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Evaluation of Hierarchical Analysis Method in Calibration of DRASTIC-LU Vulnerability Index (Study Area: Birjand Aquifer)

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Abstract

Due to population growth and political development of Birjand city, the status of aquifer vulnerability is important for development. Studies on the DRASTIC index indicate the lack of consideration of land use status and the effect of pollutant transfer on aquifer vulnerability. DRASTIC-LU index has eight parameters and since the incoming weights to this index can be a matter of taste, the model was calibrated according to the Nitrate concentration in the wells of the region. The model was calibrated by using AHP method and the completion of questionnaires was analyzed from the point of view of the importance of each parameter in terms of weight and rank. Questionnaire analysis was performed by couple comparison method and using Expert choice software. The calibrated results indicate an increase in the correlation coefficient between the vulnerability index and the Nitrate concentration at the aquifer. The results showed that land use was positive due to the surface concentration of pollutants in the agricultural and urban sectors, which played an important role in the vulnerability index of aquifers. The results also showed that the accuracy of the vulnerability index could be increased by using the proposed method of this research and calibrate weights and ranks by using the hierarchical analysis method. The correlation between Nitrate concentration and DRASTIC-LU index in the aquifer had increased from 42% to 65%.

Keywords: Vulnerability-Land use-DRASTIC-LU-Calibration-Nitrate.

1. Introduction

Groundwater management is of particular importance in arid areas facing scarcity of surface water resources (Moghaddam et al, 2021). The increasing development of human societies and the expansion of industrial activities play a major role in environmental pollution, especially in aquifers (Kardan moghaddam et al, 2017). Free aquifers with high permeability have a higher potential for contamination and vulnerability due to the high rate of contaminant transport. Vulnerability estimation should be based on an accurate scientific method and regional observational data. Numerous studies conducted since the early 1990s have shown that vulnerability assessment is a powerful and low-cost method of identifying areas prone to contamination. In addition, groundwater vulnerability assessment is an important tool for environmental plans and management decisions. Many methods have been proposed to assess aquifer vulnerability, including process methods, statistical methods, and index and overlap methods. DRASTIC index is a ranking one designed to score the vulnerability of different points by combining multiple thematic layers. Today, with the use of Geographic Information System (GIS), this task has become easier and the accuracy of these calculations has greatly increased. GIS is designed to collect a variety of data to describe spatially variable phenomena by analyzing and overlapping existing information layers. One of the biggest advantages of ranking methods is that the survey uses more input layers, which limits the impact of errors or unknown factors on the final output. The concept of groundwater vulnerability was first introduced in France in the late 1960s to warn of water pollution. Vulnerability is a relative, dimensionless and immeasurable property and depends on the geometric characteristics of the aquifer, geology and hydrogeology. You-Hailin et al 2021 examined the weighting in the model and calibrated the model using hierarchical analysis and Nitrate concentration. Sener and Davraz in 2012 used hierarchical analysis to calibrate the DRASTIC index in the Sparta area of Turkey. Their results indicated the high accuracy of using this method for calibration; they estimated the effectiveness of the lake area and agricultural lands in this index with the highest sensitivity. By using hierarchical analysis in the DRASTIC index, Tirkey et al. (2013) showed that the areas most exposed to pollution had the greatest potential for groundwater pollution due to the presence of water and geological factors in the region. Alam et al 2014 presented the DRASTIC-LU model in the central Ganga Plain of India in 2014 and identified urban and rural development and land use in the region as an effective factor in the aquifer vulnerability index. By evaluating the qualitative model of MT3DMs to predict Nitrate concentration, Kardan Moghaddam et al. calibrated the vulnerability index for the next period in 2020. Due to the high water level in part of the aquifer, large area of agricultural lands and improper use of chemical fertilizers, Birjand plain in South Khorasan province is currently one of the areas with high potential for vulnerability. Investigating the effect of land use and its effect on the transfer potential of environmental pollutants is introduced as a major parameter in vulnerability, which is discussed in this study. Studies on groundwater vulnerability have paid less attention to the role and effect of land use, and in studies that the role of land use have been highlighted, its calibration status, weighting and rankings have not been performed. Calibration of the weight and ranks of this parameter in vulnerability can cover the subtle effect of a number of parameters that have less effect on vulnerability in dry areas. In the present study, in order to investigate the vulnerability of Birjand aquifer for environmental management of groundwater resources, identified vulnerable areas using the DRASTIC index in the area. Then, using the DRASTIC-LU model, we investigate the role of land use in aquifer vulnerability and finally, using the AHP method, we have attempted to calibrate the model coefficients.

2- Materials and methods

2-1- Study area

Birjand watershed is a part of Lut desert watershed, which is located between longitude 43′ 58° to 45′ 59° and latitude 34′ 32° to 08′ 33°. The study area is 3455 square kilometers, of which 1045 kilometers are plains and the rest are elevations. The climate of the region is a function of the Mediterranean, Indian Ocean and Siberian high-pressure fronts. According to climatic classifications, it is considered as an arid region. In terms of topography, its highest point is related to the southern heights of the region in Bagheran mountain with a height of 2787 meters and its lowest point is at the exit of the plain in the village of Fadeshk with an altitude of 1240 meters above sea level. The average annual rainfall of the plain is 156 mm (average 30 years) and the average annual temperature is 16.4 ° C (figure 1).

