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A Comparative Study of Groundwater Vulnerability Assessment Methods

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Abstract

Recently, methods have emerged to assess the vulnerability of groundwater to pollution, which has been adopted by many countries that depend on groundwater as an important and supportive resource for surface water to protect groundwater and monitor and control its pollution. Assessment methods adopt vulnerability maps and compare them with the real-life pollution map of the region. The study was conducted in Al-Teeb area, which is located in the northeast of Missan province, south of Iraq. This area is about 2450 km^2. This study applied four models DRASTIC, GOD, SINTACS and Modified DRASTIC of vulnerability maps are analyzed using GIS technique and compared with the reality map which represent the nitrate concentration map as a basic comparison map; in order to choose the closest one with respect to the realistic acting. The results showed that 80.29 % of study area is classified under low vulnerability in DRASTIC method and moderate vulnerability in GOD, SINTACS and MD-DRASTIC which are covered 54.12 %, 83.18 % and 72.35 % of study area respectively. Pearson's correlation coefficient was used to compare the four methods with the nitrate concentration map, where the correlation value for DRASTIC, GOD, SINTACS and MD-DRASTIC was 73.05, 49.79, 83.23 and 87.94 %, respectively. So, the MD-DRASTIC is represented the best technique for evaluating vulnerability map in the study area which can be recommended.

Keywords: Groundwater, Vulnerability, Pollution, DRASTIC, GOD, SINTACS, MD-DRASTIC, GIS.

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1. Introduction

The application of different methodologies highlights the strengths and weaknesses in describing the most specific methods in assessing groundwater vulnerability if taking into account the impact of human activities, which can be considered to be the most vulnerable to pollution issues [1]. Different methods are applied to estimate the aquifer vulnerability to pollution. These methods are classified in three main categories: process-based simulation models, statistical methods, and overlay and index methods based on geographic information system (GIS). ArcGIS 10.7 software was used to create, process and analyze set of data to generate the final vulnerability maps. The main purpose of this study is presenting the best decisions that will give opportunities for stakeholders and decision makers to choose the veracious areas for agricultural, industrial and residential activities based on the results of the vulnerability maps.

The selecting of this area is due to the dependence of the population of the study area on well water for drinking and irrigating agricultural crops with the direction of future expansion in the area.

Vulnerability maps assist local governments and policies to lay down the systematic foundations for controlling groundwater quality, identify future plans for decision makers to take strict measures to protect groundwater resources and develop policies on planning of land use, industry establishment and agriculture activities [2].

There is no fixed model that meets all the requirements of the hydrological environments due to the different nature and circumstances of the study area and according to the data and hydrological settings. Therefore, the model must be modified to suit the needs of the study area. The choice of the right model depends on several factors, the most important of which is the availability of data, hydrological setting, and the final use of the map.

2. Materials and Methods

2.1. Study Area

The study area is located in north and north east of Missan province as shown in Fig. 1. It occurs along the mountains of the Iraqi-Iranian frontier in south of Iraq, between longitudinal-line (47°39′11″ - 47°55′1″) and latitude-line (32°29′47″ - 31°58′16″). The considered area is about 2450 km^2. The collection of required data started in the first of February of 2019. The region is characterized by the diversity of its surface topography, with mountains and high hills in the northeastern sections, plains, flat lands and valleys in the central sections, and marshes in the southern sections. There three types of aquifers, confined, semi-confined and unconfined which is encompassed most study area. There are the two most important rivers in the area, Teeb and Duriage Rivers. Rainfall in Iranian territory is considered the sole source of two rivers. The scarcity of water from the two rivers in the hot summer months and the need of the population for water so, the groundwater has special importance indispensable. Therefore, there is essential a need to monitor this important water resource and protect it from pollution.

2.2. Assessment Vulnerability Methods

Assessment of groundwater vulnerability to pollution using vulnerability models that include environmental factors for the same studied area is a proactive step to monitor and protect groundwater from pollution before it occurs because the process of removing these pollutants is costly and requires a longer period of time. Four methods of overlay and index vulnerability assessment are adopted in the study area which are DRASTIC, GOD, SINTACS, and MD-DRASTIC [3], [4].

GIS technique is the best helpful tool to create vulnerability maps of hydro-geological factors, based on data obtained from different sources. One of the most important benefits of GIS is that it gives the user the opportunity to manage the data better and update it whenever necessary. This makes vulnerability maps dynamic and consistent with land use and environmental changes.

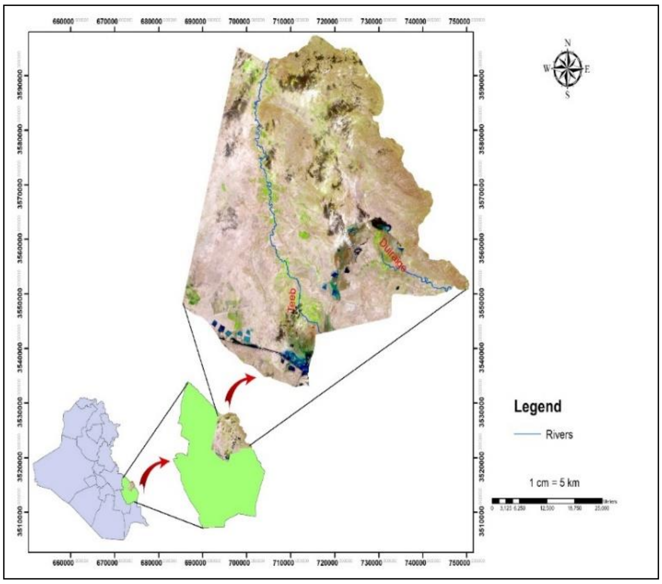

Fig. 1 Location of study area in Iraq and in Missan province.

