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Original Article

Groundwater vulnerability assessment using a GIS-based DRASTIC method in the Erbil Dumpsite area (Kani Qirzhala), Central Erbil Basin, North Iraq

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Abstract: Groundwater vulnerability assessment is a crucial step in the efficient management of groundwater resources, especially in areas with intensive anthropogenic activities and groundwater pollution. In the present study, the DRASTIC method was applied using Geographic Information System (GIS) to delineate groundwater vulnerability zones in the Erbil Dumpsite area, Central Erbil Basin, North Iraq. Results showed that the area was classified into four vulnerability classes: Very low (16.97%), low (27.67%), moderate (36.55%) and high (18.81%). The southern, south-eastern and northern parts of the study area exhibited the highest vulnerability potential, while the central-northern, northern and north-western regions displayed the lowest vulnerability potential. Moreover, results of the single-parameter sensitivity analysis indicated that amongst the seven DRASTIC parameters, the unsaturated zone and the aquifer media were the most influencing parameters. In conclustion, the correlation of 25 nitrate concentration values with the final vulnerability map, assessed using the Pearson correlation coefficient, yielded a satisfactory result of R = 0.72.

Keywords: DRASTIC; Erbil; Iraq; Groundwater vulnerability assessment; Nitrate; Pollution; Sensitivity analysis

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Introduction

Water is a vital resource on Earth, it plays a pivotal role in sustaining life and supporting food production. Consequently, a keen focus on water resources becomes imperative to meet humanitarian needs for drinking water and ensure the needs of agriculture and industry (Machiwal et al. 2018). Surface water is conventionally considered more susceptible to pollution due to direct exposure to human activities, making it more prone to contamination (Kumar et al. 2022). Despite the protective layers of the Earth safeguarding groundwater, the last few decades have witnessed a heightened risk to both the quality and quantity of groundwater. Various human activities, such as intensive agriculture, rapid urbanization, overexploitation, population growth, indiscriminate use of chemical fertilizers and pesticides, and unsustainable farming practices, have collectively contributed to the qualitative deterioration of groundwater (Green et al. 2011; Saidi et al. 2011; Kumar et al. 2018; Kirlas et al. 2022a; Taghavi et al. 2022). The extensive use of chemical fertilizers and pesticides, in particular, has led to the degradation of groundwater quality and the pervasive issue of nitrate pollution in aquifers. Nitrate pollution poses severe threats to public health and the ecosystems, underscoring the urgency of preventing groundwater pollution for effective groundwater management and the sustainability of natural resources and economic

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development (Li et al. 2017; Kumar et al. 2018).

In Iraq, the demand for water resources is escalating due to population growth and economic development, further straining this essential resource. This demand is partially offset by a decline in water resource due to increased investment and exploitation in neighboring countries (Al-Ansari, 2013). According to the United Nations (2020), Iraq ranks as the fifth-most exposed country globally to the effects of climate change, including water scarcity and food insecurity. The country is currently experiencing the rapid effects of climate change at an alarming rate, with in Iraq warning in April given by a top advisor at the Ministry of Water Resources, indicating a 50% decrease in water reserves since the previous year due to drought, insufficient rainfall, and falling groundwater levels (Mawlood, 2019). In Iraq, the Tigris and Euphrates are the primary surface water resources, with groundwater playing a secondary role. However, precise estimates of available groundwater for use are lacking, as existing studies focus on specific regions, such as the mountainous region, desert, and foothill areas.

More than 90% of the local population relies on groundwater abstraction from the basin, and residents from external areas also receive potable water from it. Rapid urbanization, industrial expansion, and agricultural growth have been prominent in recent years, with significant developments such as the Safra and Azad rice food production, yogurt factories like Erbil and Mersin, and numerous ice cream factories. While these developments have increased the supply of high-quality water, overexploitation of aquifers and sporadic decrease in yearly precipitation have exacerbated the decline in groundwater supply, leading to a substantial deterioration in both groundwater quality and quantity (Ali and Hamamin, 2012). The urgent need for a groundwater governance framework is evident to guide policymakers in protecting groundwater resources from further degradation.

Groundwater vulnerability assessment methods can be broadly categorized into three types: i) index-overlay methods, ii) statistical analysis methods, and iii) process-based methods. (Bernardo et al. 2022; Pouye et al. 2022; Koon et al. 2023; Mensah et al. 2023; Omeje et al. 2023). The choice of method depends on factors such as aquifer type, area scale, data availability and pollutant type (Etuk et al. 2022). Given the expense and complexity of groundwater monitoring, (Jain, 2023), researchers have developed economical methodologies that are easier to apply and do not require extensive data or complex computations (Kumar et al. 2015; Canora et al. 2022; Kirlas et al. 2022a). Notable groundwater vulnerability assessment methods include DRASTIC (Aller et al. 1987), GOD (Foster, 1987), AVI (Van Stempvoort et al. 1993), SINTACS (Civita 1994) and SI (Ribeiro, 2000). Amongst these, DRASTIC stands out as the most popular and widely used empirical rank/score-based index method for vulnerability evaluation, developed by Aller et al. (1987) for the U.S Environmental Protection Agency (Boufekane et al. 2021; Rezig et al. 2022; El Yousfi et al. 2023). DRASTIC method relies on seven hydrogeological parameters, namely depth to water table (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone (I) and hydraulic conductivity (C) (Metwally et al. 2023).

Despite its popularity, DRASTIC method has been criticized for its subjectivity and uncertainty in parameters' ratings and weights (Goyal et al. 2021; Ekanem et al. 2022; Xiong et al. 2022). To address these concerns, researchers have modified the method to enhance its efficiency and accuracy for specific aquifers (Fannakh and Farsang, 2022; Kirlas et al. 2023). Modifications include optimizing ratings and weights using methods such as Analytic Hierarchy Process (AHP), Fuzzy AHP, Analytic Network Process (ANP), multiple linear regression and sensitivity analysis and Shannon entropy (Sener and Davraz, 2012; Garewal et al. 2017; Jhariya et al. 2019; Alamne et al. 2022; Kirlas et al. 2022b; Shakeri et al. 2023; Torkashvand et al. 2023). Additionally, researchers have proposed the incorporation of extra factors like land use, irrigation type and water quality index (Brindha and Elango, 2015; Sarkar and Pal, 2021; Abera et al. 2022; Mkumbo et al. 2022; Rauf et al. 2022; Kirlas et al. 2023; Taghavi et al. 2023). Another limitation of the DRASTIC method is the absence of a standardized formula for examining and validating the accuracy of the final vulnerability map (Patel et al. 2022).

This study marks the first endeavor to evaluate groundwater vulnerability in Kani Qirzhala aquifer, Central Erbil Basin, North Iraq. Limited data availability necessitated the selection of the DRASTIC method due to its simplicity, clarity and modest data requirements. The results of this method can help policymakers and planners in decision-making to safeguard the aquifer system from future groundwater deterioration, offering a valuable spatial tool for a rapid assessment of the current state of the investigated aquifer. Furthermore, the accuracy of the final vulnerability map was validated using reported nitrate concentration (NO_3^-) in groundwater. Finally, the broader objective is to assess the performance, suitability, and limitations of the DRASTIC method in an area characterized by significant nitrate pollution.

1 Study area

The aquifer within the study area covers an area of approximately 100 km^2 and is located in the central Erbil basin. Tectonically, it falls under the Low Folded Zone of the Outer Platform, belonging to the Arabian Plate, characterized by elongated and narrow anticlines. Comprising Pliocene alluvial deposits, including gravels, conglomerate, sand and clay, the region experiences a semi-arid climate (Jawad and Hussien, 1988). The mean annual precipitation is approximately 370 mm, occurring primarily from November to March over approximately 82 days. Temperature fluctuations ranges from 10°C to exceeding 30°C. Groundwater levels vary from approximately 40 m to over 100 m, with the aquifer primarily composed of sand and gravels (Sissakian et al. 2022). The study area includes the Erbil dumpsite, situated on a hill at the convergence of two drainage valleys (Fig. 1), with an elevation of approximately 435 m above sea level. Operational since 2001 (Municipal ministry), the dumpsite currently receives a diverse range of solid waste and poses a potential risk of groundwa-

