

Groundwater Vulnerability Evaluation in the Nineveh Plain, Northern Iraq, using a GIS-based DRASTIC Model

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ABSTRACT

The goal of this study is to determine the vulnerability of groundwater in northern Iraq's Nineveh Plain by utilizing the DRASTIC method and geographic information systems (GIS). In the context of human or environmental systems, vulnerability refers to the potential for harm as a result of stress or disturbance, it may be related to a particular system, hazard, or group of hazards. The vulnerability map includes three vulnerability categories: very low, low, and medium. Following the results of the spatial analysis, it can be concluded that the southern and northeastern portions of the study area have been the most vulnerable to contamination under the medium vulnerability group. According to statistics acquired by removing one DRASTIC element at a time and analyzing the effect on the calculated vulnerability index, the impact of the vadose zone is the most sensitive factor (the mean value is 3.00). The aquifer type, topography, and hydraulic conductivity all have the same mean value of 1.5. The soil factor has a mean value of 0.5, making it the least effective. The research recommends the necessity of using groundwater vulnerability maps in the process of planning future lands and the protection of the Nineveh Plain area from pollution.

Keywords: Hydrogeological, Groundwater, DRASTIC, Vulnerability, Contamination, GIS

تقييم حساسية المياه الجوفية للتلوث في سهل نينوى، شمال العراق، باستخدام طريقة دراستك ونظم المعلومات الجغرافية

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المخلص

الهدف من هذه الدراسة هو تحديد قابلية حساسية الجوفية للتلوث في سهل نينوى شمال العراق من خلال استخدام طريقة دراستك (DRASTIC) ونظم المعلومات الجغرافية (GIS). في سياق الأنظمة البشرية أو البيئية، تشير حساسية المياه الجوفية للتلوث إلى احتمال حدوث ضرر نتيجة الإجهاد أو الاضطراب، وقد يكون مرتبطاً بنظام أو خطر أو مجموعة مخاطر معينة. تتضمن خريطة نقاط الضعف ثلاث فئات للحساسية: منخفضة جداً ومنخفضة ومتوسطة. من

خلال نتائج التحليل المكاني، يمكن الاستنتاج أن الأجزاء الجنوبية والشمالية الشرقية من منطقة الدراسة كانت الأكثر عرضة للتلوث ضمن مجموعة الضعف المتوسط. اعتماداً على الإحصاءات التي تم الحصول عليها عن طريق إزالة عامل واحد من عوامل دراستك في وقت واحد وتحليل التأثير وفقاً لمؤشر الضعف المحسوب، فإن تأثير المنطقة الغير مشبعة (vadose zone) هو العامل الأكثر حساسية (القيمة المتوسطة هي 3.00). نوع الخزان الجوفي والتضاريس والتوصيل الهيدروليكي جميعها لها نفس القيمة المتوسطة البالغة (1.5). عامل التربة له متوسط قيمة (0.5)، مما يجعله الأقل فعالية. يوصي البحث بضرورة استخدام خرائط حساسية المياه الجوفية للتلوث في عمليات تخطيط الأراضي المستقبلية وحماية منطقة سهل نينوى من التلوث.

الكلمات المفتاحية: هيدروجيولوجي، المياه الجوفية، دراستك، حساسية المياه الجوفية، ملوثات، نظم المعلومات الجغرافية.

INTRODUCTION

The Nineveh Plain region suffers from multi-faceted environmental stresses that have led to groundwater exposure to pollution resulting from rapid urban development and expansion in agriculture and industry. The use of land is usually done without taking into account the protection of groundwater from contamination hazards. According to studies, the water situation will deteriorate in the future as the region faces a larger scarcity of surface water supplies (Al-Khafaji, 2018). As the aquifers in some areas are shallow, they will be vulnerable to contamination from activities at ground surfaces, either point or non-point sources (Voss, *et al.*, 2013). Vulnerability is increased if the system's natural characteristics provide insufficient protection for groundwater from polluting activities on the land surface. Numerous government agencies and non-governmental organizations intend to conduct vulnerability assessments as part of their decision-making, policy formulation, and planning processes. The assessments themselves are analytical tools to understand the relationship between land use activities and groundwater contamination, as well as social and biological influences, to make informed decisions and implement protection programs to keep the quality of groundwater at a high level (Council, 1993). The study area (Nineveh Plain) is located in the northeastern part of the Mosul governorate, in northern Iraq, between the latitudes of 36°47'27 47" N and 35°59'3.57" N and the longitudes of (42°44'33.51" E and 43°33'33.91" E). It encompasses an area (2547 km²). This area stretches from Mosul Lake in the north down to the Great Zab River in the south. It is bordered on the western side by the Tigris River. The study area's highest elevation (1047 m) is observed in the northeastern section, within the Alqoosh and Ain Sifni anticlines. The study area begins to decrease towards the southwest and the lowest elevation (190 m) is observed in the river basin. The ground surface is generally flat in the central and southern parts of the region, with minor hills and valleys in the northern and northeastern parts of the same region (Fig. 1).

