Environmental Resources Research
Vol. 7, No. 2, 2019

GUASNR

Assessing the groundwater vulnerability to pollution using DRASTIC and SINTACS models, case study: Evan Plain, south west of Iran

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Received: February 2019 ; Accepted: September 2019

Abstract

Agricultural and industrial activities have affected the strategies of groundwater quality management during the past decades. Assessment of groundwater vulnerability potential is currently one of the most important devices in water resources management. During recent years, various methods for assessment of vulnerability potential have been developed such as mathematical models, statistical procedures and overlapping and ranking techniques. DRASTIC and SINTACS models are the two most popular overlapping index methods, utilized recently. Vulnerability potential evaluation of groundwater in Evan Plain was implemented applying DRASTIC and SINTACS models. Hydrogeological parameters including aquifer recharge, water table depth, hydraulic properties of the aquifer, surface topography and the soil properties were analyzed, utilizing the geographical Information system (GIS) to evaluate the susceptibility of the study area to groundwater pollution. The major portion of the Evan Plain has low to very low potential in DRASTIC model, whereas SINTACS model shows low to moderate potential of pollution. Sensitivity analysis of the models revealed that the topography parameter has the highest effect in vulnerability potential. Nitrate concentration was as the model calibration index. Nitrate concentration ranged between 8 to 33 mg/l in most parts of the Evan Plain, similar to SINTACS model results.

Keywords: Groundwater, Pollution potential, Evan Plain, DRASTIC model, SINTACS model.

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Introduction

Groundwater is the most important water resource in arid and semi-arid areas like Iran. If groundwater resource is polluted, its remediation will be costly and time consuming; this, often, is recognized when the remediation is almost impossible. Groundwater velocity is too low; however, it is a useful factor in polluted aquifer remediation of organic and radioactive materials or bacteria and virus pollutants. In this situation, the longtime groundwater holding may cause the pollutant removal (Bouwer, 1987).

Almost all groundwater resources are vulnerable in different ranges. Assessment of groundwater vulnerability potential is a key method in water resources management, whereby water resources quality limits can be determined and it will be possible to manage the land usage subsequently (Faryabi et al., 2007). Groundwater vulnerability concept has been developed due to worldwide concern about the groundwater pollution problems. Vulnerability of groundwater is a relative and dimensionless concept and it is not measureable directly (Piscopo, 2001). Basic definition of groundwater vulnerability is that some areas are more sensitive than the others to contamination. One of the most important hypotheses in groundwater vulnerability is that physical environment generates a degree of protection against the contaminants (Akhtari, 2004). It has been revealed that the groundwater vulnerability zoning method, as a good strategy, is very functional in groundwater resources protection. Vulnerability map plotting as a process consists of simplifying of the hydrogeological and geological situations (Ghosh et al., 2015). Vulnerability maps are utilized to minimize the environmental effects of the water resources development plans for the future site selection. The final goal of vulnerability mapping is to categorize a site into various sections with different potential in distinct usage and applications.

During the recent years, lots of assessment methods of groundwater vulnerability potential have been developed, which depend on the extent of the study area, available data, economic conditions and etc. The available vulnerability assessment methods are divided into three general groups: Subjective rating methods, Statistical and process-based methods and Hybrid methods.

Subjective rating methods, classify the aquifer's intrinsic vulnerability or sensitivity, as high, medium and low ranks. DRASTIC and SINTACS methods are two examples of subjective rating methods which use the hydrogeological parameters for the vulnerability potential determination. Rating methods are the most appropriate in groundwater vulnerability assessment due to their low cost, availability of the needed data and easy interpretation of results in addition to their suitability in management decision makings (Focazio et al., 2002).

Statistical and process-based methods survey the physical and chemical reactions, which are effective in contaminant transmission. These methods provide better understanding of groundwater vulnerability. Therefore, the process-based (analytical) methods may be complex but limited in terms of spatial scale, whereas, the statistical methods are proper tools in broad spatial scales. The analytical methods could not cover all deterministic portions needed due to environmental complexity of cause and effect relationships. Quantitative and qualitative numerical models are usually used for this type of evaluations (Harbaugh et al., 2000). Hybrid methods are obtained by combining rating and process-based statistical methods. These methods are classified into two categories, objective and subjective.

Objective hybrid methods include statistical or deterministic method or variables. And provide vulnerability quantitatively and in statistical form. Subjective hybrid methods, on the other hand, can be a conjugation of statistical and analytical methods with subjective variables, which finally describe the aquifer vulnerability. PATRIOT (Imhoff et al., 1993) is an example of this type.