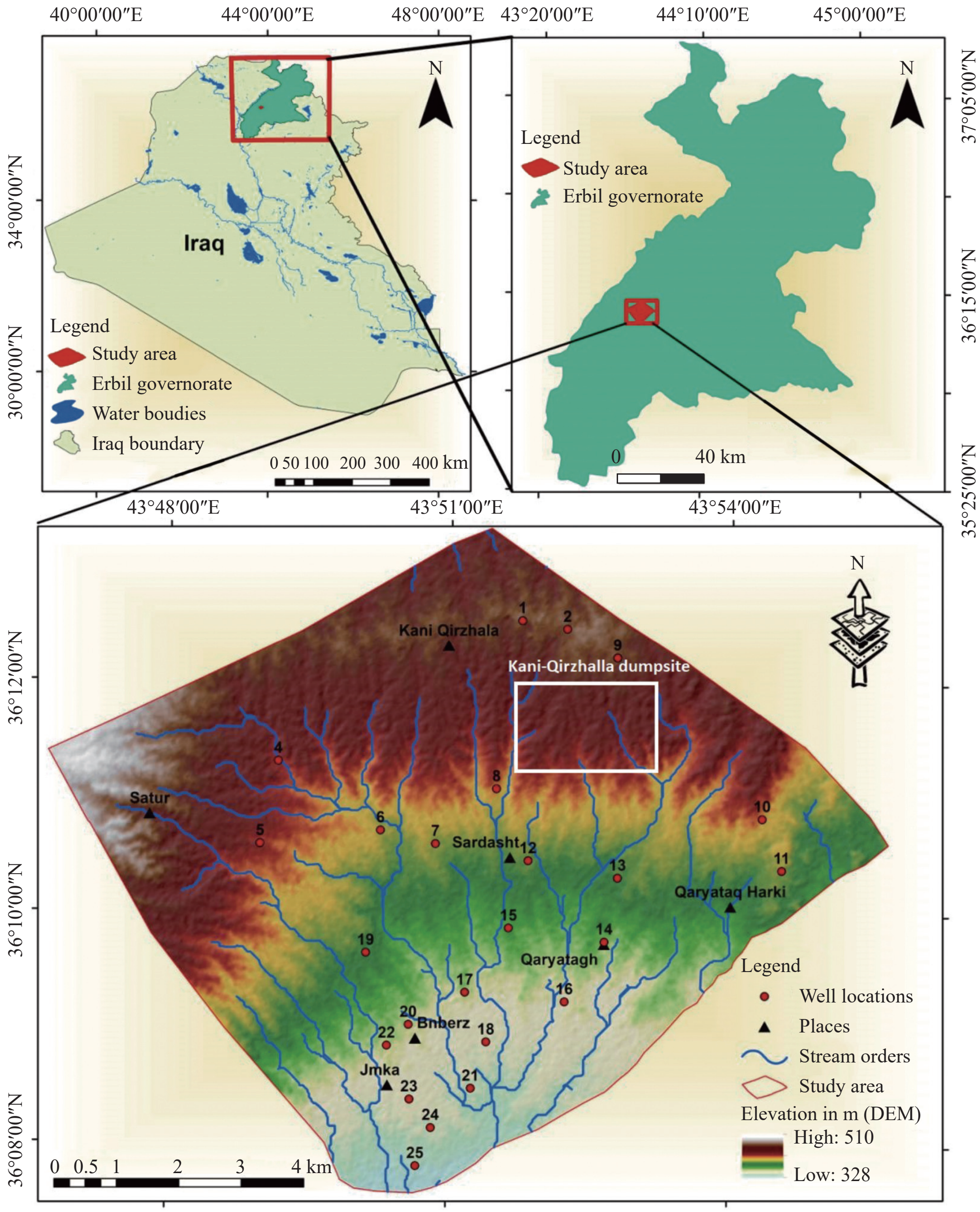

Fig. 1 Location and DEM map of the study area and the dumpsite

ter pollution. The daily disposal rate amounts to about 1.5 thousand tons of varied solid waste (Gardi, 2017). The serves as a receptacle for general household waste, including domestic waste, e.g. kitchen waste, food leftovers, paper, newspaper, metal and glass cans, packaging, plastic, glass, cartoon, wood, metals, ceramics, leather, cloths and batteries. The dumped waste, comprising a mix of materials, can spontaneously combust, emitting noxious smoke and odors, posing a greater risk to the operational management staff. Construction and demolition waste, consisting of sand, bricks and concrete blocks, is also deposited at the site. The escalating population in Erbil City (1.5 million people), the capital of the Iraqi Kurdistan Region, coupled with shifts in production and consumption patterns in recent years, continues to contribute to ongoing deterioration in groundwater quality.

2 Methodology

2.1 Methods

The DRASTIC method is widely acknowledged as the most frequently used and reliable approach for evaluating groundwater vulnerability (Ouedraogo et al. 2016; Goyal et al. 2021; Ifediegwu and Chibuike, 2021). DRASTIC is an overlay index method and was initially developed in 1987 by the US Environmental Protection Agency (EPA) and the American Water Works Association (AWWA) (Aller et al. 1987). This method relies on seven crucial hydrogeological features that primarily control groundwater flow and pollution transport, 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) (Saidi et al. 2011). According to Aller et al. (1987) the feasibility of this method is based on four key assumptions: (i) pollution sources occur at the ground surface, (ii) pollutants infiltrate the saturated zone through precipitation, (iii) pollutants travel at the same rate as water, (iv) the hydrogeological area must be at least 0.4 km^2 (Hamza et al. 2015; Oke, 2020).

In the DRASTIC method, each parameter is assigned a typical weight (w) ranging from 1 to 5, with 1 denoting the least important parameter and 5 the most crucial parameter. Moreover, each parameter is assigned a rating ranging from 1 to 10, reflecting its relative influence on pollution potential (Table 1). Lower values indicate a lesser contribution to groundwater vulnerability. Both weights and ratings are determined using the Delphi technique (Gogu and Dassargues, 2000). The final DRASTIC Index (DI) is a weighted linear combination of the parameters and is calculated by multiplying each parameter's weight by its corresponding rating, using Equation (1). Generally, the DRASTIC Index ranges from 23 to 230. It is noteworthy that Aller et al. (1987) did not propose specific classification or ranges for final vulnerability classes leaving scientists to deter-

Table 1 Weight, ranges and ratings of DRASTIC parameters (Aller et al. 1987)

DRASTIC parameter	Range/type	Rating	Standard weight
D: Depth to water (m)	35–50	7	5
	50–60	6	
	60–70	5	
	70–80	4	
	80–90	3	
	90–100	2	
	>100	1	
R: Net recharge (mm/a)	0–50	1	4
	50–100	3	
	100–175	6	
	175–246	8	
A: Aquifer media	Clay	3	3
	Silty clay	4	
	Silty sand	6	
	Sand	7	
	Sandy gravel	8	
S: Soil media	Clay	2	2
	Clay loam	3	
	Sandy loam	6	
	Silty sand	7	
	Fine sand	8	
T: Topography (%)	0–2	10	1
	2–6	9	
	6–12	5	
	12–18	3	
	>18	1	
I: Impact of vadose zone	Clay	2	5
	Silty clay	3	
	Clay loam	4	
	Silty sand	6	
	Sand	7	
	Sandy gravel	8	
C: Hydraulic conductivity (m/d)	0.04074–4.074	1	3
	4.074–12.222	2	
	12.222–28.518	4	
	28.518–40.74	6	
	40.74–81.48	8	

mine these boundaries based on their own assessment.

$$DI = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_W + C_rC_w \quad (1)$$

Where: D, R, A, S, T, I, and C indicate the seven parameters of the method, *w* signifies the weight of each parameter and *r* is the corresponding rating.

2.2 Preparation of thematic maps

Depth to water

This parameter holds significant relevance for groundwater quality degradation, representing the perpendicular distance between the ground surface and the water table (Kirlas et al. 2023). Generally, higher values of this parameter correlate with a lower likelihood of groundwater pollution, as pollutants must travel a longer distance to reach and enter the water table. On the other hand, when the groundwater table is closer to the ground surface (smaller values), it becomes more vulnerable, with an elevated pollution potential. This vulnerability arises from the reduced thickness of the unsaturated zone, facilitating easier pollutant access to the aquifer.

Net recharge

This parameter represents the total volume of surface water that percolates from the ground surface and reaches the water table (Khosravi et al. 2021). This volume plays a significant role in the movement of pollutants into the aquifer. Higher net recharge values correspond to an increased likelihood of groundwater pollution (Aller et al. 1987).

Aquifer media

This parameter refers to the characteristics of the saturated zone, influencing the flow of water within the aquifer and processes of pollutant attenuation (Hasan et al. 2019). It depends on the porosity, grain size and permeability of the constituent materials.

Soil media

Soil media refers to the topmost eroded layer of the unsaturated zone, governing the quantity of recharge that can infiltrate downward into groundwater depending on soil porosity and permeability (Babiker et al. 2005). It has a significant impact on the movement of potential pollutants into the ground.

Topography

Topography describes the variability in slope within a region, impacting the rates of infiltration and run-off. Regions with low slopes tend to exhibit a higher potential for groundwater pollution, due to the low surface run-off rate and high infiltration rate, facilitating the migration of pollutants to the aquifer. Conversely high slope areas experience lower infiltration, resulting in reduced groundwater vulnerability (Kirlas et al. 2023).

Vadose zone

This parameter refers to the unsaturated zone between the soil surface and the aquifer (Ahmed et al. 2015). The soil materials of the vadose zone play a crucial role in reducing the potential for groundwater pollution, as various biochemical processes take place in this zone, including filtration, dispersal and chemical reactions (Kirlas et al. 2022a).

Hydraulic conductivity

Hydraulic conductivity characterizes the velocity of groundwater flow into the saturated zone and depends on the aquifer materials. Pumping tests are commonly employed to evaluate this hydrogeological parameter (Kirlas, 2021). Higher hydraulic conductivity values increase the potential for groundwater pollution (Victorine Neh et al. 2015).

2.3 Sensitivity analysis

The application of sensitivity analysis can provide reliable insights into the uncertainty and the robustness of the weights assigned by DRASTIC method. In this study, an attempt was made to evaluate the influence of each parameter on the final vulnerability index through the implementation of single-parameter sensitivity analysis (Napolitano and Fabbri, 1996; Oke, 2020). In particular, this analysis compares the assigned (theoretical) weight of each DRASTIC parameter with the real (effective) weight. Moreover, this technique assists the researcher to assess the significance of subjectivity elements in the groundwater vulnerability methods (Djémin et al. 2016; Noori et al. 2019). The effective weight for every parameter was calculated using the following Equation (2).

$$W = \left(\frac{P_rP_w}{V}\right) \times 100 \quad (2)$$

Where: W refers to the effective weight of each parameter, P_r and P_w describes the rating value and the weight of each parameter, and V denotes the overall vulnerability index.

3 Results and discussion

3.1 Depth to groundwater (D)

The depth to water map was created using the groundwater level data collected from 25 observation wells during field investigation, covering the entire study area. These data were interpolated to generate a raster layer employing the Inverse

Distance Weight (IDW) method (Hasan et al. 2019; Singha et al. 2019; Gonçalves et al. 2023). Renowned for its simplicity and flexibility with irregularly spaced sample points, the IDW method is robust even with a small number of sample points. In this study, enhancements were introduced to the ranges and ratings of the Depth to Water parameter to improve the accuracy of the final vulnerability map and tailor the standard DRASTIC method to the specific conditions of the area. Consequently, the raster layer was classified into seven classes and each class was assigned a rating value accordingly (Fig. 2), as follows: For D: 35–50 m (7), for 50–60 m (6), 60–70 m (5), 70–80 m (4), 80–90 m (3), 90–100 m (2) and for D> 100 m (1). In general, the eastern, south-eastern and a region in the northern part of the study area are the most vulnerable to pollution, given the relatively shallow depth of the aquifer. Converely, the least vulnerable area concerning the depth to water is located in the north-western and western part of the study basin, where the aquifer is deeper.