2-2- Drastic Vulnerability Index

Vulnerability is the tendency or possibility of contaminants reaching a specific location in the groundwater system after production in some ground-level areas (Aller et al, 1985). In general, vulnerability is conceptually divided into two categories: intrinsic and special.

A) Intrinsic vulnerability: This type of vulnerability depends on the characteristics of the aquifer (hydraulic conductivity, hydraulic gradient and pores and stresses to the feeding system, reaction with surface water, time of movement through the saturation zone and pump blockage). In other words, the inherent vulnerability depends on the geological and hydrogeological characteristics and hydrogeology of an area and does not pay attention to the sources of pollution caused by human or natural activities.

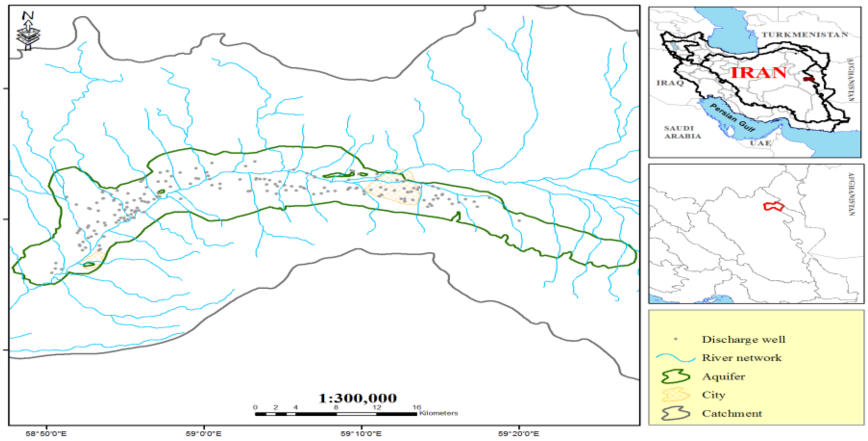

Fig. 1- Birjand aquifer area

B) Special vulnerability: This type of vulnerability indicates the vulnerability of groundwater to a specific pollutant or a group of pollutants from human activities, that is, special vulnerability arises from the reaction of pollutants with various components of intrinsic vulnerability. For example, if the aquifer is carbonate, depending on the type of human activity and the specific chemicals used, the reaction between them will create a special type of pollution for the aquifer. In fact, groundwater vulnerability depends on pollution, intrinsic sensitivity, location and type of pollution sources.

One of the indicators of vulnerability is the Drastic index, which was presented in 1987 by Aller to assess the vulnerability of groundwater resources in a descriptive ranking. This index consists of seven parameters that by weighting each of these parameters and the internal ranking of each parameter, the value of this index is obtained (Table 1). These parameters are depth to water table (D), aquifer nutrition (R), aquifer environment (A), soil type (S), topography (T), unsaturated zone (I) and hydraulic conductivity (C). The weights and ranks of the vulnerability index parameters are presented in Table (1). The vulnerability classification is also presented in Table (2).

Table 1- Introducing DRASTIC index parameters and their weighting

Depth G.W (m)		Recharge (mm)		Slope (%)		Hydraulic conductivity (m/day)		Aquifer media		Vados zone		Soil	
Class	Rank	Class	Rank	Class	Rank	Class	;rat	Class	Rank	Class	Rank	Class	Rank
0.1-1.5	10	0-50.8	1	0-2	10	0.4-4.1	1	Volcanic rock	2	Confining layer	1	Gravel	10
1.5-4.6	9	50.8-101.6	3	2-6	9	4.1-12.3	2	Silt	3	Clay/Silt	3	Sand	9
4.6-9.1	7	101.6-177.8	6	6-12	5	12.3-28.7	4	Sandstone +shale	5	Shale	3	Pit	8
9.1-15.2	5	177.8-254	8	12-18	3	28.7-41	6	Sandstone	6	limestone	3	Sandy loam	7
15.2-22.8	3	>254	9	> 18	1	41-82	8	Conglomerate	8	Sandstone	6	Loam sandy	6
22.8-30.4	2					>82	10	Sand and Gravel	8	Sand and Gravel	8	Loam	5
> 30.4	1							Basalt	9	Basalt	9	Silt-clay	4
								Karst	10	Sand and clay	10	Clay loam	3
												Impact clay	2
												Non infiltration	1
5	Weight	4	Weight	1	Weight	3	Weight	3	Weight	5	Weight	2	Weight

Table 2- DRASTIC index classification based on vulnerability

Classification Vulnerability	Class	Classification Vulnerability	Class
Can be ignored	46>	High vulnerability	137-184
Low vulnerability	47-92	Very high vulnerability	>185
Medium vulnerability	93-136		

