhibit higher groundwater pollution vulnerability, because surface run-off flow moves at a low velocity, while water infiltration is high, enhancing pollutants migration to the aquifer (Fig. 4). On the other hand, infiltration in high slope areas usually encountered at high elevations is reduced and thus vulnerability to pollution decreases (Ifediegwu and Chibuike 2021). The slope map of the study area was derived from ASTER DEM using a spatial analyst tool in ArcGIS. The slope percentage ranged between 0 and 24%. Specifically, the slope of almost 20% of the total area ranged between 0 and 2%, while more than 58% of the total area ranged between 2 and 6%. Therefore, the gentle slope on most of the area indicated a maximum effect of topography on the aquifer vulnerability.

Vadose zone

It is the unsaturated or discontinuously saturated zone between the soil cover and the water table or aquifer (Aller et al. 1987; Arya et al. 2020). The soil materials of this zone

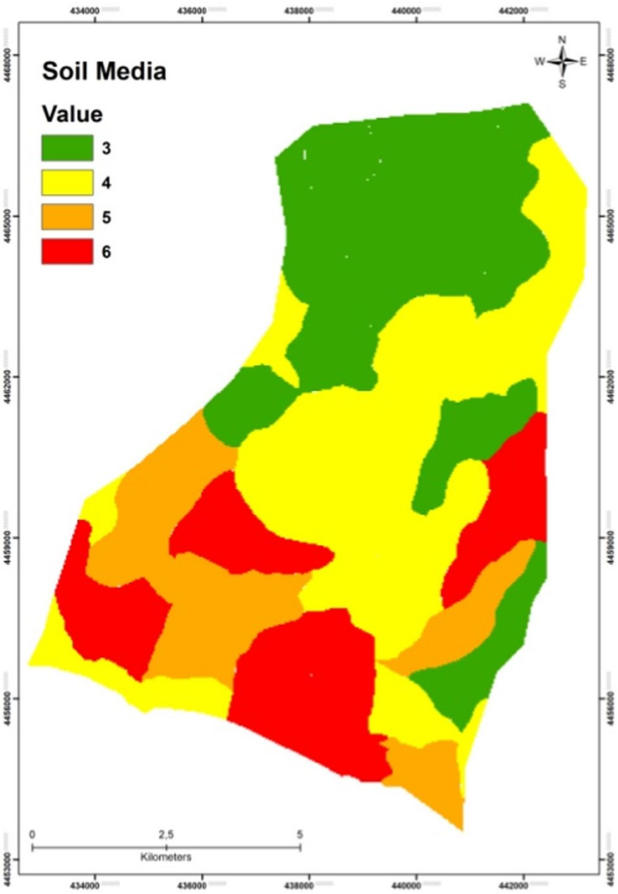

Fig. 3 Soil media of the study area

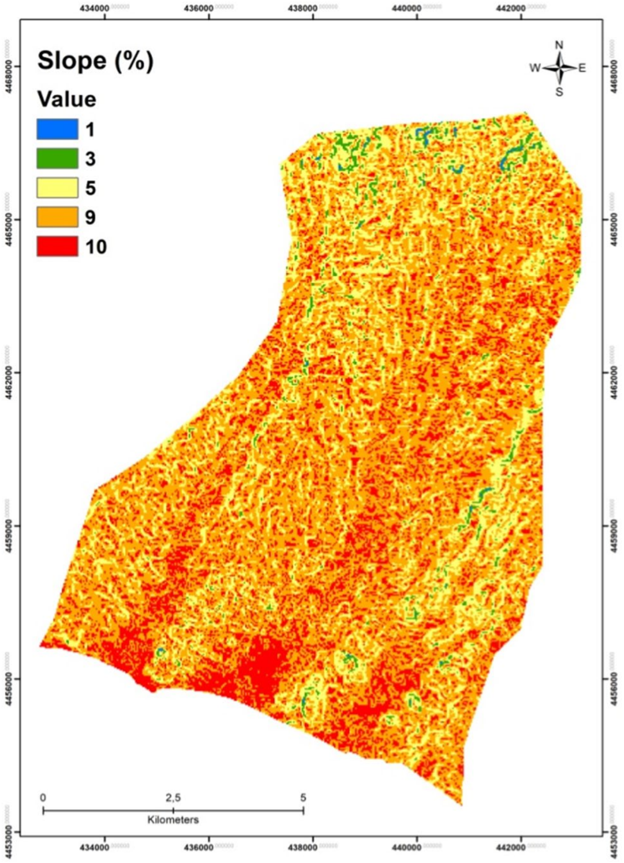

Fig. 4 Topography of the study area

play a considerable role in decreasing groundwater potential pollution due to different debilitation processes, such as dispersal and chemical reactions (Elmeknassi et al. 2021). In general, the higher the materials' grain sizes, the greater the vulnerability potential. The lithological data for this parameter were collected from 16 wells and then they were sub-classified according to their ability to allow and transmit water. The northern part, which mainly consists of red clay, was assigned with the lowest rating. On the contrary, alongside the coast the influence of this parameter on aquifer vulnerability is more significant, as the area consists of alluvial deposits, such as sand and gravel with some clay.