Vulnerability potential of Evan Plain aquifer was evaluated in the present study. The DRASTIC and SINTACS models were applied towards this aim. This study aims to compare the suitability of DRASTIC and SINTACS models for assessment of groundwater vulnerability to pollution in a semi-arid region, southwest of Iran.

Materials and methods

Study area

Evan Plain with an area of about 195.3 km^2 is located at the northwest of Khuzestan Province (140 km from Ahvaz City). It is a portion of folded Zagros sedimentary-structural basin. From the stratigraphy viewpoint, the most important sedimentary units relate to the Bakhtiyari and Lahbari formations. These formations are the main factors affecting the groundwater quality and quantity of the study area. Bakhtiyari formation consists mainly of conglomerate with lime cement. This formation doesn't have great stability and have lost its lime cement over time due to water leaching and has filled consequently a smooth syncline as an alluvium. Lahbari formation also consists of marl, siltstone and mudstone. Evan syncline, as part of Dezful great syncline, has filled out by Bakhtiyari conglomerate and Lahbari member erosion. In Evan Plain, the particle size decreases from the north and northwest to south and southeast. Coarse particles and fine grains have been originated from Bakhtiyari formation and Lahbari member erosion respectively. The most important parameters of erosion are found in great Karkheh River, seasonal Rofaeieh River and streams. In vertical direction, also, the particle size ranges from the fine and medium to coarse, then turns fine and eventually ends to a dense clay layer. Evan Plain aquifer, is located in the middle coarse graded layer.

Karkheh as the only permanent river crosses Evan Plain and has a significant role in water demand provision. Its high quality leads to high water consumption for diverse usages with the main usage being agriculture. Water extraction via pumping wells has been reduced since 2000, due to over extraction of surface water, namely the Karkheh River. The groundwater table has had a stable situation with booming trend. Owing to the abovementioned reasons, the groundwater contamination possibility has increased consequently. Aquifer recharge via the juxtaposed formations in the north and west of the plain in addition to topography are the main controlling factors of groundwater flow direction which is from northwest to southeast. In eastern parts of the plain and the adjacent Karkheh, the local direction of the groundwater is from the north to the south, considering slope and recharging role of the Karkheh River (Figure 1).

Study method

DRASTIC and SINTACS models

DRASTIC model has been developed by the US Environmental Protection Agency (USEPA) for the evaluation of groundwater vulnerability potential (Aller et al., 1987). SINTACS model, also, was applied for the first time for vulnerability assessment in south of Italy (Sappa and Vitale, 2004). These models are based on hydrogeological situation concept. Hydrogeological situation describes a combination of all geological and hydrological parameters that affect and control the water movement at input, inside and output of the aquifer (Chitsazan and Akhtari, 2009). Seven parameters are considered in these models for the assessment of groundwater contamination potential (Table 1). Utilized parameters in these two models are the same (Aboulouafa et al., 2017), but the weighting and rating of the parameters are different. Each parameter is assessed compared to the other parameters, and the relative importance of each parameter is defined and each parameter obtains a relative weight, ranging from 1 to 5 (Kumari et al., 2016). The most important parameter gains 5 and the least important gains 1. Each parameter in these models is divided into intervals with effects on contamination potential. A range of scores from 1 to 10 is also assigned to the intervals. Scores and their distribution are determined based on field experiments (Sappa and Vitale, 2004). Table 1 shows the parameters used in DRASTIC and SINTACS models. Eventually, the vulnerability index is calculated via Equation 1 as follows:

$$I_v = \sum P_{(1.7)} \times W_{(1.n)} \qquad (1)$$

where I_v is the vulnerability index, $P_{(1.7)}$ is the rank of each parameter, $W_{(1.n)}$ is the parameters weight and n is the weight classes. Groundwater contamination potential was divided into 8 ranges, since the minimum and maximum of the vulnerability index is 23 and 230 respectively (Table 2).