According to Figure (2), by using groundwater level statistics in observation wells and interpolation method, Kriging, Zoning and finally classifying the depth to the water level (water level) was performed. Due to the location of Birjand aquifer in a dry climate infiltration caused by rainfall, surface runoff and return water were introduced as aquifer feeding sources (Figure 3). By using subsurface excavations (logs of exploratory drilling, piezometry and exploitation wells) and geophysical and geological excavations of the region, the parameter of the aquifer environment was obtained according to Figure (4). According to Figure (5), the soil type of the area was extracted and ranked by using existing 1: 100000 maps. By using 1: 25000 topographic maps of the surveying organization and using D8 algorithm, digital elevation map (DEM) and using Spatial Analyst tool, the slope map of the area was obtained. This map is ranked according to the standard of the drastic method and is presented in Figure (6). By using aquifer-drilling logs, sediment characteristics between the ground surface and groundwater level were collected and ranked according to Figure (7). By using the measured soil permeability data and using drilling logs, a relatively accurate estimate of the hydraulic conductivity in the aquifer was performed and presented according to Figure (8).

Fig. 2-Depth to water table

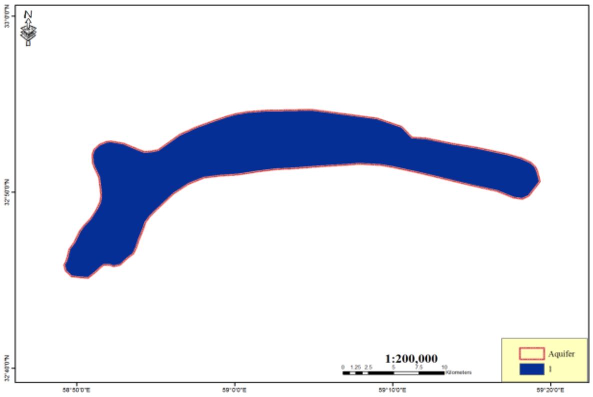

Fig 3- Aquifer recharge

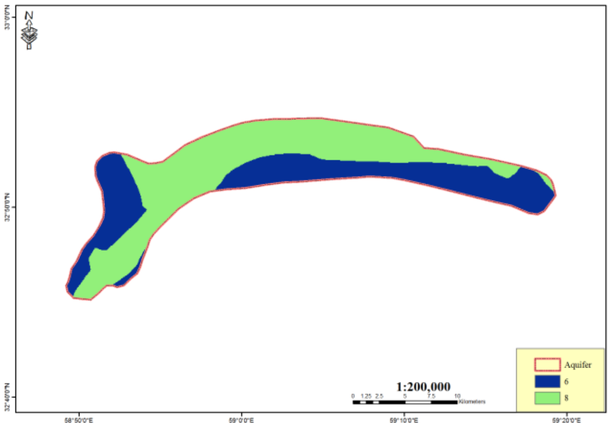

Fig. 4- Aquifer media

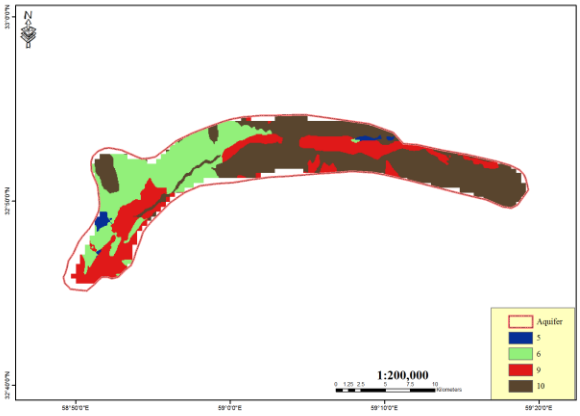

Fig. 5-Aquifer soil

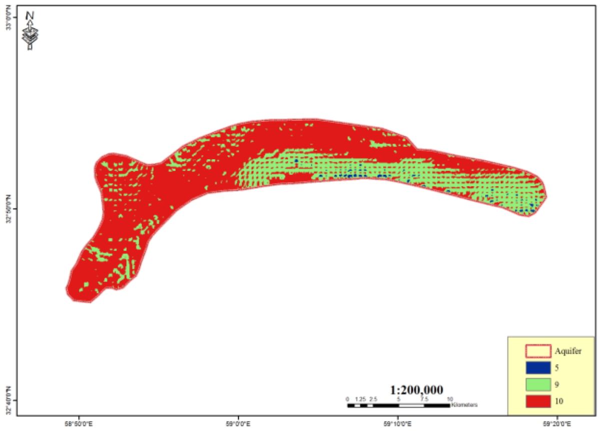

Fig. 6-Slope in aquifer

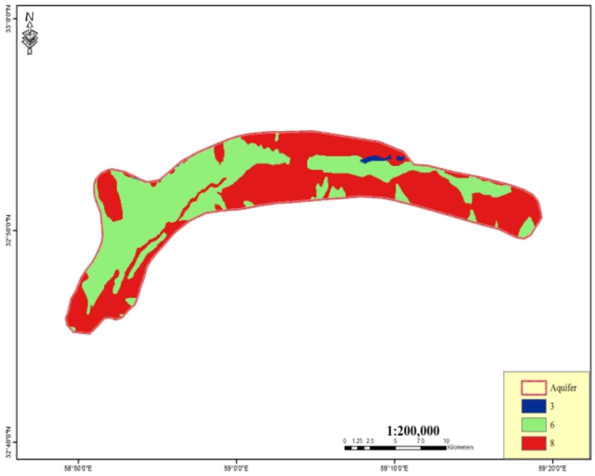

Fig. 7- Vados zone

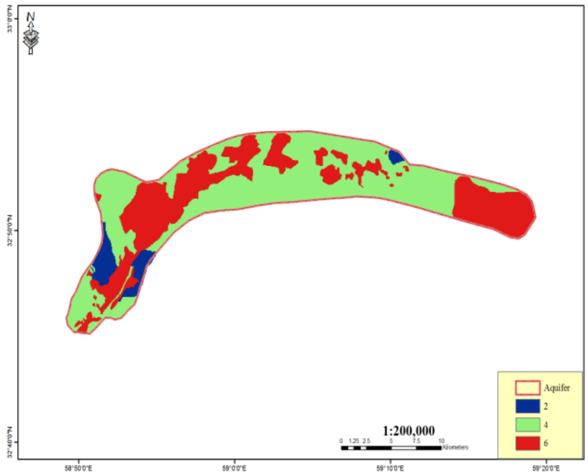

Fig. 8- Hydraulic conductivity

2-3- Analytic Hierarchy Process (AHP)

In the early 1970s, Thomas L. Saati developed a simple method for multi-criteria decision-making based on the four principles of inversion, homogeneity, dependence, and expectations. This method, which is used to make decisions with multiple criteria, allows the problem to be formulated in a hierarchical manner and has the possibility of considering different quantitative and qualitative criteria.

The weak point of the AHP method is that if even one of the factors or options to be compared are removed or added, the comparisons must be repeated and the calculations repeated. In principle, this problem is due to the nature of the two-by-two comparisons of all the factors and options evaluated in this method. Therefore, it is necessary to be extremely careful in formulating the model structure and selecting the factors and options to be compared. One of the most important advantages of the AHP method is having a mathematical basis on which the compatibility index is calculated, and if its value is greater than 0.1, it indicates that the given weights are not compatible with each other and should be reviewed. The AHP method is based on a hierarchical tree. A pair of matrices is used to determine the weight of ranks and characteristics. This matrix can be compatible or incompatible. For this purpose, we first obtain A^k.e as relations (1) and (2).

