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ABSTRACT: Hajiabad plain with an area of about 158 km^2 is located about 160 km north of Bandar Abbas in Iran. Due to the significance of this plain in terms of agricultural and drinking water supply in the region and the declining groundwater level in the region, the withdrawal of water resources has been prohibited in recent years. The purpose of this study is to determine the vulnerability of the aquifer using the DRASTIC model and the optimal method of fuzzy logic as well as the drastic method calibrated with nitrate. Finally, the final vulnerability maps were calibrated with EC values. In order to investigate the hydrogeochemical properties of groundwater resources of the plain, 26 water samples were collected from designated points in different periods of the water year 2018. Water samples were analyzed in Hormozgan soil and water laboratory. Also, the results of water sample data analyzed by Hormozgan Regional Water Organization were used. Assessment of aquifer vulnerability based on vulnerability models showed that the east and parts of the center of the plain were subject to the highest vulnerability, while the southern, southwestern, and northern slopes of the plain were of the lowest vulnerability. The determined coefficients between nitrate and DRASTIC vulnerability models and fuzzy optimization were estimated to be 0.41 and 0.36, respectively. Nitrate concentration validation demonstrated that the vulnerabilities of Hajiabad plain aquifer were almost similar under both drastic model and fuzzy optimization methods.

KEYWORDS: Hormozgan, vulnerability, fuzzy logic, groundwater, electrical conductivity, DRASTIC

TYPE: Original Research

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Introduction

Groundwater resources are important sources of water around the world. Increasing water requirements and the inevitable overuse of aquifers have led to the depletion of these valuable resources, resulting in a significant drop in groundwater levels. The entry of various pollutants into aquifers, resulting from the expansion of urban, industrial, and agricultural communities as well as improper management, has further compounded the issue. Such a phenomenon has reduced the quality of water resources and exerted irreversible environmental effects. Therefore, it seems quite necessary to conduct hydro-chemical studies as well as qualitative assessments of groundwater resources so as to protect them against pollution by natural and human phenomena. Likewise, effective management is indispensable. The identification of vulnerable aquifers is the very first step in preventing groundwater pollution (Vrba & Zoporozec, 1994). Multiple definitions of the concept of vulnerability have been put forth to this day. Warning of water pollution in France in the late 1960s, Margaret first introduced the concept of groundwater vulnerability (Al-Adamat et al., 2003). Aquifer vulnerability is defined in terms of the tendency of contaminants to penetrate the earth and spread to the groundwater aquifer (Margat, 1968). In general, aquifer vulnerability assessments could be carried out in two different types: intrinsic and specific. Intrinsic vulnerability is assessed according to the hydro-logical and hydro-geological characteristics of the region, including the characteristics of the aquifer and the stresses imposed on it. Specific vulnerability is assessed in terms of the sensitivity of the aquifer to a certain pollutant or a group of contaminants. It is a human being that arises from the interaction of pollutants with components of inherent vulnerability (Aller et al., 1987; Evans & Myers, 1990; Secunda et al., 1998).

The DRASTIC model was developed by the United States Environmental Protection Agency (EPA) to assess the groundwater vulnerability throughout the United States. The model is based on the concept of hydro-geological status that situates all geological and hydro-logical factors that affect and control the movement of groundwater at the entrance and exit of the system in an area. By making effective use of the Geographic Information System (GIS) technique, the model becomes much easier to apply and be more accurate than before. Furthermore, other methods have been employed so as to enhance the DRASTIC model. The most frequently employed methods for assessing the vulnerability index are DRASTIC, GOD, SINTACS, SI, and AVI (Anane et al., 2013; Sharadqah, 2017), and the most frequently employed one for determining the aquifer vulnerability is the DRASTIC method. To this day, it has been employed in several studies (Baalousha, 2006; Babiker et al., 2005; Jang et al., 2020; Khosravi et al., 2012; Kozłowski & Sojka, 2019; Maqsoom et al., 2020; Niknam et al., 2007; Rajput et al., 2020). In order to improve the performance of some classical vulnerability assessment methods, Artificial Intelligence (A.I.) methods are also employed, among which fuzzy methods are popular ones which are employed to classify the effective parameters in vulnerability methods (Rezaei et al., 2013).

Taking the above-mentioned facts into consideration, one could quite compellingly argue that groundwater pollution has turned into a critical issue in Iran, which led the way to an extensive research study. Due to the recent groundwater crisis and the lack of such non-renewable resources in Iran, especially

