



A GIS-based DRASTIC and pesticide DRASTIC model to evaluate groundwater vulnerability to pollution in Central Erbil basin, Kurdistan Region, Iraq

Rebwar N. Dara 

Department of Earth Sciences and Petroleum, College of Science, Salahaddin University– Erbil, Erbil, Iraq.

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ABSTRACT

Assessing groundwater vulnerability is crucial for managing groundwater resources effectively, especially in regions experiencing significant human activities and pollution. This study evaluates groundwater vulnerability in the Central Erbil Basin, northern Iraq, using a comparative approach with the DRASTIC and Pesticide DRASTIC methods, integrated with a geographic information system (GIS). Results showed the highest vulnerability in the central-western and central-eastern parts of the study area. In contrast, the south-eastern, central, and northwestern parts exhibited the lowest vulnerability. Furthermore, a single-parameter sensitivity analysis for both methods indicated that the unsaturated zone was the most influential among the seven parameters, while hydraulic conductivity was the least influential. Lastly, validation of the final vulnerability maps against real nitrate concentration measurements using the Pearson correlation coefficient showed that Pesticide DRASTIC was more accurate than DRASTIC, with $R = 0.66$ compared with $R = 0.62$ for DRASTIC.

Keywords: GIS, Groundwater vulnerability, Iraq, Nitrate, Sensitivity analysis.

Name: Rebwar N. Dara

E-mail: rebwar.dara@su.edu.krd



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نموذج DRASTIC ونموذج DRASTIC للمبيدات المعتمد على نظم المعلومات الجغرافية لتقييم

قابلية المياه الجوفية للتلوث في حوض أربيل الأوسط، إقليم كردستان، العراق

ريوار ناصر دارا

قسم علوم الأرض والنفط، كلية العلوم، جامعة صلاح الدين – أربيل، أربيل، العراق.

الملخص

يعد تقييم قابلية تأثر المياه الجوفية للخطر أمراً بالغ الأهمية لإدارة موارد المياه الجوفية بشكل فعال، وخاصة في المناطق التي تشهد أنشطة بشرية وتلوثاً كبيراً. تقوم هذه الدراسة بتقييم تعرض المياه الجوفية في حوض أربيل الأوسط، شمال العراق، باستخدام نهج مقارن للطرق، وهي طريقة DRASTIC وطريقة Pesticide DRASTIC، متكاملة مع نظام المعلومات الجغرافية (GIS). وأظهرت النتائج أن أعلى مستويات للتعرض للتلوث تم تحديدها في الأجزاء الوسطى الغربية والوسطى الشرقية من منطقة الدراسة، في حين أظهرت الأجزاء الجنوبية الشرقية والوسطى والشمالية الغربية أدنى مستويات للتعرض للتلوث. وعلاوة على ذلك، أشار تحليل الحساسية أحادي المعلمة لكلا الطريقتين إلى أن المنطقة غير المشبعة كانت الأكثر تأثيراً بين المعلمات السبعة، في حين كانت الموصلية الهيدروليكية الأقل فعالية. أخيراً، كشف التحقق بين خرائط التعرض للخطر النهائية وقياسات تركيز النترات الحقيقية، باستخدام معامل ارتباط بيرسون، أن Pesticide DRASTIC كان أكثر دقة مقارنةً بـ DRASTIC، مما أدى إلى $R = 0.66$ أعلى نسبياً، بدلاً من $R = 0.62$ لـ DRASTIC.

الكلمات المفتاحية / نظم المعلومات الجغرافية؛ تعرض المياه الجوفية؛ العراق؛ النترات؛ تحليل الحساسية.

INTRODUCTION

Water is essential for life and food production, making water resource management critical to meet humanitarian and agricultural needs, as well as industrial requirements. ⁽¹⁻³⁾ In Iraq, population growth and economic expansion are driving up the demand for groundwater resources. Nonetheless, this demand is challenged by declining water resources driven by neighboring countries' policies. ⁽⁴⁾ Recent reports indicate a drastic reduction in water reserves due to drought, decreased rainfall, and lower water levels; these factors have also led to migration. In Iraq, the Tigris and Euphrates rivers are the primary surface water sources, with groundwater being a secondary resource. Despite limited data on groundwater availability, estimates suggest variability across regions: mountainous areas, desert regions, and the foothills. ⁽⁵⁾

Groundwater levels in the Erbil basin are continuously decreasing due to climate change and

uncontrolled groundwater exploitation through wells. ^(6, 7) Erbil city is experiencing remarkable urban growth and rapid spatial expansion, compounded by a dramatic population increase due to emigration from rural areas, other parts of Iraq and unstable neighboring countries over the last three decades. More than 90% of the local population relies on groundwater from the Central Erbil Basin; urbanization, industrial needs, and agricultural growth have increased the demand for high-quality water. Overexploitation and reduced precipitation have exacerbated the decline in groundwater supply, leading to significant deterioration in both quality and quantity. ⁽⁸⁾ Therefore, a groundwater governance framework is needed to guide policymakers in protecting these resources from further degradation.