Hydraulic conductivity

The ability of aquifer materials to transmit groundwater is described as hydraulic conductivity. Hence, pollutants migration depends on hydraulic conductivity (Aller et al. 1987). Higher hydraulic conductivity portends a higher potential danger for groundwater pollution because pollutants can move faster through the aquifer. In this study, hydraulic conductivity was obtained from pumping tests and the corresponding map was prepared using the inverse distance weight (IDW) interpolation of ArcGIS. The hydraulic conductivity of the study area is rather low, and its values range from 1×10^{-6} m/s to 2×10^{-5} m/s (Latinopoulos et al. 2003; Kirlas and Katsifarakis 2020; Kirlas 2021).

Land use

Land use represents the natural and human activities that happen on the land surface. In many areas, groundwater is substantially affected by different land use types, such as agricultural, urban and industrial. For instance, in agricultural land, intensive application of chemical fertilizers and pesticides is responsible for the severe problem of the nitrate pollution of aquifers (Wu et al. 2016). Land use data are based on the classes of Corine Land Cover 2012 and its ratings have been assigned according to Table 10. In the study area, the agricultural use predominates, namely complex cultivation patterns (19.26%), fruit trees and berry plantations (26.49%), olive groves (16.61%) and non-irrigated arable land (29.89%).

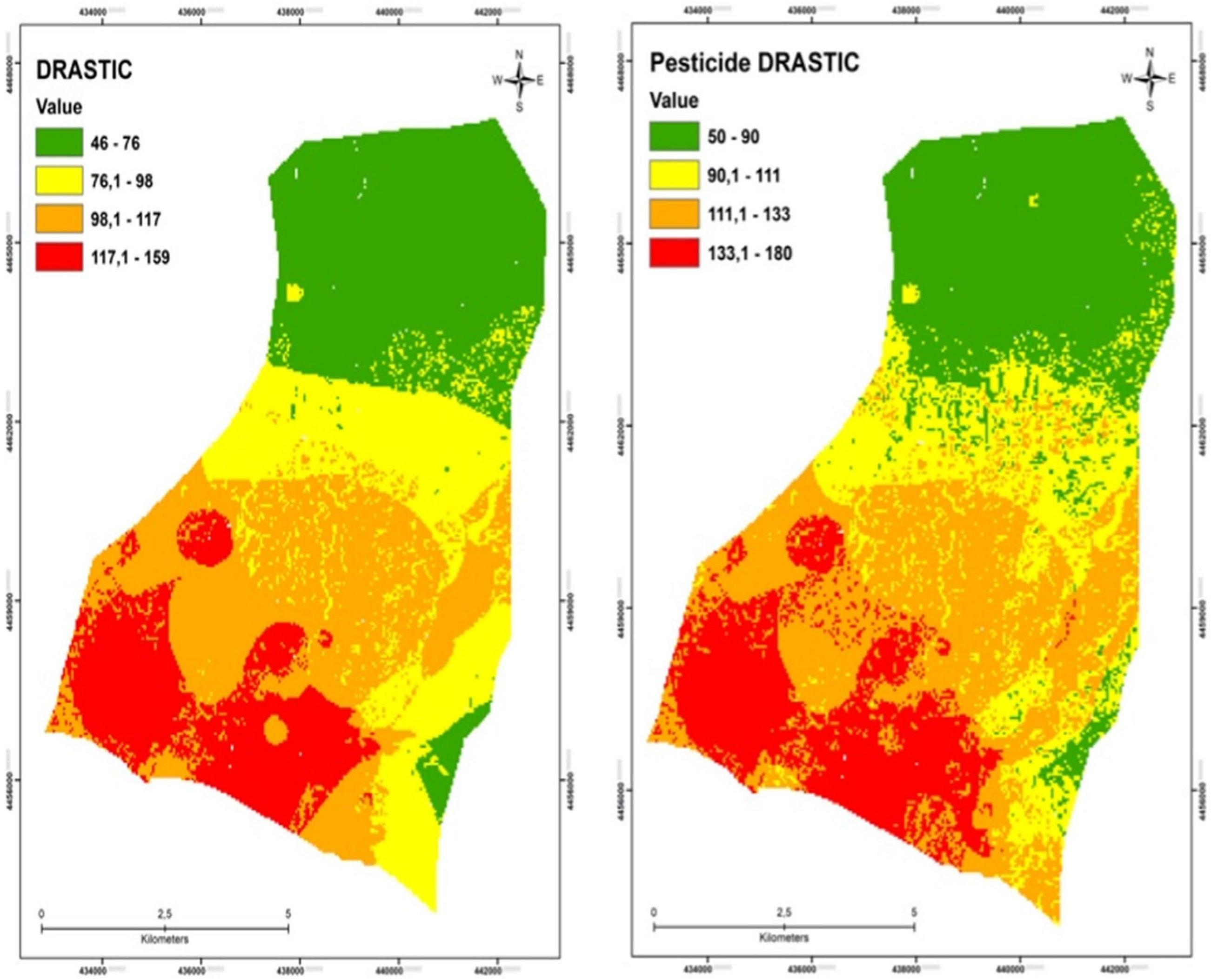

Fig. 5 **a** DRASTIC vulnerability map (left) and **b** Pesticide DRASTIC vulnerability map (right)

Results and discussion

