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

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Research Article

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Abstract

Groundwater vulnerability assessment is an essential step for 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 evaluate groundwater vulnerability zones in Erbil Dumpsite area, Central Erbil Basin, North Iraq. Results showed that the area was classified into the following vulnerability classes: very low (16.97%), low (27.67%), moderate (36.55%) and high (18.81%). The southern, south-eastern and northern part of the study area had the highest vulnerability potential, whereas the central-northern, northern and north-western portion of the study area revealed the lowest vulnerability potential. Moreover, results of the single-parameter sensitivity analysis showed that amongst the seven DRASTIC parameters the unsaturated zone and the aquifer media were the most influencing parameters. Finally, the correlation of 25 nitrate concentration values with the final vulnerability map, using the Pearson correlation coefficient, gave a satisfactory result equal to R = 0.72.

1 Introduction

Based on life and food production, water is an essential resource on Earth. As a result, it is important to pay attention to water resources, to meet all humanitarian needs for drinking water and secure the requirements for agriculture and industrial needs (Machiwal et al. 2018). Surface water is supposed to be more vulnerable to groundwater, since it is directly exposed to human activities, thus it can be easily polluted (Kumar et al. 2022). However, even though groundwater is protected by the layers of the Earth, the last few decades, the quality and quantity of groundwater are at high risk. In specific, many human activities, such as intensive agriculture, rapid urbanization, overexploitation, burgeoning population, improvident use of chemical fertilizers and pesticides, as well as abusive farming practices have contributed to the qualitative deterioration of groundwater (Green et al. 2011; Saidi et al. 2011; Kumar et al. 2018; Kirlas et al. 2022a). Specifically, the extensive use of chemical fertilizers and pesticides leads to the qualitative degradation of groundwater resources and to the immense problem of nitrate pollution of aquifers. Nitrate pollution has severe effects on public health and the ecosystems; hence, the prevention of groundwater pollution is very essential for an efficient groundwater management, as well as for the sustainability of the natural resources and the economic development (Li et al. 2017; Kumar et al. 2018).

In general, the need for water resources in Iraq is growing, due to population growth and economic development, however this need is being partially offset by a decline in this essential resource due to increased investment and exploitation of water resources in Iraq's neighbors (Al-Ansari 2013). Iraq is the fifth-most exposed country in the world to climate change's effects, including water scarcity and food insecurity. Nowadays, the country is experiencing the effects of climate change at an alarming rate, and a top advisor at the ministry of water resources in Iraq warned in April that the country's water reserves had decreased by 50% since last year as a result of drought, a lack of rainfall, and falling water levels (Mawlood 2019). Moreover, in Iraq, Tigris and Euphrates are the main surface water resources; groundwater is only second in importance in terms of use. Consequently, groundwater information is still in the development (progress) stage, and therefore there is no precise estimate of the amount of groundwater that is available for use. Nonetheless, there are estimates based on investigations that have been completed in Iraq, which cover three distinct regions instead of the entire country: the mountainous region, the desert region, and the feet of the mountains.

Furthermore, more than 90% of the population in the area receives water via groundwater abstraction from this basin, and additional residents outside the study basin also receive potable water from it. Notably, rapid urbanization, industry expansion, and agricultural activity growth have been the primary occurrences in recent years that everyone has noticed. Examples of this development in the region include the construction of the Safra and Azad rice food production, and numerous yogurt factories, such as Erbil and Mersin, as well as many ice cream factories. Whilst the overexploitation of the aquifers and the sporadic decrease of yearly precipitation have both worsened the decline of the groundwater supply, delivering water of high quality and sufficient quantity for those sectors has substantially increased (Ali and Hamamin 2012). According to a statement from the ministry of Agriculture and Water Resources in Kurdistan Region Government (KRG), due to overexploitation, groundwater levels have dropped by 500 meters during the last 20 years. As a result, this abrupt decline in groundwater level has led to substantial groundwater quality and quantity deterioration in the area. Thence, there is an insistent need for a groundwater governance framework that could endorse policymakers in decision-making, aiming to protect groundwater resources from further degradation.

In many cases, groundwater monitoring is expensive and a meticulous task to represent pollution satisfactorily on a large scale. For this reason, researchers have developed various methodologies, which are more economic and easier to apply and do not require a lot of data and complex computations (Kumar et al. 2015; Canora et al. 2022; Kirlas et al. 2022a). The most important groundwater vulnerability assessment methods are DRASTIC (Aller et al. 1987), GOD (Foster 1987), AVI (Van Stempvoort et al. 1993), SINTACS (Civita 1994) and SI (Ribeiro 2000). Amongst them, DRASTIC is 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). This method is based 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. 2022). Nevertheless, despite its popularity, DRASTIC method has some limitations, and it has been criticized for its subjectivity and uncertainty in the evaluation of its parameters' ratings and weights (Goyal et al. 2021). To overcome this problem, many researchers started modifying the method to improve its efficiency and accuracy for a specific aquifer (Fannakh and Farsang 2022). Such modifications include the optimization of the ratings and weights of DRASTIC parameters by using Analytic Hierarchy Process (AHP), Fuzzy AHP, Analytic Network Process (ANP), multiple linear regression and sensitivity analysis (Sener and Davraz 2012; Garewal et al. 2015; Jhariya et al. 2019; Lakshminarayanan et al. 2021; Kirlas et al. 2022b). Besides, other researchers proposed the incorporation of extra factors, such as land use and irrigation type (Brindha and Elango 2015; Sarkar and Pal 2021; Sresto et al. 2021). This study is the first endeavor to evaluate the groundwater vulnerability in Kani Qirzhala aquifer, Central Erbil basin, North Iraq, using the DRASTIC method. Moreover, the results of the method can help policymakers and planners in their decision-making efforts to preserve the aquifer system from future groundwater deterioration. The accuracy of the DRASTIC model was validated using reported nitrate concentration (NO_3^-) in groundwater.

2 Study Area

The aquifer of the study area covers an area of approximately 100 km^2 and is located in central Erbil basin. It consists of Pliocene alluvial deposits, such as gravels, conglomerate, sand and clay (Jawad and Hussien 1988). In this area there is also the Erbil dumpsite, which is located on a hill conjoined by two drainage valleys (Fig. 1). The elevation of this site is about 435 m above sea level. The Erbil dumpsite operation life since year 2001 (Municipal ministry), and currently receives all types of solid waste. Daily disposal is about 1.5 thousand ton of solid waste of varied types (Gardi 2017). The location is generally used for any type of general household waste. The waste dumped at this site includes 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. These wastes can spontaneously ignite and produce noxious smoke smell and which varies according to waste composition with greater risk to the operating management staff. Construction and demolition waste, which consist of sand, bricks and concrete block are also dumped. The increasing population in Erbil City (1.5 million people), as a capital of the Iraqi Kurdistan Region, as well as the changes in production and consumption patterns in the last few years results in a continuous groundwater deterioration.

3 Methodology

3.1 Materials and methods

DRASTIC is considered to be the most often used and reliable method 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). DRASTIC method employs seven important hydrogeological features, which primarily control groundwater flow and pollution transportation into groundwater, 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 seep into the saturated zone by 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. 2014; Oke 2020).