In general, methods for assessing groundwater vulnerability fall into index-overlay methods,

statistical analysis methods, and process-based methods ⁽⁹⁻¹²⁾. The choice of method depends on aquifer type, study-area scale, data availability, and pollutant type. Groundwater monitoring can be costly and complex, prompting researchers to develop more economical, user-friendly methods that require less data ⁽¹³⁻¹⁵⁾. Among these, the DRASTIC method, developed by ⁽¹⁶⁾ for the U.S. Environmental Protection Agency, is the most popular for vulnerability evaluation ^(17, 18). It uses seven hydrogeological parameters: depth to water, recharge, aquifer media, soil media, topography, Impact of the vadose zone, and hydraulic conductivity ⁽¹⁹⁾. Pesticide DRASTIC is a modified version of the original DRASTIC method, designed to assess groundwater vulnerability to specific pollutants. While it retains the same parameter ratings as the original, it applies different weights to the seven factors ⁽¹⁶⁾.

The current study focuses on the assessment of groundwater vulnerability in the Central Erbil Basin, northern Iraq, using a comparative analysis by applying two different methods, namely DRASTIC and Pesticide DRASTIC, combined with Geographical Information System (GIS) techniques. The accuracy of the final vulnerability maps was validated with the correlation (Pearson correlation coefficient (R) between actual nitrate concentration (NO_3^-) in groundwater and the outputs. Additionally, a single-parameter sensitivity analysis (SPSA) was conducted to reveal the effect of each parameter on the final vulnerability index. This combined approach aims to help policymakers and planners preserve the aquifer system by providing a useful spatial tool for assessing its current state. The study also evaluates the performance and suitability of both methods in an area with significant nitrate pollution.

1- Study Area

The research area's aquifer is located in the Erbil Basin and spans approximately 1861 km². This Basin is located in northern Iraq and is bordered by the Lesser Zab River to the south and the Greater

Zab River to the north. Hydrogeologically, the Erbil Basin is divided into three sub-basins: the north sub-basin (Kapran), the medium sub-basin (Central Erbil) and the south sub-basin (Bashtapa) ^(7, 20)(Figure 1). The geographic coordinates of the Central Erbil basin are 44.00° longitude (E) and 36.19° latitude (N), with an elevation of about 430 meters above sea level. The basin's aquifers are primarily associated with intergranular aquifers in recent deposits and the Upper Bakhtiary Formation, which consists of sand, clay, conglomerate, and gravel. ^(21, 22)(Figure 2). These lithological components contribute to a significant and productive aquifer system in the region. Geologically, the area lies within the Low Folded Zone of the Outer Platform on the Arabian Plate. A sequence of anticlines and synclines defines the basin's structural framework. It also has a semi-arid climate, with wet, cold winters and hot, dry summers. ⁽²³⁾. Average annual precipitation is about 370 mm, mostly falling between November and March. Temperatures fluctuate between 10 and 30 °C. Groundwater depths range from 40 m to over 100 m ⁽²⁴⁾.

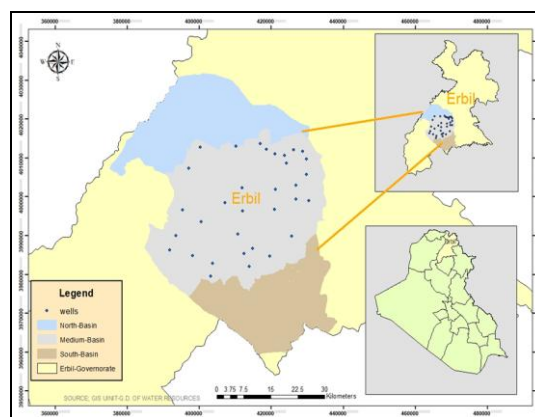


Fig. 1: Location of the central Erbil basin study area.

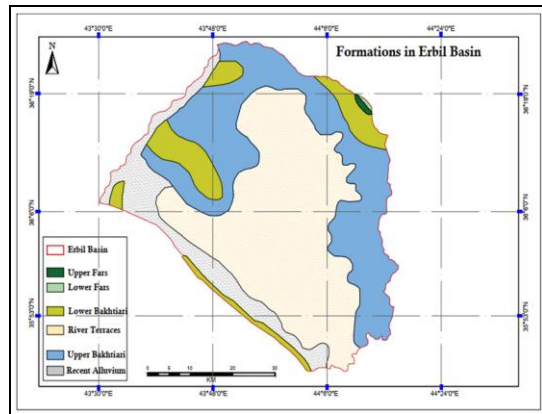


Fig. 2: Geological Formations of the Erbil Basin
modified after ⁽⁷⁾

MATERIALS AND METHODS

Methods

One of the most prevalent and reliable approaches for assessing groundwater vulnerability is the DRASTIC model ^(25, 26). DRASTIC is an overlay index method ⁽¹⁶⁾ that incorporates seven key hydrogeological parameters: depth to water, net recharge, aquifer media, soil media, topography, vadose zone impact and hydraulic conductivity. Each parameter is assigned a weight from 1 (least impact) to 5 (most impact) and a rating from 1 to 10 based on its potential contribution to groundwater contamination (Table 1). The final DRASTIC Index is calculated as the weighted linear combination of the rated parameters. According to ⁽¹⁶⁾, the method is based on four core assumptions: ⁽¹⁾ any location can act as a potential source of contamination, ⁽²⁾ pollutants reach the saturated zone primarily via precipitation, ⁽³⁾ contaminants move at the same rate as groundwater, and ⁽⁴⁾ the study area must cover at least 0.4 km². In this study, we implemented the DRASTIC model as follows. First, we digitized all seven parameters into raster layers in a GIS environment using available hydrogeological and environmental data. We then reclassified each raster according to the rating criteria proposed in ⁽¹⁶⁾ to reflect local conditions. The standard DRASTIC weights were applied to each parameter (D:5, R:4, A:3, S:2, T:1, I:5, C:3). The final index was computed using the weighted overlay method

(Eq.1). The resulting vulnerability values typically range from 23 to 230 for standard DRASTIC, and from 26 to 256 in the Pesticide DRASTIC variant.