Vulnerability assessment methods

DRASTIC vulnerability map

In Nea Moudania aquifer the final DRASTIC vulnerability map (Fig. 5a), calculated using Eq. 1, varied from 46 to 159. The study area was divided according to Jenks natural breaks method (Ersoy and Gültekin 2013; Thapa et al. 2018; Kumar and Pramod Krishna 2019; Wei et al. 2021) into the following classes: very low (< 76), low (76–98), moderate (98–117) and high (117–159). DRASTIC vulnerability map distribution showed that about 29.21%, 23.52%, 30.23% and 17.04% of the area was classified as very low, low, moderate and high vulnerability, respectively.

Specifically, the area of high vulnerability was mainly concentrated in the southern and south-western part of the study area and alongside the coastline where the depth to water is generally low, the topography is flat (0–2%) and recharge and soil permeability are slightly higher compared to the northern part. On the other hand, the northern part of the basin showed very low vulnerability, because the topography and the depth to water are higher as well as the thickness of the vadose zone and thus decreasing the pollution process. The central part of the area was classified as low to moderate vulnerability.

Pesticide DRASTIC vulnerability map

The range of the final Pesticide DRASTIC vulnerability index was between 50 and 180 and it was higher than that of the standard DRASTIC (Al-Abadiet al. 2017; Al-Mallah and Al-Qurnawi 2018) (Fig. 5b). The values of the Pesticide DRASTIC were classified according to Jenks natural breaks method into: very low (< 90), low (90–111), moderate