2.2.1. DRASTIC Method

DRASTIC is the first technique consists from seven layers processed and analyzed by GIS based computer programs to produce the final vulnerability map. This model was first developed by Aller [5]. The rate of each parameter ranges from (1 to 10) and weight ranges from (1 to 5). High vulnerability refers to rating (10) and weight (5). DRASTIC Vulnerability Index can be shortened by (DVI). Depth to water table (D) is the first parameter of DRASTIC which represents the distance from the earth's surface to the water table. It is used in all four models and abbreviated as D in the DRASTIC, GOD and Modified DRASTIC models and S in the SINTACS model. Thirty-five wells distributed randomly in the study area were used to measure the depth to groundwater, these depths range from 1.5 to 29 m. Map depth to groundwater is appeared six classes range (0-1.5, 1.5-4.5, 4.5-9, 9-15, 15-23, and 23-29), the rating of classes is (10, 9, 7, 5, 3, 2) respectively. Recharge (R) is defined as the amount of vertical infiltration water from the earth's surface to the groundwater level through the unsaturated zone which plays an important role in transporting pollutants especially when they are large quantities. The spatial distribution of the recharge is estimated from the results of the wets pass model which is an acronym for water and energy transfer between soil, plants, and atmosphere under quasi-steady state, where 12 layers were introduced for each of the months of 2020 [6]. The results showed that recharge values range from 0-16 mm/year, as the recharge values less than 50 mm/year therefore, the rating is one aquifer media (A) is known as a reservoir made of permeable materials and saturated with groundwater. Two classes of aquifer media map are showed in study area which are (sand & gravel and shale) and rating of classes is (6 and 8) respectively. Soil media (S) is the first defense layer that blocks the flow of liquid pollutants rushing into the groundwater as it passes through the unsaturated layer. Three types of soil are (sand, loamy sand and sandy loam). The rating of soil classes is (6, 7 and 9). Topography (T) refers to slope of surface area. Topographic map is constructed from digital elevation model (DEM) with accuracy of 30 m. Four classes of topographic map are (0-2, 2-6, 6-12, 12-18) percent, so the rating of these classes is (10, 9, 5, 3) respectively. Impact vadose zone (I) which represents the unsaturated layer below the surface of the earth, which is the second line of defense against pollutants heading to the groundwater. Different types of vadose zone are rated (3, 7, 8 and 9) to classes (silt or clay, sand, sand & gravel and gravel) respectively. Hydraulic conductivity (c) is one of the characteristics of aquifer that allows water to pass through it. The hydraulic conductivity ranges from 2.19 to 12 m/day so, the rating values are (1, and 2). Figures 2 and 3 show the rating map of parameters used in DRASTIC method. Statistical analysis shows that the highest contribution to the vulnerability index is made by slope (mean = 9.98). Then mean of aquifer media and soil media are 7.27. Mean values of depth to groundwater and vadose zone are 6.58 and 6.3, respectively. The values of mean hydraulic conductivity and recharge are (1.69) and (1), respectively, which contribute to the lowest to the contamination of groundwater. The coefficient of variations in vulnerability maps also showed that higher values were represented by hydraulic conductivity 27 %, and then vadose zone 26 % as shown in Table 1.

Table 1. the statistical summary of the seven parameters.

Parameters	Weights	Min	Max	Mean	SD*	Cv** (%)
D	5	2	10	6.58	1.25	19
R	4	1	1	1	0	0
A	3	6	8	7.27	0.46	6.33
S	2	5	9	7.27	0.91	12.5
T	1	3	10	9.98	0.04	0.42
I	5	3	9	6.3	1.63	26
C	3	1	2	1.69	0.46	27

* Standard Deviation

** Coefficient of variation = SD/Mean

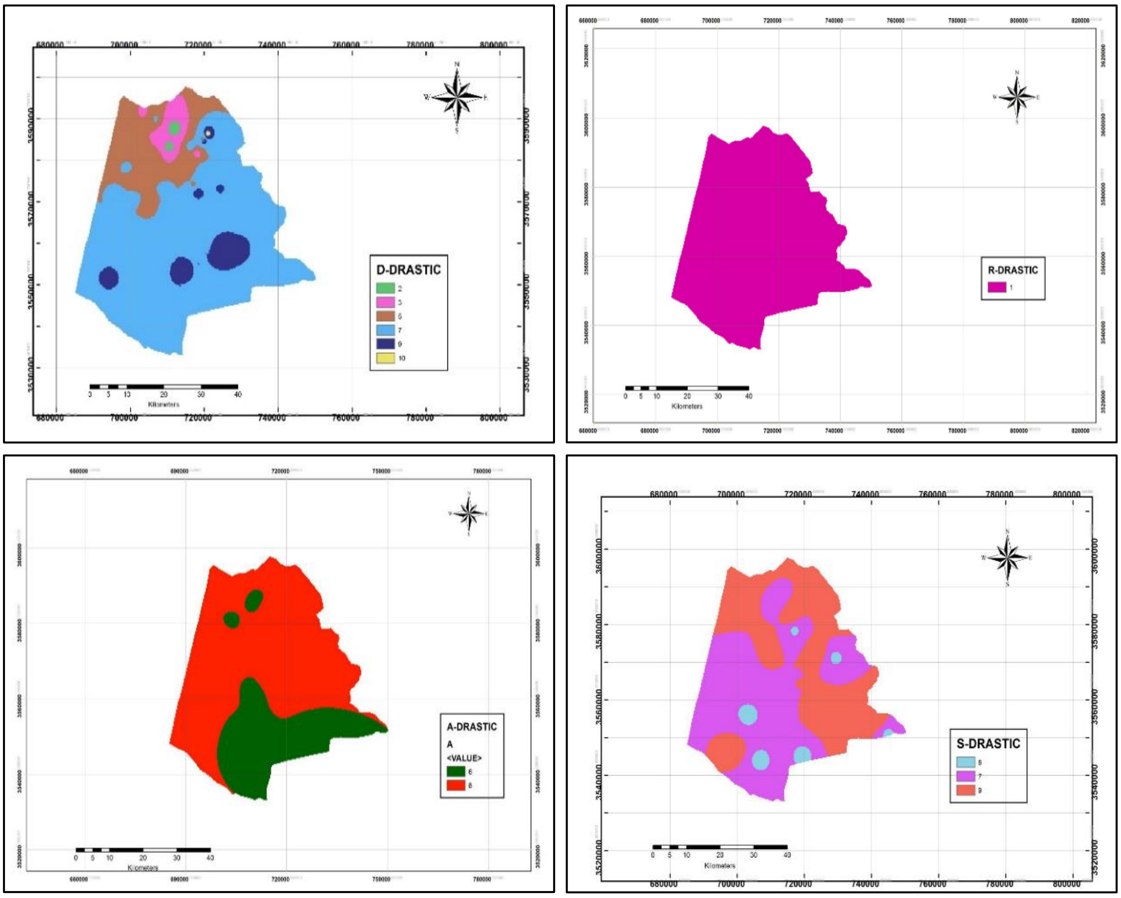

Fig. 2 the rating map of D, R, A, S used in DRASTIC method.