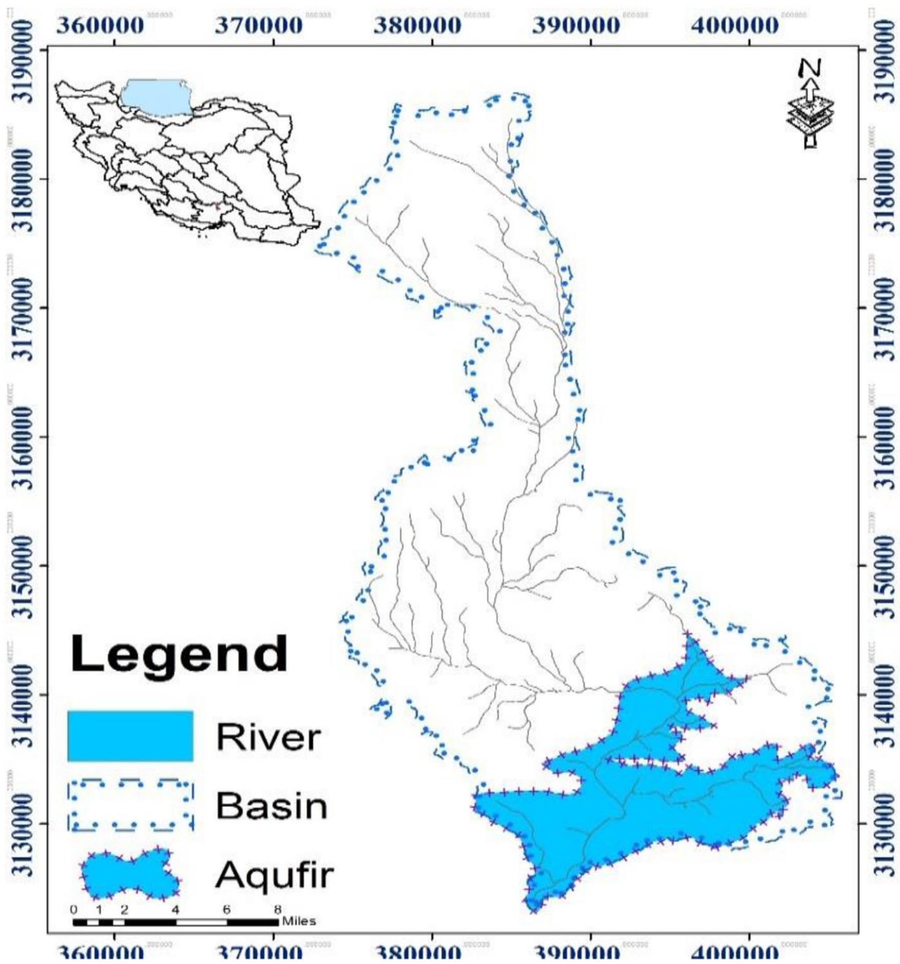

Figure 1. Location of Hajiabad catchment and aquifer areas.

in Hormozgan province, groundwater quality has been highlighted again by many researchers. Among the multiple solutions proposed to tackle the problem, one of the most effective methods to prevent groundwater pollution is to first identify vulnerable aquifer areas and subsequently manage the use of water and land resources in the area. In general, the concept of groundwater vulnerability is based on the assumption that the physical environment protects the groundwater against adverse natural effects. This assumption is specifically true in cases in which contamination reaches the soil (El-Naqa et al., 2006). The present study is an investigation into the vulnerable aquifer areas of Hormozgan, Iran so as to further explore the pollution of groundwater resources.

Materials and Methods

Area of study

Located in the south of Iran, Hajiabad plain covers an area of 45 km^2 and its catchment area is 162.1 km^2. The plain is situated about 160 km north of Bandar Abbas. The latitude and longitude of Hajiabad are 28.31118 and 55.89990, respectively. Having an average width of 4 km, it is enclosed from the north by the heights of Bibi Dokhtaran Mountain, from the west by the Sirjan-Bandar Abbas Road, from the east by the heights of Anfuzeh Mountain, and from the south by the Congomara Hills. The average temperature of the region is 19.8°C and the mean annual evaporation rate is 2,464.7 mm. The height of the plain ranges between 900 m at least and 1,030 m at most, declining toward the southwest of the plain. The movement of surface water follows the general slope of the land, that is, it flows from the northern and eastern parts toward the southwest. The locations of Hajiabad catchment and aquifer areas as well as the geological map of Hajiabad aquifer and catchment areas are given in Figures 1 and 2, respectively.

Geological formations existing in the initial Cambrian plain are composed of salt domes having gypsum, different kinds of shale, and magmas and they can be found in the western section of the plain. The lower cretaceous lime includes orbitolina lime and rodistar in the western parts of the plain. Colored mélange consists of deep marine sediments like lime and thin magma, which are frequently found in the west and north heights. Jahrom Asmari Formation comes into view throughout the northern heights as well as its eastern part and it is mainly composed of lime sediments.

The formation has received considerable attention due to its extension and available tectonics in terms of karstification. The Miocene formation generally comprises marl, lime marl, and

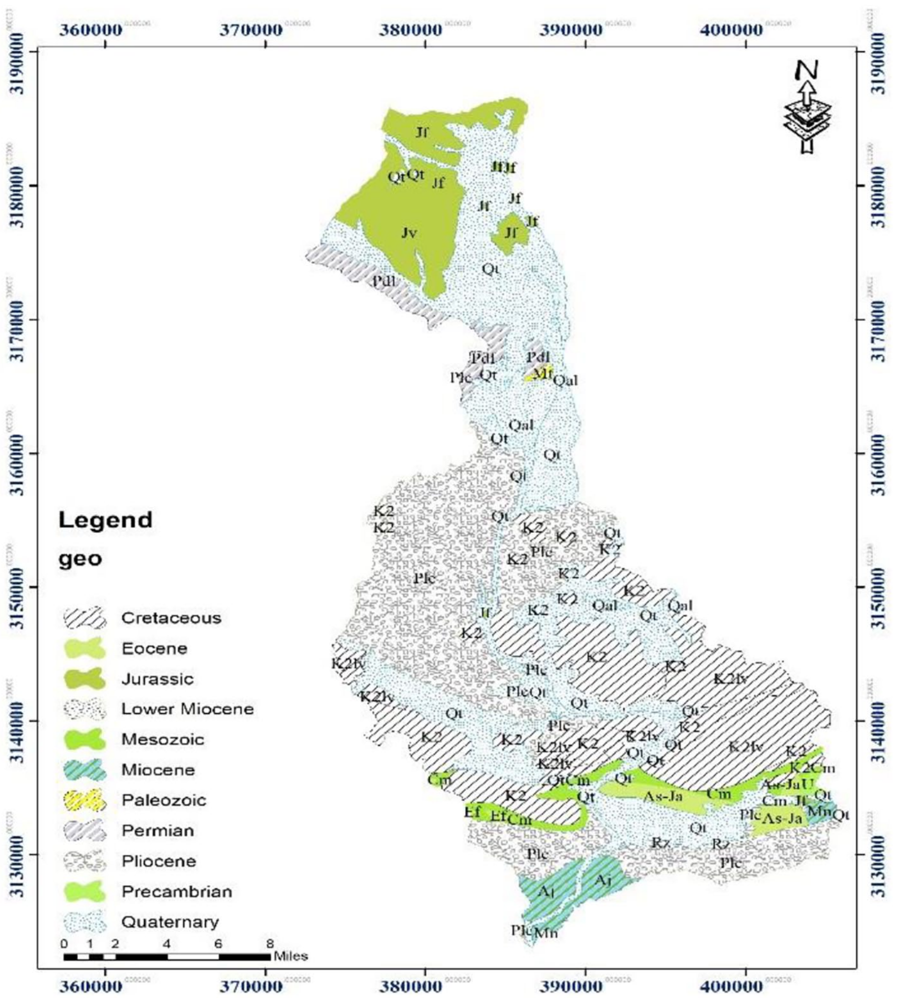

Figure 2. Geological map of Hajiabad aquifer and catchment areas.

destructive sediments forming heights of the exterior passageway of the plain. Southern parts of the studied area include the Bakhtiari formation consisting of conglomerate and grit which is likely to serve as a hydrous layer in the upper parts due to its cleavages. Eastern and north-western parts are composed of coarse-grained quartz sediments, and the amount of fine-grained sediments increases upon reaching the exterior passageway of the plain.

