Shahid Chamran University of Ahvaz

Irrigation Sciences and Engineering (JISE)
Vol. 45, No. 2, Summer 2022, p. 19-29

Original Paper

Journal homepage: https://jise.scu.ac.ir

A GIS-Based DRASTIC Model For Assessing Aquifer Vulnerability

S. Anvari[1*] and M. Rezakhani Nejad[2]

1- Corresponding Author, Assistant Professor, Department of Ecology, Institute of Science and High Technology and Environmental Science, Graduate University of Advanced Technology, Kerman, Iran. (s.anvari@kgut.ac.ir).*
2- MSc graduate in Civil Engineering, majoring in water and hydraulic structures.

ARTICLE INFO

Artlcle history:
Received: 14 June 2022
Revised: 18 August 2022
Accepted: 20 August 2022

Keywords:
Vulnerability, Underground Water, DRASTIC Model, GIS, Sirjan Plain.

TO CITE THIS ARTICLE:

Anvari, S., Rezakhani Nejad, M. (2022). 'Vulnerability, Underground Water, DRASTIC Model, GIS, Sirjan Plain.', Irrigation Sciences and Engineering, 45(2), pp. 19-29.

Abstract
Due to the increasing demand for water resources in agricultural, domestic, and industrial sectors, the quality of groundwater resources in Iran is at risk. This is more sensitive for the arid and semi-arid regions of the country where the main supply of water is from groundwater resources. The aim of this study was to investigate the vulnerability of the groundwater aquifer of Sirjan Plain (Kerman province). For this purpose, the DRASTIC model was employed, while the Geographical Information System (GIS) software was used to draw the vulnerability map. In the DRASTIC model, the effective characteristics in assessing the vulnerability of groundwater aquifers including water table depth, net recharge, aquifer type, soil type, topographic slope, the media forming the vadose zone, and hydraulic conductivity were used. They were prepared in seven layers in the ArcMap software and by weighing, ranking, and combining these layers, the final vulnerability map of Sirjan Plain with respect to contamination was produced. The results showed that the DRASTIC index for the mentioned plain was between 69 and 141 and that the southern parts of this plain were more susceptible to contamination. Moreover, the investigation of the nitrate ion on the final DRASTIC map showed that all the points with high nitrate content were in the highly contaminated zone. This can confirm the accuracy of the model.

Introduction
The increasing demand for water resources has led to the development of industrial estates and expansion of agricultural lands so that the agricultural sector is the largest consumer of water (consuming 90% of the country's water supply) as well as the most vulnerable sector in low water conditions (Dixon, 2005; Anvari et al. 2017; Anvari et al., 2019, Ranjbar et al., 2021). Statistics show that the growing demand for water resources has increased water withdrawal and put stress on surface and groundwater resources so that water withdrawal from the country's groundwater resources during the water years 1972-1973 and 2008-2009 has had an increasing trend (Synthesis report on Updating Water Master Plan of Iran Deputy of Water and Wastewater Ministry of Energy, 2017)

The trend of increased withdrawal from groundwater resources throughout the country has also existed in Kerman province and its aquifers so that the number of wells drilled in the province and consequently the amount of withdrawal from its groundwater resources from 1971 to 2013 has had a growing trend. The contamination of these water resources by chemical fertilizers as well as municipal and industrial wastes has deteriorated their quality. Consequently, knowledge of the quantitative and qualitative vulnerability of the groundwater aquifer and especially the identification of the vulnerable points have an important role in managing and planning the exploitation of the aquifer and also in preventing the ongoing process of its destruction.

One of the techniques for determining the vulnerability of groundwater resources is the DRASTIC method which is an experimental model that estimates the vulnerability of the aquifer based on the hydrogeological data of the study area (Aller, 1985; Vrba and Zaporozec, 1994; Voudouris et al., 2010; Asefi et al., 2014). Numerous studies have been conducted throughout the world to assess the groundwater contamination potential. For example, in their paper, Khodaei et al. (2006) evaluated the vulnerability of Jovin Plain aquifer using DRASTIC and GODS methods. The comparison of these two methods indicated that the DRASTIC method estimated less vulnerability for the aquifer than the GODS method (Khodaei et al., 2006). In another study, with the aim of assessing the vulnerability of the aquifer of Borujen-Faradonbeh Plain, Afroozi and Mohammadzadeh (2013) employed the DRASTIC model and used nitrate values to validate the results. The results of this study showed that the correlation coefficient between the concentration of nitrate in groundwater and the vulnerability index after modification increased from 47% to 80% (Afroozi and Mohammadzadeh, 2013).