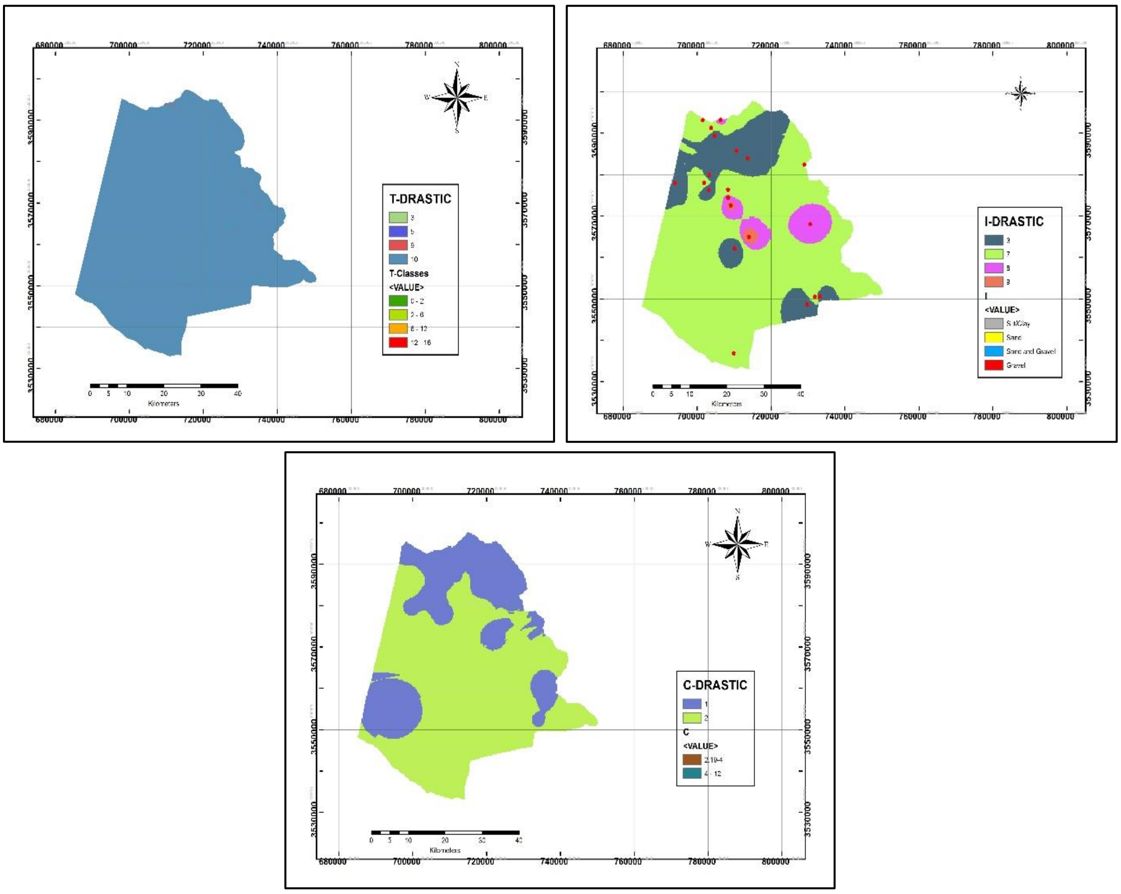

Fig. 3 the rating map of T, I, C used in DRASTIC method.

2.2.2. GOD method

This method was introduced in England by Foster [7]. The model is a quick estimation of groundwater vulnerability as a result of its reliance on three hydrogeological parameters and abbreviated three characters. GOD vulnerability index is denoted by GVI. This method depends on multiplied of the rating of each parameter without weights [8]. Where G represents (Groundwater occurrence), O represents the lithology of unsaturated zone (Overall aquifer class), and D represents (Depth to groundwater). GOD Vulnerability Index ranges from 0 to 1. Groundwater occurrence refers to types of aquifers. Three aquifer types are assigned in the study area, unconfined aquifer, semi confined aquifer, and confined aquifer. The unconfined type of aquifer is higher rating which is equal to (1) and semi-confined is the next rating by (0.3) and confined type represents the low vulnerable to pollution by rating (0.2). Overall lithology of aquifer represents the unsaturated layer through which the liquid pollutants pass into the aquifer through the properties of the particles that consists it up.

Three classes of this layer, (sand) with rating by (0.7), silt or clay) is rated by (0.4) and (sand and gravel) with rate of (0.8). The rate of groundwater depth ranges from 0.0 to 1. Figure 4 shows the rating map of parameters used in GOD method. It can be noted through the mean values of the parameter that the occurrence of groundwater and the depth to groundwater are the highest two values which are 0.82 and 0.8, respectively. Mean of overall lithology is 0.58. The coefficient of variations shows that groundwater occurrence is higher values than other parameters by 20 %, then overall lithology by 14 % and last one represents depth to groundwater by 8.5 % as clear in Table 2.

Table 2. the statistical summary of the GOD parameters.