Data checking

In order to investigate the hydro-chemical properties of groundwater in the region, 16 water samples were taken from designated groundwater wells, which were used by the Regional Water Company of Hormozgan, Iran in the water year of 2013. The position of the studied wells is presented in Figure 3.

Parameters affecting vulnerability

Groundwater depth. Groundwater depth is defined as the distance between the ground and the groundwater level. Deeper water levels are less exposed to contamination since the deeper the groundwater is, the longer it takes for pollutants to reach it. Groundwater depth is the key to the prevention of aquifer pollution. That explains why the highest rates of pollution are detected on shallow surfaces. Pollution rates identified at different groundwater depths are presented in Table 1.

Aquifer net nutrition

Net nutrition designates the amount of water that makes its way from the surface to the water table. Water enables the contaminant to first move vertically and reach the water table and subsequently, horizontally move into the aquifer (Secunda et al., 1998). Feeding represents the volume of water that enters the earth per unit area of the aquifer in a 1-year period (Bouwer, 1978). Equation (1) calculates the feed from agricultural return water (Qian et al., 2012). In this method, Thiessen polygons are generated for each well used by the farmer and the amount of feed is separately calculated for each polygon.

$$Q = \frac{\Psi \times P}{F} \tag{1}$$

In the above equation, Q denotes the annual feed of agricultural return water per polygon (mma^{-1}), p the volume of water

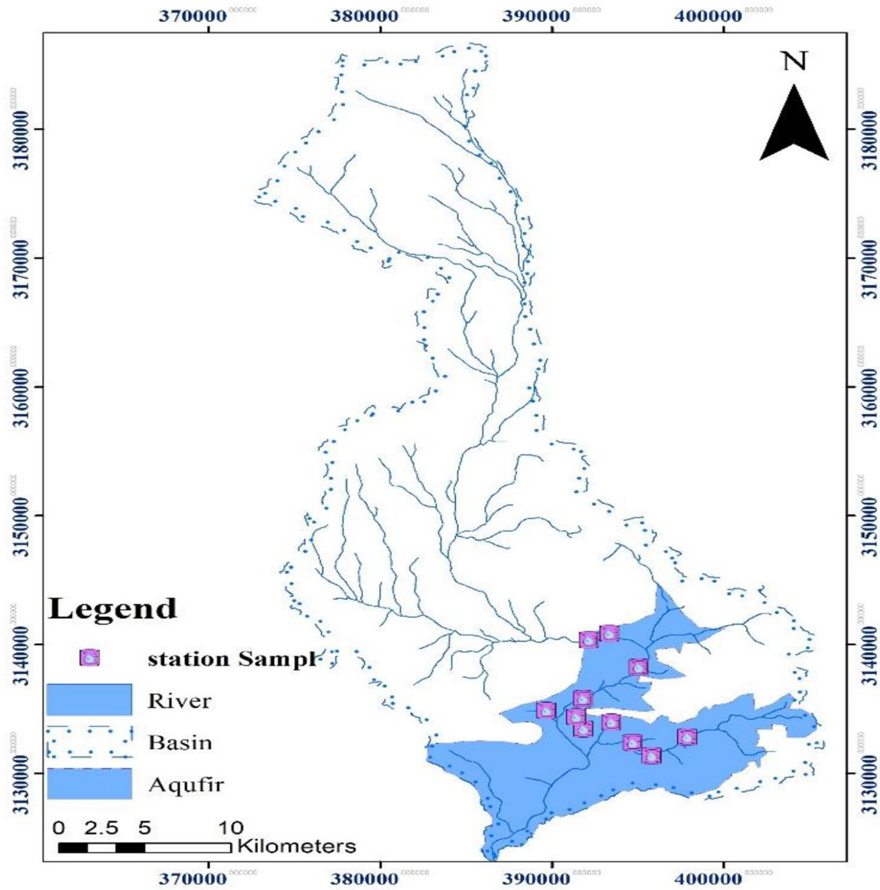

Figure 3. Location of sampling stations.

annually discharged (mm^3a^{-1}) from wells used for agriculture at level *F*, *F* the polygon area (mm^2), and Ψ the coefficient. Water penetration is considered zero.

Aquifer environment

This factor represents the properties of the constituents of the phreatic zone such as porosity, material and particle size, and particle sorting. The mentioned factor controls the dynamic rate of contamination mobility, that is, contamination dilution processes including chemical decomposition, adsorption, dispersion, and latency, as presented in Table 1.

Soil environment

It designates the aerated part of the unsaturated zone that extends to the section where the roots of plants penetrate the earth. Soil environment determines the amount of water that reaches the surface. Undoubtedly, it exerts considerable impact on how pollutants move. The texture of the soil environment affects the amount of nutrients as well as the ability of contaminants to penetrate the earth. Groundwater is exposed to less pollution when the particle size of the soil is relatively large, the soil is less permeable, and the organic matter of the soil is high, hence greater thickness. Soil environment is determined based on its textural classification and is rated based on pollution. The rates of different materials that make up the soil environment are determined and presented in Table 1.

Topography

The graphic delineation of a region, that is, formation of its slopes and their changes, is a controlling factor in the penetration of pollutants and the region's runoff formation. There is a higher chance of infiltration and aquifer pollution when the region has lower slopes. When there are slopes higher than 18°, runoff increases and infiltration decreases; consequently, pollutants are less likely to reach the groundwater system. The identified rates for different slope degrees are presented in Table 2.

Vadose zone

The vadose zone, or the unsaturated area, is profoundly influenced by the type of the soil. It extends from the land surface to the phreatic zone. It is assumed in the DRASTIC model that the environment and the conditions of the unsaturated area exert considerable effect on pollutants for their possibility to be absorbed or diluted (Aller et al., 1987). The texture of the unsaturated zone determines the time it takes for pollutants to pass through this medium. The rates identified for the various materials making up the unsaturated medium are presented in Table 2.

Table 1. Rankings and Weights of the Parameters (Aller et al., 1987).