$$A^k.e = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} . \begin{bmatrix} 1 \\ . \\ 1 \end{bmatrix} = \begin{bmatrix} \sum\limits_{j=1}^{n} a_{1j} \\ . \\ \sum\limits_{j=1}^{n} a_{nj} \end{bmatrix} \qquad (1)$$

and the result of this phrase is divided by $e^T.A^K.e$.

$$e^T.A^k.e = [11....1]. \begin{bmatrix} \sum\limits_{j=1}^{n} a_{1j} \\ \sum\limits_{j=1}^{n} a_{nj} \end{bmatrix} = \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} \qquad (2)$$

The result of the expression $\frac{A^K.e}{e^T.A^K.e}$ is to power the matrix A, then add the rows together and form a column vector, and finally normalize the vector. In addition, the decision criterion for selecting the selected weight is the use of rate criterion of the matrix incompatibility, which has chosen the results of a number less than 0.1 as a criterion (Satie, 1980). One of the most important factors to improve the weights and ranks of the drastic model using the AHP method is to consider the Nitrate concentration in the observation wells and to determine the correlation between the Nitrate concentration and the vulnerability index.

2-4- Evaluation of Nitrate concentration

Nitrate is one of the most important and effective pollutants in the environment (Javadi et al, 2020). This parameter causes many diseases and environmental pollutants by converting to nitrite. The World Health Organization (WHO) has set a maximum permissible Nitrate standard of 50 mg / L. Nitrogen is widely used as a nutrient (fertilizer) in agriculture and horticulture. In addition to fertilizer, Nitrogen is produced in the soil in organic form from the decomposition of plants and animals. Different forms of Nitrogen in the soil are converted to Nitrate (NO3 ions) by bacteria. It is desirable that nitrogen be absorbed by plants in the form of Nitrate. Nitrate, however, penetrates easily from the soil layers to the ground by dissolving in water and, due to heavy rainfall or irrigation, reaches plant roots and eventually groundwater. The main source of groundwater pollution with Nitrate is either from point sources such as sewage disposal, livestock or from non-point sources such as fertilizer application in parks, golf courses, meadows and gardens. Digging water well in the right place and improving it can be effective in reducing the burden of Nitrate contamination. In this project, in order to investigate vulnerability by drastic method, observational Nitrate data were used in Birjand aquifer, which was tested in 2011. The location of the tested wells and the Nitrate zoning in the aquifer are shown in Figure (9).