Various studies have also been conducted outside Iran to assess the vulnerability of groundwater resources. For instance, Thirumalaivasan et al. (2003) used the DRASTIC model to assess the aquifer vulnerability of the Palar Basin in India. They used land use and satellite images to prepare the vadose zone and soil media maps. Babiker et al. (2005) used the DRASTIC model to determine the points susceptible to contamination in the Kakamigahara aquifer in Japan. Their results demonstrated that the western part of the aquifer had a high vulnerability and the eastern part had a moderate vulnerability. Ashokraj et al. (2015) employed the SINTACS model which is based on the use of remote sensing (RS) and GIS techniques to prepare the groundwater vulnerability map in the Palayamkottai region in India. Similar to the DRASTIC model, this model is obtained from the combination of seven hydrological and geological variables. It is slightly different from the DRASTIC model only in the weighting of the variables. The results showed that vulnerability in the study area was in both low and medium classes. Using the DRASTIC model, Colins et al. (2016) examined the vulnerability of Kodaganar Basin and showed that the vulnerability values in the study area were in the range of 31 to 154.

Due to the importance of groundwater resources in Sirjan Plain which are used for various purposes such as drinking, agriculture, and industry, studying the aquifer vulnerability of this plain is essential. Moreover, the extensive pistachio orchards as well as using chemical pesticides in this region made us the motivation to identify the areas with nitrate contamination. Therefore, the present study attempts to detect the areas of the aquifer that are at risk of contamination. Finally, the results from the vulnerability maps will be evaluated based on the nitrate levels in the piezometric wells in the region.

Materials and methods

The study area

The study area which is located in Sirjan (code: 4419) is considered as a sub-basin of the Abargho-Sirjan Desert and has an area of 7942.9 km^2. This area is located in the west of Kerman province and lies between 54° and 57' to 56° and 26' Eastern longitude and 28° and 47' to 29° and 58' Northern latitude. The area of its plain area is 3742.7 km^2 and the heights overlooking it are 4200.2 km^2. Figure (1) shows the geographical location of Sirjan Plain in Kerman province and Iran. The alluvial aquifer in this plain is of the free type. In this study area, there are 22 rain-gauge stations (under the supervision of the Ministry of Energy and the Meteorological Organization), two evaporation stations, and one synoptic station.

 Vol. 45, No. 2, 2022, pp. 19-29

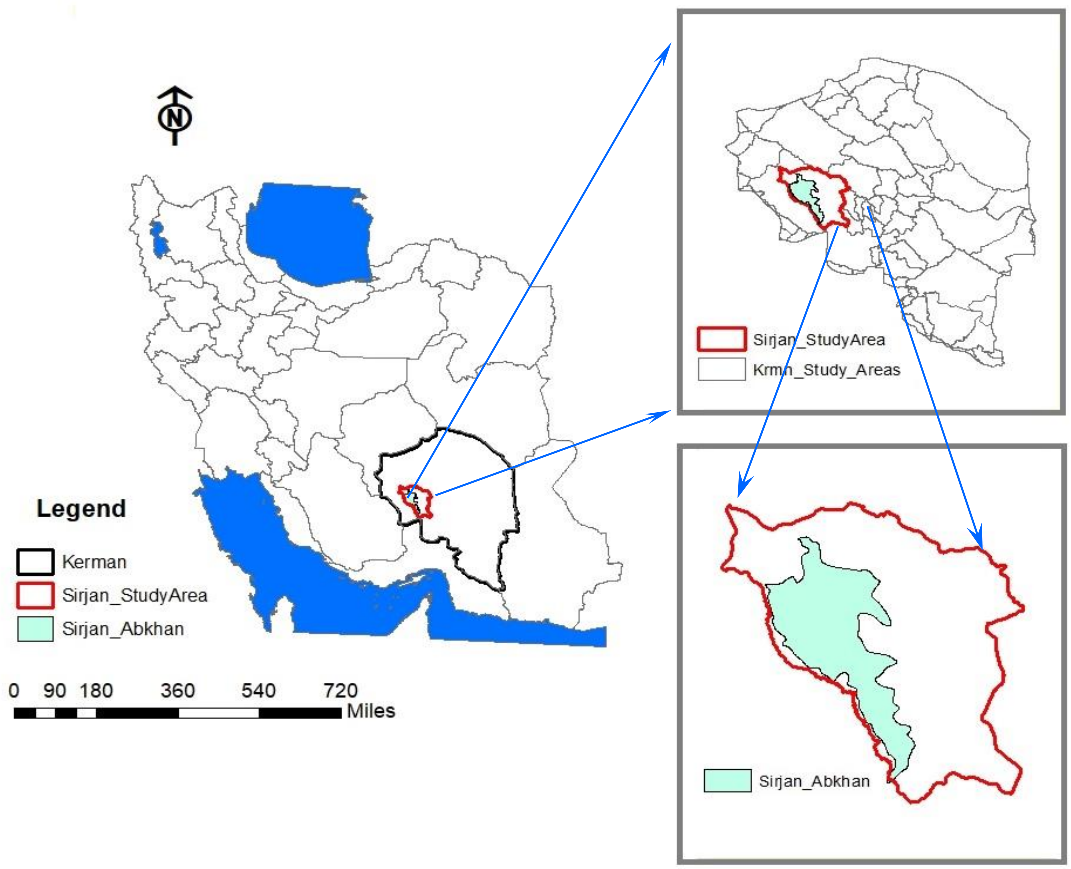


Fig. 1- The geographical location of Sirjan Plain in Kerman province

Table 1- Monthly distribution of temperature (°C) and rainfall (mm) in heights and plain of Sirjan