RANKING IN DRASTIC	LIMIT (DEPTH OF STATIC SURFACE [M])–RELATIVE WEIGHT	FUZZY RANKING	GRADE	LIMIT (PURE RECHARGE [MM])–RELATIVE WEIGHT	FUZZY RANKING
10	0–1.5	1	1	0–50.8	0
9	1.5–4.6	3	50.8–101.6		
7	4.6–9.1	6	101.6–177.8		$\frac{x_{ij}-50}{254-50}$
5	9.1–15.2	$\frac{30-x_{ij}}{30-1.5}$	8	177.8–254	
3	15.2–30.4				
1	>30.4	0			

RANKING	LIMIT (THE PERIMETER OF AQUIFER)-RELATIVE WEIGHT	FUZZY RANKING	RANKING	LIMIT (THE PERIMETER OF SOIL)-RELATIVE WEIGHT	FUZZY RANKING
2	Mass shale	0.2	10	Thin or without a layer of soil	1
3	Transformation	0.3	10	Grit	1
4	Weathering transformation	0.4	9	Sand	0.9
5	Alluvium	0.5	8	Substratum	0.8
6	Sandstone, lime, shale	0.6	7	Cracked clay	0.7
6	Mass limestone	0.6	6	Sandy loam	0.6
6	Mas sandstone	0.6	5	Loam	0.5
8	Sand	0.8	4	Silt loam	0.4
9	Basalt	0.9	3	Clay loam	0.3
10	Karst limestone	1	2	Mud	0.2
			1	Soft clay	0.1

Hydraulic conductivity

The ability to transfer aqueous constituents is referred to as hydraulic conductivity, which depends on interconnected voids in the aqueous layer (effective porosity). Hydraulic conductivity controls the movement of the contaminant and its spread from the point of penetration to the saturation zone. Therefore, the greater the hydraulic conductivity, the higher the possibility of contaminants flowing into the aquifer. The highest rate of exposure to contaminants is attributed to the greatest hydraulic conductivity. The rates identified for different values of the aquifer hydraulic conductivity are presented in Table 3.

The DRASTIC model

DRASTIC is an experimental model that was first proposed in 1987 based on the concept of hydro-geological status in order to assess the vulnerability of groundwater in the United States (Aller et al., 1987). The hydro-geological status situates all the geological and hydrological factors that control the movement of groundwater in an area (7). This method evaluates the potential contamination of an area by listing and taking into account the key factors that affect the transfer of soluble materials (6). This model has seven measurable and effective hydrogeological features in the transfer of pollution to groundwater including groundwater depth (D), net nutrition, or recharge, (R), aquifer media (A), soil environment (S), topography or the formation of surface slopes (T), unsaturated zone (I), and hydraulic conductivity (C). These features are provided in GIS technology, suitable for environmental data analysis, in seven layers in the raster format. In the DRASTIC method, each parameter is assigned a rate (from 1 to 5) depending on the significance of the parameter. The rate of DRASTIC parameters ranges from 1 to 10, 1 being the lowest and 10 the highest risk for groundwater pollution (Panagopoulos et al., 2006).

Therefore, the drag index is calculated based on the weight of a total of seven parameters as follows (Aller et al., 1987):

Table 2. Rankings and Weights of the Parameters.

RANKING	LIMIT (SLOPE %)–RELATIVE WEIGHT	FUZZY RANKING	GRADE	LIMIT (HYDRAULIC CONDUCT M/DAY)–RELATIVE WEIGHT	FUZZY RANKING
10	0–2	0	1	0.04–4.1	0
9	2–6		2	4.1–12.3	
5	6–12	$\frac{18-x_{ij}}{18-2}$	4	12.3–28.7	
3	12–18		6	28.7–41	$\frac{x_{ij}-82}{82-4}$
1	18<	1	8	41–82	
			10	82<	1
			Grade	Limit (unsaturated perimeter)-relative weight	
			1	Confining layer	0.1
			3	Silt/clay	0.3
			3	Shale	0.3
			6	Limestone	0.6
			6	Sandstone	0.6
			6	Shale, sandstone	0.6
			6	Sand and clay	0.6
			4	Transformation	0.4
			8	Sand	0.8
			9	Basalt	0.9
			10	Karst limestone	1

$$\mathrm{DI} = \mathrm{D_r D_w} + \mathrm{R_r R_w} + \mathrm{A_r A_w} + \mathrm{S_r S_w} + \mathrm{T_r T_w} + \mathrm{I_r I_w} + \mathrm{C_r C_w} \tag{2}$$

In the above-mentioned equation, *DI* is the index of vulnerability, small letter *r* is the value rate (rank), and small letter *w* is the weight assigned to each parameter.

Fuzzy Logic: The theory of fuzzy sets was put forward by Zadeh (1965). Having enormously expanded and deepened, the theory has found various applications in a wide range of sciences including electronics, natural resources, mining, and urban management and planning. A fuzzy set is an indicator of membership-dependence value that could be continuously selected from zero to one. This set is specified by membership functions. When the degree of membership relatively approximates one, it means that it belongs to the group; in addition, if the degree of membership approximates zero, it indicates less dependence on the group. In other words, a membership grade of zero indicates the least impact (non-affiliation) and a membership grade of one indicates the greatest impact on the contamination potential (full membership). After having generated a fuzzy set, one is recommended to make use of fuzzy operators such as AND, OR, fuzzy product, fuzzy sum, fuzzy gamma operator, or fuzzy inference rules so as to perform various functions. After having drawn maps related to all seven parameters, their membership values were determined using the linear membership function. Linear membership for quantitative parameters (D, R, C, and T) could be expressed in the three following ways: increased potential vulnerability corresponding to the large number of quantitative parameters according to equation (3), decreased potential vulnerability corresponding to the large number of quantitative parameters according to equation (3), and decreased potential vulnerability corresponding to the large number of parameters according to equation (4) (Pathak et al., 2008).

$$r_{ij} = \left\{ \begin{array}{ll} 0 & x_{ij} \le x_{\min j} \\ \dfrac{x_{ij} - x_{\min}}{x_{\max j} - x_{\min j}} & x_{\min j} \le x_{ij} \le x_{\max j} \\ 1 & x_{\max j} \le x_{ij} \end{array} \right\} \tag{3}$$

$$r_{ij} = \left\{ \begin{array}{ll} 0 & x_{ij} \ge x_{\min j} \\ \dfrac{x_{ij} - x_{\min}}{x_{\max j} - x_{\min j}} & x_{\min j} \le x_{ij} \le x_{\max j} \\ 1 & x_{ij} \le x_{\min j} \end{array} \right\} \tag{4}$$

Table 3. Hydraulic Conductivity Coefficient for Different Sediments.