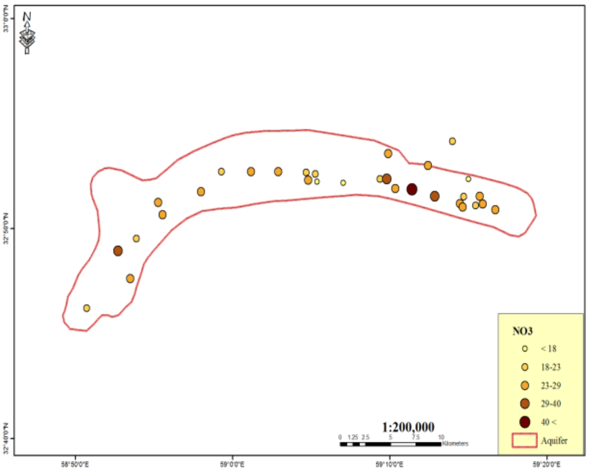

Fig. 9- Position of observation wells and Nitrate concentration in the aquifer

2-5- Land use assessment

Investigation of land use effects and various activities on land indicates the transmission of pollutants to groundwater. In this study, the situation of lands, especially in agriculture and urban, rural and industrial centers, which causes changes in ground water quality is investigated. For this purpose, by visiting the area and using satellite images, the land use map of the area was extracted and classified for modeling. According to the classification done by Alam in 2014, the rank of urban and industrial areas was selected as 10, rural and industrial developing areas as 9, and rural areas and agricultural lands as 8. In addition, the weight of land use parameter 5 was selected (Alam, Omar, Ahmad and Ahmaddar, 2014). Figure (10) shows the land use ranking in the project area.

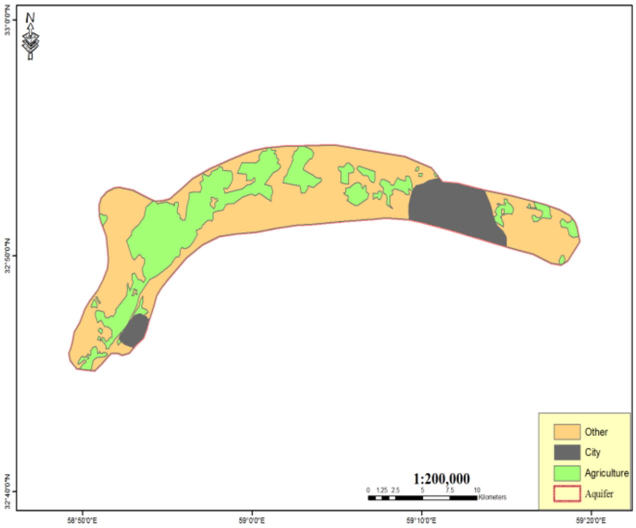

Fig. 10- Land use classification

2-6- Research method

In this study, using the collected information and Arc GIS 10.5 software, we first obtain the DRASTIC-LU vulnerability index and then by combining land use, the DRASTIC-LU index is achieved. Based on the results obtained from these two indicators, in order to increase the accuracy, we perform weighting and rankings. By using hierarchical analysis method and establishing a correlation between Nitrate concentration in observation wells and indices obtained, the weight and ranks of Drastic and DRASTIC-LU indices were calibrated. Figure (11) shows the flowchart of the work process of this research.