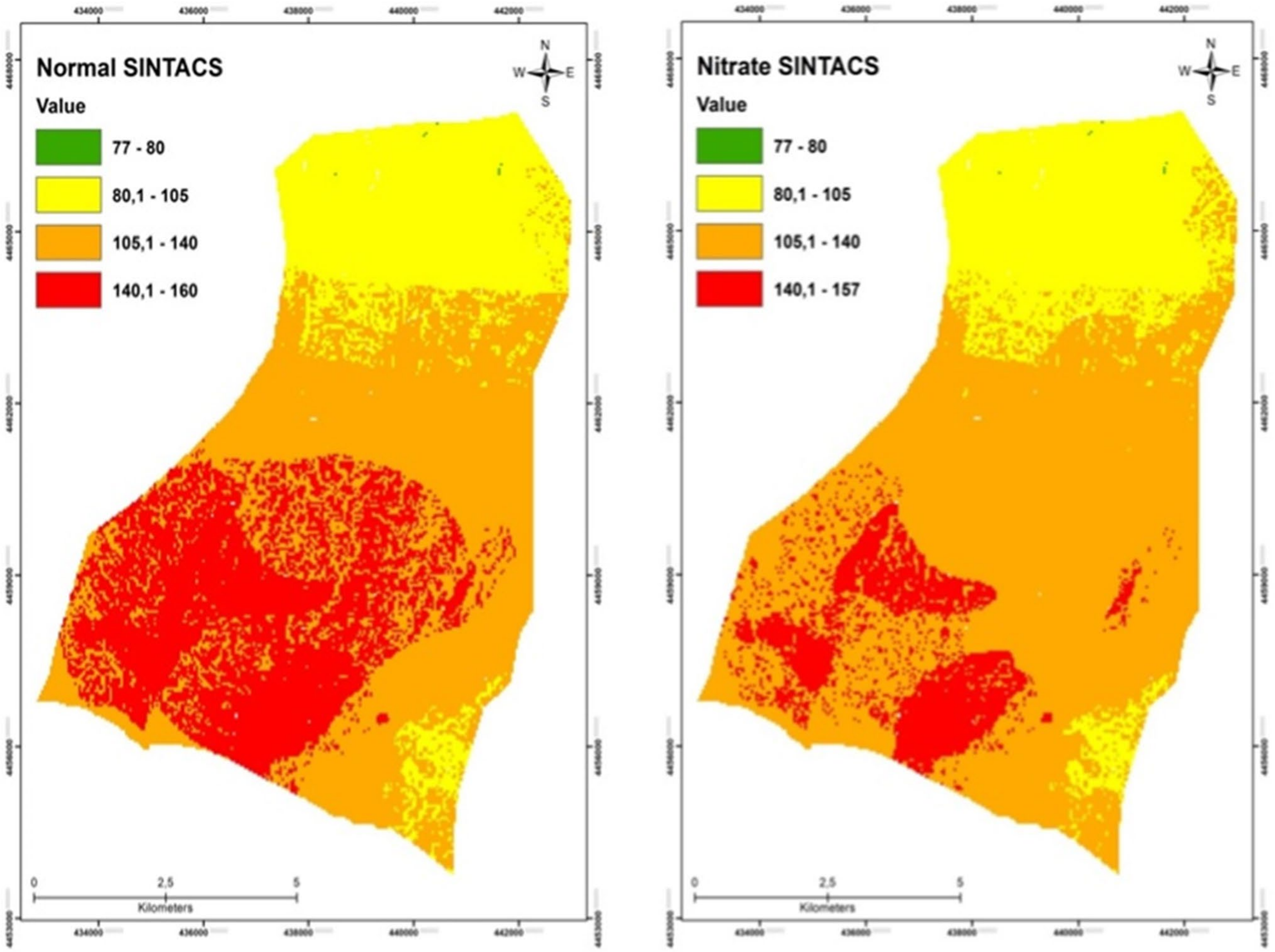

Fig. 6 **a** SINTACS vulnerability map with Normal impact assigned weights (left) and **b** SINTACS vulnerability map with Nitrate impact assigned weights (right)

(111–133) and high (133–180). Very low, low, moderate and high classes occupied an area of 26.23%, 21.60%, 34.48% and 17.69%, respectively. Pesticide DRASTIC resulted in four vulnerability classes similar to the standard DRASTIC model results. The difference between the two models was that in the Pesticide DRASTIC the very low and low classes covered a smaller area (47.83% compared to 52.73%), whereas the moderate class a larger one (34.48% compared to 30.23%). This difference is due to the different weights assigned to the parameters. The high class displayed no significant difference.

SINTACS vulnerability maps

The SINTACS index was estimated using Eq. 2 for two different scenarios, namely normal and nitrate. The first scenario represented the normal impact of the weights on the parameters, as illustrated in Table 3. The final normal SINTACS vulnerability index (Fig. 6a) varied from 77 to 160 and was classified into four vulnerability categories in accordance with Table 4: very low, low, moderate and high, which covered a 0.06%, 23.32%, 47.16% and 29.45% of the total area, respectively.

The second scenario represented the nitrate impact on the study area and each parameter weight was assigned according to Table 3. The final nitrate SINTACS vulnerability index (Fig. 6b) ranged between 77 and 157 and was classified again into four vulnerability classes as follows: very low, low, moderate and high. Each class occupied a total area of 0.01%, 24.29%, 63.92% and 11.78%, respectively.

In both scenarios the very low and low vulnerability classes were detected in the northern part of the basin and occupied the same percentage of the total area (24%). Nonetheless, the moderate class, mainly located in the central part, in nitrate SINTACS covered a significantly larger area (63.92%) compared to the normal SINTACS (47.16%). Moreover, high vulnerability zones were detected in the south and south-western part of the study area.

GOD vulnerability map

The GOD index is calculated using Eq. 3 and according to the method classification (Table 6) only two vulnerability zones were defined in the area, which correspond to low (0.1–0.3) and moderate vulnerability (> 0.3) respectively (Fig. 7). The GOD map showed a homogeneous distribution as the largest area of the basin (98.12%) was classified as low vulnerability and only a small part in the south (1.88%) belonged to the moderate vulnerability. Furthermore, the GOD index did not manage to detect any very low, high and very high vulnerability zone.

AVI vulnerability map

The AVI vulnerability index (log*c*), obtained using Eq. 4, had a range between − 0.7 and 5.1. According to the method's classification (Table 8) the study basin was divided into five vulnerability classes (Fig. 8) with their respective areas (%): very low class (27.72%), low class (35.83%), moderate class (25.91%), high class (7.13%) and very high class (3.42%).