Climate variable	Location	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Annual
Temperature (°C)	Heights	16.5	10.9	5.7	3	3.5	7	11.6	16.9	21.8	24.8	24.3	21.3	13.9
	Plains	18.7	13.2	7.9	5.2	5.7	9.2	13.8	19.2	24	27.1	26.5	23.6	16.2
Rainfall (mm)	Heights	8.8	20.8	26.8	31.7	33.9	32.5	38.8	19.0	4.5	2.6	3.0	0.1	222.5
	Plains	0.5	5.3	21.4	28.1	29.6	28.6	22.8	9.5	0.3	1.7	2.0	0.1	150.0

The population of Sirjan Plain and its environs is approximately 240000 (Management and Planning Organization of Kerman, 2006) and the economy of this region is mainly based on agricultural activities. About 98% of the water withdrawn from the groundwater aquifer in this region is used for agricultural activities especially for growing pistachio gardens (Regional Water Company of Kerman, 2008). According to the annual isothermal temperature curves, the annual temperatures of the heights and plain in the study area are 13.9 °C and 16.2 °C, respectively. In addition, using isopluvial curves, the annual rainfall in the heights and plain in this area were obtained as 222.5 and 150 mm, respectively (Table 1).

The groundwater resources in the study area include 1086 wells and 93 qanats with an annual discharge of 347.09 and 32.26 million cubic meters, respectively. Table (2) presents the number of wells and the amount of groundwater withdrawal (in million cubic meters) from the plain, heights, and alluvial aquifer in the study area (Specialized water reports of Kerman regions, 2014).

Table 2- The status of the groundwater resources in Sirjan study area (MCM)

Source Type	Plains		Heights		The sum of the study area		Alluvial aquifer	
	Number	groundwater withdrawal	Number	groundwater withdrawal	Number	groundwater withdrawal	Number	groundwater withdrawal
Well	1071	346.11	15	0.98	1086	347.09	1062	343.26
Spring	-	-	-	-	-	-	-	-
Qanat	58	27.1493424	35	5.1119856	93	32.26	38	23.49
Total	1129	373.26	50	6.09	1179	379.35	1100	366.75

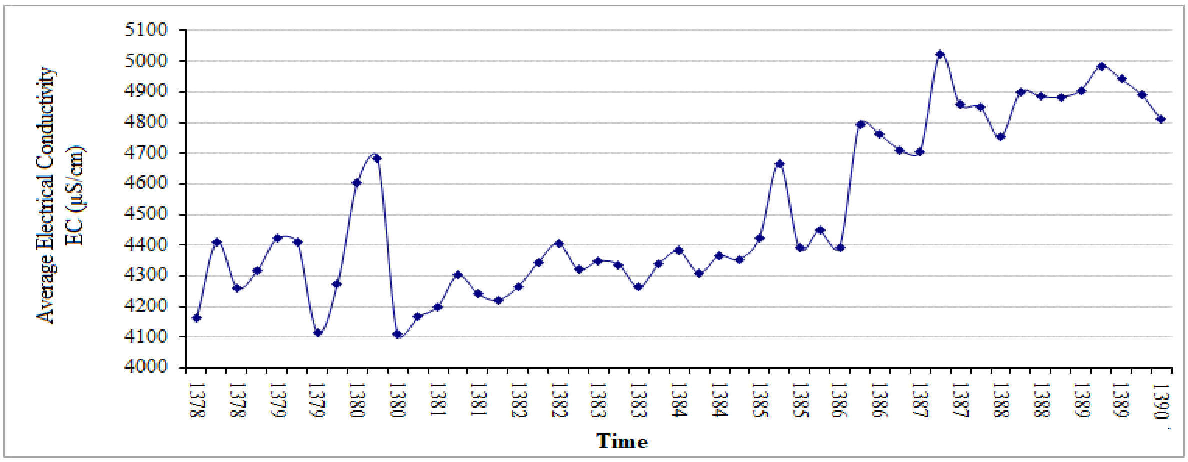


Fig. 2- The increasing trend of salinity in Sirjan aquifer between 1999 and 2011

Increased water withdrawal from Sirjan aquifer in recent years has reduced its level of groundwater resources. The statistics and data in this field show that in terms of quantity, the water table of this aquifer has always been declining from the statistical period of 1987 onwards. This means that the amount of water reservoir in the aquifer of Sirjan Plain has decreased. In addition, the comograph of this aquifer has had an upward trend during the statistical period and the average salinity of groundwater in the plain has increased from 4161 µm/cm in 1999 to 4812 µm/cm in 2011. This indicates the salinization of groundwater in this plain (Figure 2).