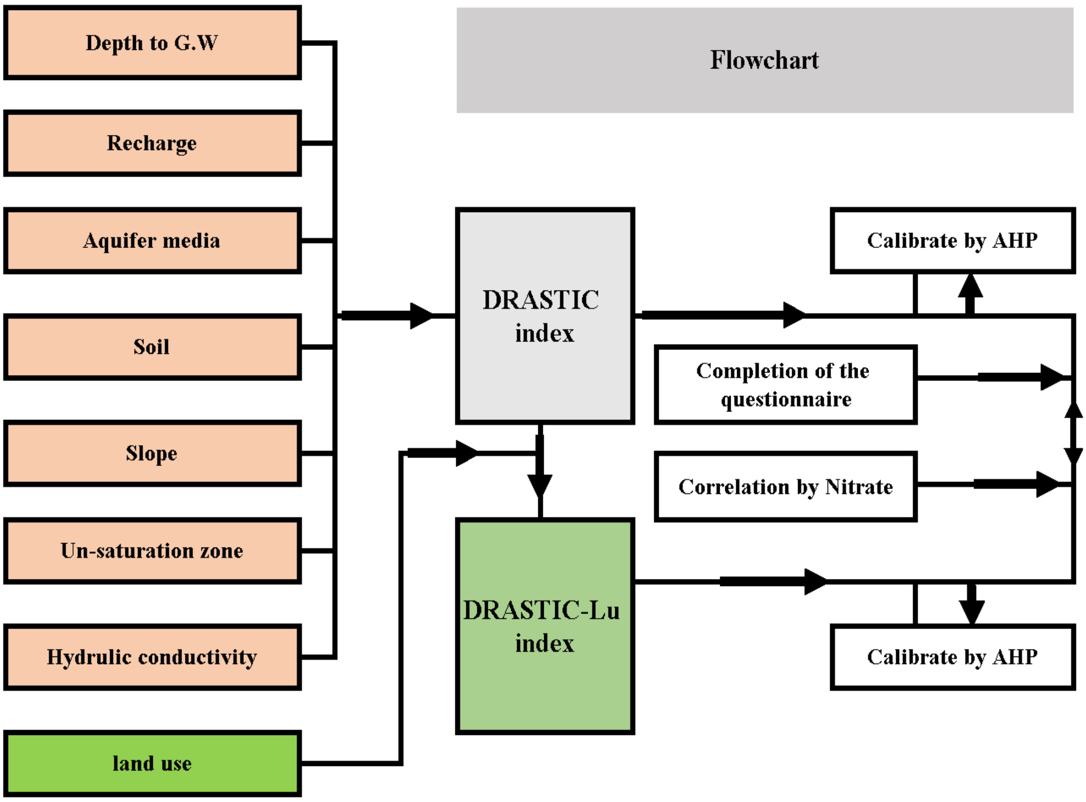

Fig. 11- Flowchart of research stages

3- Research findings

3-1 Evaluation of Drastic index and DRASTIC-LU

After preparing the required parameters for vulnerability assessment, the vulnerability map of Birjand plain aquifer was prepared by drastic method. In this method, by combining the parameters based on the following relationship, the vulnerability index is obtained in which **r** is the classified value of each parameter and **w** is the weight of each parameter.

Drastic Vulnerability Index: $D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w$

By combining the parameters according to the drastic computational relationship, the result is a network layer in which cells with larger numbers represent areas where the inherent vulnerability of groundwater to pollution is greater and cells with lower numerical value indicate areas where the inherent vulnerability of groundwater to pollution is lower. In the drastic model, the final index is the product of the numerical value of each parameter multiplied by the weight of that parameter. In this study, by using seven environmental parameters that were studied to show the vulnerability of the aquifer in the region, drastic model maps were prepared and by using these maps, the vulnerability index obtained from the linear combination of drastic parameters was calculated. Also, in order to estimate the DRASTIC-LU vulnerability index, the land use parameter is added to the accurately calculated index and finally this index is obtained. Figures (12) and (13) show the estimated DRASTIC and DRASTIC-LU models. Land use is very sensitive and effective due to the effective role of pollutants in an aquifer due to the type of activity.