In DRASTIC method, the typical assigned weight (w) for each parameter ranges between 1 and 5. Specifically, the least important parameter is assigned with a weight equal to 1, whilst the most important parameter is assigned with 5. Moreover, each parameter has an assigned rating ranging from 1 to 10, in proportion to its relative influence on pollution potential (Table 1). Lower value indicates less contribution to the groundwater vulnerability. The weights and the ratings are based on the Delphi technique (Gogu and Dassargues 2000; Chakraborty et al. 2022). The final DRASTIC Index (DI) is a weighted linear combination of the aforementioned parameters and is calculated by multiplying each parameter weight by its relative rating, using the following Eq. (1). In general, DRASTIC Index ranges from 23 to 230.

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

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

Table 1
Weight, ranges and ratings of DRASTIC parameters

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/yr)	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

DRASTIC parameter	Range / type	Rating	Standard weight
	Silty clay	3	
	Clay loam	4	
	Silty sand	6	
	Sand	7	
	Sandy gravel	8	
C: Hydraulic conductivity (m/day)	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	

3.2 Preparation of thematic maps

Depth to water

This is a significant parameter for groundwater quality degradation and it refers to the perpendicular distance between the ground surface and the water table (Elmeknassi et al. 2021). In general, higher values of the parameter are associated with smaller chance of groundwater pollution, as the pollutants must travel longer distance to reach and enter the water table. On the other hand, as the groundwater table is closer to the ground surface (smaller values), it becomes more vulnerable and it has a higher pollution potential, due to the fact that the thickness of the unsaturated zone is smaller, thus the pollutant can reach the aquifer easier.

Net recharge

This parameter represents the total volume of surface water that percolates from the earth surface and reaches the water table (Khosravi et al. 2021). This amount of water plays a significant role for the movement of pollutants into the aquifer. Therefore, higher net recharge values lead to higher possibility of groundwater pollution (Aller et al. 1987).

Aquifer media

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

Soil media

Soil media refers to the top most eroded layer of the unsaturated zone, which controls 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 possible pollutants into the ground.

Topography

Topography describes the slope variability of a region and it affects the infiltration and run-off rate. Specifically, areas with low slopes tend to have higher groundwater pollution potential, due to the fact that surface run-off rate is low, whereas water infiltration is high, enhancing pollutants migration to the aquifer. On the other hand, infiltration in high slope areas is lower; thus groundwater vulnerability is smaller (Bera et al. 2021).

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 are important for decreasing groundwater potential pollution, because different biochemical processes take place in this zone, such as filtration, dispersal and chemical reactions (Sresto et al. 2021).

Hydraulic conductivity

Hydraulic conductivity describes the groundwater velocity into the saturated zone and depends on the aquifer materials. Pumping test is a common method that is used for the evaluation of this hydrogeological parameter (Kirlas 2021). Higher hydraulic conductivity value increases the potential of groundwater pollution (Victorine Neh et al. 2015).

3.3 Sensitivity analysis

Generally, the application of sensitivity analysis can provide reliable information regarding the uncertainty and the robustness of the assigned weights proposed by DRASTIC method. In this study, an attempt was made to evaluate the influence of each parameter on the final vulnerability index by implementing the 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 Eq. (2).

$$W = \left(\frac{P_r P_w}{V}\right) x100$$

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.

4 Results And Discussion

4.1 Depth to groundwater (D)

The depth to water map was prepared using the groundwater level data of 25 observation wells which cover the entire study area. These data were interpolated for generating the raster layer by implementing the inverse distance weight (IDW) method (Hasan et al. 2019; Singha et al. 2019). Afterwards, the raster layer was classified into seven classes and its class was assigned with 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, the south-eastern and a region in the northern part of the study area are the most vulnerable to pollution, due to the fact that the aquifer is relatively shallow. On the other hand, the least vulnerable area regarding the depth to water is located in the north-western and western part of the study basin, where the aquifer is deeper.

4.2 Net recharge (R)

This parameter was calculated using the data of 25 stations which cover 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 and its class was assigned with a rating value accordingly (Fig. 3), as follows: for R: 0–50 mm/yr (1), for 50–100 mm/yr (3), 100–175 mm/yr (6), and for 175–246 mm/yr (8). Generally, results showed that the western, eastern and northern part of the study has low recharge values, whilst the southern part has relatively higher recharge values giving the area an increased vulnerability potential.

4.3 Aquifer media (A)

The aquifer media parameter was estimated using lithological datasets from 25 lithology profiles. This parameter was grouped into four classes and its class was assigned with 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). Particularly, results showed 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 of the saturated zone (large grain size and high porosity). The western part of the area showed the less vulnerability potential.

4.4 Soil media (S)

The soil media parameter was prepared using 25 soil samples from the entire area. This parameter was classified into five classes and its class was assigned with 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). Specifically, results showed that the northern and eastern part of the area were the most vulnerable, whereas the western part revealed less vulnerability potential.

4.5 Topography (T)

The topography map of this area was obtained from the digital elevation map (ASTER DEM) of 30 m spatial resolution. Then, the slope map (in percentage) was created by employing a spatial analyst tool in ArcGIS environment, 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 obvious from the aforementioned results that the basin has a flat landscape, as more than 67% of the total area has a slope that ranges between 0 and 6%. Thus, the flat topography on the majority of the area, particularly in the eastern, southern and northern parts, allows the pollutants to seep into the aquifer, indicating a maximum effect of this parameter on the overall vulnerability.

4.6 Impact of the vadose zone (I)

The vadose zone map was prepared from 25 lithological profiles, using the same interpolation technique as the previous parameters (IDW), and was classified into six classes according to the ability of the materials to allow and transmit water (Fig. 7) (Chakraborty et al. 2022). The eastern and southern part of the area consists of sand and sandy gravel showing higher vulnerability potential, whereas the north-eastern revealed the least potential, consisting of clay and silty clay.

4.7 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 by using the IDW technique in ArcGIS, and was classified into five classes and its class was assigned with a rating 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.

4.8 DRASTIC vulnerability index (DVI)

In the study area of Erbil the final DRASTIC index (Fig. 9) was calculated into ArcGIS environment, by combining all seven parameters of the method, using the Eq. The final raster format of the DRASTIC vulnerability map ranged from 53 to 150, and was further reclassified into four classes according to Jenks natural breaks method (Ersoy and Gültekin 2013; Thapa et al. 2018; Kumar and Pramod Krishna 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). Accordingly, the spatial distribution of each vulnerability zone is the following: 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 mainly concentrated in the southern, south-eastern and northern part of the study area, where the hydrogeological characteristics of the aquifer, such as the sandy unsaturated zone, the flat topography, the sandy gravel aquifer media and the relatively low depth to water favor groundwater pollution. On the other hand, the central-northern, northern and north-western portion of the study area reveals very low to low vulnerability potential, as the depth to water is higher; the materials of the unsaturated one are less permeable, the topography is slightly steeper, the recharge rate is lower and the aquifer materials are finer (less permeable).