Evaluating the aquifer vulnerability using the DRASTIC method

The most common technique for assessing intrinsic aquifer vulnerability is the DRASTIC method proposed by the National Groundwater Association in collaboration with the United States Environmental Protection Agency (Aller et al., 1987). In this method, seven factors or measurable characteristics are estimated for the hydrogeological system. These factors include groundwater depth (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I), and aquifer hydraulic conductivity (C) (Babiker et al, 2005). In this method, the vulnerability index is obtained from the sum of the product of the weight and rank of the seven mentioned parameters according to Equation (1). Higher values of the DRASTIC index indicate a higher risk of contamination in the region.

$$\text{DRASTIC Index} = \sum_{j=1}^{7} rjwj = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \quad (1)$$

In the above equation, DI is the DRASTIC index, D, R, A, S, T, I, and C are the seven above-mentioned parameters, r is the rank, and w is the weight assigned to each parameter.
It is noteworthy that the DRASTIC index is a tool for the relative assessment of the status of

the aquifer. The coefficients of this index can vary according to the characteristics of the study area. These factors are estimated numerically so that a value from 1 to 9 (1 signifies the lowest and 9 represents the highest risk for groundwater contamination) is assigned to each of them, depending on its contamination potential. According to its relative importance in its ability to transfer contamination to the groundwater system, each of these characteristics is multiplied by the weight coefficient and is quantified based on the quality criteria (1 to 5) and the judgment of an expert (Babiker et al., 2005; Panagopoulos et al., 2006). In order to prepare a vulnerability zoning map of an aquifer using the DRASTIC model, the required data are first collected and analyzed. After preparing the raster maps of the DRASTIC parameters in the GIS environment, using the raster calculator feature of this software, different layers were combined and the vulnerability zoning map was prepared.

Results and discussion

Preparing the map of each DRASTIC parameter

The groundwater depth (D): Since the water table depth has a significant effect on the contamination potential of an aquifer, the weight of 5 (the highest weight) is assigned to this factor. In order to prepare the groundwater depth layer, the water level statistics in the plain piezometers are used. Next, the interpolation of the water level data in the ArcMap environment is done using the Kriging method and the amount of water level in each piezometer (Figure 3-a). The interpolated layer is of the raster type and the weighting is based on the model designed by Aller (1985) and Aller et al. (1987) (Table 3).

The net recharge layer (R): Two main parameters, namely, isopluvial network and surface permeability map which depends on the soil type are necessary to prepare the specific annual recharge layer. Given that the permeability coefficient of rainfall is a function of the soil and slope of the land, each polygon of the land use map was given a specific coefficient using the standard table. Then, to analyze the resulting information, the map was converted to a raster (Figure 3-b). In the final step, by multiplying these two layers, the recharge layer was prepared (Table 4).

Table 3- Ranking the groundwater depth

Groundwater Depth (m)	Ranking
≤ 30	9
31-50	7
51-70	5
71-90	3
> 90	1

Table 4- Ranking the net recharge

Net Recharge (cm/year)	Ranking
0-3	1
3-5	3
5-7	5
7-9	7
> 9	9

The aquifer media (A):

The information about the aquifer environment in Sirjan Plain is obtained by drilling, geophysical, and geological investigations of the region. In Sirjan Plain, based on the exploration studies as well as the DRASTIC method, the characteristics of the aquifer environment have been ranked. According to the results, the rank of 5 for sandstone with shale and clay and the rank of 7 for sand and gravel were considered based on the type of aquifer.

Soil media (S):

This part is the top part of the unsaturated area (vadose) which extends to the root penetration of plants or the activity of organic creatures. The soil contamination potential depends on the properties of the soil such as texture, permeability, and percentage of soil organic matter. To produce this layer, the information about the soil type in the study area was used. Then, depending on the region type, a numerical value between 1 and 9 was allocated to each location and the soil type map was prepared (Figure 3-c).

The topography layer (T):

In general, gentler slopes make it easier for contaminants to infiltrate with rainfall. Therefore, they provide a greater potential for contamination. As a result, in the DRASTIC model, areas with lower slopes have a higher rank. Topography has an important role in the development and evolution of soil so that the thickness of the topsoil layer is less in steep slopes than in gentler slopes. Hence, topography affects the contamination potential also by affecting soil development. To prepare the topography layer, the DEM map was prepared from the digitized topographic map. Afterward, the slope of the area was obtained in percentage (Figure 3-d).