TYPE OF SEDIMENTS	HYDRAULIC CONDUCT (M/DAY)
Clay	0.0001
Silt-fine sand; silt, clay	1–2
Mix of clay, fine and coarse sand	5
Fine sandy clay/very fine homogeny sand/clay and sand	7
Clay sand/mix of clay and sand/sandy clay and sand	10
Mix of fine and medium-sized sands with some clay/mix of sandy clay and some sand/mix of very fine sand and some grit	12
Homogeny fine sand/mix of sand, sandy clay and grit/very fine sand, sandy clay, some grit, and stone	15
Mix of fine, medium-sized and coarse sands/mix of fine grit, sandy grit, and sandy clay	20
Mix of medium-sized and fine sands/mix of fine grit, sand, clay, and stone	25
Homogeny medium-sized sands/mix of stone, grit, clay, sand, and stone	30
Mix of fine and coarse sands with some grit	35
Mix of medium-sized and coarse sands with some grit/mix of stone, sand, sandy clay, and some grit	40
Homogeny coarse sand/mix of stone, sandy clay and grit	50
Mix of sand and grit/mix of medium-sized and coarse sand, grit and stone	60
Mix of stone, fine and medium-sized grit, and sand	70
Homogeneous fine sand/mix of stone, fine and medium-sized sand	90
Homogeneous medium-sized sand (in terms of dimension)	110
Homogeneous fine grit (in terms of dimension)	120
Homogeneous stone	130

where x_{ij} is the jth value of the Ith factor, $x_{\max j}$ and $x_{\min j}$ are the maximum and minimum values of the ith factor, respectively, for the correct model, and r_{ij} is the membership value. For qualitative parameters (A, I, and S), the linear membership function is also used; in this respect, in each layer, the ranks in the drastic model, ranging between 1 and 10, were divided by layers which were then ranked based on the fuzzy model. After ranking, each layer was weighted based on the weights in the Drastic model. To integrate the input layers, out of five fuzzy operators, the best result was achieved by the fuzzy multiplication product mode. This is because all layers of information regardless of their membership are multiplied and multiplying a few numbers by less than one results in a smaller number. Among the operators, the fuzzy multiplication operator was used in line with the professed objective of this study. Figure 4 shows the flowchart of the vulnerability map of the plain.

Results and Discussion

Vulnerability assessment by the DRASTIC method

In this study, the data collected through observations and analyses of information obtained from observation wells (97–98), exploitation wells, aquifer well logs, observation and exploration well logs, meteorological stations, and the digital elevation model of the plain were employed so as to prepare the necessary layers for vulnerability. Raster layers, related to the seven DRASTIC parameters, with a resolution of 50×50 m, were prepared. The layer of the groundwater depth was measured using Kriging interpolation (D). To prepare the net feeding layer (R), rainfall and water returning from agriculture were used as the main sources of aquifer nutrition. In addition, the raster layer was calculated separately. Finally, by overlapping the two layers and ranking them according to the above-mentioned classification (7), the net nutrition layer was obtained, as presented in Figure 4. In order to obtain nutrition through precipitation, the groundwater surface layer was prepared for both the rainy month (May) and the less rainy month (August). The August layer was subsequently subtracted from the May layer, the result of which was multiplied by the 3% storage coefficient of the aquifer layer so as to measure the raster of the rainfall (Soltanidizeji, 2012). Aquifer storage coefficient was considered 2%. To prepare the aquifer (A), the soil environment (S), the unsaturated zone (I), and the hydraulic conductivity (C) layer, the logs of observation wells in the study area were used.

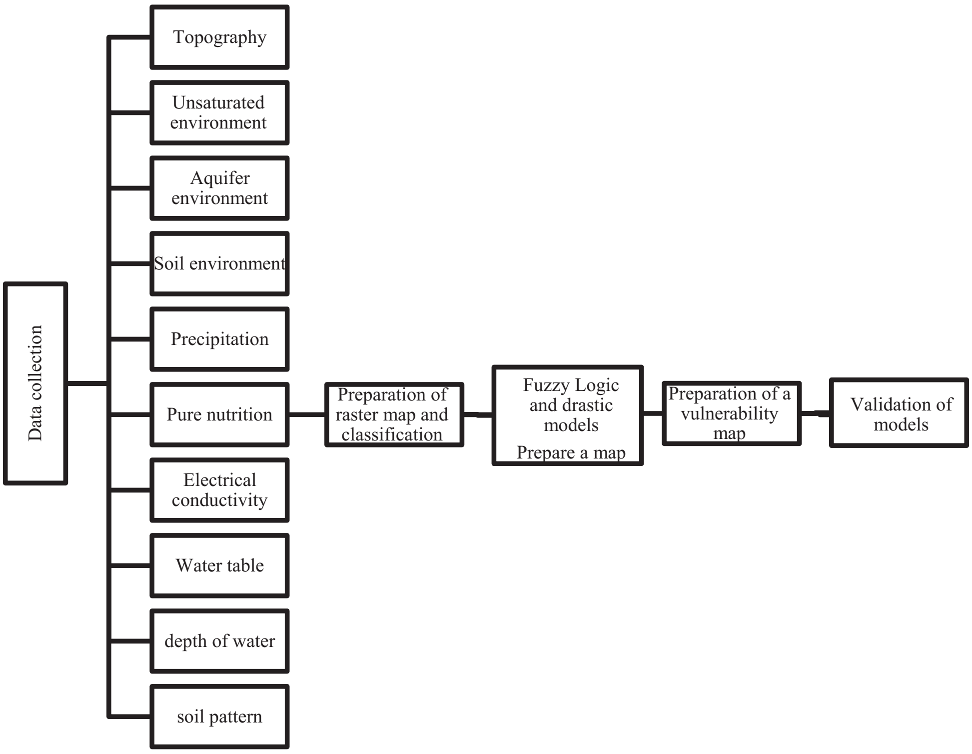

Figure 4. Flowchart of preparing vulnerability maps.