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

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

The single-parameter sensitivity analysis was conducted for the seven hydrogeological parameters of DRASTIC method, to estimate the effective (real) weight of the each parameter on the final vulnerability index, compared to its theoretical one. Results given in Table 3 exhibited variation from the theoretical weights. The Impact of the vadose zone is the most effective parameter in the vulnerability mapping, with an effective weight value (29.76%) significantly higher than the theoretical one (21.74%). Notably, this result confirms several other studies (Muhammad et al. 2015; Sener and 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 effective parameter is the Aquifer Media, which has an effective weight (19.31%) higher than its assigned one (13.04%) and this result is also in agreement with other studies (Muhammad et al. 2015; Victorine Neh et al. 2015; Neshat and Pradhan 2017). Furthermore, in this study the third most effective parameter is the Depth to water, having, however, a fairly lower effective weight (17.23% instead of 21.74%). Recharge and hydraulic conductivity have markedly lower effective weights (8.74% and 5.56%) compared with their theoretical values (17.39% and 13.04, accordingly), thus they appear to be less important for the assessment of the final result. On the other hand, the Soil media and the Topography seem to be more important for the elaboration of the final vulnerability map, due to the fact that they reveal a higher effective weight (11.90% and 7.51%) than their theoretical one (8.70% and 4.35%, respectively).Generally, the final results of the DRASTIC show the significance of the parameters on vulnerability as follows I > A > D > S > R > T > C, compared with the theoretical D ~ I > R > A ~ C > S > T. To sum up, based on the results, it is important to obtain accurate and detailed data for the most significant parameters in the study area, namely the Impact of the vadose zone and the Aquifer Media.

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

4.10 Validation

After the creation of the final DRASTIC vulnerability map, an important step is the validation of it, in order to verify and check its appropriateness and accuracy in this specific area (Saidi et al. 2011; Hamza et al. 2014). Even though there is not 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 is a pollutant that occurs only in very low concentrations in groundwater (1–3 mg/l). Therefore, its increasing trend is highly associated with various human activities, such as intensive agriculture, fertilizers, increasing food production, urbanization and changes in land use (Salih and Al-Manmi 2021). Moreover, high concentrations of nitrate in groundwater (> 50 mg/l) has acute effects on public health (can cause methemoglobinemia, anemia, lung disease, cardiovascular disease, hypothyroidism, colon cancer), as well as on the ecosystems. Hence, governments and local policymakers must define a threshold on groundwater and on products associated with agricultural activities, such as chemical fertilizers (Khosravi et al. 2018; Khosravi et al. 2021).

Nitrate concentration values of 25 observation wells were used to validate the DRASTIC vulnerability map (Fig. 10). In general, in the study area the nitrate concentration values varied from 16 to 86 mg/l, with a mean value equal to 47 mg/l. This value is very close to the maximum allowable level of nitrate in water, as set by U.S (45 mg/l) or by the European Union (50 mg/l), revealing a significant problem of nitrate pollution in the aquifer. Besides that, 8 out of 25 nitrate values were above 50 mg/l. The validation of the DRASTIC index with nitrate concentration resulted in a significant linear correlation, giving a result equal to R = 0.72.

5 Conclusions

Groundwater is very important for many human activities and thus a proper groundwater planning and management is critical for the prevention of groundwater pollution. An efficient tool for the delineation of potential pollution zones is groundwater vulnerability mapping. This present study is the first endeavour to assess the intrinsic groundwater vulnerability to pollution in an area with severe groundwater quality deterioration. The evaluation was conducted by employing the DRASTIC framework alongside with Geographical Information System (GIS) techniques. The DRASTIC method uses seven geological and hydrogeological parameters, which control the groundwater flow and pollution, and defines the potential vulnerability areas. The DRASTIC index varied from 53 to 150 and the study area was divided into four classes (from very low to high). Generally, the zone of high vulnerability potential is mostly concentrated in the southern, south-eastern and northern part of the study area, thus the protection of these areas is of crucial importance. Conversely, the central-northern, northern and north-western portion of the study area shows very low to low vulnerability potential. Single-parameter sensitivity analysis in the study area reveals the significance of the unsaturated zone and the aquifer media as the two parameters with the highest influence on vulnerability map, whereas the hydraulic conductivity seems to be the less important parameter on the intrinsic vulnerability. Results of the validation of DRASTIC vulnerability map with nitrate concentration values showed a satisfactory linear correlation, giving a result equal to R = 0.72. Notably, these results could be useful for policymakers and water authorities for an efficient groundwater resources management at a regional level. Finally, the design and the maintenance of a groundwater quality monitoring network in order to ascertain the aquifer's status of pollution, particularly in the high vulnerability zones, is recommended.