3.2 Net recharge (R)

The Net Recharge parameter was calculated using data from 25 stations, providing coverage across the entire study area. The raster layer of recharge map was created by interpolating the data, using the inverse distance weight (IDW) method in ArcGIS. The net recharge index layer was classified into four classes, each assigned a rating value accordingly (Fig. 3), as follows: For R: 0–50 mm/a (1), for 50–100 mm/a (3), 100–175 mm/a (6), and for 175–246 mm/a (8). Generally, the results indicated that the western, eastern and northern part of the study exhibits low recharge values, whilst the southern part demonstrates relatively higher recharge values, contributing to an increased vulnerability potential in that region.

3.3 Aquifer media (A)

The aquifer media parameter was estimated using lithological datasets obtained from 25 lithology profiles during field investigation. This parameter was categorized into four classes, each assigned a rating value accordingly (Fig. 4), as follows: For A: Clay (3), for silty clay (4), silty sand (6), sand (7), and for sandy gravel (8). Results highlighted that the eastern, the southern and a part in the northern study area were the most vulnerable due to the characteristics of the constituent materials in the saturated zone, characterized by large grain size and high porosity. Conversely, the western part of the area exhibited a lower vulnerability potential.

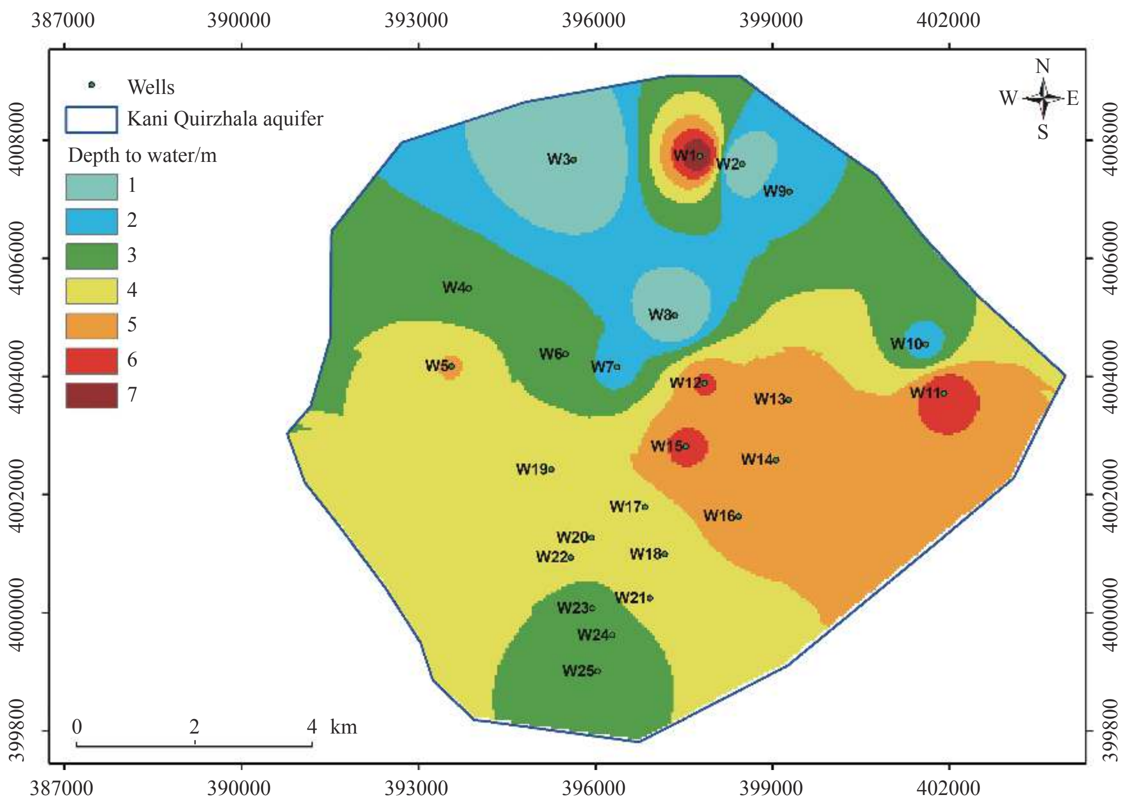

Fig. 2 Depth to water map of Kani Qirzhala aquifer

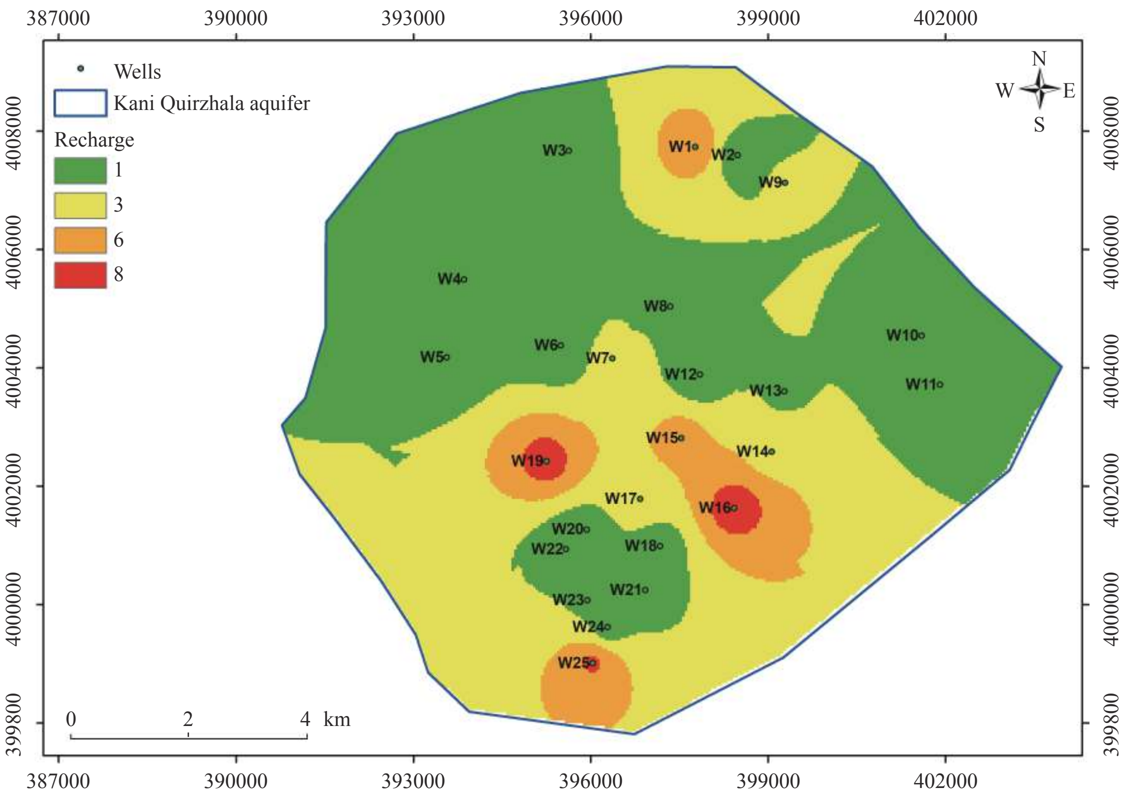

Fig. 3 Recharge map of Kani Qirzhala aquifer

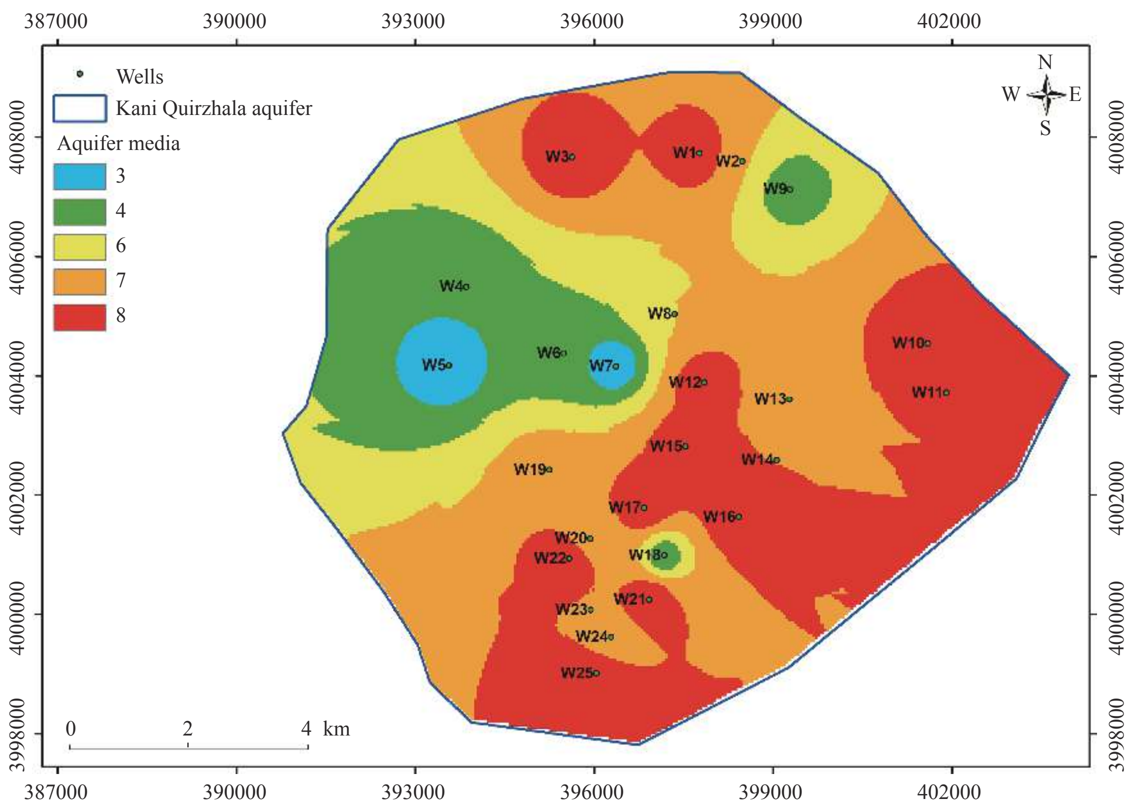

Fig. 4 Aquifer media map of Kani Qirzhala aquifer

3.4 Soil media (S)

The soil media parameter was derived from 25 soil samples collected across the entire area. This parameter was categorized into five classes, each assigned a rating value accordingly (Fig. 5), as follows: For S: clay (2), for clay loam (3), sandy loam (6), silty sand (7), and for fine sand (8). The results indicated that the northern and eastern parts of the area were the most vulnerable, whereas the western part exhibited a lower vulnerability potential.