Parameters	Min	Max	Mean	SD	Cv (%)
G	0.2	1	0.82	0.16	20
O	0.3	0.9	0.58	0.08	14
D	0.6	1	0.8	0.068	8.5

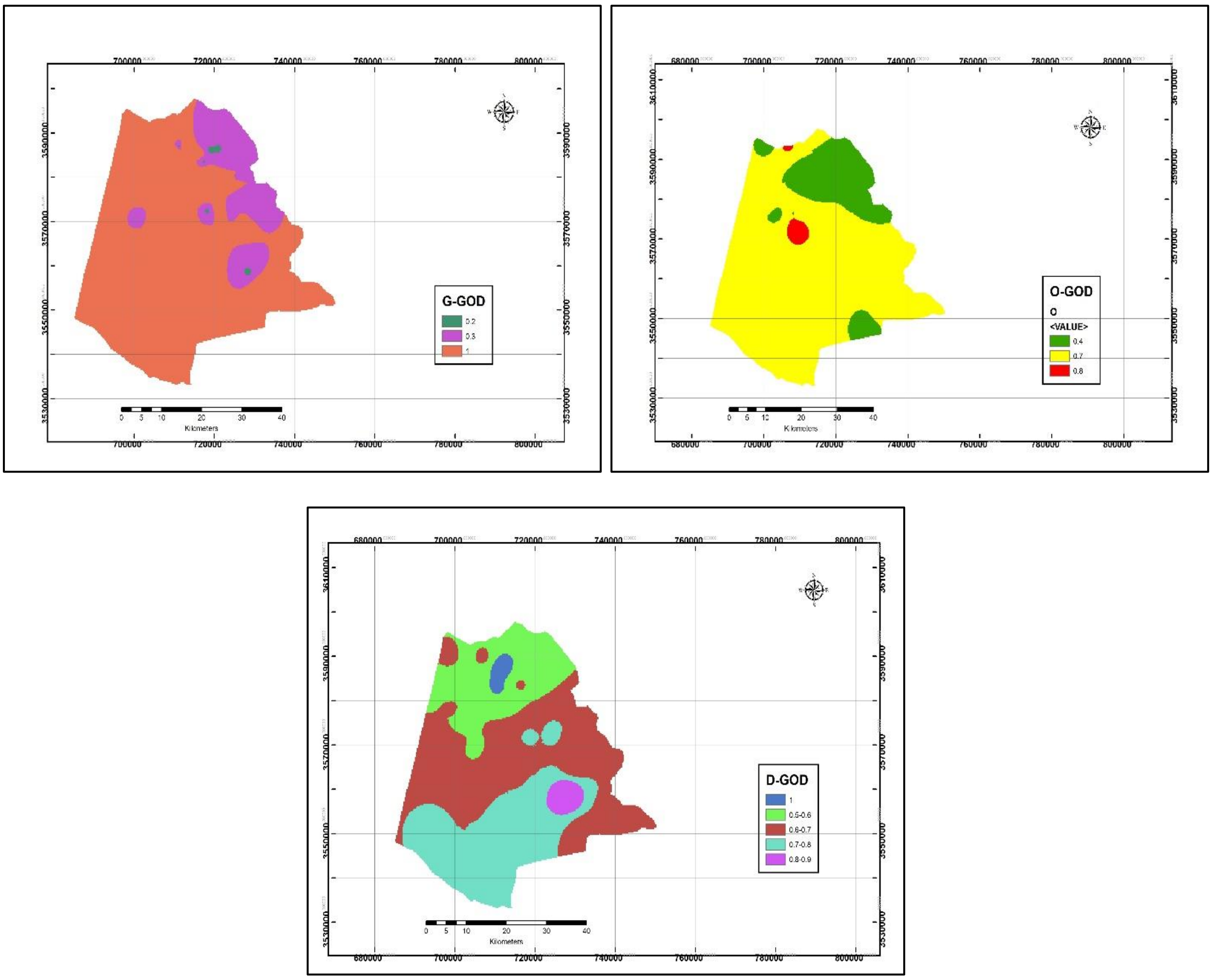

Fig. 4 the rating map of G, O, D used in GOD method.

2.2.3. SINTACS method

This model is developed by (Civita and De Maio) [9] and depended on seven parameters which are water table depth (S), Effective infiltration (I), Unsaturated zone (N), Soil media (T), Aquifer media (A), Hydraulic conductivity zone (C), Topographic slope (S). SINTACS vulnerability index is denoted by SVI. These parameters are classified into ranges and rating. Each parameter is multiplied by specified weight in contribution of aquifer vulnerability. The rating scale varies from 1 to 10 and assigned weight ranges from 1 to 5. SINTACS method is developed from DRASTIC method [10]. There are six classes ranges of groundwater depth (S) (0-2, 2-4, 4-7, 7-10, 10-20, and 20-29) which are rating of (10, 9, 7, 6, 5, 3) respectively. Effective infiltration (I), the values of effective infiltration less than 50 mm/year so the rating is (1) and in one color. Five classes rate of unsaturated zone are (3, 5, 7, 8, and 9). Soil media (T) is classified to three classes (sandy loam, loamy sand and sand) so, the rating of soil classes is (6, 7 and 8) as assigned respectively. The rate map of the aquifer media (A) shows two classes which are (3 and 8) to clay and (sand and gravel) respectively. The rate map of hydraulic conductivity (C) is (1, 2 and 3) of classes ranges from 2.19 to 12 m/day. Topography (S) indicates the inclination of the earth's surface, which has an important effect in assessing vulnerability, through which it is set whether liquid pollutants will be surface runoff or infiltrate out into the aquifer.

The rate map of topography is (10, 9 and 1) of classes (0-2, 2-6, and more than 18) percent of this layer. Figures 5 and 6 illustrate the parameters map used in SINTACS method. Mean values indicate that the highest contribution to the vulnerability index is made by slope (S) (10), aquifer media (A) (6.5), depth to groundwater (S) (6.45) then soil median (T) (6.17). The unsaturated zone (N), hydraulic conductivity (c), and effective infiltration (I) are (4.89, 1.87, 1) respectively. The coefficient of variations indicates that a high contribution to the variation of vulnerability index is made by hydraulic conductivity (37.97 %), then the aquifer media (A) by (35.23 %). Table 3 is showed the statistical results of SINTACS method.

Table 3. the statistical summary of the SINTACS parameters.