No formal classification or threshold values for vulnerability categories were proposed in ⁽¹⁶⁾; therefore, we interpreted the index based on the relative distribution of values across the study area.

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (1)$$

where D, R, A, S, T, I, and C represent the seven parameters of the technique, w represents the weight assigned to each aspect, and r represents its score.

Table 1: Weights, ranges and ratings of Standard and Pesticide DRASTIC parameters modified from ⁽¹⁶⁾

DRASTIC parameter	Range/type	Rating	Standard weight	Pesticide DRASTIC weight
D: Depth to water (m)	10-20	10	5	5
	20-30	9		
	30-40	8		
	40-50	7		
	50-60	6		
	60-70	5		
	70-80	4		
	80-90	3		
	90-100	2		
	>100	1		
R: Net recharge (mm/yr)	0-50	1	4	4
	50-100	3		
	100-180	6		
	180-250	8		
	>250			
A: Aquifer media	Massive Shale	3	3	3
	Metamorphic/ Igneous	4		
	Weathered metamorphic/ igneous, clay with sand			
	Glacial till,			

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	clay with gravel			
	Bedded sandstone, limestone, and shale sequences	6		
	Massive sandstone			
	Massive limestone			
	Sand and gravel	7		
	Basalt			
	Karst limestone	8		
S: Soil media	Non-shrinking and non-aggregated clay 1	1	2	5
	Muck	2		
	Clay loam	3		
	Silty loam	4		
	Loam	5		
	Sandy loam	6		
	Shrinking clay and/or aggregated 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			
	Shale			
	Limestone			

	Sandy clay	3		
	Sandstone	4		
	Sand, gravel, and silt	6		
	Metamorphic/ igneous			
	Sand and gravel	7		
	Basalt			
	Karst limestone	8		
C: Hydraulic conductivity (m/day)	0.0432-4.32	1	3	2
	4.32-12.96	2		
	12.96-28.51	4		
	28.51-43.20	6		
	43.20-86.40	8		
	>86.40	10		

3.2 Preparation of thematic maps

We prepared rating maps for all parameters in ArcGIS using IDW interpolation; Table 2 summarizes the thematic maps for DRASTIC parameters.

Table 2: Spatial and hydrogeological data for the study area

Depth to water	The proximity of the water table to the ground surface is a key factor impacting the risk of groundwater pollution. Generally, the greater the distance, the lower the pollution potential; the closer the groundwater is to the surface, the more susceptible it is to contamination ⁽²⁷⁾ . Data for this parameter were obtained from the Erbil Groundwater Directorate in 2023/ Ministry of Agriculture and Water Resources.
Net recharge	It is the quantity of recharge from the surface through infiltration that actually reaches the water table. The greater the value of net recharge, the greater the possibility of groundwater contamination. The data for this parameter are estimated using a water

	balance method derived from a study by ⁽²⁸⁾ .
Aquifer Media	This pertains to the properties of the saturated zone, which affect pollutant attenuation and water flow within the aquifer. The lithology of the saturated zone was obtained from the lithological column of the wells, which was obtained from the Erbil Groundwater Directorate/Ministry of Agriculture and Water Resources.
Soil media	Soil media plays a key role in controlling groundwater recharge through its porosity and permeability ⁽²⁹⁾ .
Topography	This parameter affects runoff rates and infiltration. Regions with low slopes tend to have a higher potential for groundwater pollution because low surface runoff and high infiltration facilitate pollutant migration to the aquifer ⁽¹⁵⁾ . The study area slope was derived from a 30m resolution DEM.
Vadose zone	It reduces the risk of groundwater pollution through various biochemical activities such as filtration and dispersal ⁽³⁰⁾ . The lithology of the vadose zone was derived from well lithological columns obtained from the Erbil Groundwater Directorate/Ministry of Agriculture and Water Resources.
Hydraulic conductivity	Refers to the velocity of groundwater flow into the saturated zone and depends on the aquifer material. Higher hydraulic conductivity increases the likelihood of groundwater contamination ⁽³⁰⁾ . The hydraulic conductivity data used in this study are derived from a study conducted by ⁽²⁸⁾ .

3.3 Sensitivity analysis

Sensitivity analysis provides valuable information about the uncertainty and robustness of the weights

given to the various parameters by the DRASTIC and Pesticide DRASTIC methods. For both DRASTIC and pesticide DRASTIC, the standard DRASTIC weights were used as proposed by ⁽¹⁶⁾, and a single-parameter sensitivity analysis was conducted to measure each factor's impact on the final vulnerability index ⁽²⁹⁾. This exploration compares each DRASTIC parameter's hypothetical weight with its actual weight, enabling researchers to evaluate the role of prejudice in groundwater vulnerability assessments ⁽¹⁵⁾. The researchers calculated each parameter's effective weight using the following equation (Eq. 2) to better understand each parameter's importance in the final index ⁽³¹⁾.

$$W = ((P_r P_w) / V) \times 100 \quad (2)$$

where W = the effective weight of each parameter, P_r = the rating value of each parameter, P_w = the weight of each parameter, and V = the overall vulnerability index.