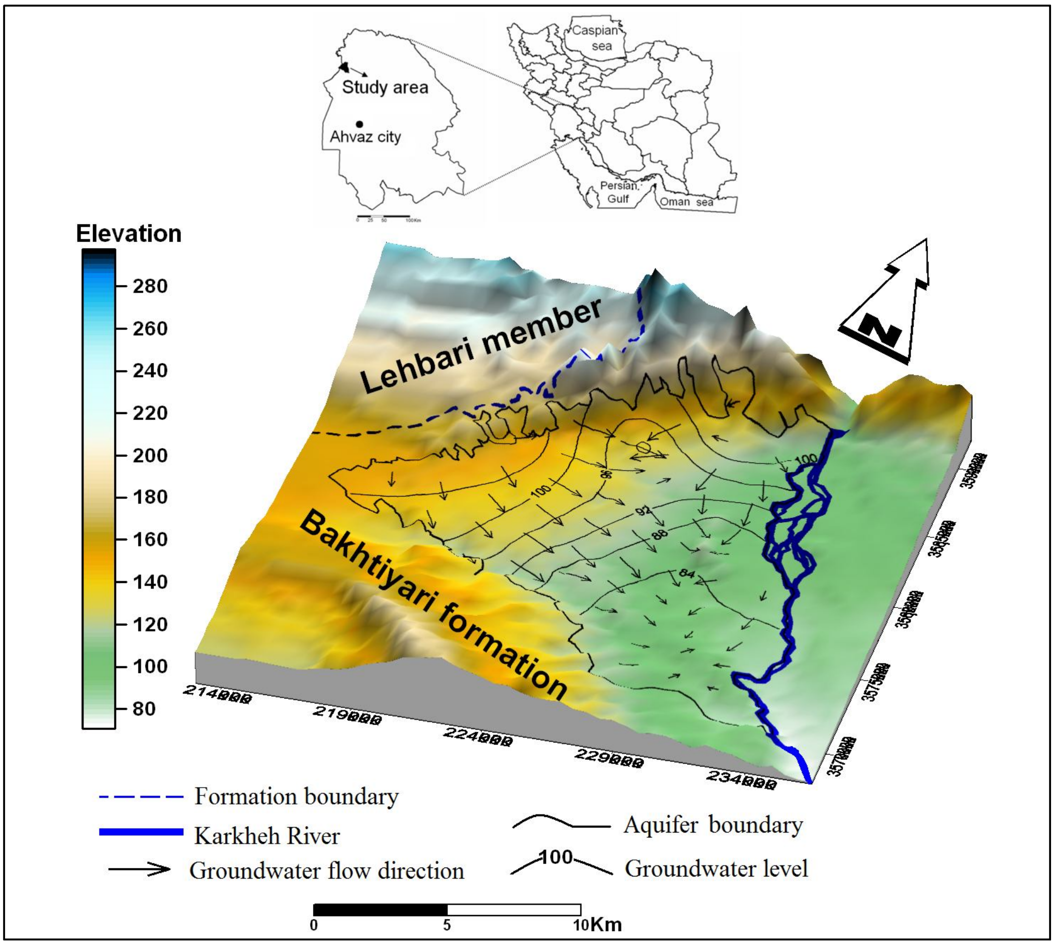


Figure 1. Location and 3D map of the study area

Table 1. Utilized parameters in assessment of vulnerability potential in DRASTIC and SINTACS models

Parameter	Description	Symbol in Model	
		DRASTIC	SINTACS
Depth to water table	Distance between the ground surface and water table	D	S
Recharge	Amount of recharge from surface to groundwater	R	I
Aquifer media	Properties and kind of sediments in saturated zone	A	A
Soil media	Properties of the superficial soil	S	T
Topography	Ground surface slope	T	S
Unsaturated media	Properties of sediments in unsaturated zone	I	N
Aquifer hydraulic conductivity	Aquifer ability in passing the water	C	C

Table 2. The vulnerability potential based on vulnerability index (Yarmohammadi, 2007)

Vulnerability potential	Vulnerability index	Vulnerability potential	Vulnerability index
Negligible	< 63	Moderate to high	120-139
Very Low	63 -79	High	140-159
Low	80-99	Very High	160-179
Moderate	100-119	Extremely vulnerable	> 180

Models development

The DRASTIC and SINTACS parameters were provided as layers in GIS media. The procedures for the preparation of the layers are discussed below.

For providing the depth to water table, data of the monitoring wells were used and average depth of water table was calculated for a 10 year period. Then, the depth to the water table layer was provided, considering the related ranks (Figure 2a and Figure 3a). The net recharge layer was provided using the Piscopo procedure (Piscopo 2001). In the Piscopo method, the net recharge rates are obtained using the three common parameters: topographic slope, precipitation amount and soil permeability. The slope of the study area was extracted using the Digital Elevation Model (DEM). Slope, soil and precipitation maps were overlapped, and the net recharge was calculated using Equation 2. Figures 2b and 3b show the net recharge layers. Maximum recharge belongs to adjacent areas to Bakhtiyari formation in the north of the study area.