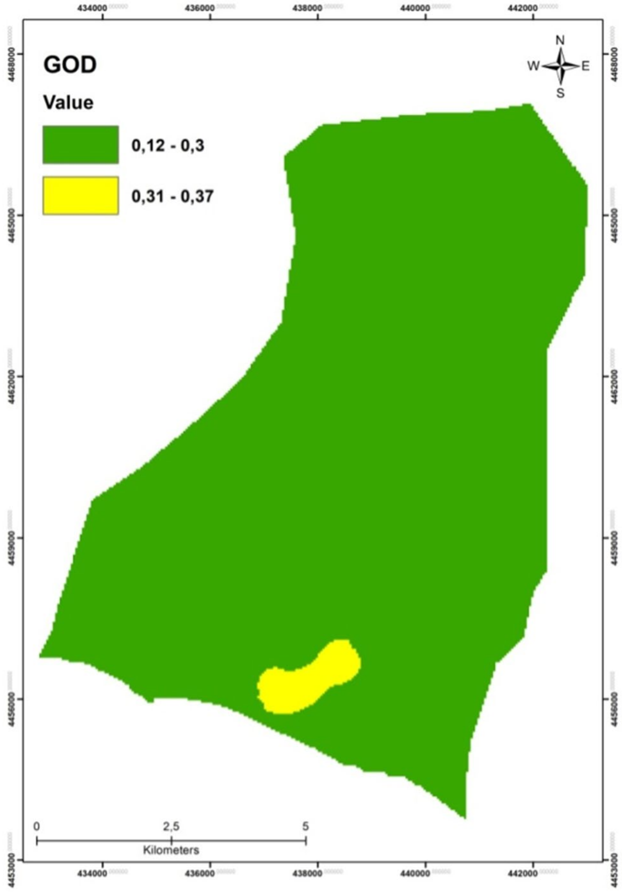

Fig. 7 GOD vulnerability map

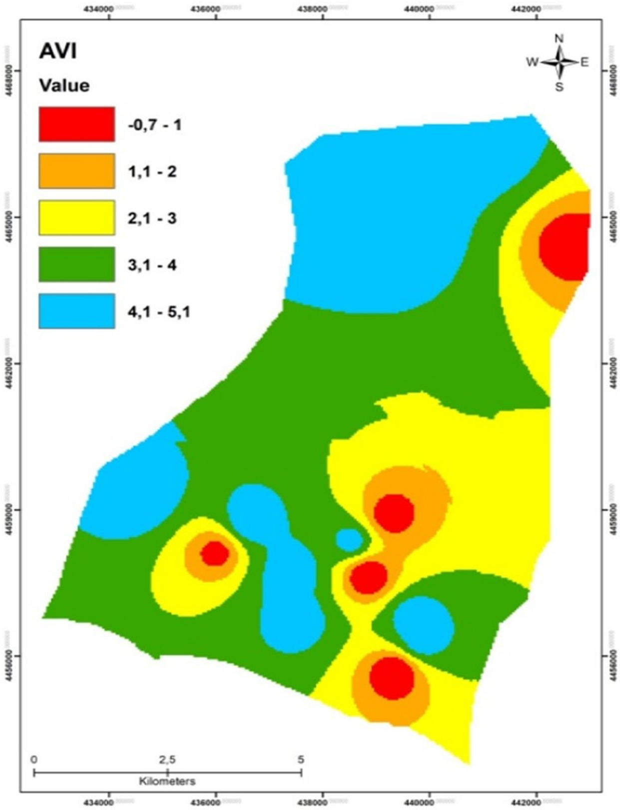

Fig. 8 AVI vulnerability map

Areas with very low vulnerability were mainly found in the northern and northwestern part with some smaller parts in the south; low vulnerability zone was concentrated in the central and western part of the basin; moderate vulnerability zone covered the eastern part; high and very high vulnerability class was detected in south-western and southeastern parts of the area, along with a small part in the northeast that no other method classified in this class.

SI vulnerability map

The SI vulnerability map was created by summing up all the assigned parameters according to Eq. 5. The final groundwater vulnerability index (Fig. 9) varied from 31 to 80 and was classified into five vulnerability classes: very low (30–40), low (40–50), moderate to low (50–60), moderate to high (60–70) and high (70–80). The covered area for each vulnerability class was 2.40%, 38.43%, 32.38%, 20.52% and 6.27%, respectively. Very low vulnerability only covered a very small region in the northern of the study area. Low vulnerability covered the largest part of the studied area and was distributed from the center to the northern parts of the basin. Moderate to low vulnerability was significantly spread from the center to the southern and southeastern parts of the area. Finally, moderate to high and high vulnerability classes were