4. RESULTS AND DISCUSSION

4.1 Depth to groundwater (D)

We used groundwater-level data from field investigations across the entire research area to create the depth-to-water map. We interpolated these data using the ArcGIS IDW method ^(19, 32). This method is simple and flexible for irregularly spaced sample points and is not sensitive to a small number of sample points. In this study, we adjusted the ranges and ratings of the depth to water parameter to improve the accuracy of the final vulnerability map and adapt the standard DRASTIC method to the conditions of the specific area ^(15, 19, 33-35). Consequently, the raster layer was categorized into seven classes, and each class was assigned a corresponding rating value (Table 1 and Figure 3). Because the aquifer is shallow, the southeastern and northwestern areas of the research region are particularly sensitive to contamination. Only the northwestern and southeastern sections of the research basin are the least vulnerable due to water depth.

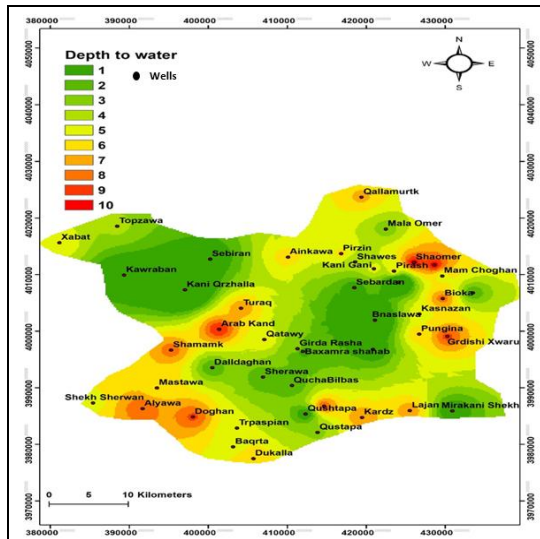


Fig. 3: Depth to groundwater rating map in Central Erbil Basin

4.2 Net recharge (R)

We derived the metric from data measured at 46 sites within the study area. We interpolated the recharge map raster using the converse distance weighting algorithm implemented in ArcGIS. The net recharge index layer was divided into two classes, each rated with a common value (Figure 4): 0-50 mm/yr and 50-100 mm/yr, which were rated as 1 and 3, respectively. Results show that the southeast, southwest, and northeast regions have low recharge values. In contrast, the rest of the area has considerably higher recharge values, indicating greater potential concern for groundwater vulnerability.

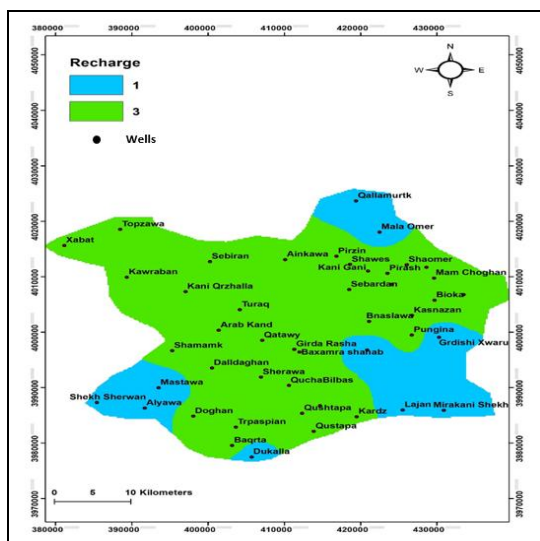


Fig. 4: Recharge rating map in Central Erbil Basin

4.3 Aquifer media (A)

Another aquifer media factor was projected using lithological data from 46 field-collected drilling-well samples and divided into four classes, each assigned a ranking value. For example, clay with gravel received a rating of 5, while sandy gravel received a rating of 8 (Figure 5). The parameter rating followed (15, 19). Based on the IDW results, sandy gravel is the dominant aquifer medium in the investigation area. Sandy gravel has larger grain sizes and is therefore more porous, increasing the potential risk of groundwater vulnerability.

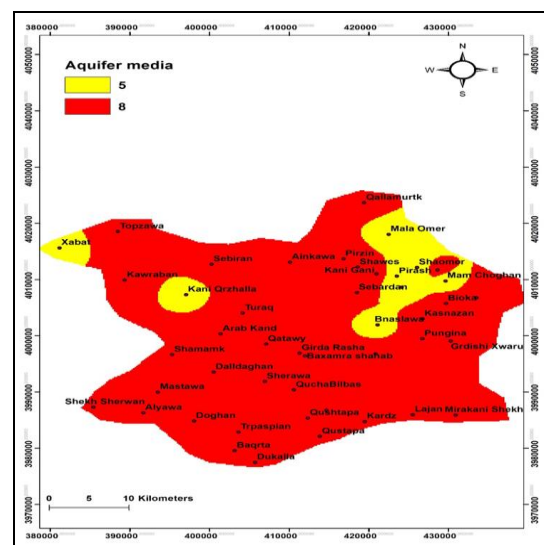


Fig. 5: Aquifer media rating map in Central Erbil Basin

4.4 Soil media (S)

This parameter was computed using 46 soil samples collected across the study area. These samples were divided into five classes, each rated according to the values shown in Figure 6. The results show that the highest-ranking class, which covers the largest area in the study area, is silty clay, which has the lowest vulnerability potential. The more detailed map shows that the less vulnerable sections of the area are indeed the majority, although patches, especially in the center and along the western edges, show lower vulnerability, hence the presence of more permeable soil types.