Recharge = slope percent + precipitation amount + Soil permeability (2)

Geologic well logs were used to provide the aquifer media layer. Generally, the aquifer consists of sand sediments with different portions of silt and clay. Considering the rank of DRASTIC and SINTACS models, the aquifer environment layer was generated (Figure 2c and 3e). The soil layer is shown in Figures 2d and 3d. This layer has been extracted using the soil map of the Evan Plain. The topography layer was also provided by DEM and the slope map was obtained using DEM (Figure 2e and 3g). The surface slope is less than 3% in a vast part of the study area. The unsaturated environment layer (Figures 2f and 3c) was extracted via geologic logs of the abstraction and monitoring wells. The unsaturated zone in the northern margin generally consists of coarse gravel and sand sediments. In the south of the study area, the unsaturated layer consists of clay and silty-clay. The hydraulic conductivity layer was extracted using the pumping test results and isothickness map of the aquifer (Figure 2g and 3f). Hydraulic conductivity in Evan Plain ranges from 2 to 12 m/day. The maximum hydraulic conductivity is found in Bakhtiyari formation margin in the north of the study area.

Models validation

GIS ability was used for assessment of DRASTIC and SINTACS parameters. Each parameter was provided as a layer in GIS and the final vulnerability map obtained via combination of the layers. The sensitivity analysis was implemented using map removal suggested by Lodwick et al. (1990) and single parameter analysis introduced by Napolitano and Fabri (1996). Nitrate concentration of abstraction wells was utilized for the models calibration.

The map removal method evaluates the model sensitivity via deletion of one or more map layers. For this, each layer was removed from calculations and variability index was measured. In this way, the most effective parameter on groundwater contamination potential, could be obtained. The equation for this method is as belows (Lodwick et al., 1990):

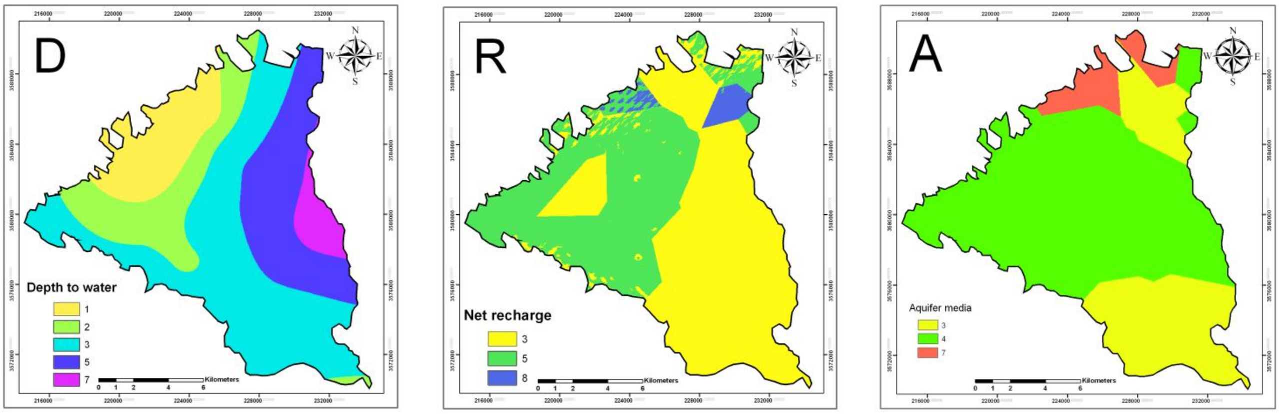
$$S = (| V/N - V'/n | / N) \times 100 \qquad (3)$$

where S shows the sensitivity value or variability index. V and V′ are undisturbed and disturbed indices respectively. N and n are the number of used layers in V and V′ calculation respectively. Real vulnerability index, obtained by overall parameters, is considered as undisturbed vulnerability, while the calculated vulnerability with lesser layers is considered as the disturbed vulnerability index.

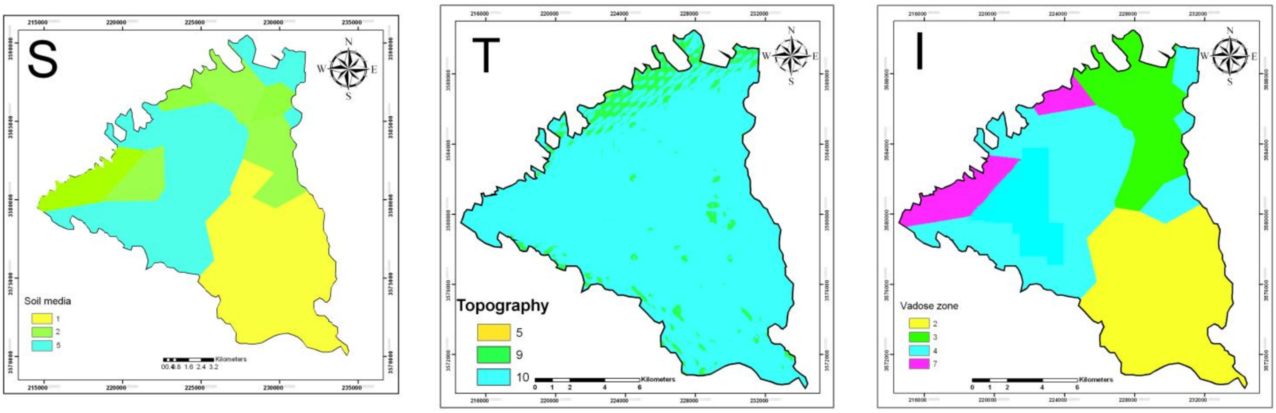
In the single parameter sensitivity analysis, the effective weight or real weight of each parameter in every pixel is compared to the theoretic weight of that parameter. The effective weight in every pixel is calculated using Equation 4 as follows (Napolitano and Fabri, 1996):