Parameters	Weights	Min	Max	Mean	SD	Cv (%)
S	5	3	10	6.45	0.97	15
I	4	1	1	1	0	0
N	5	1	8	4.89	1.25	26
T	4	5	7	6	0.57	9.5
A	3	2	9	6.13	0.95	15.5
C	2	1	10	10	0	0
S	3	1	3	1.43	0.61	43

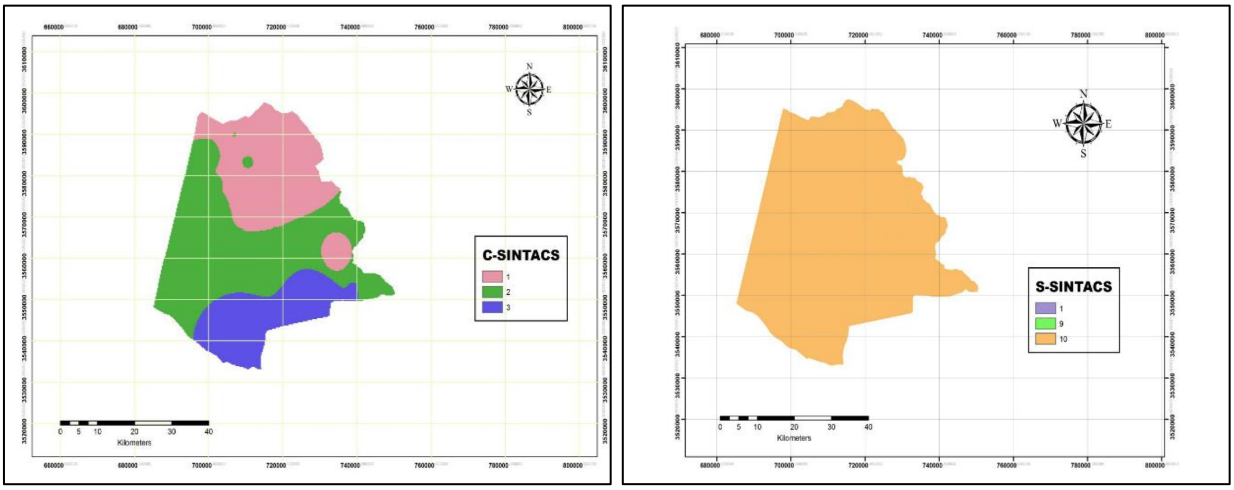

Fig. 5 the rating map of C, S used in SINTACS method.

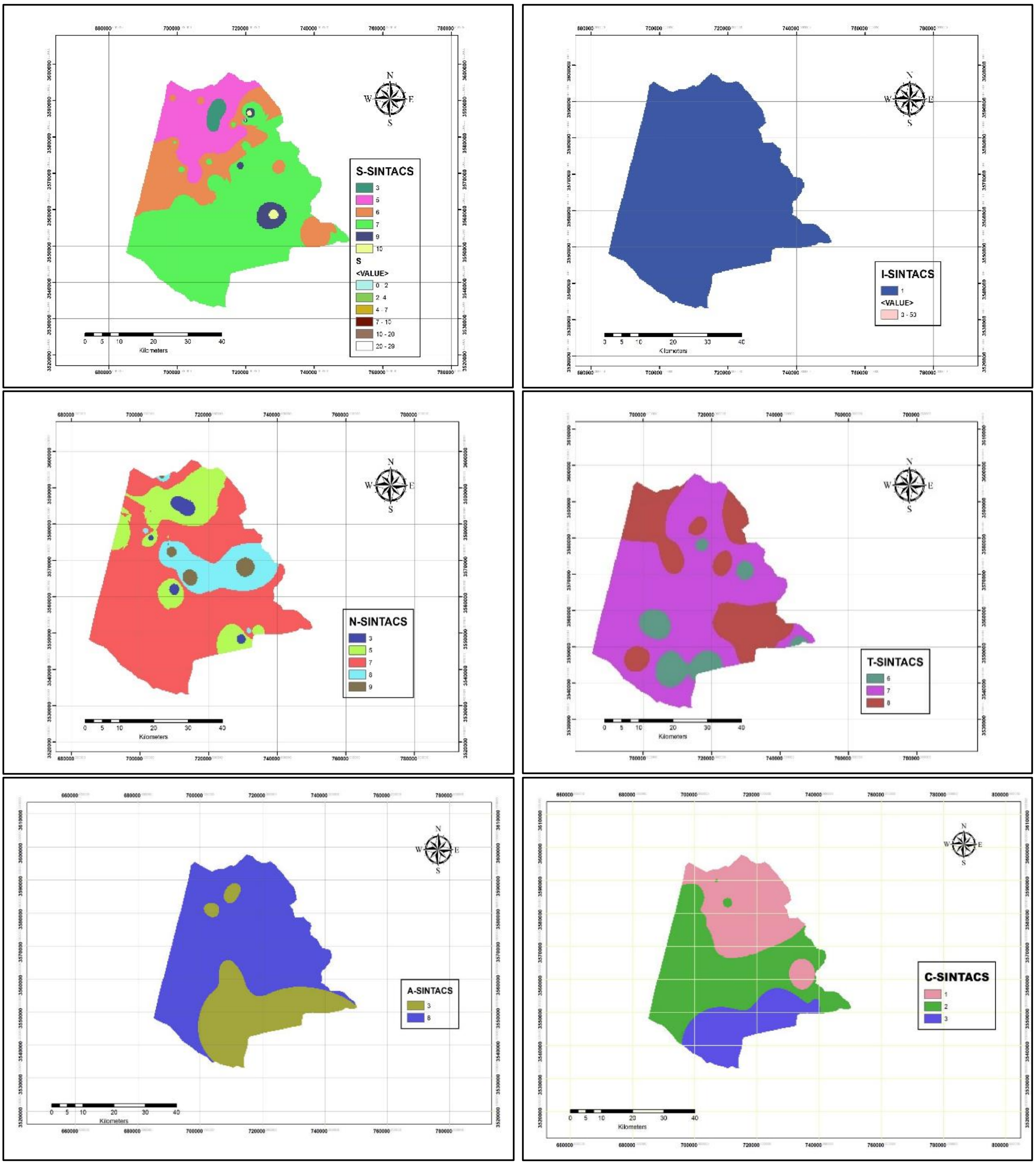

Fig. 6 the rating map of S, I, N, T, A, C used in SINTACS method.

2.2.4. MD-DRASTIC Map

MD-DRASTIC vulnerability map is resulted from eight layers which add the LULC (land use and land cover) layer to seven layers of DRASTIC method [11]. The availability of remote sensing data and their compliance with the application of the studied area, as well as the accuracy that depends on categorization, are two of the most significant variables that influence the choice of this technology.