3.5 Topography (T)

The topography map of this area was obtained from the digital elevation map (ASTER DEM) with a spatial resolution of 30 m. Subsequently, a slope map (in percentage) was generated using the spatial analyst tool in ArcGIS, and was classified into five classes accordingly (Fig. 6). The spatial distribution of the assigned ratings is the following: 0.24% of the area was assigned with 1; 3.18% was assigned with 3; 29.53% was assigned with 5; 53.6% was assigned with 9; 13.53% was assigned with 10. It is evident from the results that the basin exhibits a predominantly flat landscape, with more than 67% of the total area having a slope ranging between 0 and 6%. The flat topography, on the majority of the area, particularly in the eastern, southern and northern parts, facilitates the seepage of pollutants into the aquifer, indicating a significant influence of this parameter on the overall vulnerability.

3.6 Impact of the vadose zone (I)

The vadose zone map was created from 25 lithological profiles, using the same interpolation technique as the previous parameters (IDW). It was then classified into six classes according to the materials' ability to allow and transmit water (Fig. 7). The eastern and southern parts of the area predominantly consist of sand and sandy gravel, indicating a higher vulnerability potential. In contrast, the northeastern part exhibits the least potential, characterized by the presence of clay and silty clay.

3.7 Hydraulic conductivity (C)

The values for the vulnerability map were obtained from the soil lithology and the pumping test in the study area. This parameter was interpolated using the IDW technique in ArcGIS, and was classified into five classes, with each class assigned a rating

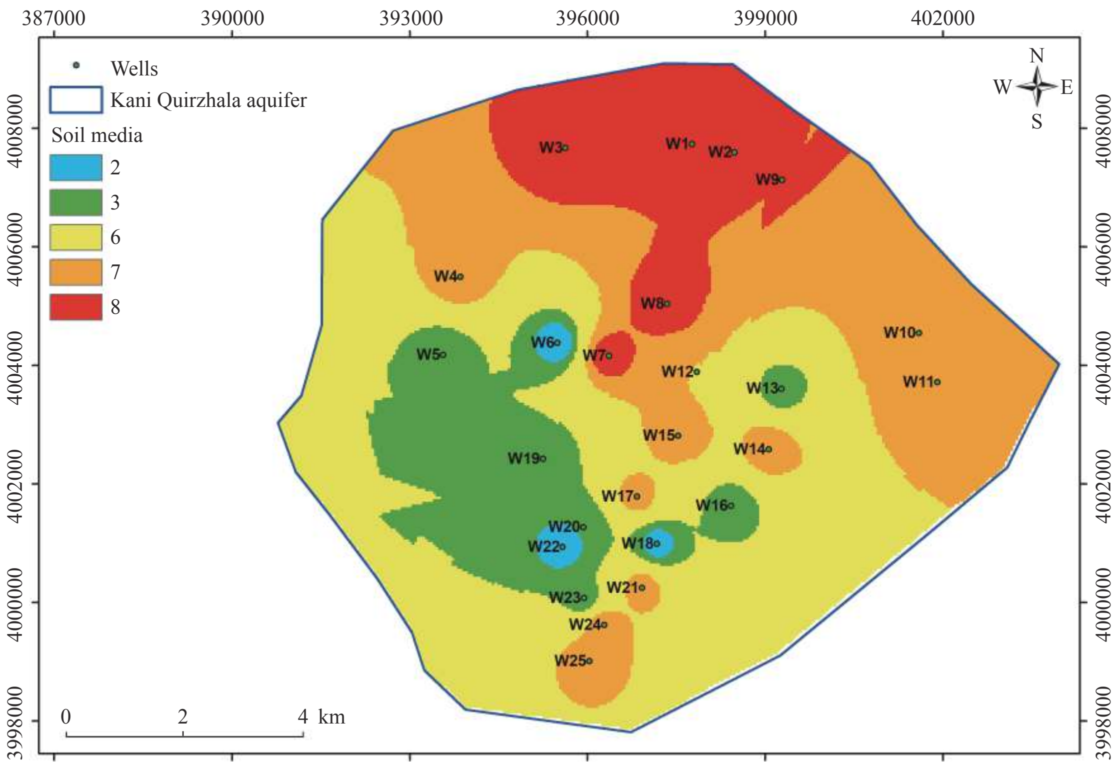

Fig. 5 Soil media map of Kani Qirzhala aquifer

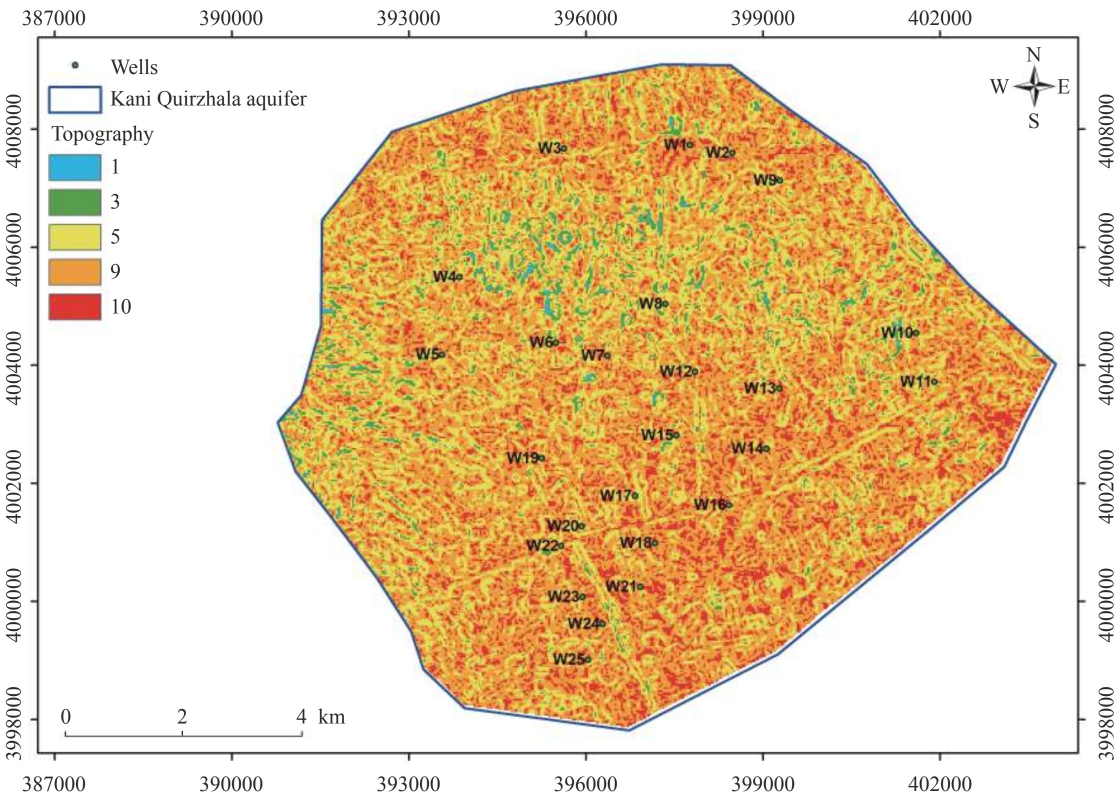

Fig. 6 Topography map of Kani Qirzhala aquifer

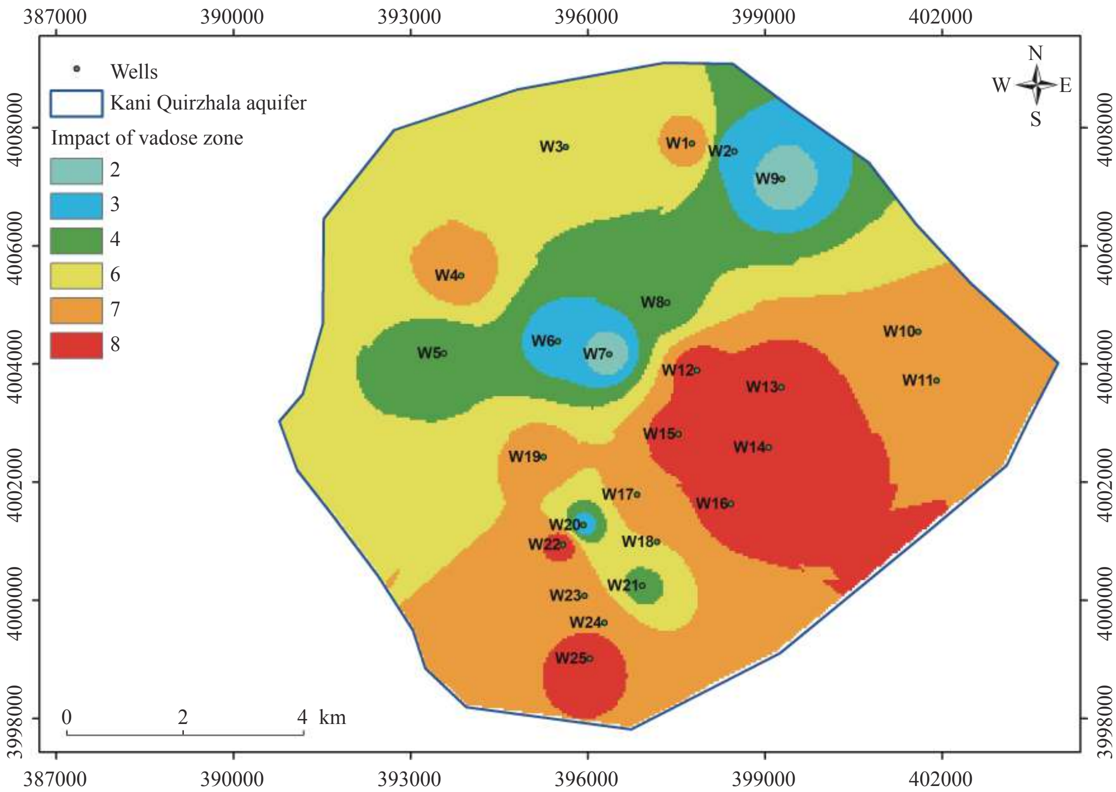

Fig. 7 Impact of the vadose zone map of Kani Qirzhala aquifer

value accordingly (Fig. 8). In general, the hydraulic conductivity in most regions of the study area is relatively low, particularly in the northern and eastern part.