$$W = \left(P_r P_w / V\right) \times 100 \qquad (4)$$

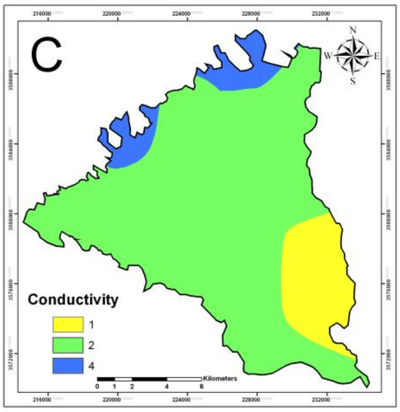
where W is the effective weight of each parameter, P_r and P_w are rate and weight of each parameter respectively and V is the final vulnerability index.



a. Depth to water b. Net recharge c. Aquifer media

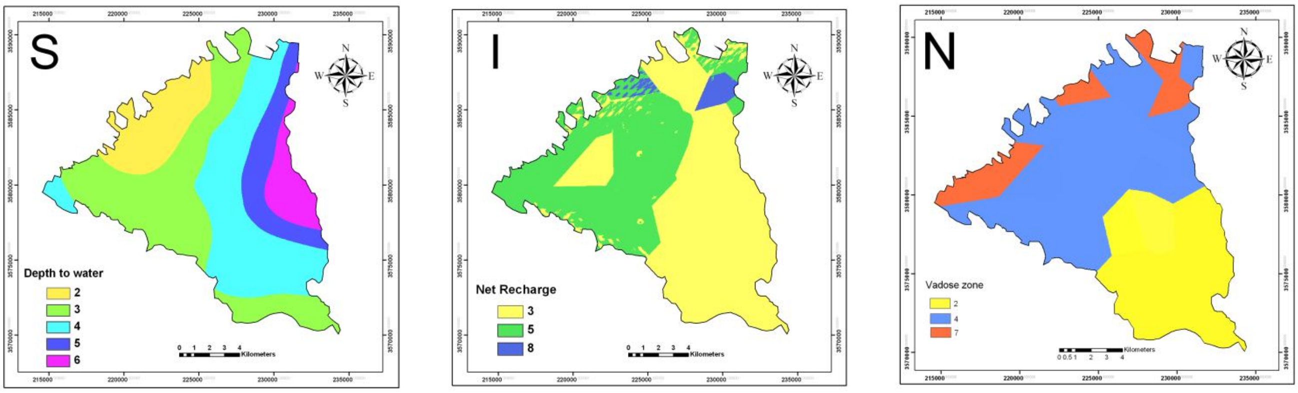


d. Soil media e. Topography f. Unsaturated zone

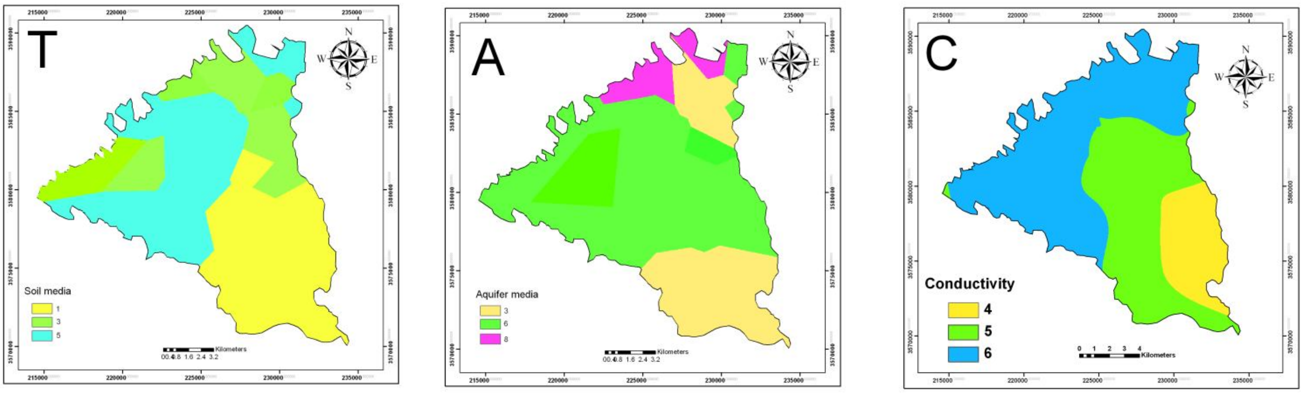


g. Hydraulic conductivity

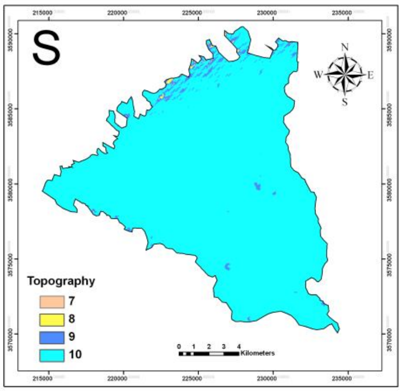
Figure 2. Used parameters in DRASTIC model



a. Depth to water b. Net recharge c. Unsaturated zone



d. Soil media e. Aquifer media f. Hydraulic conductivity



g. Topography

Figure 3. The parameters used in SINTACS model

Results and discussion

Aquifer vulnerability potential