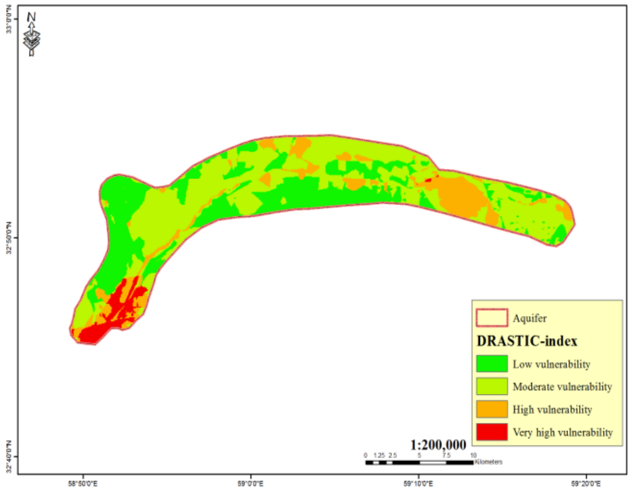

Fig. 12- Drastic model in the aquifer

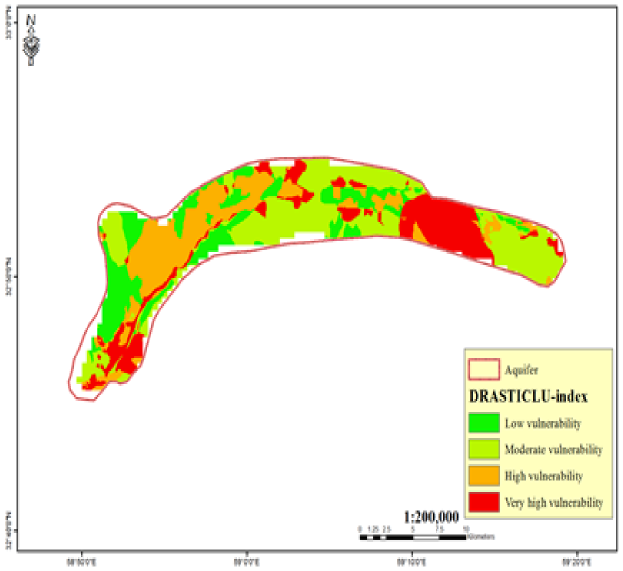

Fig. 13- DRASTIC-LU model in the aquifer

3-3- Calibration of DRASTIC and DRASTIC-LU models using AHP method

Considering the presentation of two vulnerability indicators and the compilation of weights and ranks based on the theory of these indices, it is necessary to check the accuracy of the vulnerability results in relation to the amount of contamination in the aquifer. For this purpose, by using the Analytic Hierarchy Process (AHP) and completing expert opinions in the form of a questionnaire of weight and rank of each parameter, two vulnerability indices were calibrated (Rahimzadeh kivi et al, 2015). A correlation was established between Nitrate concentration in aquifer measuring wells and the results obtained from Drastic and DRASTIC-LU indices to calibrate the weight of the parameters and a correlation was established between the parameters of vulnerability index and Nitrate for calibration of ranks. Tables (2) and (3) show the final weights and ranks of both Drastic and DRASTIC-LU before and after calibration. According to the definition of incompatibility coefficient in this method as a constraint for extracting coefficients, this coefficient is 0.08 in the initial case and 0.09 in the case of land use layer, which is accepted as safe values. By using the AHP method in Expert choice software, figures (14) and (15) show the weights obtained. Spearman correlation (ρ) between Nitrate concentration in the measured wells and vulnerability index obtained before and after calibration according to Table (4) was used for accuracy in calibration. Preliminary results showed that land use had an important role in vulnerability and the study of its effect on vulnerability index could be more accurate in identifying areas prone to pollution. So that the correlation value in Drastic index has increased from 0.21 to 0.42. In addition, after calibration of DRASTIC-LU index, the correlation between Nitrate concentration and vulnerability index value increased to 0.65, indicating the appropriate accuracy for calibration. The results of correlation in different cases of vulnerability index and Nitrate concentration have been presented in Table (4).

Table 2 - Weight and calibration ratios with hierarchical analysis method for Drastic model

Parameter name	Drastic Initial *Weight	Drastic correction Weight	Rank					
Depth to G.W	0.217	0.314	Initial Rank	1	2	3	5	7
			Rank with AHP	0.469	0.267	0.141	0.082	0.041
Slope	0.174	0.031	Initial Rank	5	9	10		
			Rank with AHP	0.667	0.222	0.111		
Hydraulic conductivity	0.13	0.186	Initial Rank	2	4	6		
			Rank with AHP	0.667	0.222	0.111		

Zone Vados	0.087	0.18	Initial Rank	3	6	8	
			Rank with AHP	0.731	0.188	0.081	
Soil	0.043	0.072	Initial Rank	2	4	5	6
			Rank with AHP	0.469	0.315	0.137	0.079
Recharge	0.217	0.166	Initial Rank	1	3		
			Rank with AHP	0.75	0.25		
Aquifer media	0.13	0.051	Initial Rank	6	8		
			Rank with AHP	0.75	0.25		

Table 3- Weights and Calibration Ranks by Hierarchical Analysis Method for DRASTIC-LU Model

Parameter name	DRASTIC-LU Initial weight *	DRASTIC-LU correction weight	Rank					
Slope	0.179	0.276	Initial Rank	1	2	3	5	7
			Rank with AHP	0.427	0.287	0.15	0.086	0.05
Hydraulic conductivity	0.143	0.025	Initial Rank	5	9	10		
			Rank with AHP	0.7	0.22	0.08		
Vados Zone	0.107	0.152	Initial Rank	2	4	6		
			Rank with AHP	0.65	0.25	0.1۱		
Soil	0.071	0.163	Initial Rank	3	6	8		
			Rank with AHP	0.73	0.2	0.07		
Recharge	0.036	0.061	Initial Rank	2	4	5	6	
			Rank with AHP	0.42	0.33	0.16	0.09	
Aquifer media	0.179	0.122	Initial Rank	1	3			
			Rank with AHP	0.7	0.3			
Slope	0.107	0.043	Initial Rank	6	8			
			Rank with AHP	0.78	0.22			
land use	0.179	0.158	Initial Rank	0	8	9	10	
			Rank with AHP	0.02	0.086	0.235	0.659	

* - The initial weights of the model are presented in a normalized way.

Inconsistency = 0.08
with 0 missing judgments.

Fig. 14- Estimation of drastic model parameters in Expert choice software

Inconsistency = 0.09
with 0 missing judgments.

Fig. 15- Estimation of DRASTIC-LU model parameters in Expert choice software

Table 4-Correlation between the implemented models with the Nitrate concentration of the region

Row	Model Name	Correlation Coefficient	Row	Model Name	Correlation Coefficient
1	DRASTIC	0.21	3	DRASTIC calibrated	0.37
2	DRASTIC-LU	0.42	4	DRASTIC-LU calibrated	0.65

After calibrating the weight and rankings of Drastic and DRASTIC-LU vulnerability indices, these two indices were prepared in GIS software and presented in Figures (16) and (17). The results show that in the DRASTIC-LU index, the role of land use clearly shows its effect and the location of Birjand city and agricultural lands that have high potential for production and transmission of pollution are in moderate and high vulnerability. The results of vulnerability assessment studies based on the index DRASTIC-LU indicate the important and effective role of land use in its accurate determination. Studies Ncibi et al (2020), Kumar and Pramod Krishna (2020) and Zafane et al, 2017 also indicate an increase in the accuracy of the vulnerability index in increasing land use.