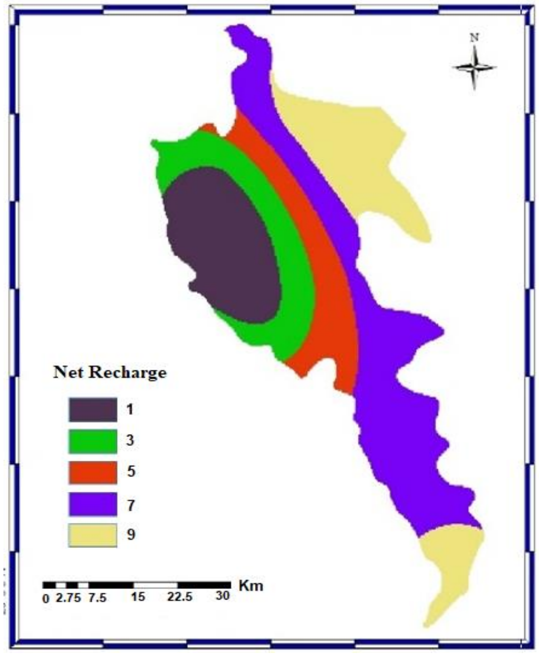
Impact of the vadose zone (I):

This layer is located between the soil layer and the aquifer water table. Like the soil layer, the vadose layer affects the contamination potential and its effects are a function of permeability and the properties of the vadose zone. The method for gathering information about the vadose zone is the same as that of the aquifer environment except that, in this case, the gradation and characteristics of the sediments between the groundwater surface and the surface of the earth are taken into account. The rank of the vadose zone for silt or clay, clay, and silt classes with a small amount of fine grain, limestone, and sandstone was considered to be 1, 3, 5, and 9, respectively (Figure 4-a).

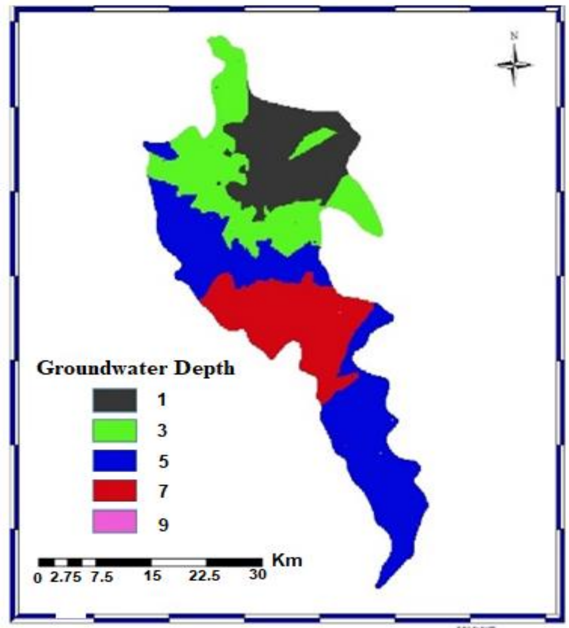
The hydraulic conductivity layer (C):

The information about hydraulic conductivity is obtained from pumping test analysis. In areas where the pumping test has not been performed, the type and texture of the sediments forming the hydraulic aquifer are estimated based on the sample values and similar structures. The hydraulic conductivity map was extracted from the results of the mathematical model of the groundwater in Sirjan Plain (Figure 4-b).