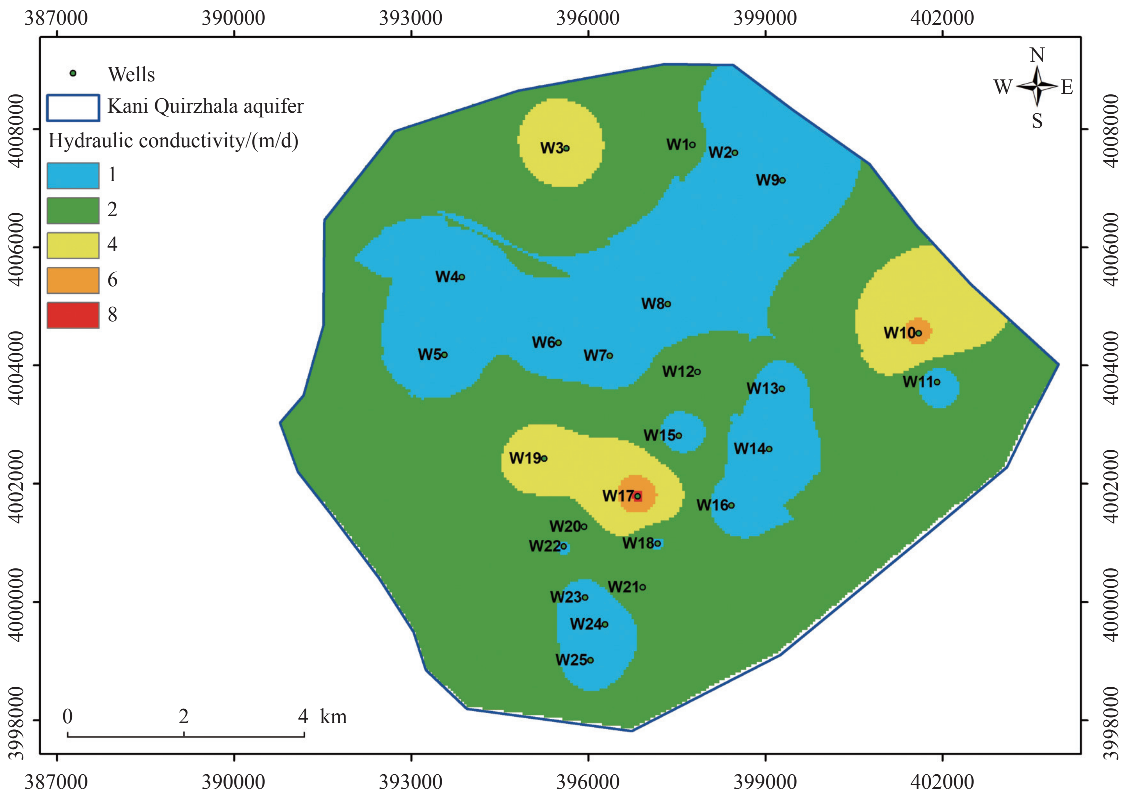

Fig. 8 Hydraulic conductivity map of Kani Qirzhala aquifer

3.8 DRASTIC Vulnerability Index (DVI)

In the Erbil area, the final DRASTIC index (Fig. 9) was calculated within ArcGIS by combining all seven parameters of the method, using the Eq. The final raster of the DRASTIC vulnerability map ranged from 53 to 150, and was further reclassified into four classes using the Jenks natural breaks method (Ersoy and Gültekin, 2013; Thapa et al. 2018; Jhariya et al. 2019; Wei et al. 2021). Each class corresponds to a vulnerability zone as follows: Very low (< 83), low (83–101), moderate (101–120) and high (120–150). The spatial distribution of each vulnerability zone is as follows: 16.97% of the total area belongs to the very low vulnerability, 27.67% to low vulnerability, 36.55% to moderate vulnerability, and 18.81% to high vulnerability (Table 2).

Specifically, the high vulnerability zone is concentrated mainly in the southern, south-eastern and northern part of the study area, where the hydrogeological characteristics, such as the sandy unsaturated zone, the flat topography, sandy gravel aquifer media and relatively low depth to water favor groundwater pollution. On the other hand, the central-northern, northern and north-western portions of the study area reveal very low to low vulnerability potential, as the depth to water is higher; the materials of the unsaturated zone are less permeable, the topography is slightly steeper, the recharge rate is lower, and the aquifer materials are finer (less permeable).

An assessment of the underlying uncertainties of the final DRASTIC vulnerability map can be summarized as follows: 1) lack of consideration of temporal changes, such as seasonal changes in water level, land use and seasonal climate change, 2) limited spatial resolution resulting in a less rigorous illustration of vulnerability assessment locally, 3) assumption of homogenous aquifer properties, whereas the aquifer properties can vary spatially, 4) uncertainty in the boundary conditions, particularly in large study areas, 5) uncertainty in the weighting scheme of each parameter without considering the specific hydrogeological conditions of the study area, 6) limited consideration of human activities, such as agriculture, urbanization and industry, and 7) limited hydrochemical data covering the entire study area.

3.9 Single-parameter effect of weight-rating factors on DRASTIC

A single-parameter sensitivity analysis was conducted for the seven hydrogeological parameters of DRASTIC method to estimate the effective (real) weight of each parameter on the final vulnerability index, compared to its theoretical one (Patle et al.

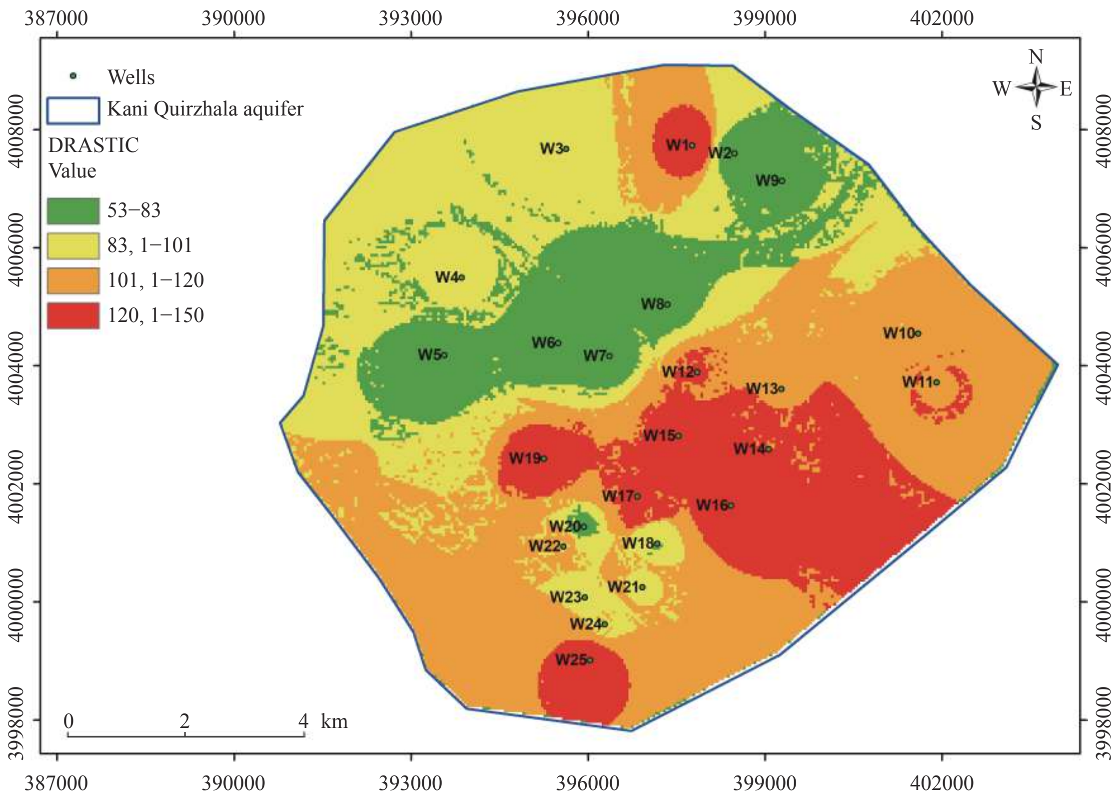

Fig. 9 DRASTIC vulnerability map of Kani Qirzhala aquifer

Table 2 Drastic index classes and spatial distribution

Vulnerability class	DRASTIC Index	Area (km^2)	Area (%)
Very low	53–83	17.11	16.97
Low	83–101	27.92	27.67
Moderate	101–120	36.87	36.55
High	120–150	18.97	18.81

2022). Results presented in Table 3 exhibited variations from the theoretical weights. The Impact of the Vadose Zone is the most influential parameter in vulnerability mapping, with an effective weight value (29.76%) significantly higher than the theoretical one (21.74%). Notably, this result aligns with several other studies (Muhammad et al. 2015; Sener, 2013; Sener, 2015; Victorine Neh et al. 2015; Djémin et al. 2016; Ouedraogo et al. 2016; Allouche et al. 2017; Oke, 2020; Phok et al. 2021; Kirlas et al. 2022a).