The topographic layer was obtained by preparing the slope via the digital elevation model of the plain. The layers were then classified and rated according to the standard method. The obtained maps of the parameters are separately presented in Figure 5b.

According to Figure 5, approximately 70% of the study area has a slope degree ranging between 12% and 18% in the medium of which the potential for vulnerability decreases. About 20% of the northern part of the region has a slope degree of <5%, in which the potential for vulnerability increases, clearly evident in the vulnerability map. In terms of slope, Hajiabad plain is less exposed to pollution. In nearly 80% of the area, the distance between the ground level and the water table is <5 m and based on the DRASTIC and fuzzy ranking, it could be deduced that depths <5 m increase the vulnerability potential. The hydraulic conductivity parameter indicates the ability to transfer water and its contaminants. On average, the main parts of the study area cover hydraulic conductivity of 12 m/day. This situation could strictly limit the vulnerability potential of the study area since >85% of the aquifer has hydraulic conductivity of <12 m/day.

Groundwater feeding enables the contaminant to be vertically transported to the water table and subsequently, horizontally to the aquifer. This parameter controls the volume of water that disperses and dilutes the contaminant in saturated and unsaturated areas. Usually, the higher the nutrition, the greater the potential for groundwater contamination. It is natural for the possibility of contamination to be significantly reduced when the nutrition is extremely low. In Hajiabad plain, approximately 85% of the total area experiences a range of 177.8 to 254 mm feeding per year and the maximum amount of feeding is 215 mm per year. Therefore, in the study area, the parameters of hydraulic conductivity and net feeding, subsequently followed by depth to water table, are the factors that increase the potential for vulnerability. An appropriate degree of impact as well as the amount of sand in shallow and deep soils also increase the vulnerability potential.

The main map of the DRASTIC model was prepared to evaluate the vulnerability of the plain by applying the weights related to each parameter and combining the layers using the overlap function (Figure 5). According to the DRASTIC map, the vulnerability of the plain was estimated to range between 94 and 128. The most vulnerable parts of the plain were detected to be parts of the center of the plain (near the villages of Aliabad and Hajiabad), while the least vulnerable parts were identified to be the northern slope of Hajiabad plain. According to the DRASTIC vulnerability index presented by Aller et al. (1987) and compiled in Table 4, the vulnerability of the plain is divided into the following three categories: very low, low, and moderate.

Furthermore, it is clearly demonstrated in Figure 6 that in the fuzzy logic method, very low and low potential pollution classes are detected in the northern and western parts of the plain, accounting for 13.6% and 76.4% of the total aquifer, respectively. Areas with moderate pollution, accounting for 10% of the total aquifer, are seen in the central and eastern

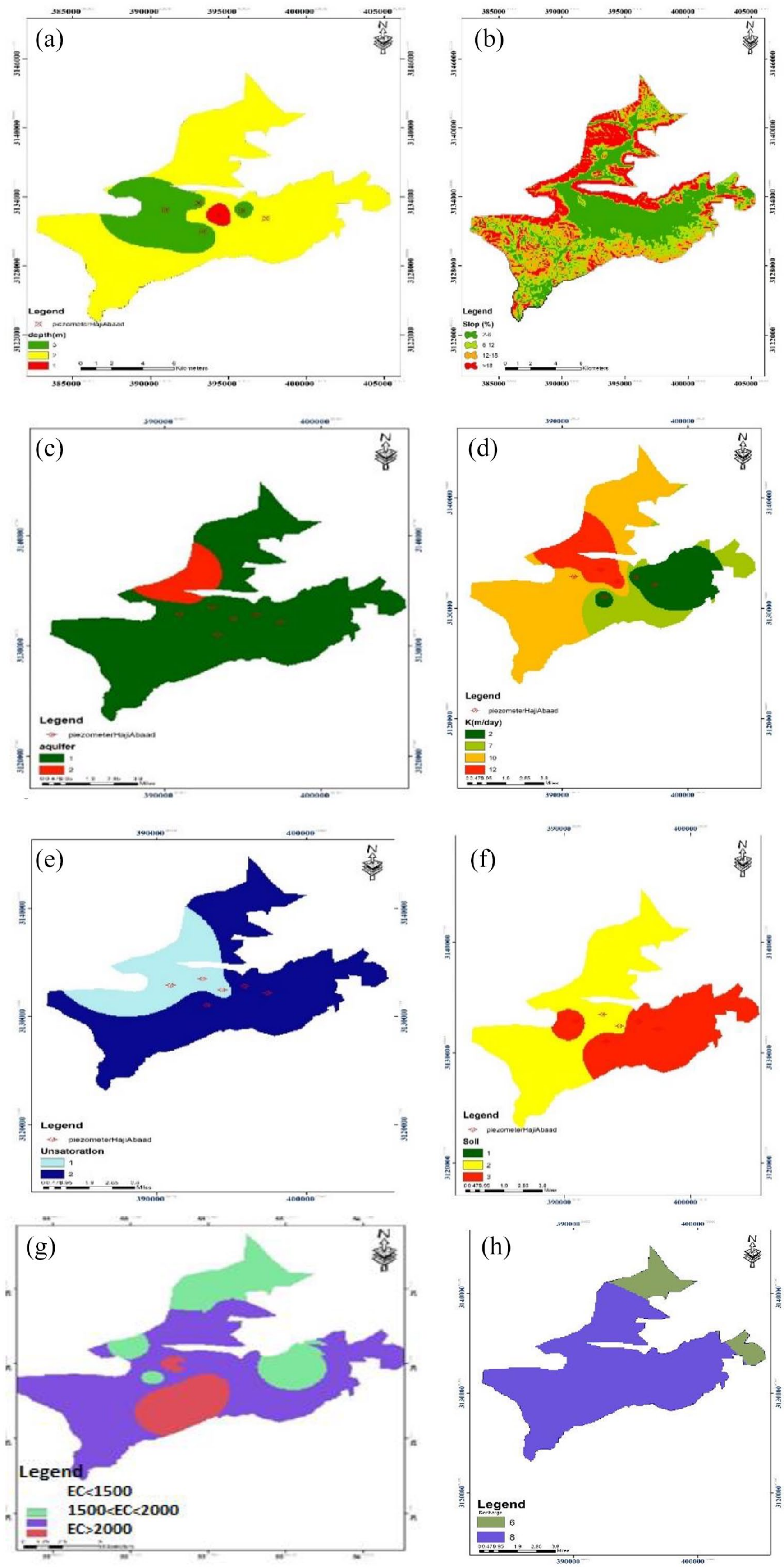

Figure 5. Shows the zoning map with the following parameters: (a) groundwater depth, (b) topography, (c) aquifer environment, (d) hydraulic conductivity, (e) effect of unsaturated area, (f) soil environment, (g) net nutrition, and (h) electrical conductivity.