The Evan Plain vulnerability potential maps (Figure 4 and 5) were generated via combination of the spatial layers of DRASTIC and SINTACS models and rated based on Table 2. The DRASTIC model results show the very low to low vulnerability potential in vast parts of the Evan Plain, whereas the SINTACS model results revealed that a wide part of the study area has low to moderate vulnerability potential. Generally, the SINTACS model shows more vulnerability potential than the DRASTIC model.

Models sensitivity analysis

Sensitivity analysis of a model to different parameters is one of the key steps in every modeling. In the process, the most effective parameters on a natural system changes are determined. The utilized parameters in DRASTIC and SINTACS models were investigated statistically in Tables 3 and 4.

Topography showed the highest score among the parameters, most impacting groundwater vulnerability to pollution.

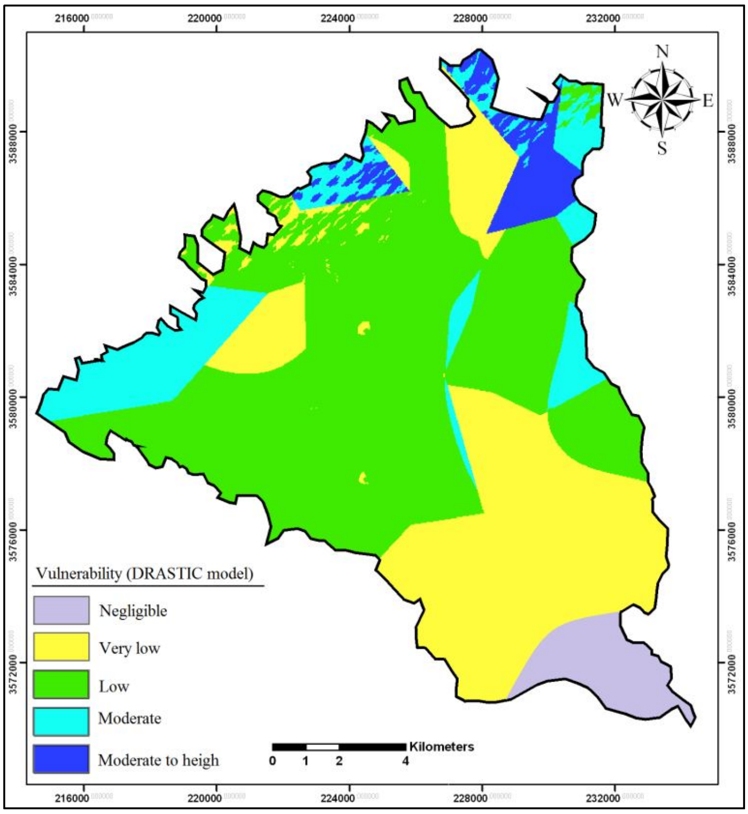


Figure 4. Final map of vulnerability potential (DRASTIC model)