Declarations

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Competing Interests

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Author contributions

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Figures

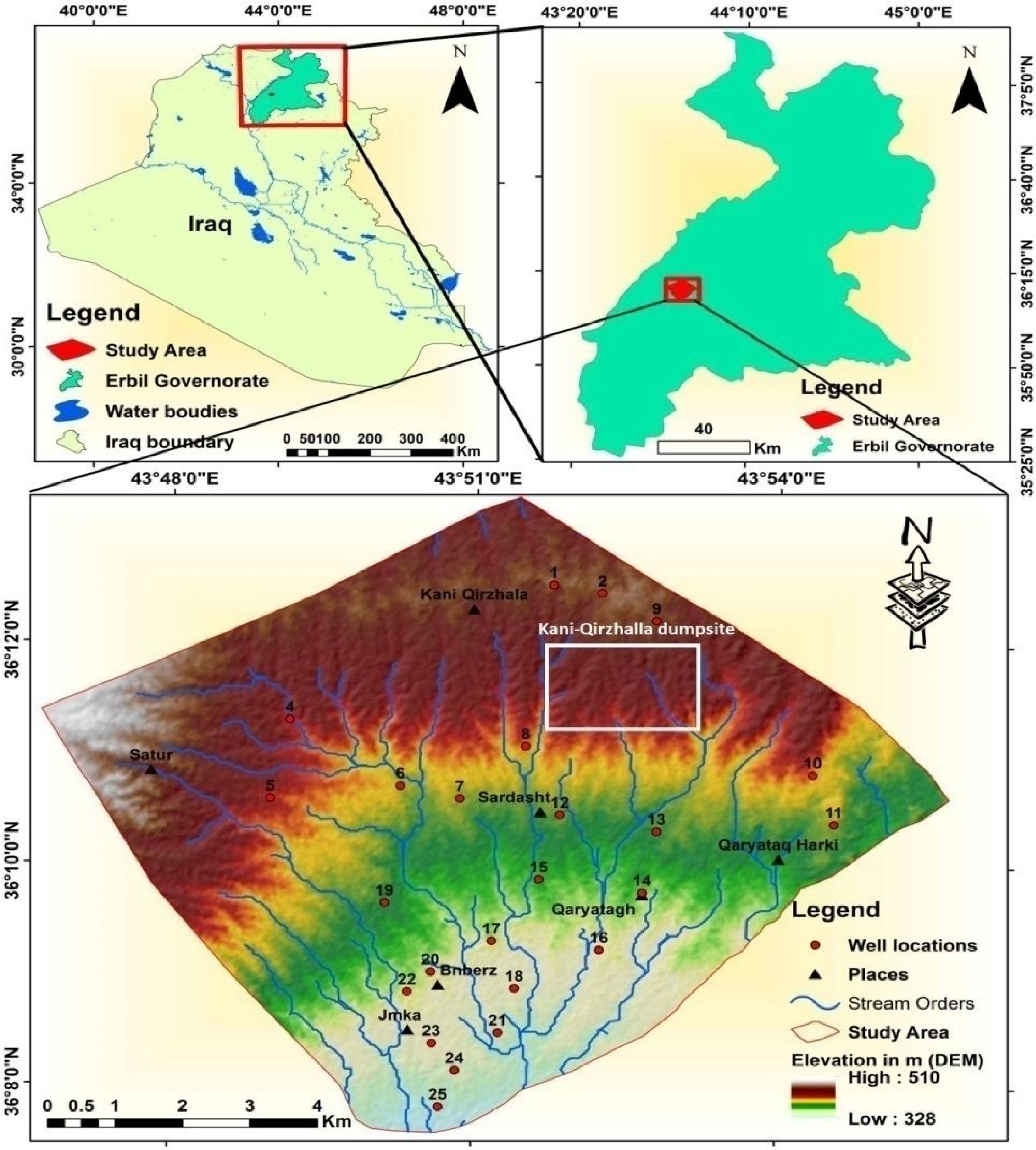

Figure 1

Location and DEM map of the study area and the dumpsite

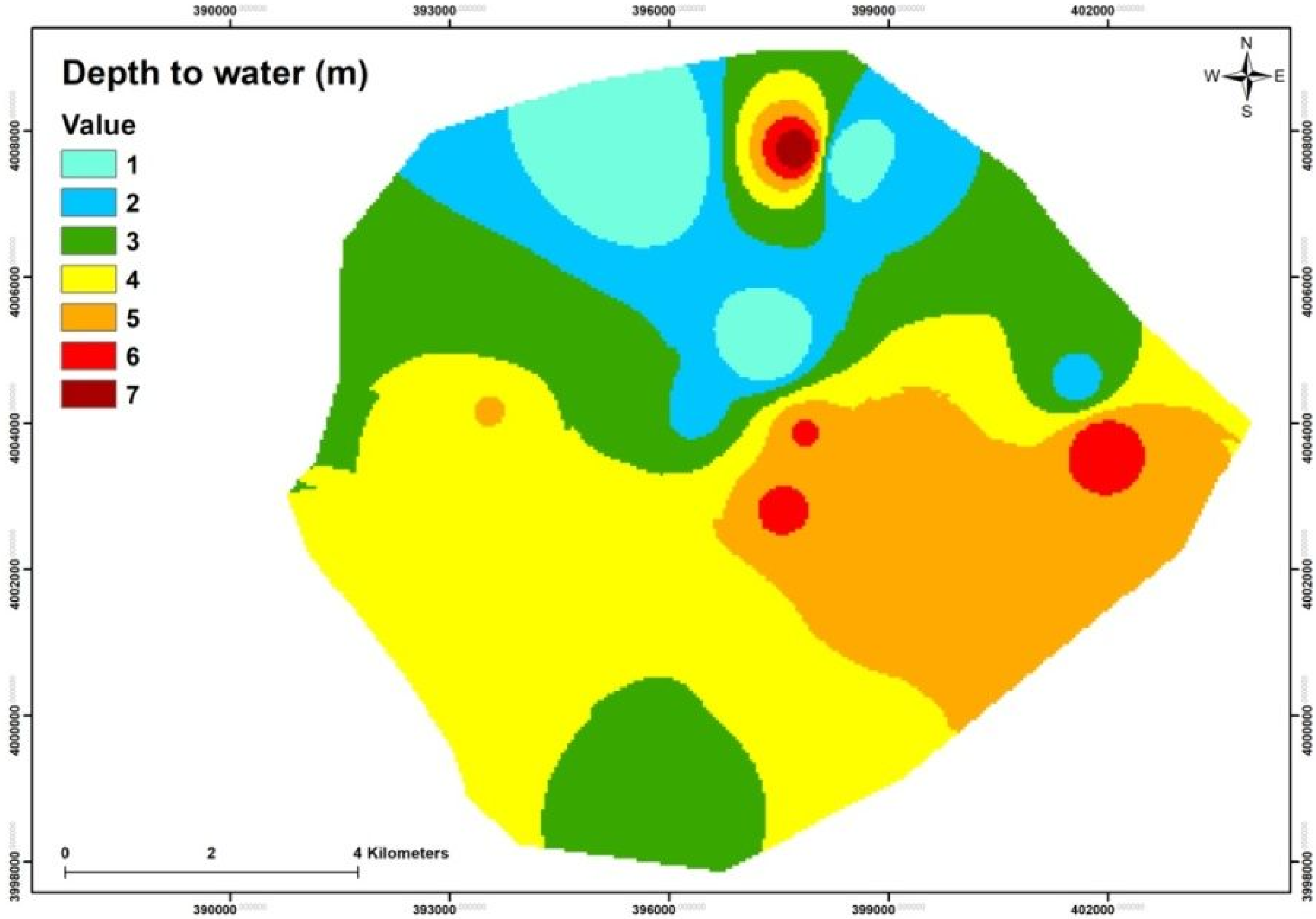

Figure 2

Depth to water map