The primary objective of adopting this model is to build a variety of models and methodologies for assessing the vulnerability of groundwater to contamination to establish strategies for protecting groundwater and identifying places where its use is restricted (Schmoll, *et al.*, 2006). The DRASTIC model, established by the United States Environmental Protection Agency (US-EPA), is one of the most widely used models for assessing the vulnerability of groundwater to contamination (Al-Abadi, *et al.*, 2017). The

word DRASTIC is derived from the initials of the seven hydrogeological parameters that have a major influence on groundwater vulnerability. It is used in a wide range of countries worldwide.

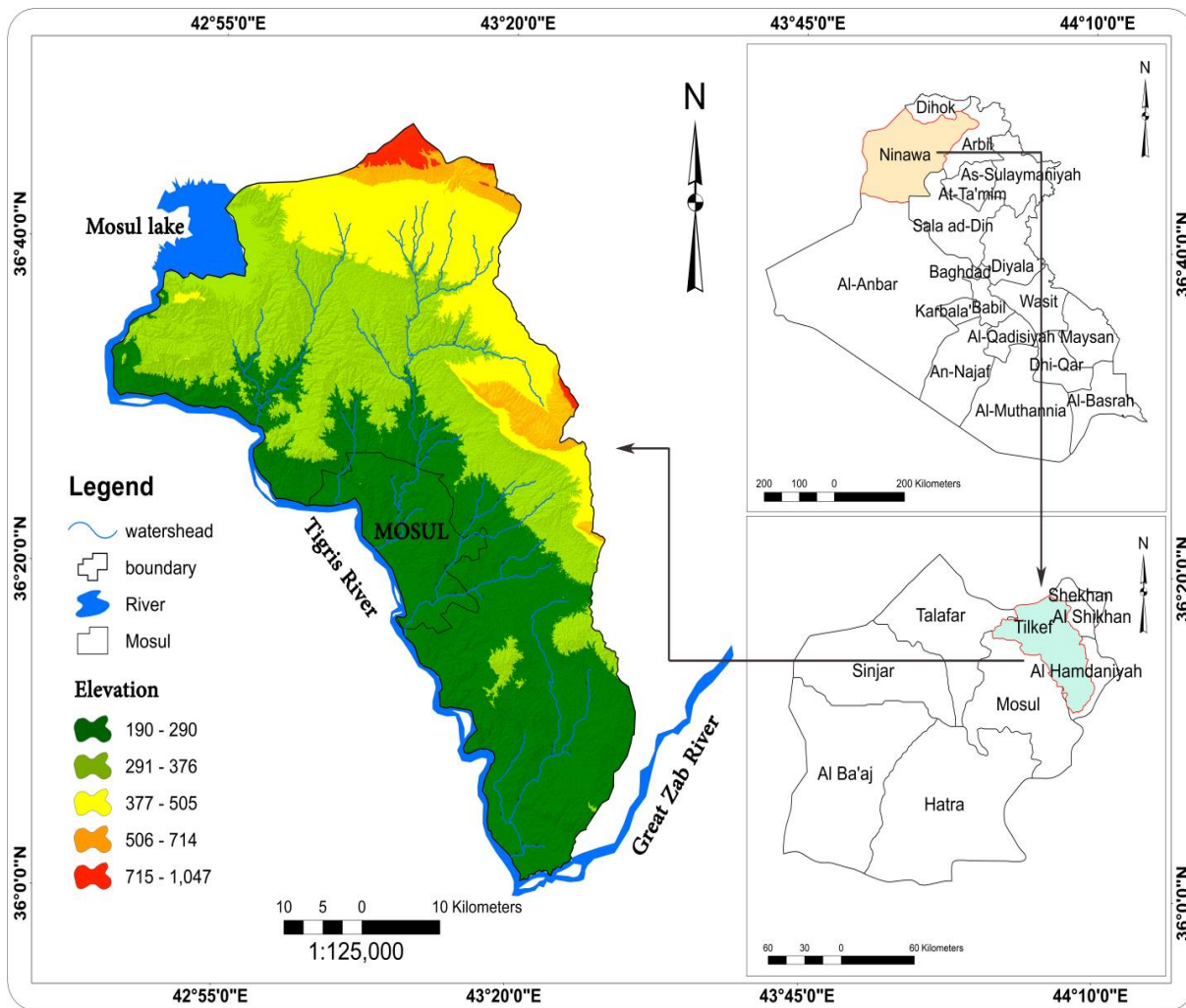


Fig. 1: Location and Topography of the study area.

METHODOLOGY

Seven standard criteria were used to create the DRASTIC maps: (D) depth to groundwater, (R) recharge, (A) aquifer type, (S) soil properties, (T) topography, (I) vadose zone impact, and (C) hydraulic conductivity. DRASTIC's numerical ranking system is composed of three components: weight, range, and rating (Aller *et al.*, 1987):

Weights (w): Each DRASTIC factor is weighed concerning the others to determine its relative importance. Each factor is assigned a relative weight between 1 and 5 (five being the most significant, one being the least significant), as shown in table (1). DRASTIC weights are classified into two categories: one for normal conditions (standard) and another for situations involving extensive agricultural operations (Pesticide Index) (Fig. 2a).