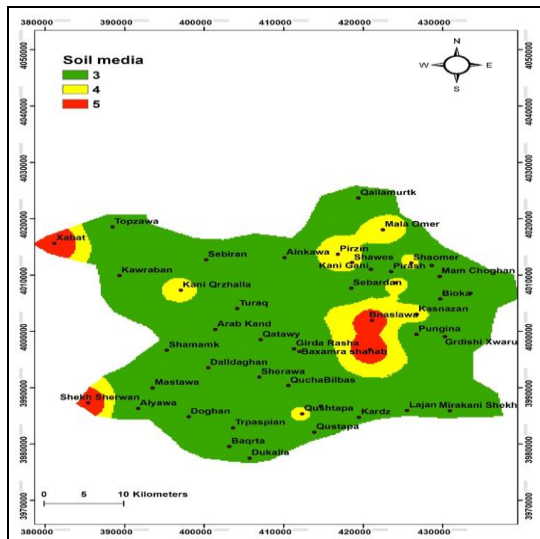


Fig. 6: Soil media rating map in Central Erbil Basin

4.5 Topography (T)

We produced a topography map using a digital elevation model with a 30 m spatial resolution from the ASTER DEM. We then prepared the gradient map in ArcGIS using a Spatial Analyst tool and categorized it into five classes. The distribution was done as follows: 1.24% of the area had a slope range of 0-2% rated with 1; 4.61% had a slope range of 2-6% rated with 3; 23.3%, had a slope range of 6-12% rated with 5; 54.01%, had a slope range of 12-18% rated with 9; and 16.84%, had a slope range of >18% rated with 10 (Table 1 and Figure 7). The flat geography, interspersed with hummocky land, especially in the eastern, southern, and northern areas, allows pollutants to infiltrate aquifers more easily, strongly influencing an area's overall groundwater vulnerability.

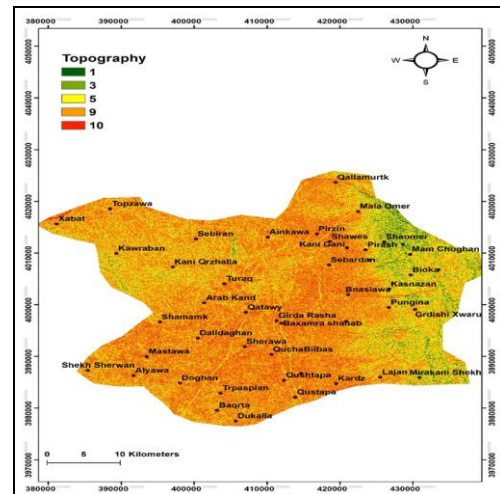


Fig. 7: Topography rating map in Central Erbil Basin

4.6 Impact of the vadose zone (I)

The vadose zone map was created identically to the previous one, with the same parameters (IDW) from 46 lithological profiles. It was divided into three classes based on the material's ability to accept and transport water (Figure 8). The area consists of gravel, mixed sand, and silt in the east and west, and clay, silt, and mixed sand in the center and south. Coarse-grained materials, such as gravel and conglomerate, are rated 8; gravel with mixed sand and silt is rated 7; and fine-grained materials, such as sandy silt with clay, are rated 6.

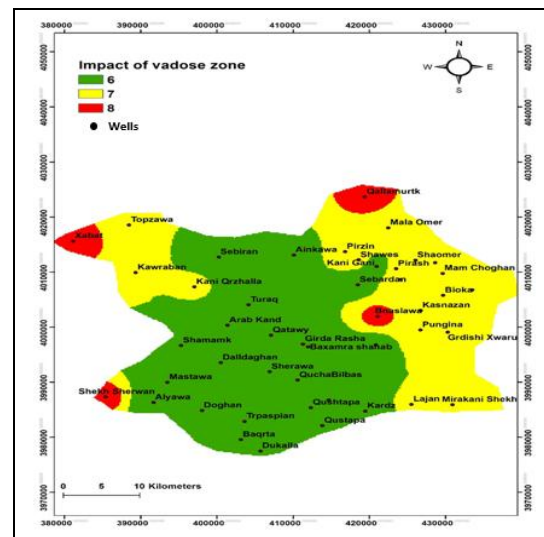


Fig. 8: Impact of the vadose zone rating map in Central Erbil Basin

4.7 Hydraulic Conductivity

The vulnerability map for this element was generated using IDW in ArcGIS software, based on soil lithology and pump test data. It was then divided into five groups and graded. Aquifer

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hydraulic conductivity varies from 0.06 to 6.3 m/day. Aquifers with 0.06-3.9 m/day were rated as 1, and those with 4.1-6.3 m/day were rated as 2. The results indicate that hydraulic conductivity is predominantly low throughout most of the exploration area, with a central-to-eastern trend (Figure 9).