Table 4. Vulnerability Drastic Index.

VULNERABILITY	EXTENT OF VULNERABILITY
No risk of vulnerability	<79
Very low	80–99
Low	100–119
Low to medium	120–139
Medium to high	140–159
High	160–179
Very much	180–199
Contamination total	<199

parts of the plain. As illustrated by the DRASTIC model, a large part of the plain was characterized by low to very low risk.

Figure 7 shows the vulnerability map of the fuzzy optimization model. As demonstrated by the results, it could be stated that the potential for the spread of pollution to the neighborhood of Aliabad and Hajiabad is moderate. The central areas of the plain have a high potential for pollution due to the shallow depth of their groundwater and the presence of sand texture in the unsaturated and saturated alluvium zones. The above-mentioned situation exists because the higher the water level, the shorter the movement time and, hence, the least possibility of contaminant remediation. It could furthermore be stated that the larger the soil texture through which the contaminant passes, the less the possibility of contaminant remediation, as underground resources would be connected much faster.

Validation and sensitivity analysis of the models

Aquifer vulnerability assessment models should be validated in order to determine whether or not the combination of parameters is properly made. In the process of validation, if the difference between the actual and measured results and those predicted by the model is insignificant, it could be concluded that the combination of parameters used is correctly made. However, if the model is inadequate in simulating the conditions of the aquifer, it can arguably be deduced that the combination of parameters used is not made correctly (Chitsazan & Akhtari, 2009). Since the main fertilizers employed in the study area were solutes, soluble ions, and electrical conductivity were measured in samples taken from 22 wells in Hajiabad plain.

In the samples taken from 22 wells in the Hajiabad plain, soluble ions and nitrate content were measured. Figure 5h shows the division of the nitrate values into three groups. By definition, nitrate concentrations <20 mg/l, with 20 to 45 mg, and >45 mg/l in water were classified as constituting slightly contaminated, contaminated, highly contaminated water, respectively. According to this map, low nitrate levels are found in the northern, western, and northwestern parts of the plain, while the area with a nitrate content of >20 mg/l is located in the eastern and central parts of the plain. To investigate the accuracy of the model, its verification was statistically tested. To measure its statistical accuracy for each of the points with the already determined nitrate, the drastic number and vulnerability of the fuzzy model were obtained according to the local vulnerability index map. Upon dividing the nitrate concentration by the obtained index, a constant Sabbath (Q) was obtained. The closer this ratio to all points is, the more accurate the model will be. For the Hajiabad plain, the value of this ratio is almost close to different points, and based on the data in Table 5, it can be concluded that this model enjoys high accuracy. The correlation coefficient was used to ensure the correlation of two variables without dependence on the unit of measurement of data.

By using the multivariate statistical method in ArcGIS 10.3, that is, a software product that performs principal component analysis, the correlation coefficient between the electrical conductivity layer in the wells and the pollution potential map of the area obtained from the DRASTIC model and fuzzy logic was calculated, the results of which are presented in Table 6. According to this table, the correlation coefficient between the map produced using the DRASTIC model and the electrical conductivity map was 0.19, and the same value for the fuzzy region was 0.25, only slightly different from each other. It could therefore be concluded that both methods functioned somewhat similarly. Overall, the measured value of correlation coefficient is low and weak. One reason for the low correlation coefficient is that in these methods, the vertical movement of solutes toward the groundwater with no transfer and reaction in the soil and the aquifer environment (such as preferential flows) is taken into account (Akhavan et al., 2011).

In the DRASTIC model, rankings are assigned to effective factors. By doing so, the differences between the values of a parameter in a particular time period are ignored. That is, all the values are assigned specific ranks. Therefore, the DRASTIC model is unable to properly reflect the effect of changes in hydrogeological factors on groundwater vulnerability. In fuzzy logic, however, the parameters are classified and ranked using fuzzy operations, leading to more accurate values than in the case of the DRASTIC model (Cameron & Peloso, 2001).

The correlation between the electrical conductivity map and the input layers used in both the DRASTIC and fuzzy models was calculated so that the most effective parameter would be identified. The results are presented in Table 6. As indicated by the table, the highest correlation exists between the parameter of the material of the unsaturated zone and the electrical conductivity layer. In other words, the parameter of the unsaturated zone is the most effective parameter for determining the potential pollution of the aquifer in the Hajiabad plain. After investigating this layer, the parameters of depth up to the water table and the materials of the unsaturated zone have almost the same correlation coefficient with the electrical conductivity

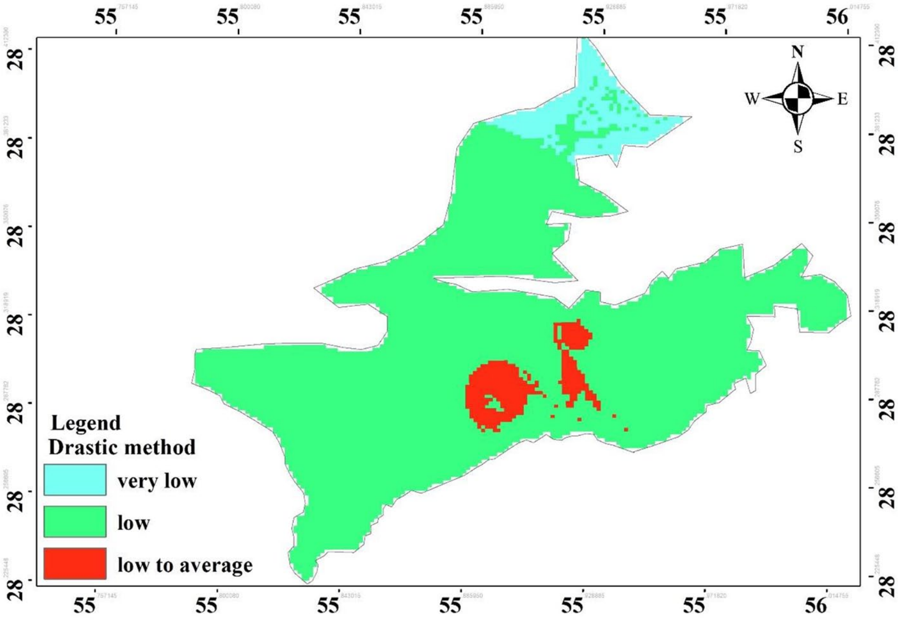

Figure 6. The vulnerability map of the DRASTIC model and the EC value in observation wells.