Table 1: DRASTIC rating and weight values for the study area

Parameter	Range/Value	Rating	Standard	Pesticide
			DRASTIC	DRASTIC
Depth groundwater (m)	0 - 1.5	10	50	50
	1.5 - 4.5	9	45	45
	4.5 - 9	7	35	35
	9 - 15	5	25	25
	15 - 22	3	15	15
	22 - 30	2	10	10
	> 30.4	1	5	5
Net recharge (mm/year)	0 - 50	1	4	4
	50 - 100	3	12	12
	100 - 180	6	24	24
	180 - 250	8	32	32
	> 250	9	36	36
Aquifer media	1 - 3	2	6	6
	2 - 5	3	9	9
	3 - 5	4	12	12
	4 - 6	5	15	15
	5 - 9	6	18	18
	4 - 9	6	18	18
	4 - 9	6	18	18
	4 - 9	8	24	24
	2 - 10	9	27	27
	9 - 10	10	30	30
Soil media	Thin or Absent	10	20	50
	Gravel	10	20	50
	Sand	9	18	45
	Peat	8	16	40
	Shrinking and/ or aggregated clay	7	14	35
	Sandy Loam	6	12	30
	Loam	5	10	25
	Silty Loam	4	8	20
	Clay Loam	3	6	15
	Muck	2	4	10
	Non - shrinking and non - aggregated clay	1	2	5
Slope (%)	0 - 2	10	10	30
	2 - 6	9	9	27
	6 - 12	5	5	15
	12 - 18	3	3	9
	>18	1	1	3
Vadose zone	Confining layer	1	5	4
	Silt / Clay	2 - 6	15	12
	Shale	2 - 5	15	12
	Limestone	4 - 7	30	24
	Sandstone	4 - 8	30	24
	Bedded Sandstone, Limestone, and Shale sequences	4 - 8	30	24
	Sand and gravel with significant silt and clay	4 - 8	30	24
	Metamorphic / Igneous	2 - 8	20	16
	Sand and Gravel	6 - 9	40	32
	Basalt	2 - 10	45	36
	Karst Limestone	8 - 10	50	40
	0.0432 - 4.32	1	3	2

Hydraulic conductivity	4.32 - 12.96	2	6	4
	12.96 - 28.51	4	12	8
	28.51 - 43.20	6	18	12
	43.20 - 86.40	8	24	16
	> 86.40	10	30	20

Range: Each DRASTIC component assigns a range of significant media types that can pollute the environment, as shown in table (1).

Rates (r): Each range is assessed for each DRASTIC component to establish its relative importance in terms of contamination potential (Table 1). The rating value is allocated to each DRASTIC factor, ranging from 1 to 10 (The higher the rating, the greater the risk of contamination). The final vulnerability index is calculated as follows:

$$\text{Vulnerability index} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \dots (1)$$

(D, R, A, S, T, I, C)_r: rating for ranges of factors.

(D, R, A, S, T, I, C)_w: weight for the factors.

In 1987, Aller et al. made no classification suggestions. So the vulnerability ranges of the drastic index employed in this study match those of the most generally used references in the literature, such as (Civita and De Regibus, 1995), and (Civita and De Regibus, 1996) (Table 2).

Sensitivity analysis

To determine the effects of each parameter rating and weighting value, as well as the relevance of the subjective factors, sensitivity analyses are performed (Gogu and Dassargues, 2000). When it comes to determining the vulnerability of groundwater, two types of sensitivity analysis approaches are frequently used. The first is map removal and the second is the variation index (Lodwick, *et al.*, 1990; Napolitano and Fabbri, 1996). When one or more maps are removed from the vulnerability assessment, the map removal analysis is used to determine how sensitive the vulnerability map is to the removal of those maps. This metric can be calculated using the formula:

$$S_i = \left[\frac{v}{N} - \frac{\hat{v}}{n} \right] \quad (2)$$

Where, S_i is the sensibility, the unperturbed and perturbed vulnerability indices are denoted as v and $\hat{v}$, respectively. N and n are the numbers of data layers used to compute v and $\hat{v}$.