The second most influential parameter is Aquifer Media, which has an effective weight (19.31%) higher than its assigned one (13.04%). This result is consistent with findings in other studies (Muhammad et al. 2015; Victorine Neh et al. 2015; Neshat and Pradhan, 2017). Furthermore, in this study, the third most influential parameter is the Depth to Water, although with a slightly lower effective weight (17.23% instead of 21.74%). Recharge and hydraulic conductivity exhibit markedly lower effective weights (8.74% and 5.56%)

Table 3 Statistics of single-parameter sensitivity analysis for DRASTIC

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (%)			
			Mean	Min	Max	SD
D	5	21.74	17.23	4.85	33.98	5.83
R	4	17.39	8.74	3.88	31.07	5.44
A	3	13.04	19.31	8.74	23.30	2.91
S	2	8.70	11.90	3.88	15.53	2.33
T	1	4.35	7.51	0.97	9.71	1.75
I	5	21.74	29.76	9.71	38.83	5.83
C	3	13.04	5.56	2.91	23.30	4.08

compared with their theoretical values (17.39% and 13.04, accordingly), suggesting a diminished importance in the assessment of the final result.

On the other hand, Soil media and Topography appear to be more influential in elaborating the final vulnerability map, as they demonstrate higher effective weights (11.90% and 7.51%) than their theoretical ones (8.70% and 4.35%, respectively). In summary, the final results of the DRASTIC method highlight the significance of the parameters on vulnerability in the order of I>A>D>S>R>T>C, as opposed to the theoretical D~I>R>A~C>S>T. These results underscore the importance of obtaining accurate and detailed data for the most significant parameters in the study area, namely the Impact of the Vadose Zone and Aquifer Media. Notably, these findings can be extrapolated to a broader context in the field of groundwater vulnerability assessment methods and techniques.

3.10 Validation

Following the creation of the final DRASTIC vulnerability map, a crucial step involves its validation to verify its appropriateness and accuracy in this specific area (Saidi et al. 2011; Hamza et al. 2014). Although there isn't a typical and standard method for groundwater vulnerability validation, the most common and widely used method is the correlation between the final DRASTIC index values and the nitrate concentration in groundwater, using the Pearson correlation coefficient (R) (Jmal et al. 2022).

Nitrate, a pollutant occurring in very low concentrations in groundwater (1–3 mg/L), exhibits an increasing trend linked to various human activities, such as intensive agriculture, fertilizer use, increased food production, urbanization and changes in land use (Salih and Al-Manmi, 2021). Elevated nitrate concentrations in groundwater (> 50 mg/L) have acute health effects (e.g. methemoglobinemia, anemia, lung disease, cardiovascular disease, hypothyroidism, colon cancer), and impact ecosystems. Governments and policymakers often set thresholds on groundwater and associated agricultural products, such as chemical fertilizers (Khosravi et al. 2021; El Yousfi et al. 2023).

The 25 nitrate concentration values were interpolated using the IDW method and the final nitrate concentration map (Fig. 10) was classified as follows: 17–30 mg/L (low concentration), 30–40 mg/L (moderate concentration), 40–50 mg/L (high concentration), and > 50 mg/L (very high concentration). In general, nitrate concentration values in the study area ranged from 17 mg/L to 86 mg/L, with a mean value of 47 mg/L–close to the maxi-

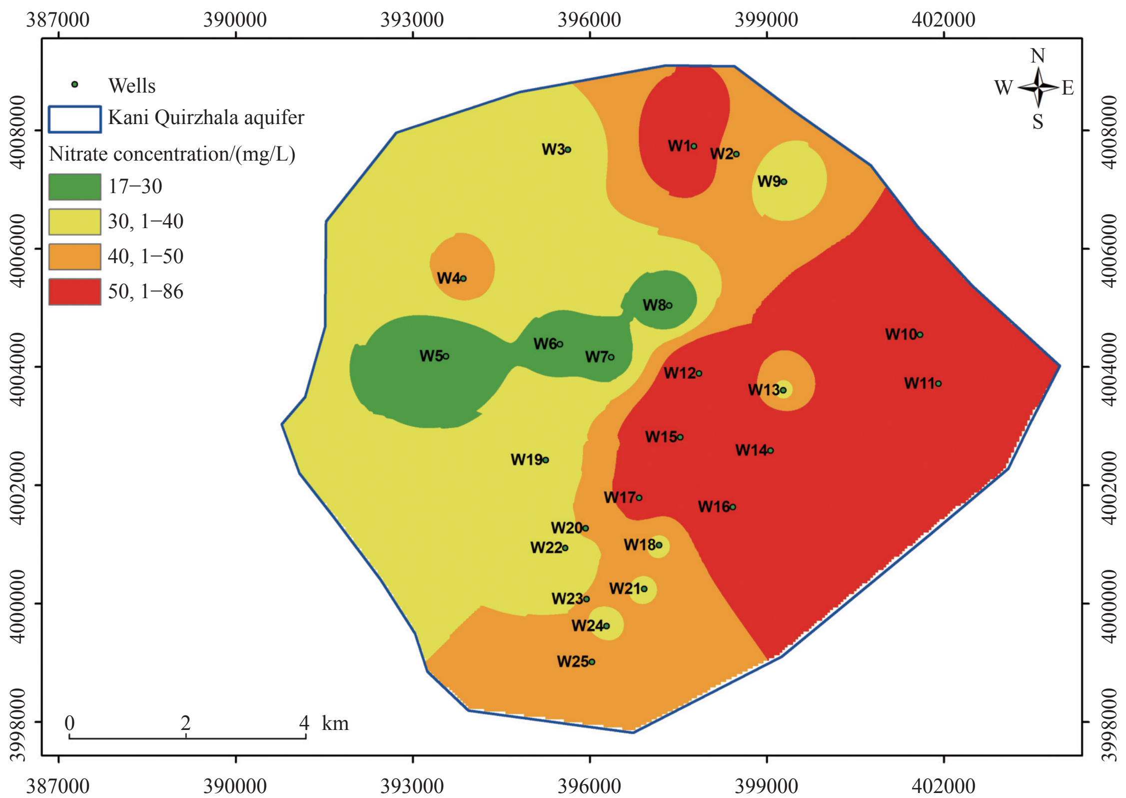

Fig. 10 Nitrate concentration distribution

mum allowable levels set by U.S. (45 mg/L) or by the European Union (50 mg/L), highlighting a significant nitrate pollution issue in the aquifer. Addtionally, 8 out of 25 nitrate values exceeded 50 mg/L. The spatial distribution of nitrate concentration aligns with the DRASTIC high vulnerability zone, particularly in the southern, south-eastern, and northern parts of the study area.

Furthermore, a point level comparison was conducted between the 25 nitrate concentration values from the observation wells and the DRASTIC vulnerability map (Fig. 11). The validation of the DRASTIC index with nitrate concentration resulted in a significant linear correlation, yielding a result of R = 0.72. Finally, the spatial distribution comparison between Figs. 9 and 10, created in ArcGIS using the spatial analyst tool and collection statistics, resulted in a correlation of 0.69, indicating sufficient accuracy.

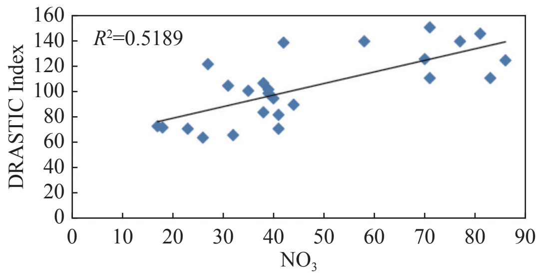

Fig. 11 Correlation of DRASTIC index with NO_3 values

4 Conclusions and suggestions

Groundwater holds paramount importance in various human activities, underscoring the critical need for effective planning and management to prevent groundwater pollution. Groundwater vulnerability mapping serves as an efficient tool for delineating potential pollution zones. This study represents the first endeavour to assess the intrinsic groundwater vulnerability to pollution in an area with severe groundwater quality deterioration. The assessment employed the DRASTIC framework in conjunction with Geographical Information System (GIS) techniques. The DRASTIC method uses seven geological and hydrogeological parameters to identify potential vulnerability areas.

While the DRASTIC method proves valuable, its limitations include subjectivity and uncertainty in evaluating parameter ratings and weights, as well as the selection of the parameters (e.g. the exclusion of parameters that they are considered important, such as land use and anthropogenic activities). The DRASTIC index, ranging from 53 to 150, classified the study area into four vulnerability classes, from very low to high. High vulnerability potential primarily are concentrated in the southern, south-eastern and northern part of the study area, emphasizing the critical needs for protecting these areas. Conversely, the central-northern, northern and north-western zones exhibited very low to low vulnerability potential.

Single-parameter sensitivity analysis underscored the significance of the Unsaturated Zone and Aquifer Media as the two parameters with the highest influence on the vulnerability map. Hydraulic Conductivity appeared less important for intrinsic vulnerability. Validation of DRASTIC vulnerability map with nitrate concentration values exhibited a satisfactory linear correlation, with a coefficient of R = 0.72. These findings offer actionable insights for policymakers and water authorities in efficiently managing groundwater resources at a regional level.

The study's results also provide valuable benchmarks for comparison with global areas sharing similar geological characteristics and facing groundwater quality challenges, facilitating an assessment of the DRASTIC method's performance and suitability. Future research improvements should focus on the integration of land use, considering variations over recent decades, as an additional parameter to the DRASTIC method. This integration aims to define specific vulnerability zones to pollution, offering a more comprehensive understanding of aquifer vulnerability and supporting sustainable development and robust aquifer management. Finally, the design and maintenance of a groundwater quality monitoring network are recommended to ascertain the aquifer's pollution status, particularly in high vulnerability zones.

References

Abera KA, Gebreyohannes T, Abrha B, et al. 2022. Vulnerability mapping of groundwater resources of mekelle city and surroundings, tigray region, Ethiopia. Water, 14(16): 2577. DOI：10.3390/w14162577.

Ahmed I, Nazzal Y, Zaidi FK, et al. 2015. Hydrogeological vulnerability and pollution risk mapping of the Saq and overlying aquifers using the DRASTIC model and GIS techniques, NW Saudi Arabia. Environmental Earth Sciences, 74(2): 1303−1318. DOI：10.1007/s12665-015-4120-5.