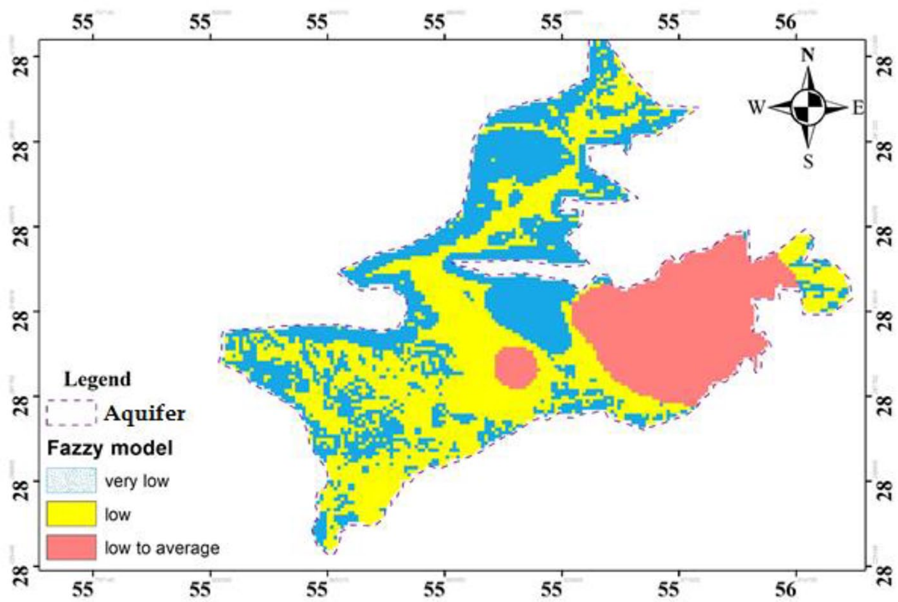

Figure 7. Vulnerability map of fuzzy optimization model.

Table 5. Vulnerability Classes and Areas of Each Class in Haji Abad Plain.

VULNERABILITY POTENTIAL	DRASTIC MODEL		FUZZY LOGIC METHOD	
	AREA (KM^2)	AREA (%)	AREA (KM^2)	AREA (%)
Very low	10.23	6.5	20.5	13.6
Low	140.6	88.9	121.73	76.4
Medium	7.2	4.6	15.8	10

layer, the reason for which could best be interpreted as follows. In areas where the water table is shallow, pollutants are less likely to be separated from intrusive water by physical (filtration), chemical (reaction to unsaturated), and biological (biological removal) processes present in the unsaturated area. Therefore, pollutants reach the groundwater much faster.

Table 6. Correlation Coefficient Between Hydraulic Connectivity Maps and Maps of Vulnerability Obtained Using Both Methods of Drastic and Fuzzy Input Layers.

LAYER	FUZZY MODEL	DRASTIC MODEL	D	R	A	S	T	I	C
Nitrate	0.41	0.36	0.65	0.12	0.23	0.18	0.32	0.28	−0.11

Note. A = aquifer environment; S = soil environment; I = unsaturated zone; C = hydraulic conductivity; D = depth to water table; T = topography; R = net feeding.

However, in areas with deep water tables, these processes have plenty of opportunities to remove the contaminants from the infiltrating water; consequently, in these areas, the possibility for aquifer contamination is much lower (Soltanidizeji, 2012).

The correlation between the nitrate map and the input layers used in both drastic and fuzzy models was calculated to find the most effective parameter, the results of which are shown in Table 6. The numbers in this table indicate that there exists the highest correlation between the depth to the water table and the nitrate layer. In other words, this is the most effective parameter for determining the potential of polluting the Hajiabad plain aquifer. The corresponding reason can be interpreted in the following way. In areas where the water table is shallow, pollutants are less likely to be separated from intrusive water through physical (filtration), chemical (reaction to unsaturated), and biological (biological removal) processes in the unsaturated area. Therefore, they reach the groundwater faster. However, in areas with a deep water table, the mentioned processes have a greater opportunity to remove contaminants from the infiltrating water. Therefore, in these areas, the chance for aquifer contamination is lower (Soltanidizeji, 2012). After dealing this layer, the parameters of soil environment and material of unsaturated environment with nitrate layer have an almost similar correlation coefficient.

Conclusion

Given the significance of water quality in human health or its use in various applications, it is essential that researchers carry out scientific, purposeful, and comprehensive studies on water resources in the region and, also, on water quality to facilitate necessary conditions to manage and optimize the use of water resources, deal with possible hazards, and improve water quality. To ensure finding an appropriate method to protect groundwater resources against pollution that threatens their future, an assessment of water resources' vulnerability was developed and conducted. Currently, there are various methods for determining the possibility of contamination for freshwater resources. In this research, aquifer vulnerability was investigated employing DRASTIC models and fuzzy logic. In order to validate the results, nitrate concentration data were used. The outcome demonstrated that the values obtained for drought index of the Hajiabad plain were between 94 and 128 which included the highest vulnerability in the central part and the lowest in other parts. In this study, both methods predicted the risk potential in Hajiabad aquifer with almost equal accuracy. Increase in the correlation coefficient between the nitrate data point and the vulnerability map from 0.41 to 0.36 indicated that the optimal fuzzy logic index outperformed the drastic model in terms of determining the contamination vulnerability of an area. As demonstrated by both of the studied models, contamination potential was quite low in the northern and southern regions due to the significant groundwater depth and low hydraulic conductivity. Upon comparing the models and finding the coefficient of determination between nitrate concentration and vulnerability parameters, it was made clear that the highest correlation belonged to the parameters of slope layer, depth to the water table, and unsaturated environment type.

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