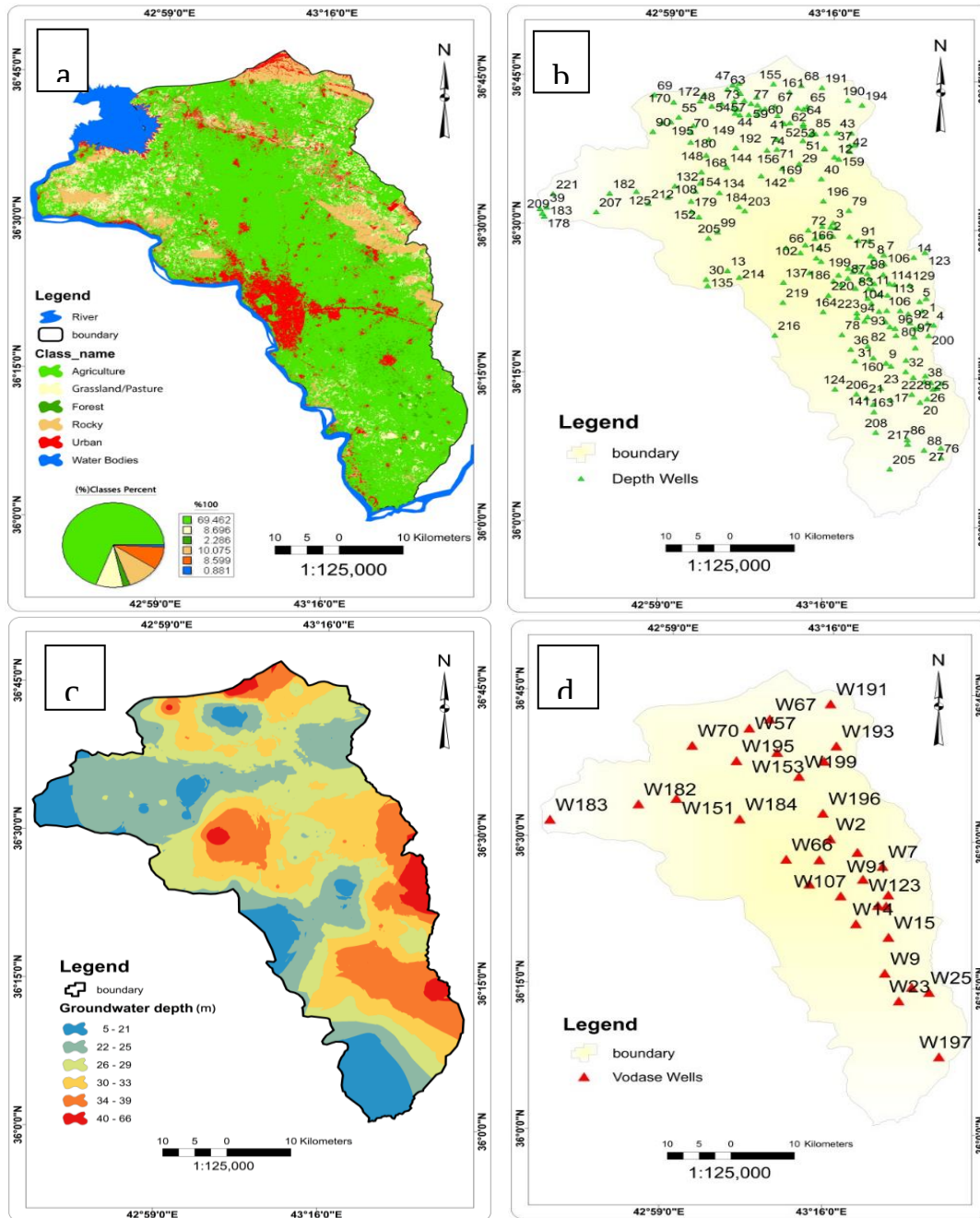


Fig. 2: (a) LULC, (b) Wells location, (c) Groundwater depth, and (d) Vodase wells.

Table 2: Criteria for determining the levels of vulnerability (Civita, and De Regibus, 1995; Corniello, *et al.*, 1997).

Degree of Vulnerability	DRASTIC Index
< 80	Very Low
80 – 120	Low
120 – 160	Moderate
160 – 200	High
> 200	Very High

The variation index v_{xi} is related to map removal analysis and is computed as:

$$v_{xi} = \frac{v-\bar{v}}{v} \quad (3)$$

The database was developed to be used to investigate the relationships between the aquifer's sensitivity to pollution and different surface activities using the technique of GIS. The lands in the Nineveh Plain were divided according to table (2) into three sections depending on the possibility of vulnerability, and the aquifer areas were identified that have a higher potential for contamination. By integrating spatial and descriptive data and maps conducted in geographic information systems, a planning document was produced in the form of a map representing the potential of groundwater for pollution.

DRASTIC factors description

DRASTIC is a mathematical system for point equations, and the method includes seven elements that are derived from seven hydrogeological factors which affect groundwater, as follows (Aller, *et al.*, 1987):

1- The depth (D) parameter represents the distance between the earth's surface and the water table. The depth factor is critical because it defines the thickness of the material that a contaminant must pass through before it reaches groundwater. As a result, pollution of groundwater near the surface is more likely than of groundwater far from the surface (Rahman, 2008). Based on the water levels in 218 wells (Fig. 2b), a map of groundwater depth was created, where the water depths ranged between (11-66m) (Fig. 2c). The depth values are reclassified into six categories regarding the DRASTIC rating system. The depth of the water table is rated from 1 to 10, with 1 being "low vulnerability" and 10 being "high vulnerability." The depth to groundwater rating and weighting values for groundwater depth were reviewed in table (1). Figure (3D) explains the depth to groundwater level rating.

2- Net Recharge (R) refers to the annual quantities of water that percolate into an aquifer. Contaminations can easily migrate through groundwater, depending on the amount of water that has infiltrated from the surface (Babiker *et al.*, 2005). The amount of annual recharge is assessed using the groundwater level fluctuation method (Healy and Cook, 2002). Six wells were chosen throughout the study area to monitor the fluctuation of groundwater levels caused by rainwater feeding (Table 3). The annual average rainfall is 333.64 mm per year within the period from 2000 to 2019 (Al-Ozeer, *et al.*, 2020). The amount of recharging was estimated by using the following equation:

$$R = \Delta h * S_y \quad (4)$$

Where:

R: Recharge amount.