LULC maps may be created using remote sensing data and a field survey of the region to corroborate the categorization based on observations [12]. The USGS classification system has five levels, ranging from I to V, the resolution of remote sensing data determines the difference between them. utilized for categorization. The digital image categorization of the study basin was created using ArcMap 10.7 software. The categorization of supervision was done at the USGS level. Field work was used to conduct the analysis, which included choosing numerous places using GPS and collecting photos to verify the validity of the final categorization map. LULC map may be classified into three classes (wet land, agriculture land and barren land). The rate map of LULC is (5, 7, and 8) of classes (barren land, wet land, and agriculture land) respectively. The high vulnerability area (8) represents the agriculture land is occupied by (15 %) of study area while (7) vulnerable area which represents the wet land is comprised by (4 %) of study area and the high percentage of occupation (81%) represents the barren land with low vulnerable area. All classes of rating are multiplied with weight of 5. Figures 7 and 8 show the rating and classes of LULC map. Table 4 shows the statistical summary of the MD-DRASTIC parameters. MD-DRASTIC vulnerability index is denoted by MDVI.

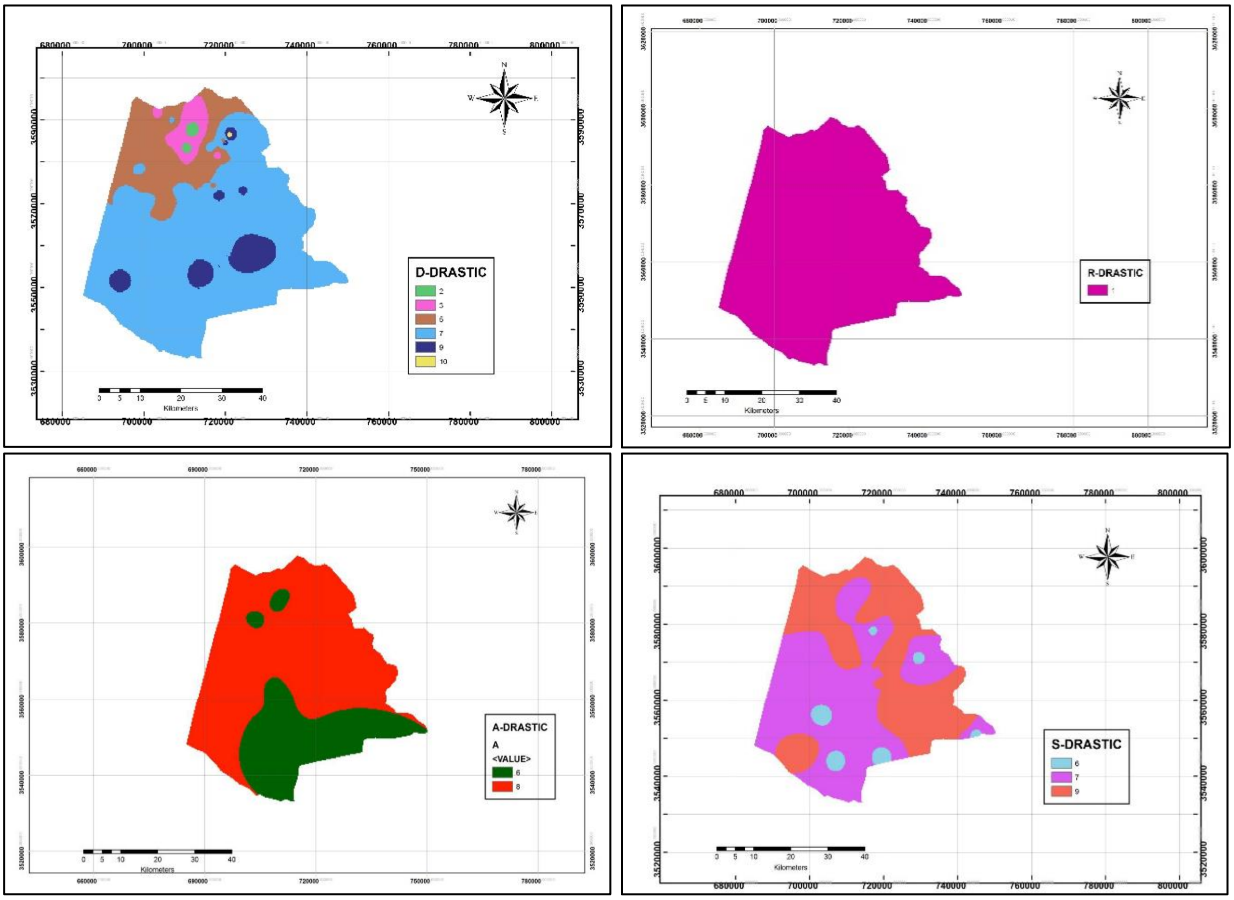

Fig. 7 the rating map of D, R, A, and S used in MD-DRASTIC method.