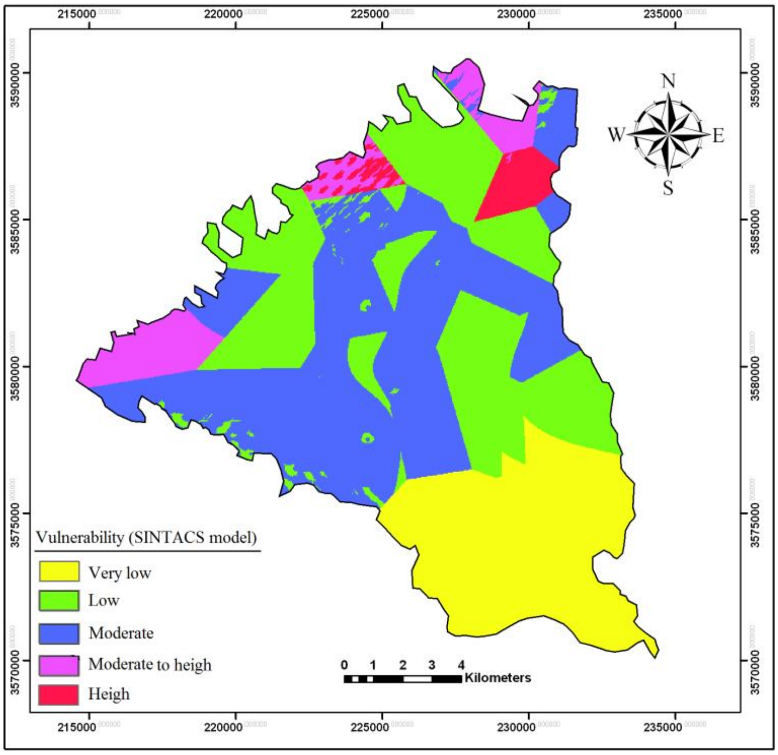


Figure 5. Final map of vulnerability potential (SINTACS model)

Table 3. Statistical summary of DRASTIC model parameters

	D	R	A	S	T	I	C	DRASTIC
Min	1	3	3	1	5	2	1	59
Max	4	8	8	8	10	8	7	138
Mean	2.02	3.97	4.36	2.49	9.93	3.70	3.14	84.13
SD	0.64	1.20	1.51	1.70	0.28	1.67	1.51	15.95

Table 4. Statistical summary of SINTACS model parameters

	S	I	N	T	A	C	S	SINTACS
Min	2	3	1	1	3	4	7	64
Max	6	8	8	9	8	6	10	152
Mean	3.60	3.97	3.44	2.59	4.42	5.36	9.98	95.61
SD	1.08	1.20	1.93	1.96	1.56	0.72	0.16	18.54

Results of the map removal method are shown in Table 5. As can be seen in this table, the most important effective parameter on DRASTIC vulnerability index is the soil media, with about 16.25 %. Vulnerability index also shows high sensitivity to depth of water table, hydraulic conductivity and unsaturated media parameters. This high sensitivity can be originated from the high assigned ranks. Topography has been selected as the most significant effective parameter, based on SINTACS model results (table 5), with average changing index equal to 60.72%. Due to the assumptions of DRASTIC and SINTACS models, the lower slope cause more contaminant persistence and gives them more opportunity to penetrate to groundwater consequently.

Table 5. Results of DRASTIC and SINTACS sensitivity analysis using map removal method

Removed parameter	Variability Index (DRASTIC model)			Variability Index (SINTACS model)		
	Average	Max	Min	Average	Max	Min
Depth to water table	14.51	57	4	15.46	42	5
Net recharge	11.04	28	2	7.12	28	2
Aquifer media	5.1	42	1	40.39	90	9
Soil media	16.25	29	5	20.07	29	8
Topography	5.58	29	1	60.72	90	7
Unsaturated media	14.93	57	4	16.43	57	6
Hydraulic conductivity	12.58	43	1	8.41	28	2

Tables 6 and 7 show results of the single parameter method. Investigation of Tables 6 and 7 revealed that the effective and theoretic weights are not similar and have substantial difference in some cases. The largest difference of effective and theoretic weights belongs to topography. It was revealed that topography has more effectiveness than assumed in both models. In DRASTIC model, the effective weight of net recharge and aquifer media is more than the theoretic one (table 6) which shows their importance in assessment of the aquifer vulnerability potential. Topography, aquifer media and hydraulic conductivity have more importance in vulnerability potential of the study area, due to single parameter sensitivity analysis of SINTACS model (table 7). They have more effective weights than theoretic weights while the unsaturated media, net recharge and water table depth have less effective weights than the theoretic assumed weights.