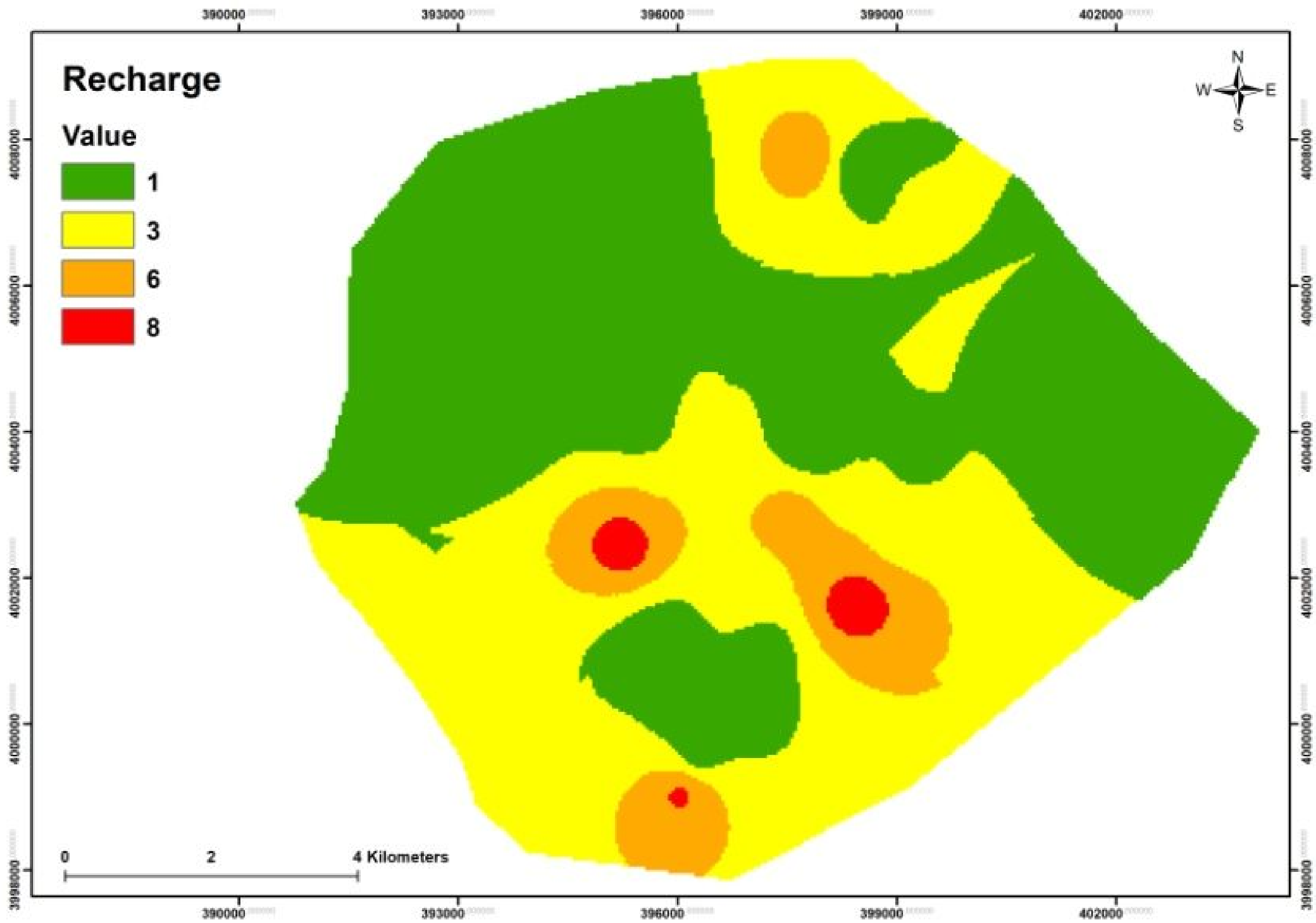

Figure 3

Recharge map

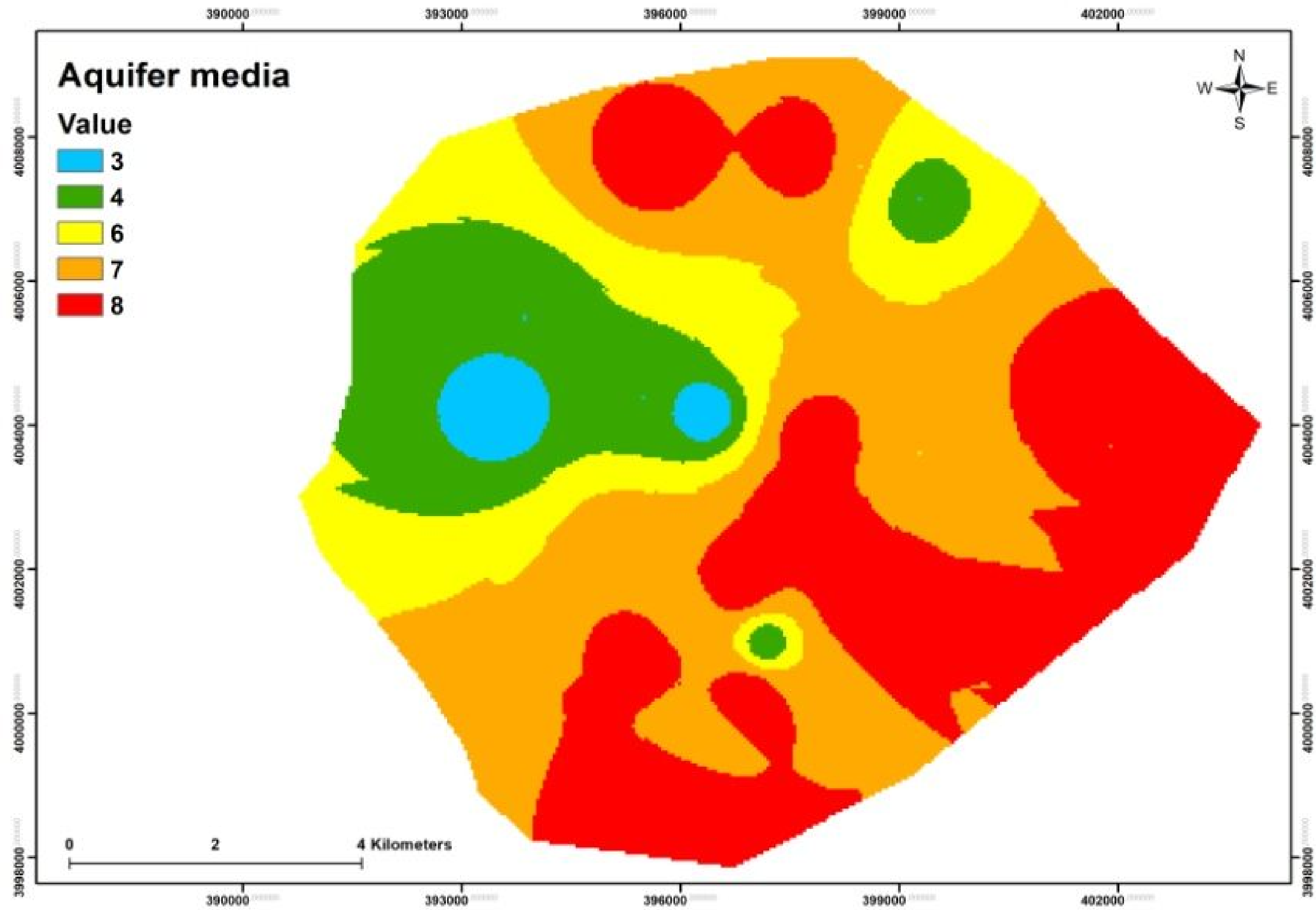

Figure 4

Recharge map

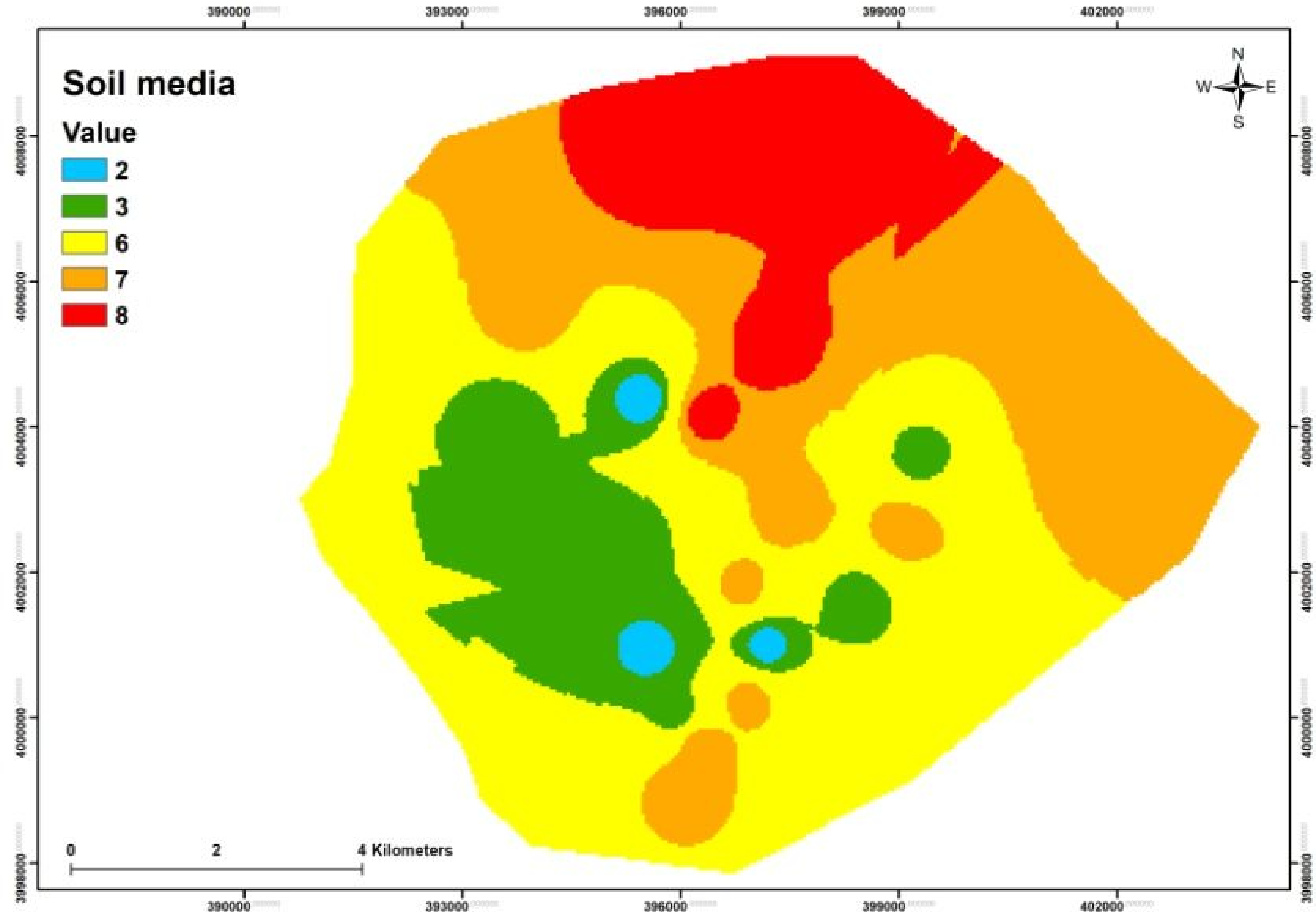

Figure 5

Soil media map