Alamne SB, Assefa TT, Belay SA, et al. 2022. Mapping groundwater nitrate contaminant risk using the modified DRASTIC model: A case study in Ethiopia. Environmental Systems Research, 11(1): 8. DOI: 10.1186/s40068-022-00253-9.

Al-Ansari NA. 2013. Management of water resources in Iraq: Perspectives and prognoses. Engineering, 5(8): 667−684. DOI: 10.4236/eng.2013.58080.

Ali SS, Hamamin D. 2012. Groundwater vulnerability map of basara basin, sulaimani governorate, Iraqi Kurdistan region. Iraqi Journal of Science, 53(3): 579−594.

Aller L, Bennett T, Lehr JH, et al. 1987. DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings. US Environmental Protection Agency Report (EPA/600/2-87/035), Robert S. Kerr Environmental Research Laboratory: 455.

Allouche N, Maanan M, Gontara M, et al. 2017. A global risk approach to assessing groundwater vulnerability. Environmental Modelling & Software, 88: 168−182. DOI: 10.1016/j.envsoft.2016.11.023.

Babiker IS, Mohamed MAA, Hiyama T, et al. 2005. A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. Science of the Total Environment, 345(1−3): 127−140. DOI: 10.1016/j.scitotenv.2004.11.005.

Bernardo B, Candeias C, Rocha F. 2022. Integration of electrical resistivity and modified DRASTIC model to assess groundwater vulnerability in the surrounding area of hulene-B waste dump, Maputo, Mozambique. Water, 14(11): 1746. DOI: 10.3390/w14111746.

Boufekane A, Yahiaoui S, Meddi H, et al. 2022. Modified DRASTIC index model for groundwater vulnerability mapping using geostatistic methods and GIS in the Mitidja Plain area (Algeria). Environmental Forensics, 23(5−6): 539−556. DOI: 10.1080/15275922.2021.1913674.

Brindha K, Elango L. 2015. Cross comparison of five popular groundwater pollution vulnerability index approaches. Journal of Hydrology, 524: 597−613. DOI: 10.1016/j.jhydrol.2015.03.003.

Canora F, Muzzillo R, Sdao F. 2022. Groundwater vulnerability assessment in the metaponto coastal plain (basilicata, Italy). Water, 14(12): 1851. DOI: 10.3390/w14121851.

Civita M. 1994. Le carte della vulnerabilita degli acquiferi al linquinamiento: Teoria e pratica [Contamination Vulnerability Mapping of the Aquifer: Theory and Practice]. Quaderni di Tecniche di Protezione Ambientale, Pitagora.

Djémin JÉ, Kouamé JK, Deh KS, et al. 2016. Contribution of the sensitivity analysis in groundwater vulnerability assessing using the DRASTIC method: Application to groundwater in dabou region (southern of Côte d'Ivoire). Journal of Environmental Protection, 7(1): 129−143. DOI: 10.4236/jep.2016.71012.

Ekanem AM, Ikpe EO, George NJ, et al. 2022. Integrating geoelectrical and geological techniques in GIS-based DRASTIC model of groundwater vulnerability potential in the raffia city of Ikot Ekpene and its environs, southern Nigeria. International Journal of Energy and Water Resources. DOI: 10.1007/s42108-022-00202-3.

El Yousfi Y, Himi M, Aqnouy M, et al. 2023. Pollution vulnerability of the ghiss nekkor alluvial aquifer in Al-hoceima (morocco), using GIS-based DRASTIC model. International Journal of Environmental Research and Public Health, 20(6): 4992. DOI: 10.3390/ijerph20064992.

Ersoy AF, Gültekin F. 2013. DRASTIC-based methodology for assessing groundwater vulnerability in the Gümüshaciköy and Merzifon basin (Amasya, Turkey). Earth Science Resource Journal, 17(1): 33−40.

Etuk M, Viaroli S, Ogbonnaya I, et al. 2022. Vulnerability mapping as a tool to foster groundwater protection in areas subject to rapid population expansion: The case study of Abuja Federal Capital Territory (Nigeria). Journal of Hydrology: Regional Studies, 42: 101158. DOI: 10.1016/j.ejrh.2022.101158.

Fannakh A, Farsang A. 2022. DRASTIC, GOD, and SI approaches for assessing groundwater vulnerability to pollution: A review. Environmental Sciences Europe, 34(1): 77. DOI: 10.

1186/s12302-022-00646-8.
Foster SSD. 1987. Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. Vulnerability of Soil and Groundwater to Pollutants. Hydrology Research Hague, Proceding and Information, 38: 69–86.
Gardi SQS. 2017. Environmental impact assessment of Erbil Dumpsite area-west of Erbil City-Iraqi Kurdistan Region. Journal of Tethys, 5(3): 194−217.
Garewal SK, Vasudeo AD, Landge VS, et al. 2017. A GIS-based Modified DRASTIC (ANP) method for assessment of groundwater vulnerability: A case study of Nagpur city, India. Water Quality Research Journal, 52(2): 121−135. DOI：10.2166/wqrj.2017.046.
Gogu RC, Dassargues A. 2000. Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. Environmental Geology, 39(6): 549−559. DOI：10.1007/s002540050466.
Gonçalves V, Albuquerque A, Carvalho P, et al. 2023. Groundwater vulnerability assessment to cemeteries pollution through GIS-based DRASTIC index. Water, 15(4): 812. DOI：10.3390/w15040812.
Goyal D, Haritash AK, Singh SK. 2021. A comprehensive review of groundwater vulnerability assessment using index-based, modelling, and coupling methods. Journal of Environmental Management, 296: 113161. DOI：10.1016/j.jenvman.2021.113161.
Green TR, Taniguchi M, Kooi H, et al. 2011. Beneath the surface of global change: Impacts of climate change on groundwater. Journal of Hydrology, 405(3−4): 532−560. DOI：10.1016/j.jhydrol.2011.05.002.
Hamza SM, Ahsan A, Imteaz MA, et al. 2015. Accomplishment and subjectivity of GIS-based DRASTIC groundwater vulnerability assessment method: A review. Environmental Earth Sciences, 73(7): 3063−3076. DOI：10.1007/s12665-014-3601-2.
Hasan M, Islam MA, Aziz Hasan M, et al. 2019. Groundwater vulnerability assessment in Savar upazila of Dhaka district, Bangladesh—a GIS-based DRASTIC modeling. Groundwater for Sustainable Development, 9: 100220. DOI：10.1016/j.gsd.2019.100220.
Ifediegwu SI, Chibuike IE. 2021. GIS-based evaluation of shallow aquifer vulnerability to pollution using DRASTIC model: A case study on Abakaliki, southeastern, Nigeria. Arabian Journal of Geosciences, 14(23): 2534. DOI：10.1007/s12517-021-08811-8.
Jain H. 2023. Groundwater vulnerability and risk mitigation: A comprehensive review of the techniques and applications. Groundwater for Sustainable Development, 22: 100968. DOI：10.1016/j.gsd.2023.100968.
Jawad SB, Hussien KA. 1988. Groundwater monitoring network rationalization using statistical analyses of piezometric fluctuation. Hydrological Sciences Journal, 33(2): 181−191. DOI：10.1080/02626668809491237.
Jhariya DC, Kumar T, Pandey HK, et al. 2019. Assessment of groundwater vulnerability to pollution by modified DRASTIC model and analytic hierarchy process. Environmental Earth Sciences, 78(20): 610. DOI：10.1007/s12665-019-8608-2.
Jmal I, Ayed B, Bahloul M, et al. 2022. Contribution of GIS tools and statistical approaches to optimize the DRASTIC model for groundwater vulnerability assessment in arid and semi-arid regions: The case of Sidi Bouzid shallow aquifer. Arabian Journal of Geosciences, 15(10): 974. DOI：10.1007/s12517-022-10149-8.
Khosravi K, Sartaj M, Karimi M, et al. 2021. A GIS-based groundwater pollution potential using DRASTIC, modified DRASTIC, and bivariate statistical models. Environmental Science and Pollution Research, 28(36): 50525−50541. DOI：10.1007/s11356-021-13706-y.
Kirlas MC, Karpouzos DK, Georgiou PE, et al. 2023. A GIS-based comparative groundwater vulnerability assessment using modified-DRASTIC, modified-SINTACS and NV index in a porous aquifer, Greece. Environments, 10(6): 95. DOI：10.3390/environments10060095.
Kirlas MC. 2021. Assessment of porous aquifer hydrogeological parameters using automated groundwater level measurements in Greece. Journal of Groundwater Science and Engineering, 9(4): 269−278. DOI：10.19637/j.cnki.2305-7068.2021.04.001.

Kirlas MC, Karpouzos DÎ, Georgiou PE, et al. 2022a. A comparative study of groundwater vulnerability methods in a porous aquifer in Greece. Applied Water Science, 12(6): 123. DOI：10.1007/s13201-022-01651-1.

Kirlas MC, Karpouzos DK, Georgiou PE, et al. 2022b. Groundwater vulnerability assessment in Nea Moudania (Chalkidiki) aquifer, using the DRASTIC and AHP-DRASTIC methods. 15th Conference of the Hellenic Hydrotechnical Association (H. H. A.)

Koon AB, Anornu GK, Dekongmen BW, et al. 2023. Evaluation of groundwater vulnerability using GIS-based DRASTIC model in Greater Monrovia, Montserrado County, Liberia. Urban Climate, 48: 101427. DOI：10.1016/j.uclim.2023.101427.

Kumar P, Bansod BKS, Debnath SK, et al. 2015. Index-based groundwater vulnerability mapping models using hydrogeological settings: A critical evaluation. Environmental Impact Assessment Review, 51: 38−49. DOI：10.1016/j.eiar.2015.02.001.

Kumar P, Sharma R, Bhaumik S. 2022. MCDA techniques used in optimization of weights and ratings of DRASTIC model for groundwater vulnerability assessment. Data Science and Management, 5(1): 28−41. DOI：10.1016/j.dsm.2022.03.004.