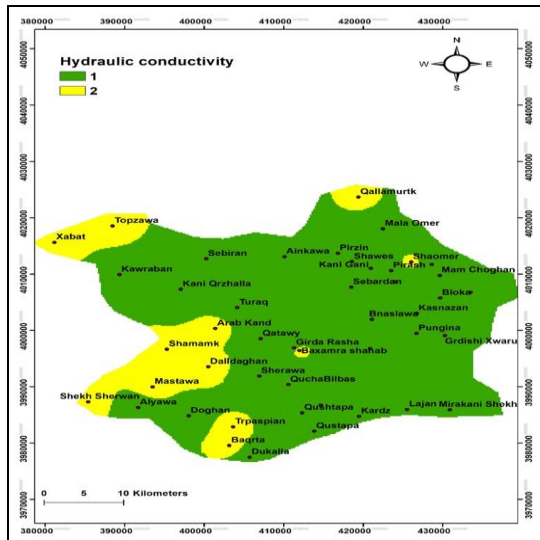


Fig. 9: Hydraulic conductivity rating map in Central Erbil Basin

4.8 DRASTIC vulnerability map

We integrated all seven DRASTIC parameters in ArcGIS to compute the final DRASTIC index for the Central Erbil Basin, as explained in Eq. 1. The resulting vulnerability map, in raster format, ranged from 74 to 139 (Figure 10). We used Jenks' natural breaks classification method (36) to classify the map into four vulnerability classes: very low (<92), low (92-102), moderate (102-112), and high (112-139). Numerous researchers have used this method (15, 37-40). The spatial distribution classes showed 15.85% of the area in a very low vulnerability zone, 27.13% in a low vulnerability zone, 32.77% in a moderate vulnerability zone, and 24.24% in a high vulnerability zone (Table 3). The highly susceptible zone mostly lies in the central west and central east of the research area. This is because of the favorable hydrogeological conditions, including a sandy unflooded zone, level topography, a sandy grit aquifer medium, and a comparatively shallow water table-all contributing to an increase in the potential for groundwater

pollution. In contrast, the central, northwestern, and southeastern areas have very low to low susceptibility. This reduced susceptibility is due to greater depth to water, less permeable unsaturated materials, slightly steeper topography, lower recharge rates, and finer, less permeable aquifer materials characteristic of these regions. The final DRASTIC vulnerability map also has uncertainties because it does not account for temporal changes such as seasonal water levels, land-use changes, and climate shifts. Moreover, the limited spatial resolution leads to inadequate local vulnerability assessments, and assuming homogeneous aquifer properties overlooks spatial variations. Additionally, boundary conditions remain uncertain, particularly in large study areas, and the parameter weighting scheme may not accurately reflect the study area's specific hydrogeological conditions. Finally, the map gives limited consideration to human activities such as agriculture, urbanization, and industry, and comprehensive hydrochemical data are lacking across the entire study area.

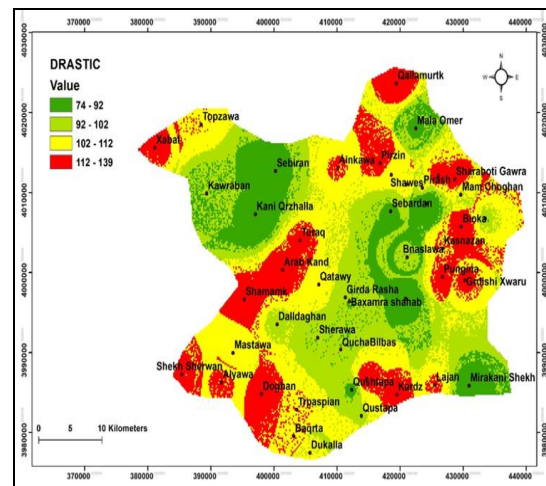


Fig. 10: DRASTIC vulnerability map in Central Erbil Basin

Table 3: DRASTIC index classes and spatial distribution

Vulnerability class	DRASTIC Index	Area (km²)	Area (%)
Very low	74-92	290.19	15.85
Low	92-102	496.66	27.13
Moderate	102-112	599.87	32.77
High	112-139	443.80	24.24

4.9 Pesticide DRASTIC vulnerability map

The Pesticide DRASTIC vulnerability index ranged from 80 to 158, which was higher than the standard DRASTIC index range ^(41, 42). (Fig. 11). Using the ⁽³⁶⁾ natural breaks classification, the Pesticide DRASTIC values were categorized into: very low (<107), low (107–120), moderate (120–131), and high (131–158). The area distribution for these classes was 11.09% for very low, 35.77% for low, 29.53% for moderate, and 23.61% for high (Table 4). Although Pesticide DRASTIC produced the same four vulnerability classes as the standard DRASTIC model, the area coverage differed. Table 5 summarizes the comparison of Groundwater Vulnerability based on both models.

Table 4: Pesticide DRASTIC index classes and spatial distribution

Vulnerability class	DRASTIC Index	Area (km ²)	Area (%)
Very low	80-107	202.94	11.09
Low	107-120	654.84	35.77
Moderate	120-131	540.59	29.53
High	131-158	432.29	23.61

Table 5: Comparison of Groundwater Vulnerability Classification: Standard DRASTIC vs. Pesticide DRASTIC Models

Vulnerability Class	Area Coverage (%) in Standard DRASTIC	Area Coverage (%) in Pesticide DRASTIC
Very low and low	42.98	46.86%
Moderate	32.77%	29.53%
High	No notable difference	