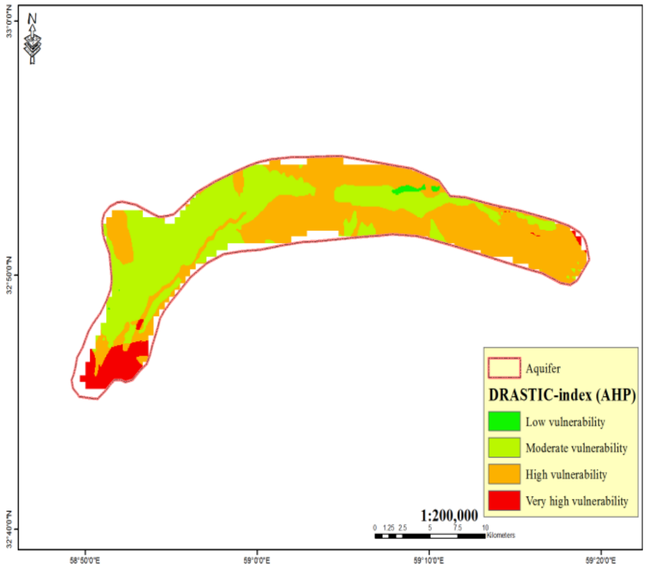

Fig. 16- Drastic model calibrated with AHP in the aquifer

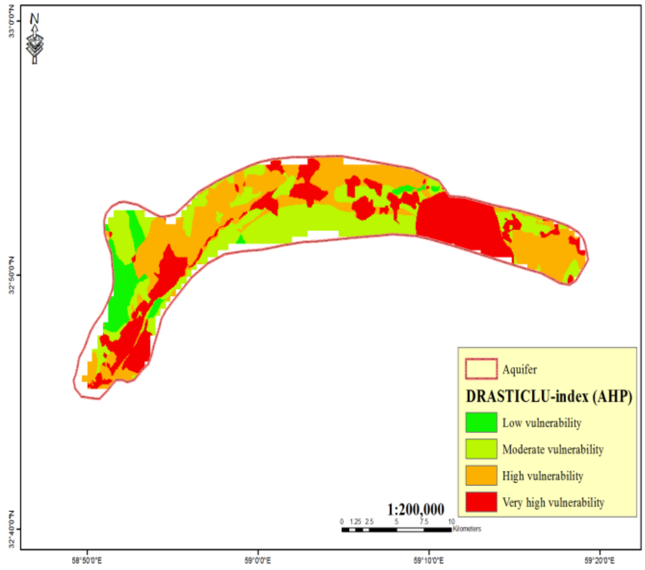

Fig. 17- DRASTIC-LU model calibrated with AHP in the aquifer

4- Discussion and conclusion

In recent years, the use of groundwater vulnerability outcomes has become an effective tool for designing and deciding on aquifer conservation (Vias, Andre, Perles, & Carrasco, 2005; Gingai, Yanjin, Zhubo, & Tang, 2007). The results of the drastic model showed that the model did not have sufficient accuracy in identifying vulnerable areas and needed to calibrate the weights and ranks of the model. Various studies have been performed to calibrate the Drastic Vulnerability Index, each of which, in addition to improving the weight and ranks of the index, has been able to identify sensitive areas in terms of the potential for infection. Investigation of the effect of different land uses on the inherent vulnerability of the aquifer can also be seen in the Drastic index due to its effect on the volume, transmission and transfer rate of contaminants. In 2014, Elm introduced the new DRASTIC-LU index by adding a land use parameter to the Drastic index. The role and effect of land use is important according to the volume of water returned from drinking, industrial and agricultural uses and the type of use in terms of production of point pollutants (domestic and industrial uses) and regional pollutants (agricultural lands). In this study, after using the new model to evaluate the efficiency of the model, the correlation of the final index with the Nitrate concentration in the region was used. The results of correlation indicate a high ratio between DRASTIC-LU and Nitrate concentration in the region. The correlation rate of 0.65 was introduced as a suitable criterion for selecting vulnerable areas and by using the Analytic Hierarchy Process (AHP) and Expert Choice software with eight parameters, the model input and their internal rankings were analyzed and calibrated. The results of weight calibration show that the depth to the water table in the DRASTIC-LU index has decreased compared to the Drastic correction index, which is due to the low groundwater level in arid areas and its lower impact on the vulnerability. In addition, considering land use and its effect on the transfer of pollutants, especially in agriculture and drinking in dry areas can determine the vulnerability of the aquifer more accurately.

5- Conflicts of Interest

No potential conflict of interest was reported by the authors.

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