Kumar P, Thakur PK, Bansod BKS, et al. 2018. Groundwater: A regional resource and a regional governance. Environment, Development and Sustainability, 20(3): 1133−1151. DOI：10.1007/s10668-017-9931-y.

Li X, Ye S, Wang LH, et al. 2017. Tracing groundwater recharge sources beneath a reservoir on a mountain-front plain using hydrochemistry and stable isotopes. Water Supply, 17(5): 1447−1457. DOI：10.2166/WS.2017.036.

Machiwal D, Jha MK, Singh VP, et al. 2018. Assessment and mapping of groundwater vulnerability to pollution: Current status and challenges. Earth-Science Reviews, 185: 901−927. DOI：10.1016/j.earscirev.2018.08.009.

Mawlood DK. 2019. Sustainability of aquifer and ground water condition in Erbil Basin/Iraq. Zanco Journal of Pure and Applied Sciences, 31(6). DOI：10.21271/zjpas.31.6.6.

Mensah DO, Appiah-Adjei EK, Asante D. 2023. Groundwater pollution vulnerability assessment in the Assin municipalities of Ghana using GIS-based DRASTIC and SINTACS methods. Modeling Earth Systems and Environment, 9(2): 2955−2967. DOI：10.1007/s40808-022-01680-4.

Metwally MI, Armanuos AM, Zeidan BA. 2023. Comparative study for assessment of groundwater vulnerability to pollution using DRASTIC methods applied to central Nile Delta, Egypt. International Journal of Energy and Water Resources, 7(2): 175−190. DOI：10.1007/s42108-022-00198-w.

Mkumbo NJ, Mussa KR, Mariki EE, et al. 2022. The use of the DRASTIC-LU/LC model for assessing groundwater vulnerability to nitrate contamination in Morogoro Municipality, Tanzania. Earth, 3(4): 1161−1184. DOI：10.3390/earth3040067.

Muhammad AM, Tang ZH, Dawood AS, et al. 2015. Evaluation of local groundwater vulnerability based on DRASTIC index method in Lahore, Pakistan. Geofísica Internacional, 54(1): 67−81. DOI：10.1016/j.gi.2015.04.003.

Napolitano P, Fabbri A. 1996. Single-parameter sensitivity analysis for aquifer vulnerability assessment using DRASTIC and SINTACS. Application of Geographic Information Systems in Hydrology and Water Resources Management (Proceedings of the Vienna Conference, April 1996). IAHS Publication, 235: 559–566.

Neshat A, Pradhan B. 2017. Evaluation of groundwater vulnerability to pollution using DRASTIC framework and GIS. Arabian Journal of Geosciences, 10(22): 501. DOI：10.1007/s12517-017-3292-6.

Noori R, Ghahremanzadeh H, Kløve B, et al. 2019. Modified-DRASTIC, modified-SINTACS and SI methods for groundwater vulnerability assessment in the southern Tehran aquifer. Journal of Environmental Science and Health. Part A, Toxic/Hazardous Substances & Environmental Engineering, 54(1): 89−100. DOI：10.1080/10934529.2018.1537728.

Oke SA. 2020. Regional aquifer vulnerability and pollution sensitivity analysis of drastic application to Dahomey Basin of Nigeria. International Journal of Environmental Research and

Public Health, 17(7): E2609. DOI: 10.3390/ijerph17072609.

Omeje ET, Obiora DN, Okeke FN, et al. 2023. Investigation of aquifer vulnerability and sensitivity analysis of modified drastic and sintacs models: A case study of Ovogovo Area, Eastern Nigeria. Acta Geophysica, 71(5): 2439−2464. DOI: 10.1007/s11600-022-00992-4.

Ouedraogo I, Defourny P, Vanclooster M. 2016. Mapping the groundwater vulnerability for pollution at the pan African scale. Science of the Total Environment, 544: 939−953. DOI: 10.1016/j.scitotenv.2015.11.135.

Patel P, Mehta D, Sharma N. 2022. A review on the application of the DRASTIC method in the assessment of groundwater vulnerability. Water Supply, 22(5): 5190−5205. DOI: 10.2166/ws.2022.126.

Patle D, Nema S, Awasthi MK, et al. 2022. Groundwater vulnerability assessment using DRASTIC model in Niwari District of Bundelkhand Region, Madhya Pradesh, India. Arabian Journal of Geosciences, 15(20): 1590. DOI: 10.1007/s12517-022-10870-4.

Phok R, Kosgallana DWN, Sumana BW, et al. 2021. Using intrinsic vulnerability and anthropogenic impacts to evaluate and compare groundwater risk potential at north-western and western coastal aquifers of Sri Lanka through coupling DRASTIC and GIS approach. Applied Water Science, 11(7): 117. DOI: 10.1007/s13201-021-01452-y.

Pouye A, Faye SC, Di Ãdhiou M, et al. 2022. An evaluation of groundwater vulnerability assessment methods in a rapidly urbanizing city: Evidence from Dakar, Senegal. Environmental Earth Sciences, 81(16): 410. DOI: 10.1007/s12665-022-10531-5.

Rauf LF, Ali SS, Al-Ansari N. 2022. Groundwater vulnerability of halabja-khurmal sub-basin using modified DRASTIC method. Water, Air & Soil Pollution, 233(11): 440. DOI: 10.1007/s11270-022-05903-3.

Rezig A, Marinangeli L, Saggai S. 2022. Comparative study for assessing vulnerability to pollution in El Asnam plain, North of Algeria. Water Supply, 22(6): 5894−5914. DOI: 10.2166/ws.2022.216.

Ribeiro L. 2000. SI: A new index of aquifer susceptibility to agricultural pollution. Internal report, ERSHA/CVRM, Instituto Superior Técnico, Lisbon, Portugal: 12.

Saidi S, Bouri S, Ben Dhia H, et al. 2011. Assessment of groundwater risk using intrinsic vulnerability and hazard mapping: Application to Souassi aquifer, Tunisian Sahel. Agricultural Water Management, 98(10): 1671−1682. DOI: 10.1016/j.agwat.2011.06.005.

Salih AO, Ali Al-Manmi D. 2021. DRASTIC model adjusted with lineament density to map groundwater vulnerability: A case study in Rania Basin, Kurdistan, Iraq. Environmental Science and Pollution Research, 28(42): 59731−59744. DOI: 10.1007/s11356-021-14912-4.

Sarkar M, Pal SC. 2021. Application of DRASTIC and modified DRASTIC models for modeling groundwater vulnerability of malda district in West Bengal. Journal of the Indian Society of Remote Sensing, 49(5): 1201−1219. DOI: 10.1007/s12524-020-01176-7.

Sener EH, Davraz A. 2013. Assessment of groundwater vulnerability based on a modified DRASTIC model, GIS and an analytic hierarchy process (AHP) method: The case of Egirdir Lake Basin (Isparta, Turkey). Hydrogeology Journal, 21(3): 701−714. DOI: 10.1007/s10040-012-0947-y.

Sener E, Sener Ş. 2015. Evaluation of groundwater vulnerability to pollution using fuzzy analytic hierarchy process method. Environmental Earth Sciences, 73(12): 8405−8424. DOI: 10.1007/s12665-014-4001-3.

Shakeri R, Alijani F, Nassery HR. 2023. Comparison of the DRASTIC Land modified VABHAT models in vulnerability assessment of Karaj aquifer, central Iran, using MCDM, SWARA, and BWM methods. Environmental Earth Sciences, 82(4): 97. DOI: 10.1007/s12665-023-10773-x.

Singha SS, Pasupuleti S, Singha S, et al. 2019. A GIS-based modified DRASTIC approach for geospatial modeling of groundwater vulnerability and pollution risk mapping in Korba district, Central India. Environmental Earth Sciences, 78(21): 628. DOI: 10.1007/s12665-019-8640-2.

Sissakian VK, Al-Ansari N, Adamo N, et al. 2022.

Flood hazards in erbil City Kurdistan region Iraq, 2021: A case study. Engineering, 14(12): 591−601. DOI：10.4236/eng.2022.1412044.

Taghavi N, Niven RK, Kramer M, et al. 2023. Comparison of DRASTIC and DRASTICL groundwater vulnerability assessments of the Burdekin Basin, Queensland, Australia. Science of the Total Environment, 858: 159945. DOI：10.1016/j.scitotenv.2022.159945.

Taghavi N, Niven RK, Paull DJ, et al. 2022. Groundwater vulnerability assessment: A review including new statistical and hybrid methods. Science of the Total Environment, 822: 153486. DOI：10.1016/j.scitotenv.2022.153486.

Torkashvand M, Neshat A, Javadi S, et al. 2023. Groundwater vulnerability to nitrate contamination from fertilizers using modified DRASTIC frameworks. Water, 15(17): 3134. DOI：10.3390/w15173134.

United Nations. 2020. Climate change exacerbates existing conflict risks, likely to create new ones, Assistant Secretary-General Warns Security Council. https://www.un.org/press/en/2020/sc14260.doc.html

Van Stempvoort D, Ewert L, Wassenaar L. 1993. Aquifer vulnerability index: A GIS - compatible method for groundwater vulnerability mapping. Canadian Water Resources Journal, 18(1): 25−37. DOI：10.4296/cwrj1801025.

Victorine Neh A, Ako Ako A, Richard Ayuk A, et al. 2015. DRASTIC-GIS model for assessing vulnerability to pollution of the phreatic aquiferous formations in Douala-Cameroon. Journal of African Earth Sciences, 102: 180−190. DOI：10.1016/j.jafrearsci.2014.11.001.

Wei A, Bi P, Guo J, et al. 2021. Modified DRASTIC model for groundwater vulnerability to nitrate contamination in the Dagujia river basin, China. Water Supply, 21(4): 1793−1805. DOI：10.2166/ws.2021.018.

Xiong HX, Wang YZ, Guo X, et al. 2022. Current status and future challenges of groundwater vulnerability assessment: A bibliometric analysis. Journal of Hydrology, 615: 128694. DOI：10.1016/j.jhydrol.2022.128694.