Δh : Groundwater level fluctuation.

S_y : Specific yield

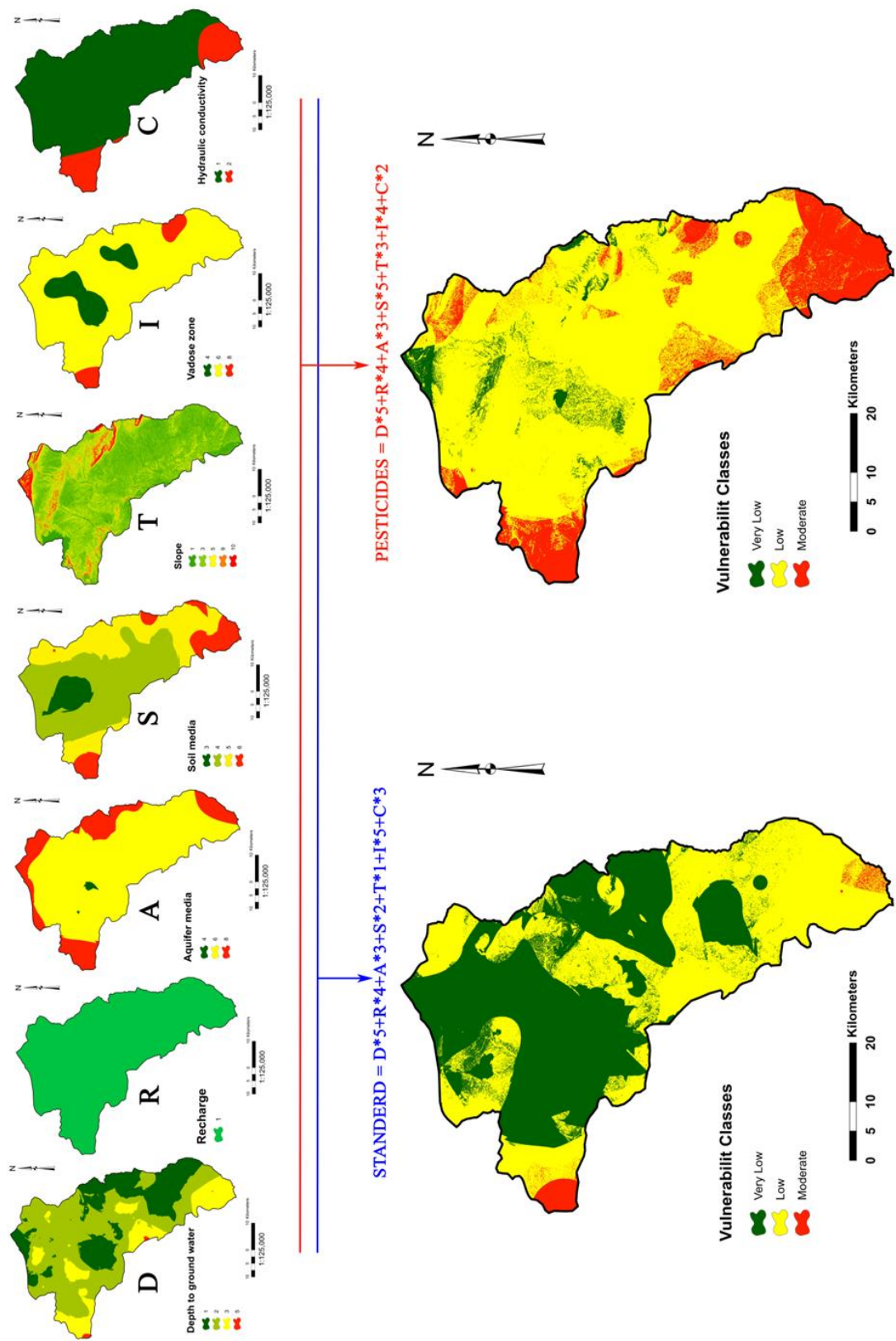


Fig. 3: Aquifer vulnerability classes for the study area.

According to drastic, a rating of 1 was given for each study area based on the calculated recharge values in table (3), which in all wells were less than 50 mm (Fig. 3R).

Table 3: The lower and upper limits of the fluctuation of groundwater levels in the study area.