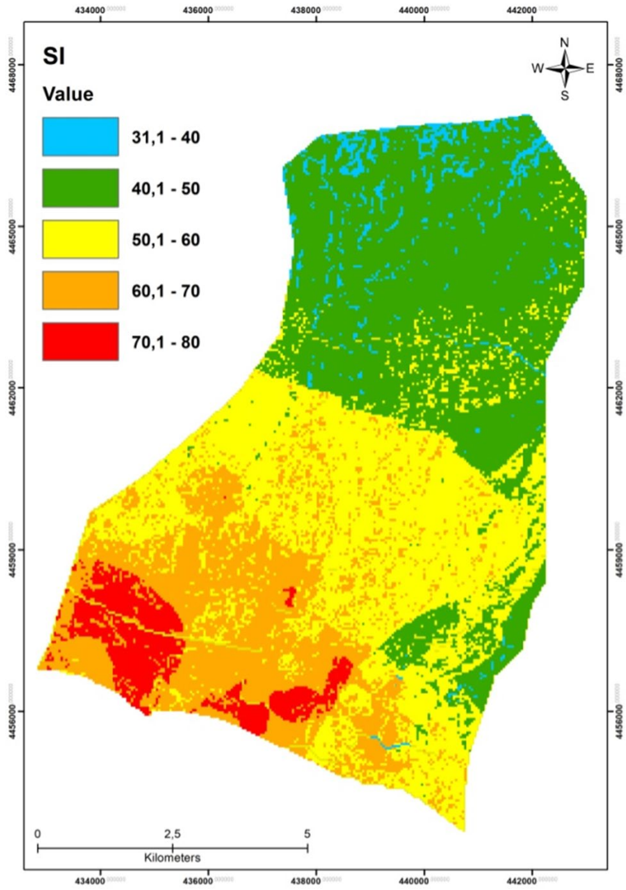

Fig. 9 SI vulnerability map

mainly located in the south and south-western regions of the area, covering together more than 25% of the study basin.

Finally, a comparison between the various groundwater vulnerability methods is useful and it is recommended, as it shows the similarities and the dissimilarities of the models, assisting researchers to select which of the applied methods is the most suitable and performs the best in a specific aquifer. Results summarized in Table 13 show that: regarding the very low vulnerability, the DRASTIC, Pesticide DRASTIC and AVI methods indicate the same results (≈27.5%), while the two SINTACS methods and GOD do not attribute any area in this class; regarding the low vulnerability the DRASTIC, Pesticide DRASTIC, Normal SINTACS and Nitrate SINTACS cover the same area (≈24%), while AVI and SI methods show exactly the same result (38%) but relatively higher than the other methods; moderate vulnerability class covers approximately the same area (≈33%) in Pesticide DRASTIC and SI method; DRASTIC, Pesticide DRASTIC and SI result approximately in the same percentage (≈18%) of high vulnerability area.

Single-parameter effect of weight-rating factors on DRASTIC and SINTACS methods

The single-parameter sensitivity analysis was carried out for the seven input parameters of the methods DRASTIC and Pesticide DRASTIC (Table 14) as well as for the parameters of Normal SINTACS and Nitrate SINTACS (Table 15). The effective (real) weight of the parameters of the aforementioned methods is a function of the assigned (theoretical) weight and the reciprocal influence with the other parameters of each method (Babiker et al 2005).

According to Table 14, in this study the weights of DRASTIC parameters exhibited some deviations from the theoretical weights. Impact of the vadose zone tends to be the most effective parameter in this model, with an effective weight value (32.26%) significantly higher than the theoretical one (21.74%). This result is in agreement with several studies (Muhammad et al. 2015; Sener and Sener 2015; Djémin et al. 2016; Ouedraogo et al. 2016; Allouche et al. 2017; Oke 2020; Phok et al. 2021). This is followed by Aquifer Media, which has an effective weight (19.84%) higher than the theoretical one (13.04%) and this value is also in agreement with other researches (Muhammad et al. 2015; Neshat and Pradhan 2017). Moreover, the effective weight of Topography (8.81%) is significantly higher compared with its low theoretical value (4.35%) (Berhe Zenebe et al. 2020). Nevertheless, Depth to water and Hydraulic conductivity have considerably higher theoretical weights (21.74% and 13.04%) than their effective weights, 10.59% and 3.23%, respectively (Allouche et al. 2017). The influence

Table 13 Percentage of aquifer vulnerability in seven methods

Groundwater vulnerability methods							
Vulnerability classes	DRASTIC	Pesticide DRASTIC	Normal SINTACS	Nitrate SINTACS	GOD	AVI	SI
Very low	29.21%	26.23%	0.06%	0.01%	0.00%	27.72%	2.40%
Low	23.52%	21.60%	23.32%	24.29%	98.12%	38.83%	38.43%
Moderate	30.23%	34.48%	47.16%	63.92%	1.88%	25.91%	32.38%
High	17.04%	17.69%	29.45%	11.78%	0.00%	7.13%	20.52%
Very high	0.00%	0.00%	0.00%	0.00%	0.00%	3.42%	6.27%

Table 14 Statistics of single-parameter sensitivity analysis for DRASTIC and Pesticide DRASTIC