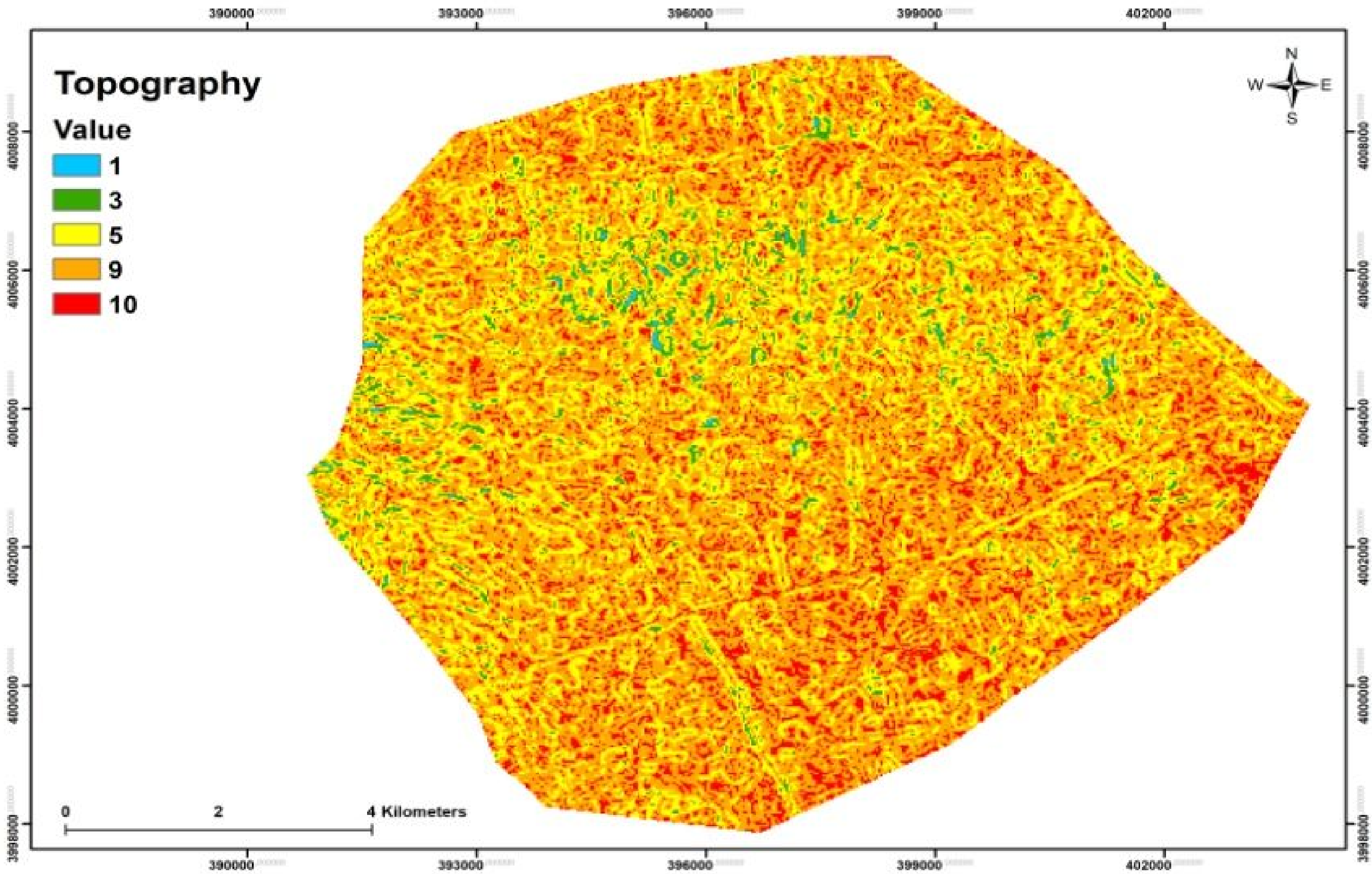

Figure 6

Topography map

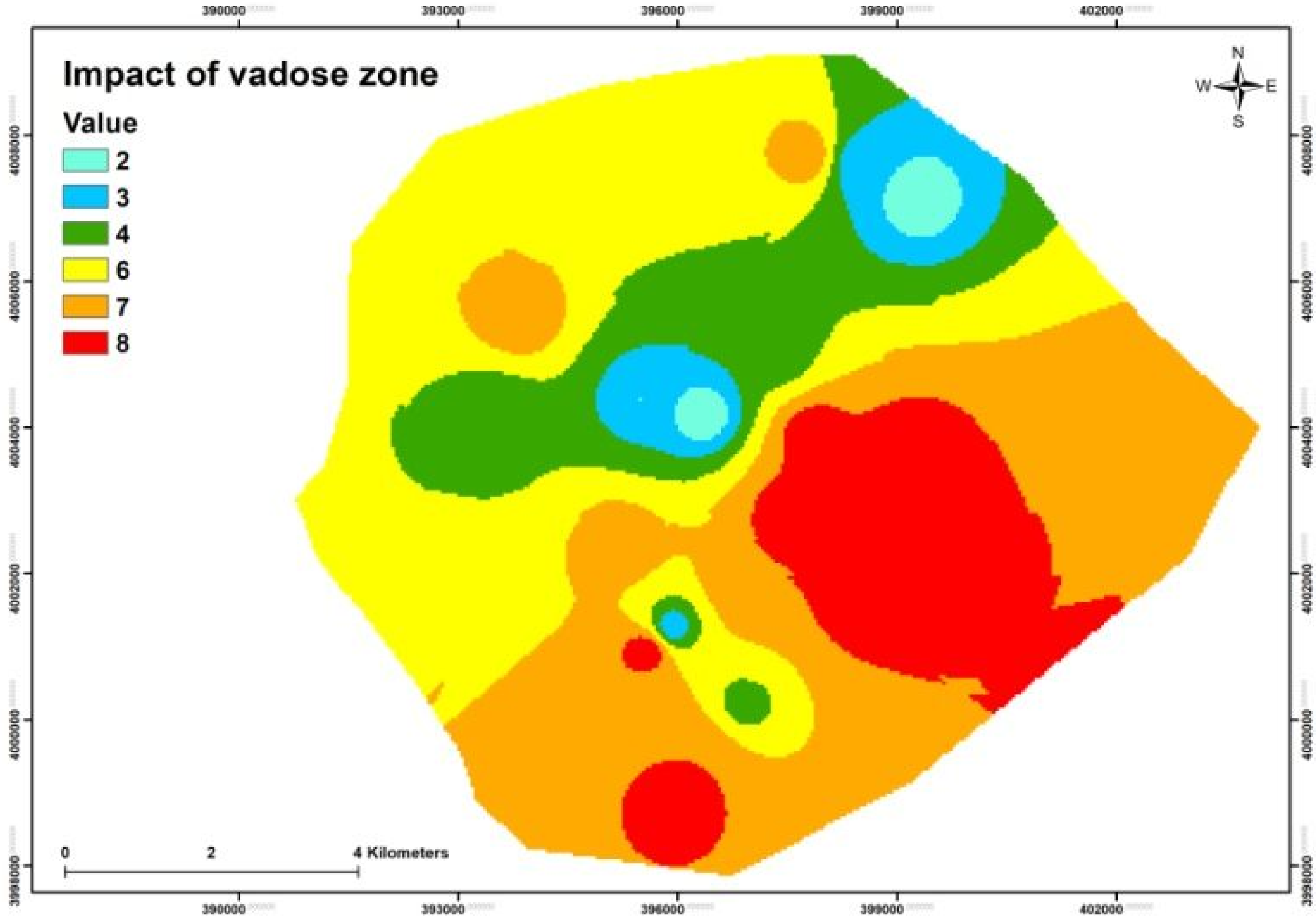

Figure 7

Impact of the vadose zone map

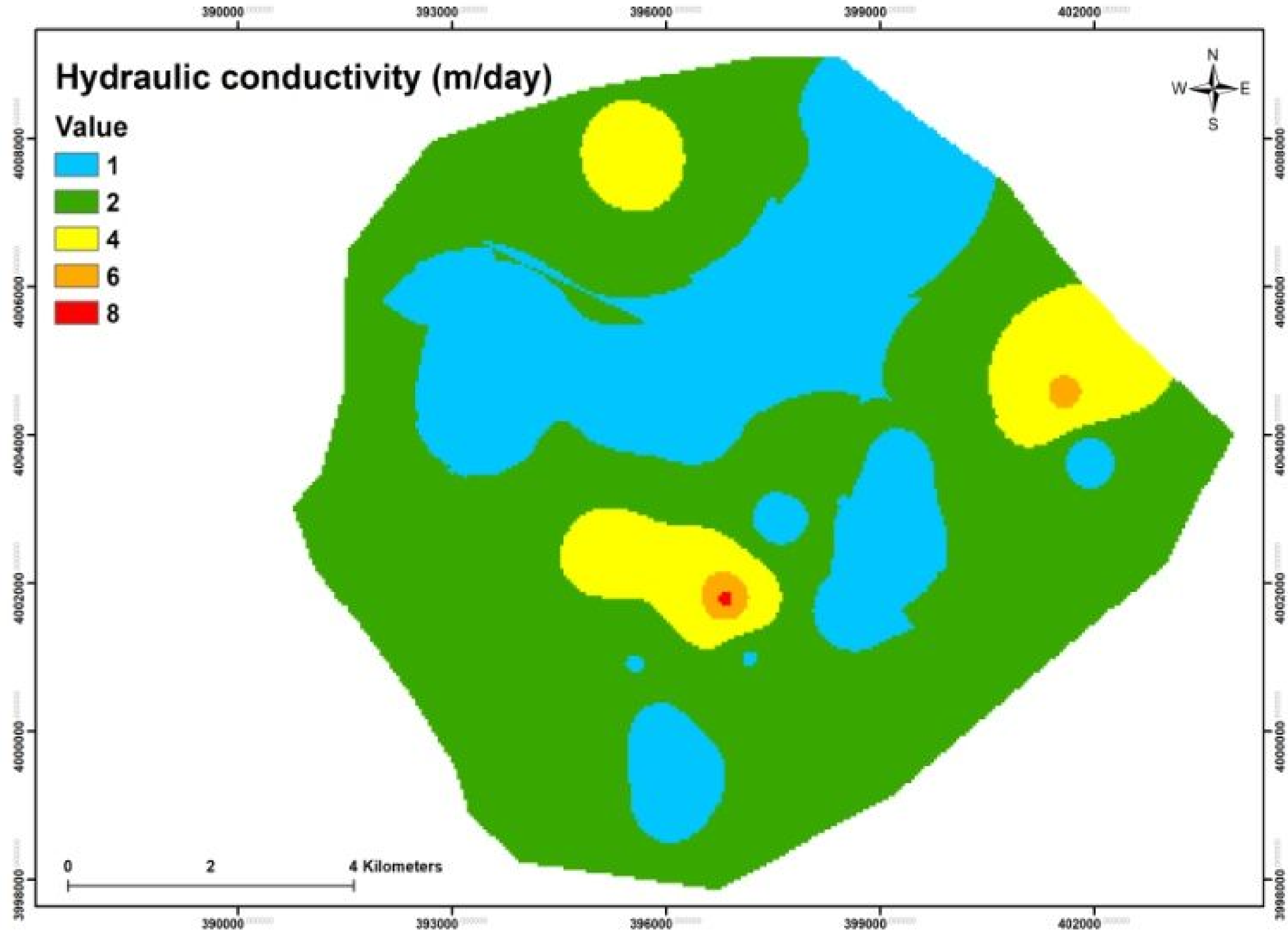

Figure 8