BH. No.	Max	Min	$\Delta h(m)$	$\Delta h(mm)$	Sy%	Recharge(mm)
BH 2	20.35	12.75	7.6	7600	0.00467	35.492
BH 107	49.8	46.35	3.45	3450	0.00467	16.1115
BH 8	31.65	27.6	4.05	4050	0.00467	18.9135
BH 223	22.36	21.3	1.06	1060	0.00467	4.9502
BH 185	33.72	31.85	1.87	1870	0.00467	8.7329
BH 36	44.4	42.45	1.95	1950	0.00467	9.1065

3- The aquifer media (A) is a term that refers to the hydrogeological characteristics of a subsurface rock unit that works as an aquifer and can be either consolidated or unconsolidated in nature (Aller, *et al.*, 1987). Primary porous rocks are those that produce water through their pore spaces, while those that produce water from fractures and solution openings have secondary porosity. The path length, together with the hydraulic conductivity and gradient, is an important governing factor in determining the amount of time available for dilution processes such as reaction, sorption, and dispersion to take place. The aquifer media rating map is created based on the well log data of 41 wells (Fig. 2d). The lithological components (gravel, sand, silt, clay) of the saturated area were calculated for each well in a relative formula, and then the value of each well was given according to table (1), and Fig. (3A).

4- Soil media (S): The texture of soil components and the size of its particles have a vital and influential role in controlling the amount of water that percolates from the surface, and as a result, they limit the number of pollutants that accompany this water (Ghazavi and Ebrahimi, 2015). The greater thickness of the soil increases the attenuation processes such as sorption, biodegradation, and filtration (Aller *et al.*, 1987). A texture name was assigned to soil samples collected from 36 sites in the study area relying on the calculator of USDA web-based soil texture (<https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey>). According to the soil texture, the soil was categorized into a group of hydrological soils (Fig. 4a). The research areas hydrological soil groups represent the soil's capacity to infiltration. The soil is less infiltrated from group A to group D. According to table (1), these groupings have 2, 4, and 6 ratings to represent the capacity for infiltrate water and contaminants (Fig. 3S).

5- Topography (T): This factor shows the variations in slope and slope throughout the land surface. It controls the ability of the runoff to evacuate pollutants or leave them on the ground for a longer period to infiltrate the groundwater (Kaliraj, *et al.*, 2015). When the slope is large, the velocity of surface runoff is high and it works to transmit the largest possible amount of suspended or dissolved substances (Abdullah, *et al.*, 2015). The topographic map (Slope) of the study area was created based on the Digital Elevation Model (DEM) values by using ArcGIS 10.8 (Fig. 4b). The slope value was calculated in percentage (%) which ranged from (0-66). The slope rating is assessed using the DRATIC model

criterion, Table (1). Where the number (10) represents the region most sensitive to pollution, and conversely, the number (1) represents the region with the least potential for contamination (Fig. 3T).