Parameter	Theoretical weight		Theoretical weight (%)		Effective weight (%)							
					Mean		Min		Max		SD	
D	5	5*	21.74	19.23*	10.59	8.57*	5.38	4.35*	53.76	43.48*	9.68	7.83*
R	4	4*	17.39	15.38*	16.26	13.15*	4.30	3.48*	21.51	17.39*	3.44	2.78*
A	3	3*	13.04	11.53*	19.84	16.04*	12.90	10.43*	25.81	20.87*	2.58	2.09*
S	2	5*	8.70	19.23*	9.10	18.39*	6.45	13.04*	12.90	26.09*	1.29	2.61*
T	1	3*	4.35	11.53*	8.81	21.37*	1.08	2.61*	10.75	26.09*	1.94	4.70*
I	5	4*	21.74	15.38*	32.26	20.87*	16.13	10.43*	43.01	27.83*	5.38	3.48*
C	3	2*	13.04	7.69*	3.23	1.74*	3.23	1.74*	3.23	1.74*	0.00	0.00*

*Values for Pesticide DRASTIC

Table 15 Statistics of the single-parameter sensitivity analysis for SINTACS methods

Parameter	Theoretical weight		Theoretical weight (%)		Effective weight (%)							
					Mean		Min		Max		SD	
S	5	5*	19.23	19.23*	16.24	16.60*	16.08	16.43*	36.18	36.98*	4.02	4.11*
I	4	5*	15.38	19.23*	9.65	12.33*	9.65	12.33*	9.65	12.33*	0.00	0.00*
N	5	4*	19.23	15.38*	24.12	19.72*	12.06	9.86*	32.16	26.29*	4.02	3.29*
T	3	5*	11.53	19.23*	10.20	17.38*	7.24	12.33*	14.47	24.65*	1.45	2.47*
A	3	2*	11.53	7.69*	14.83	10.11*	9.65	6.57*	19.29	13.15*	1.93	1.31*
C	3	2*	11.53	7.69*	4.82	3.29*	4.82	3.29	4.82	3.29*	0.00	0.00*
S	3	3*	11.53	11.53*	20.14	20.58	2.41	2.47*	24.12	24.65*	4.34	4.44*

*Values for Nitrate SINTACS

of Recharge and Soil media is almost the same, since theoretical and effective weights have similar values. In general, the results of DRASTIC show the importance of the parameters on vulnerability as follows I > A > R > D > S > T > C, compared with the theoretical D ~ I > R > A ~ C > S > T.

In Pesticide DRASTIC model the Topography and the Impact of the vadose zone parameters seem to be the most effective, with a mean value of 21.37% and 20.87% instead of their theoretical 11.53% and 15.38% ones, respectively (Table 14). The effective weight of Aquifer media (16.04%) indicates a greater impact in this study compared to its theoretical value (11.53%). Additionally, Recharge and Soil media have slightly lower impact compared to their theoretical values. The least effective parameters are Depth to water and Hydraulic Conductivity with weight values 8.57% and 1.74%, respectively. In this study the impact of parameters contribution for this method is the following: T > I > S > A > R > D > C instead of the theoretical S > D > I > R > T > A > C.

In SINTACS method with normal impact assigned weights the most effective parameter, likewise with DRASTIC, is N (unsaturated zone), having a mean value equal to 24.12%, instead of the theoretical 19.23% (Table 15). The second most influential parameter is S (slope), having a mean weight equal to 20.14%, which is higher than its theoretical value (11.53%). Aquifer media (*A*) has a higher mean effective weight (14.83%) compared to its theoretical (11.53%). On the contrary, the remaining parameters Depth to water (*S*), effective infiltration (*I*), Soil media (*T*) and Hydraulic conductivity (*C*) have lower effective weights than their assigned weights.

Finally, in SINTACS method with nitrate impact the most effective parameters are Slope (*S*) and Unsaturated zone (*N*) with assigned weights 20.58% and 19.72%, respectively, larger than their theoretical weights 11.53% and 15.38% (Table 15). Except from Aquifer media which has a higher effective weight (10.11%) compared with its assigned (7.69%) the rest of the parameters recorded lower effective weights.

In general, results show that the first two most effective parameters in Pesticide DRASTIC, Normal SINTACS and Nitrate SINTACS are the same, namely, impact of the unsaturated zone and topography and thus it is important to acquire accurate, detailed and representative data about these parameters (Muhammad et al. 2015; Shahab et al. 2018). Furthermore, in all applied vulnerability methods the Hydraulic conductivity recorded the lowest effective weight, due to its low value in the study area.