4.10 Single-parameter effect of weight-rating factors

We subjected all seven hydrogeological parameters of the DRASTIC approach to a single-parameter sensitivity examination to assess their impact on the final vulnerability index using their imaginary weights ⁽¹⁹⁾. The results indicated the difference between effective and theoretical weights for all parameters, as shown in Table 6. The vadose zone

achieved an effective weight of 31.31%, which is significantly higher than its theoretical weight of 21.74%. This agrees with another research ^(10, 30). In addition, Aquifer Media was the most important parameter, with an actual weight of 22.21%, higher than its theoretical weight of 13.04%. This agrees with the literature ^(30, 43). The third most important influencing parameter was depth to water, with an effective weight of 19.60%, lower than its theoretical weight of 21.74%. The sensitivity analysis showed that the effective weights for recharge, soil media, and hydraulic conductivity were much lower than theoretical weights. Thus, they were 9.76%, 6.14%, and 3.37%, respectively, compared with the theoretical weights of 17.39%, 8.70%, and 13.04%. This suggests less importance in the final vulnerability assessment. Topography, by contrast, became more important in the vulnerability map, with an actual weight of 7.61% compared to its theoretical value of 4.35%. Overall, the ranking of the parameters in terms of vulnerability from the results of DRASTIC is represented as: Impact of the Vadose Zone (I) > Aquifer Media (A) > Depth to Water (D) > Recharge (R) > Topography (T) > Soil Media (S) > Hydraulic Conductivity (C). This implies a general theoretical sequence of $D \sim I > R > A \sim C > S > T$. Therefore, the vadose zone and Aquifer Media are critical parameters that inform broader groundwater vulnerability assessment techniques. In the Pesticide DRASTIC model, the vadose zone and topography emerge as the most influential parameters, with average weights of 21.40% and 19.50%, surpassing their theoretical values of 15.38% and 11.54%, respectively (Table 7). Furthermore, the Aquifer media's effective weight (18.98%) also shows a significantly stronger influence in this study than its theoretical value (11.54%). In contrast, Recharge and Soil media show a lower impact than expected. Specifically, Recharge has an effective weight of 8.34%, well below its theoretical value (15.38%), while Soil media's actual weight is 13.11%, matching its theoretical value (13.11%). The Depth to water

also shows a slightly lower impact (16.75%) than expected (19.23%). Moreover, Hydraulic Conductivity is the least influential parameter on the final vulnerability map, with an effective weight of 1.92%. Finally, the order of parameter contribution in this study is $I > T > A > D > S > R > C$, differing from the theoretical sequence of $S > D > I > R > T > A > C$.

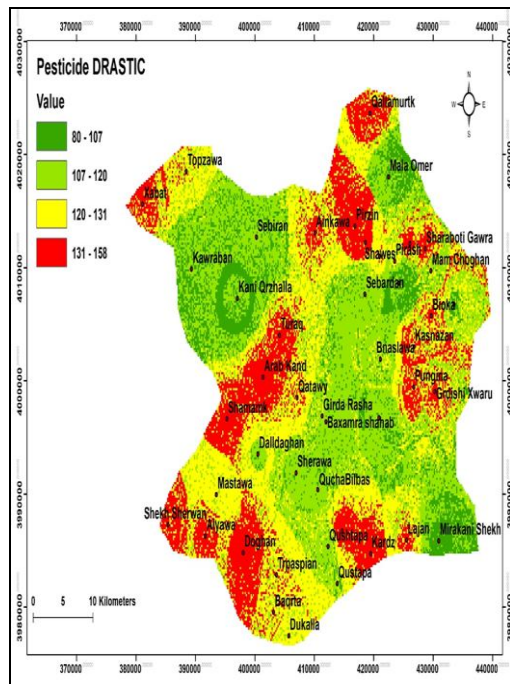


Fig. 11: Pesticide DRASTIC vulnerability map in Central Erbil Basin

Table 6: Statistics of single-parameter sensitivity analysis for DRASTIC

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (%)			
			Mean	Min	Max	SD
D	5	21.74	19.60	4.84	48.40	8.71
R	4	17.39	9.76	3.87	11.62	1.55
A	3	13.04	22.21	14.52	23.23	1.74
S	2	8.70	6.14	5.81	9.68	0.77
T	1	4.35	7.61	0.97	9.68	1.74
I	5	21.74	31.31	29.04	38.72	1.94
C	3	13.04	3.37	2.90	5.81	0.58

Table 7: Statistics of single-parameter sensitivity analysis for Pesticide DRASTIC