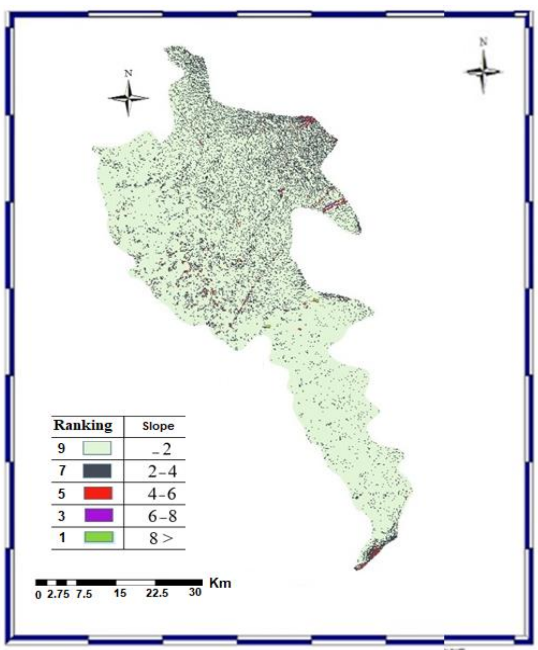
Vol. 45, No. 2, 2022, pp. 19-29



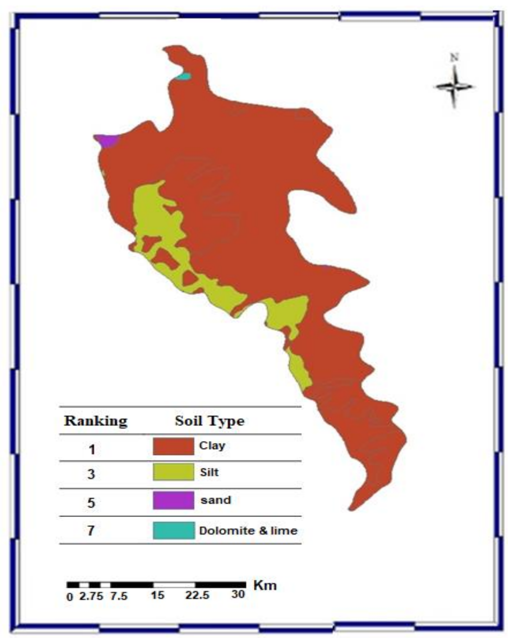
b) Ranking the net recharge



a) Ranking the water table depth



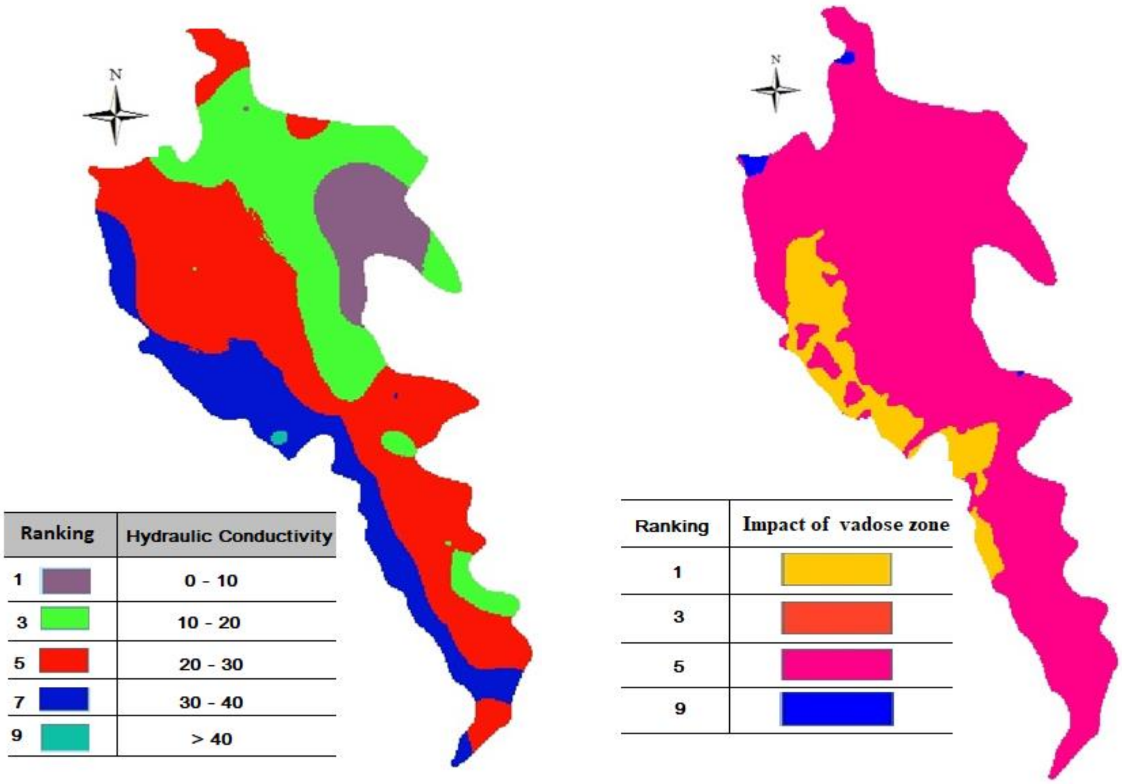
d) The slope ranking map



c) The ranking map of the soil type

Fig. 3- The ranking map of a number of groundwater vulnerability indices in Sirjan Plain

 DOI: 10.22055/JISE.2022.41088.2033



b) The ranking map of hydraulic conductivity **a) The ranking map of the type of the vadose zone**

Fig. 4-The ranking map of a number of groundwater vulnerability indices in Sirjan Plain

Combining the layers and preparing the vulnerability map

After preparing the seven layers needed to use the DRASTIC model, the layers were combined by overlapping the indices. In combining the layers, the following points should be taken into account: 1) all layers should be in the raster form; 2) the pixel size should be the same in all layers; 3) all layers should be prepared in a similar coordinate system. The combination of layers is done by software by summing the numerical value of each pixel with its corresponding pixel in the other layers. The ranking is relative, is determined by the user's opinion, and takes a numerical value from 1 to 9. Ranking or scoring for all layers should have a logical relationship with the physical reality.