Validation of the vulnerability maps

Validation is an important procedure in order to verify the results of the seven vulnerability models that were applied and to check which model is the most appropriate in Nea Moudania aquifer (Saidi et al. 2011; Hamza et al. 2014; Khan and Jhariya 2019). The criterion used to test the authenticity of the applied methods was computation of R^2 value between nitrate concentration (actual pollution) in groundwater and the vulnerability index produced by each method. Nitrate is a typical groundwater pollutant and is associated with intensive agricultural activity, fertilizers and urbanization. Nitrate has high solubility and mobility and as a result can easily reach and pollute an aquifer (Khosravi et al. 2018). Thus, the local policymakers and planners should determine a threshold or a specific amount of chemical fertilizers that can be employed on agricultural fields (Khosravi et al. 2021). A higher correlation with nitrate concentration results in a more efficient and precise vulnerability model.

Nitrate concentration, taken from 23 observation wells, was used for the validation of the aforementioned seven models. The calculation of correlation is seen in Table 16. In this study the least reliable models were AVI ($R^2=0.5045$) and GOD ($R^2=0.5348$). Notwithstanding, these two methods require fewer parameters (two and three, respectively) compared to the other methods, they are simple to implement and they can be used for a quick evaluation of groundwater vulnerability. The SI method, which uses five parameters, showed a greater correlation ($R^2=0.6084$) and it is considered more accurate than AVI and GOD. Regarding the DRASTIC, Pesticide DRASTIC, Normal SINTACS and Nitrate SINTACS models, the R^2 value accomplished a progressive improvement. Results showed that the most efficient and precise models in the study area were Pesticide DRASTIC and Nitrate SINTACS with $R^2=0.6475$ and 0.6438, respectively (R^2 improved by 14% compared to AVI). Both methods have a slightly higher determination coefficient compared with the DRASTIC and Normal SINTACS, a fact that indicates a better applicability of the methods for a specific pollutant (nitrate) in an agricultural area like Nea Moudania. In addition, both methods detect that high and very high pollution areas are mainly located in the south and south-western side of the basin. Summarizing, in this study the DRASTIC methods (standard and typical) and the SINTACS methods (normal and nitrate) indicate stronger correlation compared to the other three vulnerability methods (AVI, GOD and SI).

Table 16 R^2 values of the various methods

Model name	R^2
DRASTIC	0.6264
Pesticide DRASTIC	0.6438
Normal SINTACS	0.6392
Nitrate SINTACS	0.6475
GOD	0.5348
AVI	0.5045
SI	0.6084

Conclusion

This study is the first endeavor to delineate the groundwater vulnerability in Nea Moudania aquifer, Greece, using a comparative assessment of various methods. The evaluation and identification of the groundwater vulnerability zones was accomplished by using seven different vulnerability methods, namely DRASTIC, Pesticide DRASTIC, SINTACS, Nitrate SINTACS, GOD, AVI and SI alongside with Geographical Information System (GIS) techniques. These methods employ the inherent geological and hydrogeological parameters, which affect the vulnerability of the aquifer, giving an insight about the potential groundwater pollution and its spatial distribution. In general, the southern and south-western part of the study area has the highest pollution potential; in the northern part, the corresponding potential is lower. Single-parameter sensitivity analysis has revealed the significance of the unsaturated zone and the topography in vulnerability assessment, highlighting the importance of accurate, detailed and representative data of these parameters.

Conversely, the hydraulic conductivity recorded the lowest effective weight in all models due to its low value in the study area. The seven aquifer vulnerability maps were validated with nitrate concentrations in groundwater by using the R^2 coefficient. Results showed that, among the methods used, the Pesticide DRASTIC and the Nitrate SINTACS were the most efficient and precise methods for prediction of groundwater vulnerability in Nea Moudania aquifer ($R^2=0.64$), which is mainly characterized by agricultural activities. On the contrary, the least efficient and accurate models were AVI ($R^2=0.50$) and GOD ($R^2=0.53$). The rest of the models, namely SI, DRASTIC and Normal SINTACS performed 0.60, 0.62 and 0.63, respectively. Notably, these results could provide a useful spatial tool that could support policymakers and planners in regional decision-making. The main limitation of groundwater vulnerability methods is the uncertainty associated with parameters' values, which might overlook local variability on a specific area, and optimal weights estimation. In this study, the elaboration of an ensemble of vulnerability estimations combined with a sensitivity analysis on the weights' significance and a nitrate data validation is performed to increase the reliability of the assessment results.

In a more general framework, the results of the comparative assessment of the seven methods, can serve for the selection of the most appropriate tools for estimating aquifer vulnerability in other agricultural areas. Moreover, the comments on the effective weights of the parameters used can help improve final estimates.

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Declarations

Conflict of interest The authors have no conflict of interest to declare that are relevant to the content of this article.

Ethical approval The manuscript is an original work with its own merit, has not been previously published in whole or in part, and is not being considered for publication elsewhere.

Consent to participate The authors have read the final manuscript, have approved the submission to the journal, and have accepted full responsibilities pertaining to the manuscript's delivery and contents.

Consent to publish The authors agree to publish this manuscript upon acceptance.

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