Table 6. Results of single parameter sensitivity analysis of DRASTIC model

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (%)			
			Mean	Max	Min	S.D
D	5	21.74	18.76	42	3	9.43
R	4	17.39	18.26	25	9	3.81
A	3	13.04	15.23	33	6	4.70
S	2	8.70	5.11	14	1	2.72
T	1	4.35	11.71	16	4	2.2
I	5	21.74	20.65	36	11	5.98
C	3	13.04	6.79	17	3	2.34

Table 7. Results of single parameter sensitivity analysis of SINTACS model

Parameter	Theoretical weight	Theoretical weight (%)	Effective weight (%)			
			Mean	Max	Min	S.D
S	5	21.74	19.30	36	6	7.50
I	4	17.39	16.01	21	9	2.99
N	5	21.74	16.34	29	5	6.99
T	2	8.70	4.37	13	1	2.75
A	3	13.04	13.32	26	5	3.99
C	3	13.04	16.67	25	11	2.55
S	1	4.35	10.28	15	5	2.15

Models Calibration

The most important contamination source in Evan Plain comes from the chemical fertilizers, used in agriculture that is why we expected that the major contaminant in groundwater to be nitrate, originated from fertilizer's leaching. Nitrate, therefore, was selected as groundwater pollution index in the present study. Bebiker et al. (2004) and Bebiker et al. (2005) have determined the groundwater contamination degree based on nitrate concentration (Table 8). Nitrate concentration was measured in some wells of the study area to determine the contamination degree of groundwater in Evan Plain. Results showed that Nitrate concentration ranges from 5 to 40 mg/lit. Figure 6 shows the nitrate concentration distribution in the study area. A great portion of the Evan Plain has low to moderate degree of contamination, considering the Bebiker et al. suggested contamination degree (Figure 6).

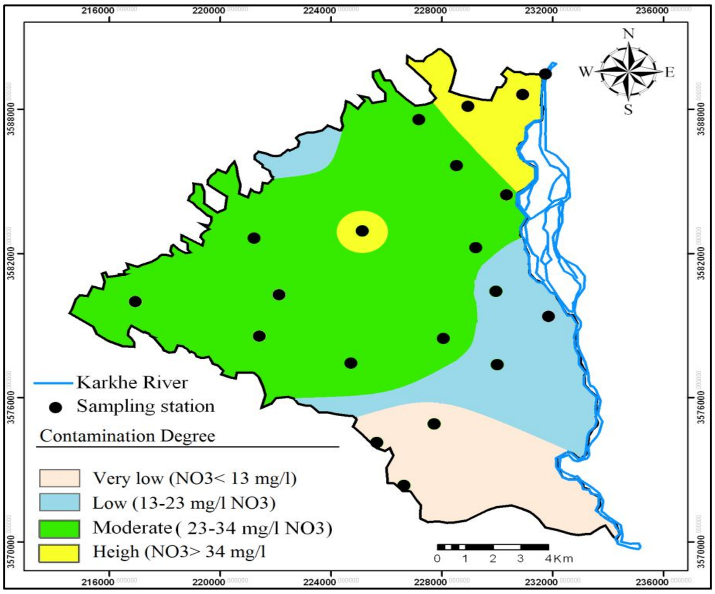


Figure 6. Groundwater contamination degree based on nitrate concentration

Table 8. Determination of the groundwater contamination degree, considering the nitrate concentration (Bebiker et al., 2004)

Contamination degree	Nitrate (mg /l)
Very low	< 13
Low	13- 23
Moderate	23 - 33
High	33 - 44
Very high	> 44

Conclusion

DRASTIC and SINTACS models have been used in the present study for assessment of Evan Plain groundwater vulnerability potential. Geographical information system (GIS) was utilized for analyzing different parameters of the models. Different parameters, used in DRASTIC and SINTACS models, were provided as separated data layers. Combination of the layers generated the final map of vulnerability potential. Sensitivity analysis and calibration were also done in GIS environment.

DRASTIC model results showed very low to low contamination potential for a vast area in Evan Plain, while contamination potential was low to moderate in SINTACS model. Statistical analysis of parameters, applied in DRASTIC and SINTACS models, revealed that the topography has the highest score among the parameters and has, thus, more effect on groundwater vulnerability potential. Sensitivity analysis through map removal showed that soil media is the most effective parameter in vulnerability potential of DRASTIC model, whereas the most effective parameter in SINTACS model was found to be topography. Results of single parameter sensitivity analysis depicted that the highest difference between effective and theoretic weights in both models belongs to topography. This reveals the higher effect of topography on vulnerability potential. Generally, the topography parameter revealed to be the most important and effective parameter in Evan Plain groundwater vulnerability potential. Nitrate concentration in groundwater was utilized for calibration. Groundwater nitrate concentration in the vast part of the study area ranged from 8 to 33 mg/lit which shows a low to moderate range of contamination. This case has more conformity to SINTACS model results. SINTACS model, however, is more functional than DRASTIC in groundwater vulnerability potential assessment, considering the study results.

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