Validating the model results

In the discussion of the overlap of the layers, by combining seven layers of weighted information, the DRASTIC index and as a result the vulnerability map of the area were prepared. Since the weight ratios considered for the layers vary, it is necessary to have a criterion for comparing and verifying the results obtained from the combination of the layers. According to the initial theory of the DRASTIC model, the weights for the nitrate ion are calibrated and this calibration can also be used for other regions. If the nitrate ion concentration is available in points with proper spatial distribution and for a specific time period, the validation stage can be performed within the study area. In Sirjan Plain, the concentration of nitrate ion was measured from 15 points with relatively proper spatial distribution in the area. The final DRASTIC map showed that all the points with a high nitrate content were in the high contamination zone. This can validate the accuracy of the model (Figures 5 and 6).

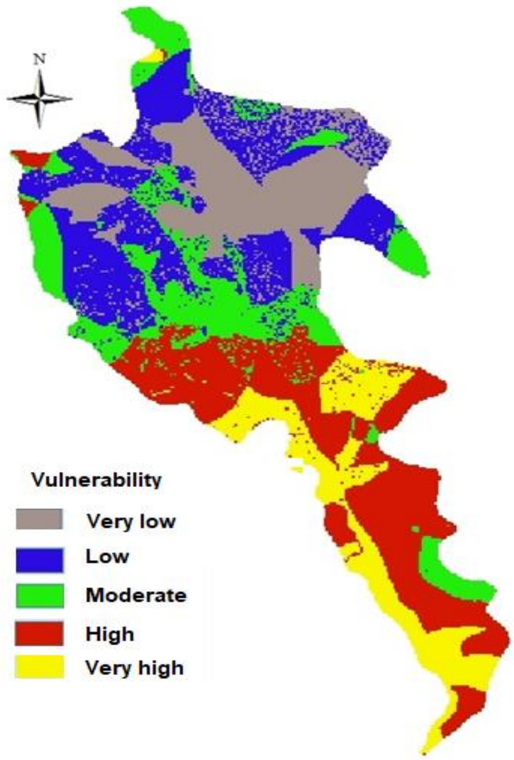


Fig. 5- The vulnerability map of Sirjan Plain

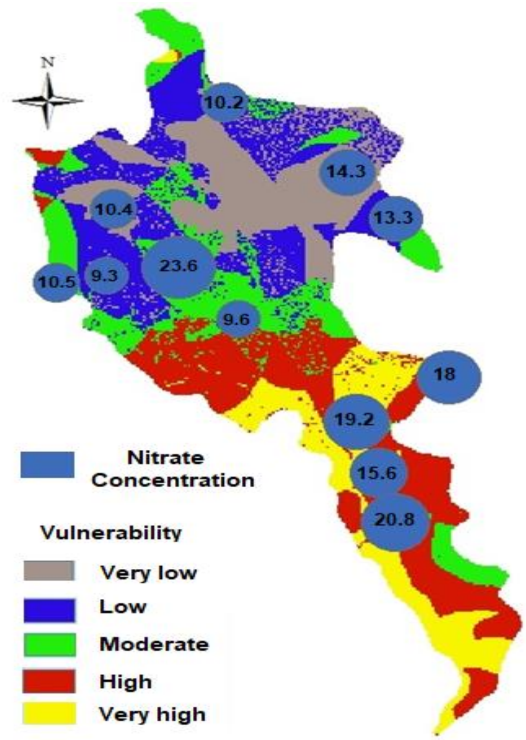


Fig. 6- Overlaying the DRASTIC map and nitrate concentration in Sirjan Plain

The mean nitrate concentrations in the wells of the region with very high and low vulnerability were approximately 20 mg/L and 10 mg/L, respectively. Therefore, the increase in groundwater vulnerability potential correlates with the increase in nitrate concentration in the region. The reasons for the high vulnerability of groundwater to contamination in the regions are the low water table depth and the types of media forming the aquifer. Considering the identified vulnerability and its classification, the qualitative confines of the aquifer are determined and some measures should be taken in order to protect the aquifer.