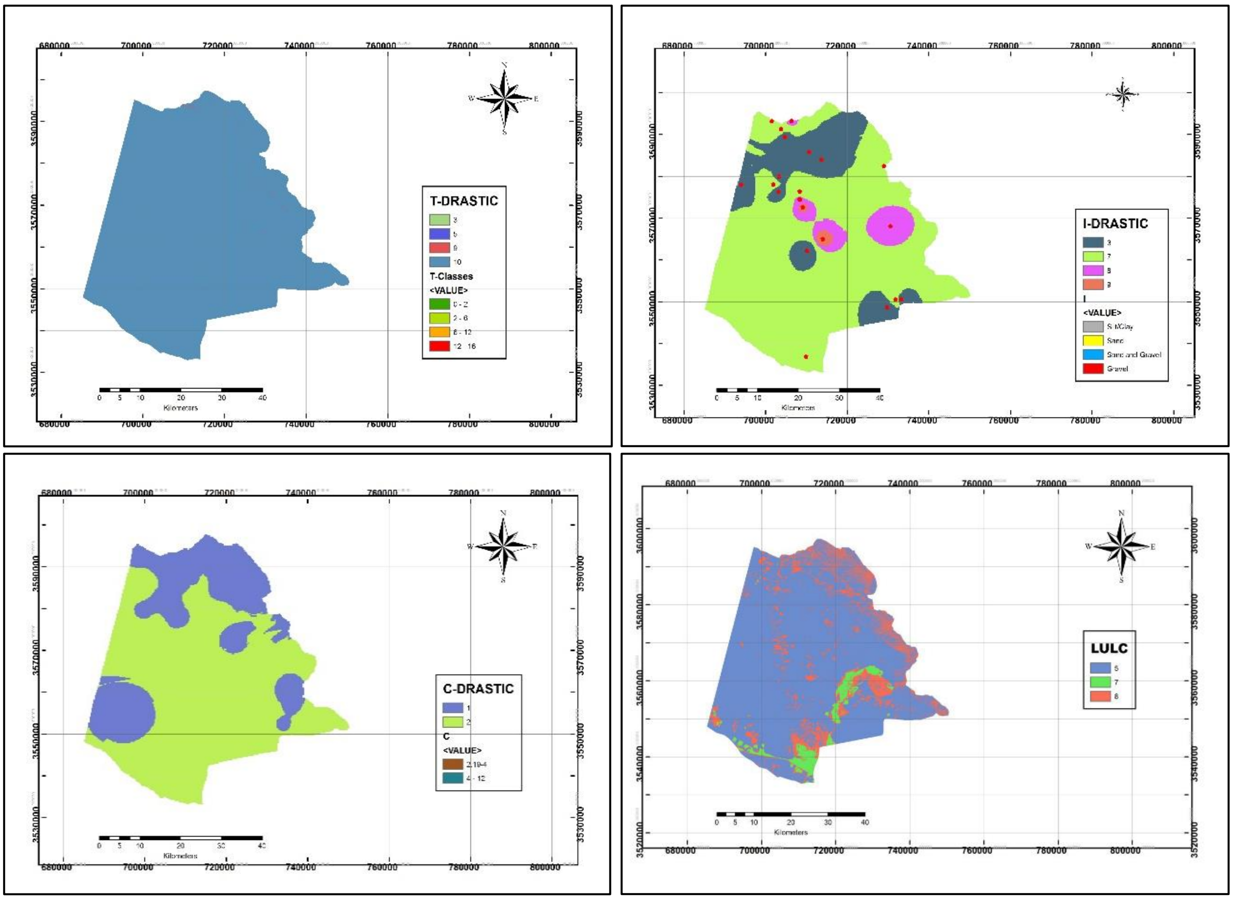

Fig. 8 the rating map of T, I, C, and LULC used in MD-DRASTIC.

Table 4. the statistical summary of the eight parameters.

Parameters	Weights	Min	Max	Mean	SD	Cv (%)
D	5	2	10	6.58	1.25	19
R	4	1	1	1	0	0
A	3	6	8	7.27	0.46	6.33
S	2	5	9	7.27	0.91	12.5
T	1	3	10	9.98	0.04	0.42
I	5	3	9	6.3	1.63	26
C	3	1	2	1.69	0.46	27
LULC	5	5	8	5.5	1.09	20

3. Results and Discussions

Results of final vulnerability maps of each model are showed that the DRASTIC model included three categories, the low vulnerability category occupied the largest percentage in the study area by 82.29 %, while the three models (GOD, SINTACS and MD-DRASTIC) models that included four categories where the medium vulnerability category included most of the study area by 54.12, 82.81 and 72.35 % respectively. Three methods (DRASTIC, SINTACS and MD-DRASTIC) are similar that southern and eastern parts are more vulnerable to pollution than northern and western except the GOD method which represented the southern and western parts are more vulnerable to pollution than other segments. Parameters such as shallow groundwater depths and soil type such as sand and the effect of the vadose zone have effectively made the eastern and southern parts of the study area more vulnerable to pollution than others. Table 5 shows the percentage of each class in study area for different techniques and Figures 9 and 10 show the classes of vulnerability of four methods.

Table 5. the percentage of each class of four methods.

Vulnerability Classes	Vulnerability Indices							
	DRASTIC	**Area %**	**GOD**	**Area %**	**SINTACS**	**Area %**	**MD-DRASTIC**	**Area %**
Very Low	60-100	7.84	0-0.1	0.29	77-80	0.35	85-100	0.6
Low	100-125	80.29	0.1-0.3	44.32	80-105	1.75	100-125	6.45
Medium	125-139	11.87	0.3-0.5	54.12	105-140	82.82	125-150	72.35
High	-	-	0.5-0.6	1.3	140-160	15.08	150-179	20.5