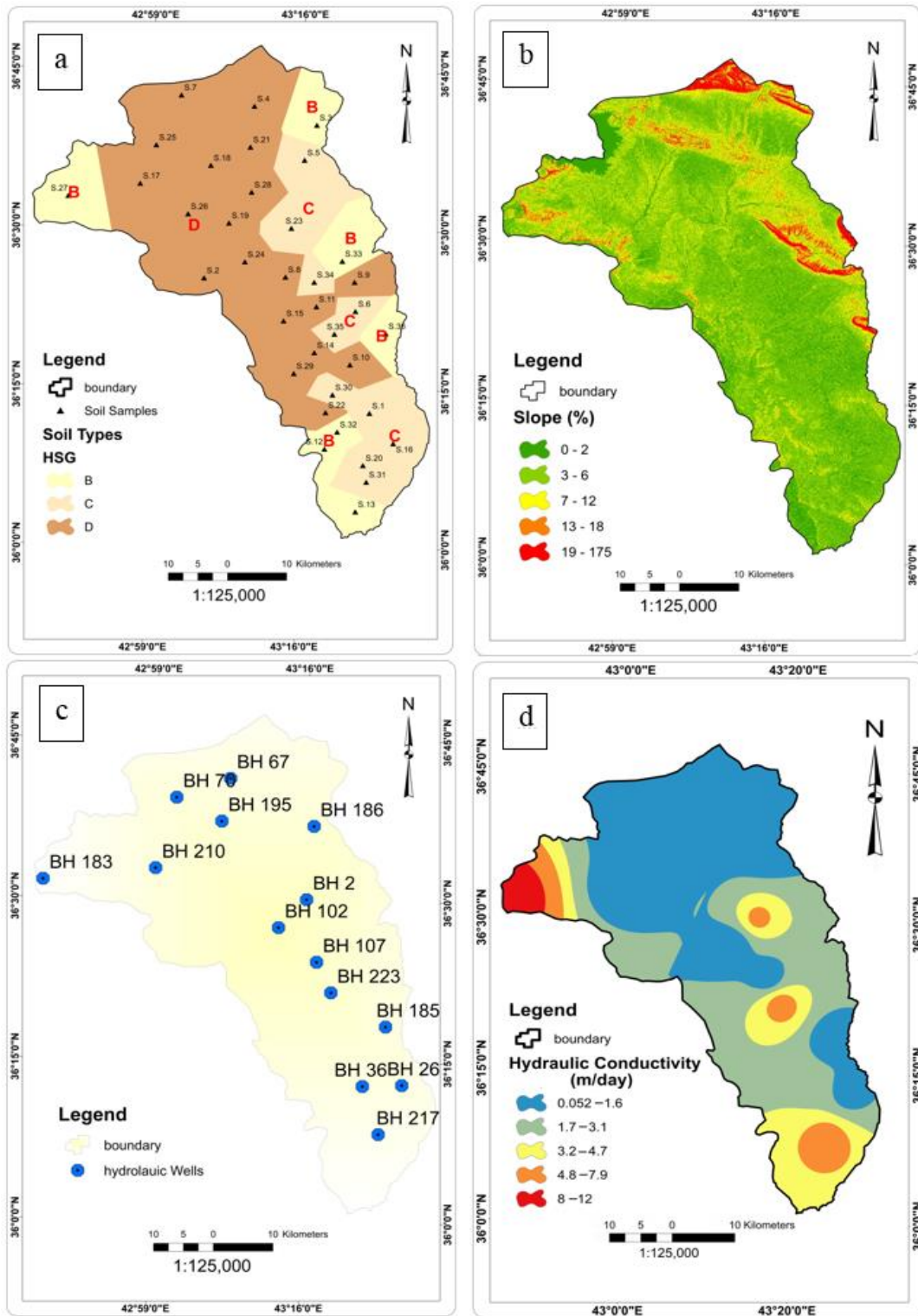


Fig. 4: (a) Soil, (b) Slope, (c) Hydraulic wells, and (d) Conductivity.

6- Impact of vadose zone (I): This factor represents the unsaturated zone above the groundwater level, which controls the passage and attenuation of pollutants based on thickness, porosity, and permeability. Accordingly, the higher the permeability and low thickness of the vadose media, the greater the chance for pollutants to reach the groundwater and vice versa (Aller, *et al.*, 1987). The information for the vadose zone map was created based on the well log data of 41 wells. The lithological components (Gravel, Sand, Silt, Clay) of the unsaturated zone were calculated for each well in a relative formula, and then the value of each well was given according to Table (1). Therefore, the vadose zone of the confined and unconfined parts is rated at 3 and 8, depending on the criteria of the DRASTIC model (Fig. 3I).

7- Hydraulic conductivity (C): This factor represents the ability of the aquifer materials to transmit water under the influence of hydraulic gradients, which, in turn, controls the movement of water and its transmission through the porous media and thus controls the movement of contaminants away from their point of contact (Aller, *et al.*, 1987). The hydraulic conductivity values were obtained during the fieldwork, pumping tests of wells for 14 well (Fig. 4c), and previous studies of the study area, as well as through the archives of the Groundwater Department. Hydraulic conductivity values in the majority of the research region range between 0.5 and 4 (m/d), with a rating value of 1. While the hydraulic conductivity values varied from 4 to 12 (m/d) for a small portion of the research region, with a rating value of 2 (Fig. 4d), and (Fig. 3C).

RESULTS AND DISCUSSIONS

The statistical summary in Table 4 shows that the average values of the effect of topography, depth of groundwater, and hydraulic conductivity are 61.43, 54.81, and 33.33 respectively. The impact of the vadose zone, aquifer type, and soil has moderate impact, and the recharge factor has no impact. Due to the factor's low variability, it contributes little to the variation in the vulnerability index across the research area. The statistics in table (5) related to removing one DRASTIC component at a time and the effect on the estimated vulnerability index revealed that the impact of the vadose zone is the factor that is most sensitive to being removed (the mean value is 3.00). The aquifer type, topography, and hydraulic conductivity all have the same mean value of 1.5. The less effective factor is soil with a mean value of 0.5.

Table 4: A statistical summary of the DRASTIC factor maps

Factor	Min	Max	Mean	Standard deviation	Coefficient of variation (Cv)
D	1	5	2.7	1.48	54.81
R	1	1	1	0	0
A	4	8	6	1.63	27.17
S	3	6	4.5	1.11	24.67
T	1	10	5.6	3.44	61.43
I	4	8	6	1.63	27.17
C	1	2	1.5	0.5	33.33

Table 5: Statistics on sensibility to remove one DRASTIC factor

Factor removed	Min	Max	Mean	Standard deviation
D	0	2	1	0.81
R	0	2	1	0.81
A	0	3	1.5	1.11
S	0	1	0.5	0.5
T	0	3	1.5	1.11
I	1	5	3	1.41
C	1	2	1.5	0.5

The range of spatial vulnerability in the research area for both standard and pesticides DRASTIC indicates that spatial sensitivity classes ranged between very low, low, and moderate. The standard DRASTIC index map indicates that 864.6 km² (34%) of the study region has a very low level of groundwater pollution vulnerability, while 1620.9 km² (63.7%) of the study area has a low level of groundwater contamination risk. 60.6 km² (2.4 %) of the research area is classified as moderate, while there are no regions classified as high or extremely high. The pesticides DRASTIC version also includes three zones (very low, low, and moderate), with 40.4 km² (1.6%) of the study area classified as having very low groundwater vulnerability, 1913.0 km² (75.1%) as having a low vulnerability, and 592.7 km² (23.3 %) as having a moderate vulnerability, Table (6). There are no areas classified as having high or very high groundwater vulnerability (Fig. 5).

Table 6: Vulnerability classes of the study area.