Conclusion

The present study was an attempt to calculate the spatial map of vulnerability by the DRASTIC method using the information layers related to the hydrological, hydrogeological, and geological characteristics of Sirjan Plain aquifer. The DRASTIC method was used to determine the vulnerability potential of Sirjan Plain since it is one of the most practical methods of ranking compared to other methods of determining the vulnerability potential of the plain to contamination and uses a higher number of variables in preparing the model. In this study, overlapping functions were used to produce raster layers and to combine them in the GIS environment. These functions combine the information layers both mathematically and by using weight. For this purpose, all layers along with the coefficients were defined as percentages for the model and then the layers were combined. The final vulnerability map of the aquifer to contamination divided into the five parts of very low, low, medium, high, and very high vulnerability was presented. By overlaying the nitrate ion on the final DRASTIC map, it was found that all points with high nitrate content were in the high contamination potential region, confirming the accuracy of the model. Moreover, according to the final map, the highest vulnerability belonged to the southern region of the study area which has moderate to high and high vulnerability. With the help of the prepared map, the areas prone to contamination were determined based on which the groundwater quality management of the aquifer can be performed.

Acknowledgment
This research work was supported by the Graduate University of Advanced Technology (Institute of Science and High Technology and Environmental Science) (No. 98/2561). The authors gratefully acknowledge this help

References

1- Afroozi, M. and Mohammadzadeh, H. 2013. Vulnerability assessment of Borujen-Faradnabeh plain aquifer using DRASTIC model based on nitrate, *Iranian Journal of Water Research*, 7(12): 213-218 (In Persian).

2- Aller, L. 1985. DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeologic settings. Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, US Environmental Protection Agency.

3- Aller, L., Bennett, T., Lehr, J., Petty, R. J. and Hackett, G. 1987. DRASTIC: A standardized system for evaluating ground water pollution potential using hydrogeologic settings. US Environmental Protection Agency.

4- Anvari S., Kim JH. and Moghaddasi M. 2019. The role of meteorological and hydrological uncertainties in the performance of optimal water allocation approaches, *Irrigation and Drainage*; 68(2): 342-53.

5- Anvari S, Mousavi SJ. and Morid S. 2017. Stochastic dynamic programming-based approach for optimal irrigation scheduling under restricted water availability conditions. *Irrigation and Drainage*, 66(4):492–500.

6- Asefi, M., Zarei, H., and Radmanesh, F. 2014. Improvement of SINTACS method using analytical hierarchy process in geographic information system environment to evaluate aquifer vulnerability (case study: Andimeshk plain). *Journal of Irrigation and Water Engineering*, 18(4): 109-125.

7- Ashokraj, C., Kirubakaran, M. and Colins Johnny, J. 2015. Estimation of Groundwater Vulnerability using Remote Sensing and GIS Techniques. *International Journal for Innovative Research in Science and Technology*, 1(9): 2349-6010.

8- Babiker, I. S., Mohamed, M. A., Hiyama, T., and Kato, K. 2005. A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. *Science of the Total Environment*, 345(1): 127-140.

9- Colins, J., Sashikkumar, M. C., Anas, P. A., and Kirubakaran, M. 2016. GIS-based assessment of aquifer vulnerability using DRASTIC Model: A case study on Kodaganar basin. *Earth Sciences Research Journal*, 20(1), 1-8.

10- Dixon B. 2005. Applicability of neuro-fuzzy techniques in predicting ground-water vulnerability: a GIS-based sensitivity analysis. *Journal of Hydrology*. 309 (1-4): 17-38.

11- Kerman Planning Management Organization, 2006.

12- Khodaei K., Shahsavari A.A., Etebari B. 2006. Evaluation Of Aquifer Vulnerability Of Jovein Plain Using Drastic And Gods Methods, *Iranian Journal Of Geology*, 2(4): 73-87. (In Persian).

13- Panagopoulos, G. P., Antonakos, A. K., and Lambrakis, N. J. (2006). Optimization of the DRASTIC method for groundwater vulnerability assessment via the use of simple statistical methods and GIS. *Hydrogeology Journal*, 14(6): 894-911.

14- Ranjbar, N., Anvari, S., and Delavar, M. 2021. The application of harmony search and genetic algorithms for the simultaneous optimization of integrated reservoir–FARM systems (IRFS). *Irrigation and Drainage*, 70(4), 743-756.

15- Specialized water reports of Kerman regions, 2014.

16- Synthesis report on Updating Water Master Plan of Iran Deputy of Water and Wastewater Ministry of Energy, 2017.

17- Thirumalaivasan, D., Karmegam, M., and Venugopal, K. 2003. AHP-DRASTIC: software for specific aquifer vulnerability assessment using DRASTIC model and GIS. *Environmental Modelling and Software,* 18(7): 645-656.

18- Voudouris. K., Nazakis. N., Polemio. M. and Kareklas. K., 2010. Assessment of intrinsic vulnerability using the DRASTIC model and GIS in the Kiti aquifer, Cyprus, *European Water,* 30: 13-24.

19- Vrba, J. and Zaporozec, A. 1994. Guidebook on mapping groundwater vulnerability. Heise.