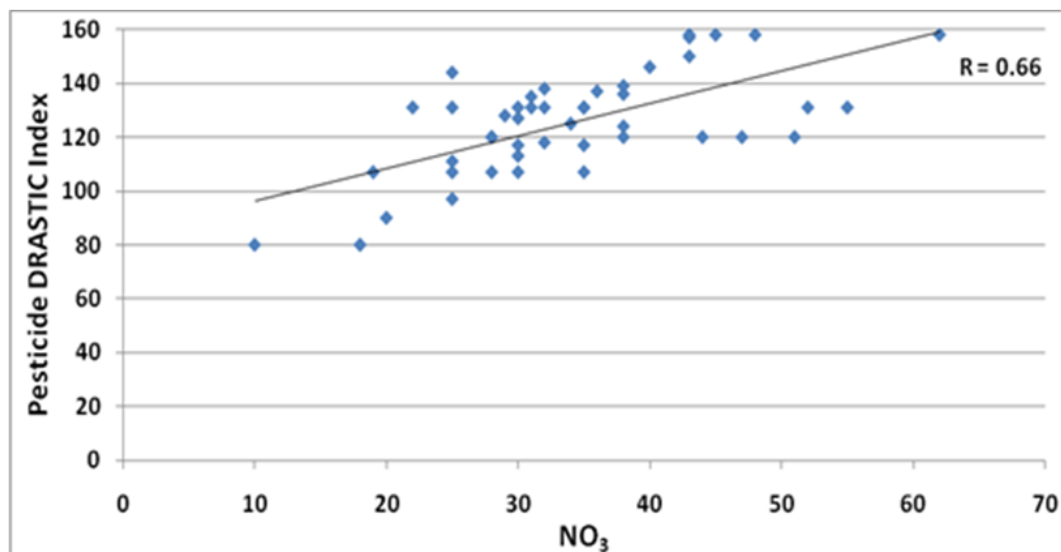
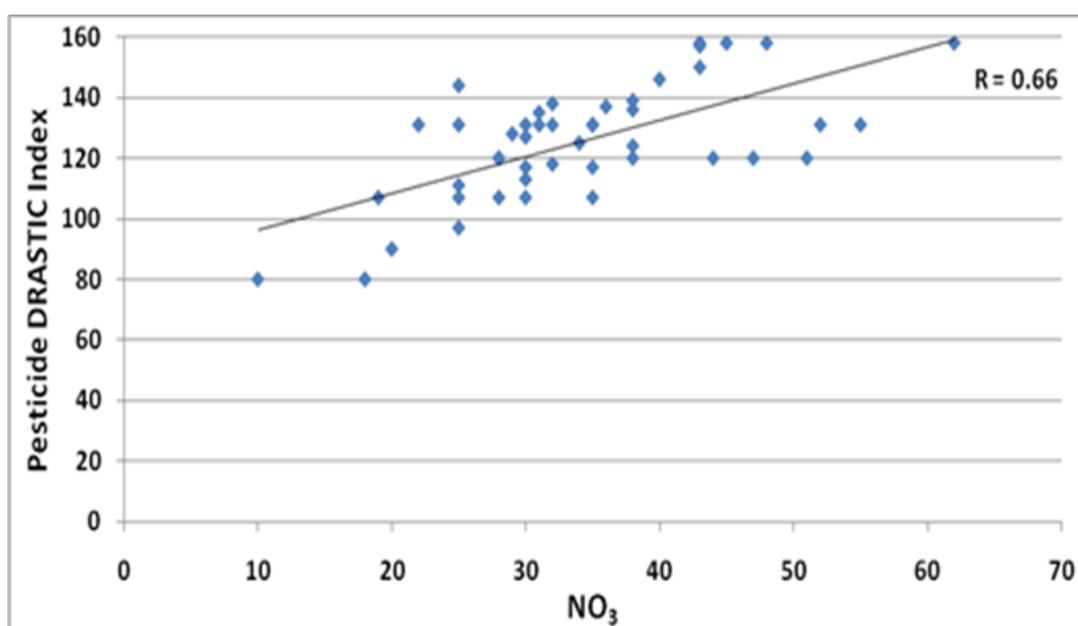
Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (%)			
			Mean	Min	Max	SD
D	5	19.23	16.75	4.14	41.35	7.44
R	4	15.38	8.34	3.31	9.92	1.32
A	3	11.54	18.98	12.41	19.85	1.49
S	5	19.23	13.11	12.41	20.68	1.65
T	3	11.54	19.50	2.48	24.81	4.47

4.11 Validation

After generating the final DRASTIC and Pesticide DRASTIC vulnerability maps, we validated them to assess their relevance to the location. Although no standard validation method exists for groundwater vulnerability, we used the Pearson correlation coefficient (R) to relate DRASTIC index values to groundwater nitrate concentrations (38). Nitrate is a key indicator of aquifer vulnerability; because of extensive fertilizer use, among other factors, intensive agriculture has increased its importance in assessing groundwater water quality.

Nitrate concentrations ranged from 10 to 62 mg/l, with a mean of 34 mg/l in the study area. These values are close to the maximum levels allowed by US and European Union guidelines (45 mg/l and 50 mg/l, respectively). This proximity indicates significant problems with nitrate-related aquifer pollution. Moreover, nitrate concentration data from 46 observation wells, when plotted against the DRASTIC and Pesticide DRASTIC vulnerability maps, showed a satisfactory linear correlation ($R = 0.62$ and $R = 0.66$, respectively), indicating that areas with high vulnerability scores exhibit high nitrate levels (Figure 12, Figure 13).

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Fig. 13: Correlation of Pesticide DRASTIC index with NO_3 valuesFig. 13: Correlation of Pesticide DRASTIC index with NO_3 values

CONCLUSION

1. The calculated values of the DRASTIC index vary between 74 and 139, and the Pesticide DRASTIC index varies between 80 and 158. Based on the thematic map, the research zone was classified into four classes of vulnerability that range from very low to very high.
2. The highest class of vulnerability is concentrated in the central-west and central-east regions and

should be suitably protected. In contrast, very low-vulnerability classes occur in the central part and in the northwest and southeast of the area of interest.

3. Based on the single-parameter sensitivity analysis, the impact of the vadose zone is the factor that plays the most influential role in the development of the vulnerability map, while the hydraulic conductivity class is the least effective.
4. In this study, the derived DRASTIC and Pesticide DRASTIC maps were tested with real nitrate concentration data. Results show a

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reasonable linear correlation for both methods (0.62 and 0.66, respectively), indicating that Pesticide DRASTIC is relatively more accurate.

5. This type of outcome could provide important measures for policymakers to manage groundwater supplies at the regional level efficiently. The results will also provide a basis for comparing regions worldwide with similar geological characteristics and groundwater-quality conditions to assess the applicability and effectiveness of the DRASTIC and Pesticide DRASTIC methods.

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