DRASTIC version	Vulnerability classes	Area occupied	
		km ²	%
Standard	Very Low	864.6	34
	Low	1620.9	63.7
	Moderate	60.6	2.4
Pesticides	Very Low	40.4	1.6
	Low	1913	75.1
	Moderate	592.7	23.3

CONCLUSIONS

- The hydraulic conductivity is high in the middle part of the studied area and increases towards Tigris River in the south and west due to the increase in the granular size of sediments and the thickness of the aquifer begins to thin in this direction. Values of the Transmissivity parameter also increase in the middle part of the studied area and increase towards the Tigris River in the south.

- According to a statistical summary of the results, the land's topography had the greatest impact, followed by groundwater depth and hydraulic conductivity.

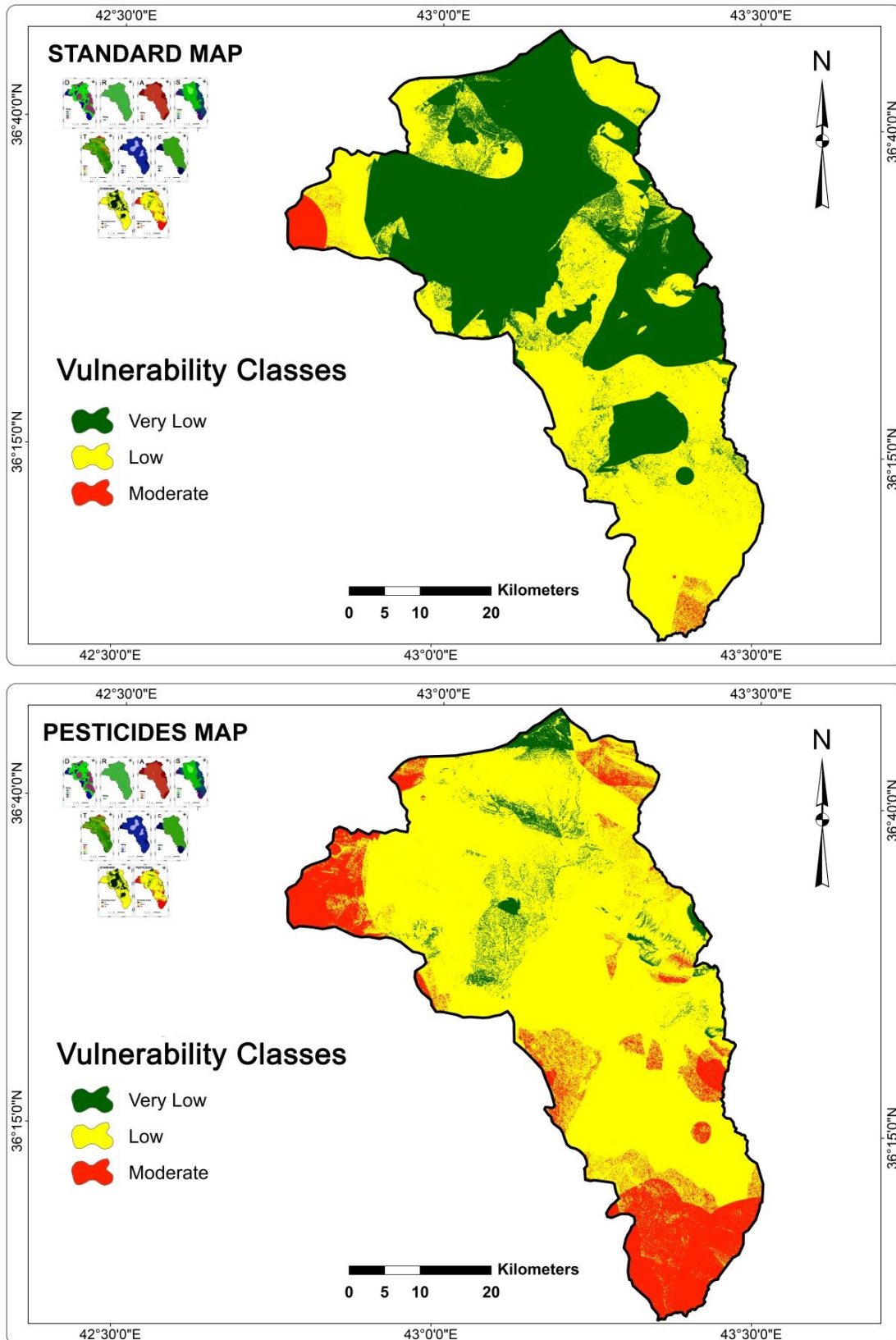


Fig. 5: Aquifer vulnerability classes for the study area.

- The southern and northeastern regions of the study area are the most sensitive to contamination. This is attributed to the groundwater level, which is close to the surface in these areas, in addition to the nature of the incoherent rock components resulting from highly permeable river sediments. On the other hand, specifically in the northeastern regions, represented by the areas of folds within the limestone rocks, where the rate of cracks, faults, and joints is high due to the structural activity, all this makes it more sensitive to pollution due to the transfer of pollutants from rainwater through these faults to the groundwater directly.

- The percentage of the observed increase in the medium range was determined by analyzing the results of the pesticide versions, and this represents evidence of the study area's sensitivity to contamination with agricultural pesticides.

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