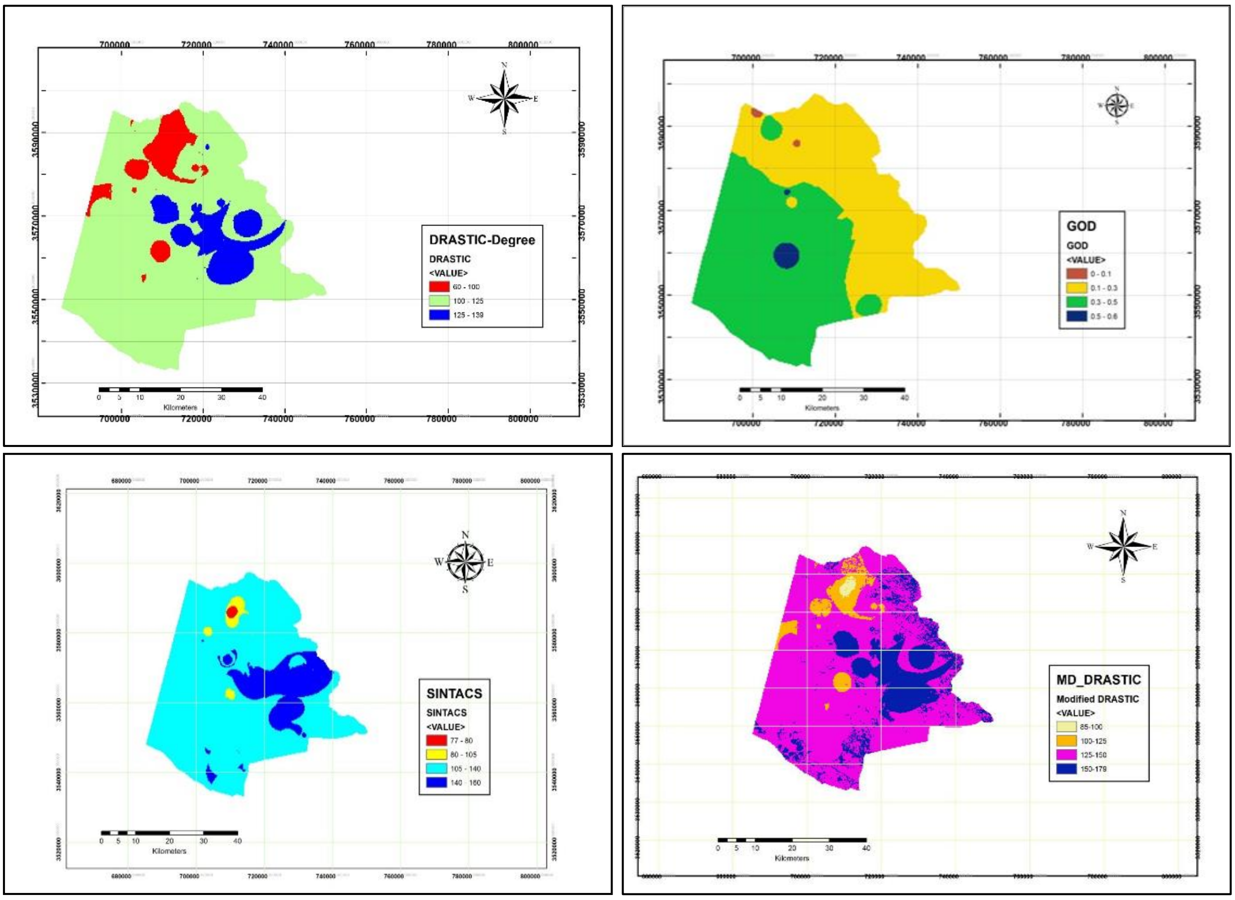

Fig. 9 Final vulnerability maps of four methods.

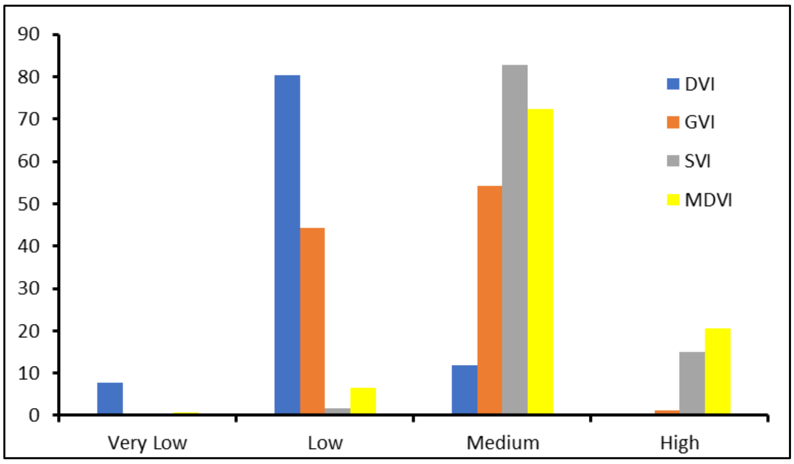

Fig. 10 Classes of vulnerability results of four methods.

3.1. Validation

It is not right to compare different models for assessing the vulnerability of groundwater contamination as they use different parameters in their operations. Despite the fact that the goal of all of these models is to estimate the risk of groundwater pollution. All risk assessment methods create final vulnerability maps that reveal groundwater pollution and its spatial distribution. Theoretically, such results are evaluated by comparing vulnerability maps from different models on the same study area. According to these reasons, the different models are validated with field data. Field data was carried out with the water quality data with respect to nitrate concentration. Table 6 represents the nitrate concentrations in groundwater for (17) wells distributed over the study area at wet and dry season.

The samples were collected at the end of June 2019 for dry season and end of April 2020 for wet season. Nitrate concentration was used to verify the accuracy of groundwater risk map [13]. For each vulnerability map, Pearson's correlation coefficients were used to compare it to the rate of nitrate concentration as a spatial distribution map by special technology of GIS which identify technology is applied between vulnerability map and groundwater risk map represented nitrate concentration. Results of validation are showed that Pearson correlation coefficient for (DRASTIC, GOD, SINTACS and MD-DRASTIC) are (73.05 %, 49.79 %, 83.23 % and 87.94 %) respectively. The MD-DRASTIC method is best method to achieve a strong association with the real pollution map of the region so it is recommended.

Table 6. Nitrate concentrations in groundwater (mg/l).

well	x	y	Wet	Dry
Well-1	698565	3564920	1.6813	3.455
Well-2	702552.1	3572517	1.389	4.356
Well-3	702000.5	3585663	20.885	36.758
Well-4	703741.7	3591337	18.015	20.555
Well-5	710781.6	3585843	11.717	14.705
Well-6	715932.4	3582193	3.232	7.456
Well-7	720347	3586048	17.04	20.775
Well-8	701785.2	3578141	1.788	5.705
Well-9	705699	3542477	10.26	12.26
Well-10	706386.1	3550040	32.19	36.23
Well-11	744784.3	3550890	3.532	7.737
Well-12	735674.3	3554435	22.237	22.941
Well-13	731948.5	3548710	1.863	5.111
Well-14	726156.8	3554219	41.596	61.606
Well-15	732906.1	3561891	4.172	6.762
Well-16	723748.9	3572964	18.727	24.185
Well-17	728151.8	3569303	14.212	25.385

4. Conclusions

The vulnerability maps showed that the DRASTIC model included three categories, the low vulnerability category occupied the largest percentage in the study area by 82.29 %, while the three models (GOD, SINTACS and MD-DRASTIC) that included four categories where the medium vulnerability category included most of the study area by 54.12 %, 82.81 % and 72.35 % respectively. The verification results showed that the Pearson correlation coefficients for (DRASTIC, GOD, SINTACS and MD-DRASTIC) are 73.05, 49.79, 83.23, 87.94 %, respectively. Therefore, the MD-DRASTIC method is the best way to achieve a strong correlation with the real pollution map of the area, so it is recommended.

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