Hydraulic conductivity map

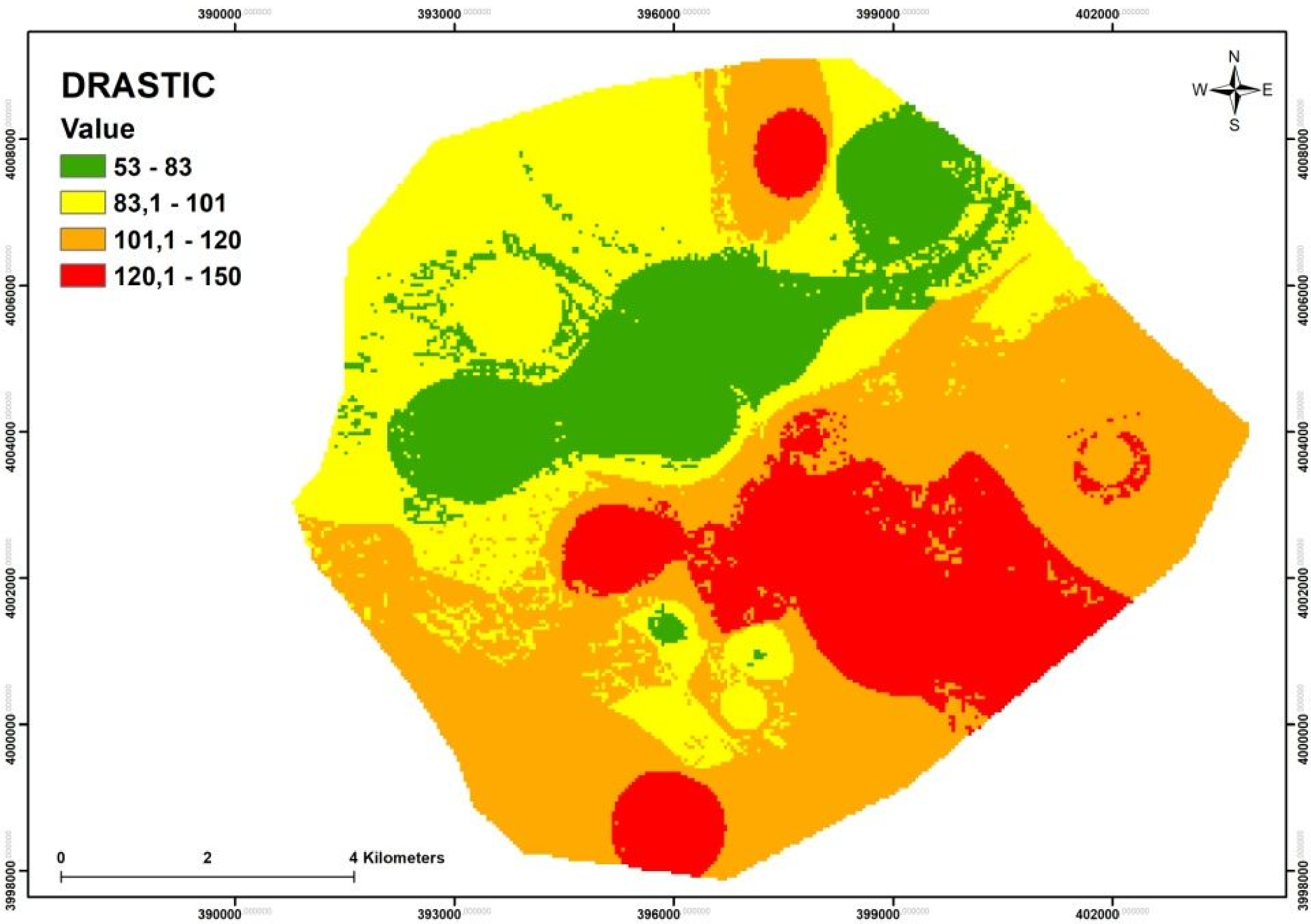

Figure 9

DRASTIC vulnerability map

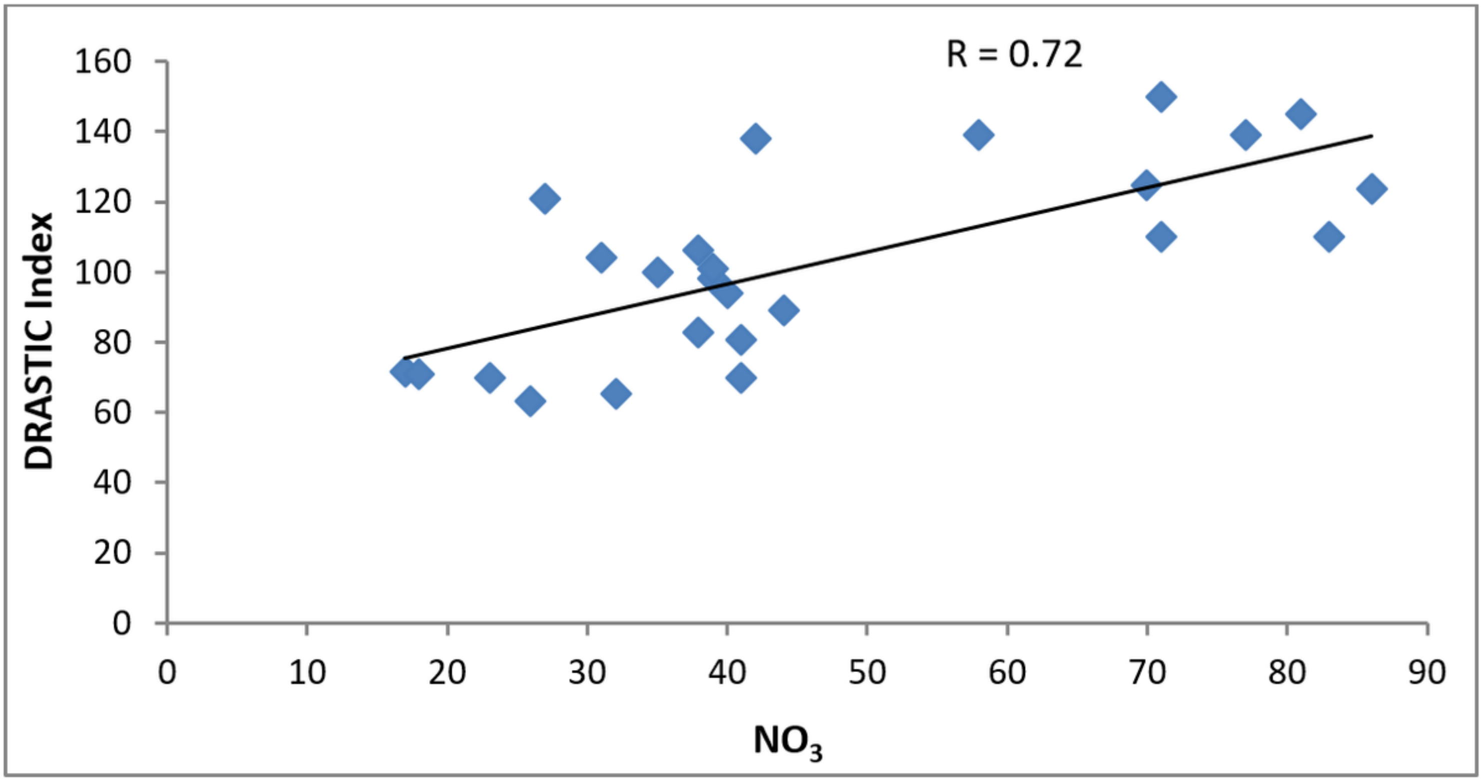

Figure 10

Correlation of DRASTIC index with NO3values