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Assessment of groundwater vulnerability and sensitivity to Pollution in Aquifers Zanjan Plain, Iran

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Abstract: Groundwater pollution caused by human activity is a serious environmental problem in cities. Pollution vulnerability assessment of groundwater resources provides information on how to protect areas vulnerable to pollution. The present study is a detailed investigation of the potential for groundwater contamination through construction of a vulnerability map for the study aquifer in Zanjan plain. The parameters used in the DRASTIC model are depth-to-water table, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity. The overlying index, GIS and AHP were used with the modified DRASTIC model to evaluate the vulnerability of the alluvial Zanjan aquifer to nitrates. AHP was used to determine the rate coefficient of each parameter. The correlation coefficients were produced by comparing the vulnerability index with the nitrate concentrations in the groundwater. The results show that the DRASTIC index values for the study area ranged from 82 to 186 and were divided into low, medium, and high vulnerability classes. GIS was found to provide an efficient environment for such analyses. The DRASTIC aquifer vulnerability map indicates the dominance of the medium vulnerability class in the most parts of the study area (49.033%). The high correlation coefficient for the modified DRASTIC index (0.92) and nitrate layer than for the standard DRASTIC model (0.74) suggests that the actual condition in the study area can be better explained by the modified DRASTIC model.

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The greatest challenge of assessing groundwater vulnerability is the optimal balance between the complexity of methods, costs and uncertainty of results' evaluation and it is important to consider accuracy and validity of vulnerability zoning in previous neglected studies for vulnerability zoning methods.

Abundant groundwater can play a role in providing emergency water for sustainable urban development. However, there are still few studies on the prevention and control of groundwater pollution in Zanjan. Therefore, research on groundwater vulnerability is essential to ensure groundwater quality and to achieve sustainability of groundwater resources. Vulnerability zoning the of the mentioned plain on nitrate ion as an contamination index from agricultural and urban wastewater sources has been performed by correcting the weight of DRASTIC parameters based on Analytical Hierarchy Process (AHP) in geographic information system (GIS).

Validation of groundwater vulnerability to evaluate the role of nitrate by DRASTIC model: To validate the application of DRASTIC model, the relationship between the vulnerability index and nitrate concentration values from 14 underground water samples was examined. To determine the statistical relationship between groundwater nitrate concentration and aquifer vulnerability maps, simple linear regression analysis for DRASTIC model was used in Excel software. The calculated correlation coefficient between the vulnerability index and nitrate concentration was 0.81 (Fig.). With the help of observations, this correlation value shows that calibration and correction of DRASTIC model can be done to obtain the vulnerability of groundwater.

Calibration and correction of weight of the model indices: The weight of indices indicates their relative importance. Similar indices in different regions have different effect on the vulnerability of groundwater. The weight of indices in DRASTIC model may not be definite and needs to be corrected. In this study, the hierarchical analysis process method was used to determine the optimal weight of each parameter. Verification of weights was obtained by examining each parameter with nitrate concentration at sampling points. The Analytic Hierarchy Process (Saaty, 1980) has been developed based on the separation and breakdown of complex issues into simpler parameters and sub-parameters. In this method, parameters are binary compared to one another and are valued the relative weights of each parameter are calculated from the resulting matrix. Huge data and the dependency of parameters are other challenges ahead in using this method, which their effects are determined after the calculation of incompatibility coefficient. According to the above description, seven parameters of DRASTIC model were prioritized based on the importance of determining the vulnerability and then the matrix was established, which inputs were weights determined by the expert's knowledge and outputs were relative weights related to the criteria. Results of weighing the criteria in DRASTIC model using the AHP method are given in Table.

Then data layers were combined based on weights obtained from the hierarchical analysis process and finally, the correlation between vulnerability and nitrate concentration was determined. After applying the corrected weights of these parameters, the correlation between vulnerability and nitrate concentration increased to 0.90. After applying these parameters, the correlation between risk and nitrate concentration reached 0.90.

Study Area: The study area is located in Zanjan plain in northwestern Iran from 47°25′ to 48°54′ longitude and the Ghezel Ozan River to the east and between 36°27′ and 37°15′ N latitude. This area is located in the Zanjanrood watershed and it encompasses 2286 km2. The average rainfall is 290.9 mm/year with temperatures ranging from 25.8°C in the daytime in summer to -1.4°C in winter. The area features quartzite deposits and is surrounded by the Soltaniyeh and Taromeh mountains. The surrounding heights are composed of Precambrian formations relative to the surrounding Horst faults. The study aquifer has been classified as unconfined.

MATERIALS AND METHODS

The seven parameters of the DRASTIC model used in this study. As know, the DRASTIC vulnerability index is divided into four classes ranging from no vulnerability risk to completely vulnerable (Piscopo, 2001). The method yields a numerical index that is derived from ratings and weights associated with the seven parameters. The significant classes of each parameter represent the ranges, which are rated from 1 to 10 based on their relative effect on the aquifer vulnerability. The seven parameters are then assigned weights ranging from 1 to 5 to reflect their relative importance. A numerical value, the vulnerability index, is then obtained by multiplying the rating with its corresponding weight in the DRASTIC model. The DRASTIC index is computed applying a linear combination of all mentioned factors according to the following equation:

$$\text{DRASTIC Index} = DrD_W + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw$$

where the letters D,R,A,S,T,I, and C stand for the seven parameters used in the model and the indices r and w represent the rating and the weight assigned to a parameter, respectively. The intrinsic DRASTIC vulnerability index is derived by multiplying the parameter weight and its corresponding rating (Al-Adamat et al., 2003). The numerical ratings and weights, which are established using the Delphi technique (Aller et al., 1987), are well defined and used worldwide (Dixon, 2005; Anwar and Rao, 2003; Chandrasekhar et al, 1999; Al-Adamat et al., 2003).

DRASTIC Parameters: Assessment of aquifer vulnerability to pollution

Depth-to-water table: The depth from the ground surface to the water table in an unconfined aquifer and to the bottom of the confining layer in a confined aquifer is termed the depth-to-groundwater. The depth-to-water affects the time available for a contaminant to undergo chemical and biological reactions. In other words, it represents the depth across which a contaminant should travel to reach the water table. A high depth-to-water parameter will result in a lower vulnerability probability (Rahman, 2008). The depth-to-water layer was prepared based on existing piezometric data for the study area. The Raster calculator was then used to develop a Raster model for depth-to-water table.

Net recharge: The net recharge is the total amount of water applied at the ground surface that infiltrates to reach the aquifer. A higher net recharge value results in a higher vulnerability rating; therefore, the amount of recharge positively correlates with the vulnerability rating. The net recharge index can be calculated using the Piscopo method (2001) based on the following equation:

$$\text{Recharge Index} = \text{Slope } (\%) + \text{Rainfall} + \text{Soil Permeability}$$

To do this, a digital elevation model (DEM) of the study area was generated using the topographic map. The slopes in the study area were then derived from the DEM. The resulting slope map was converted into grid coverage by basing the pixel values in this grid coverage on the slope ratings. Both grids were combined with the rainfall rating, which equaled 1 in the study area.

Aquifer media: The aquifer media and its constituents affect the ability of the aquifer to transmit water; thus, it determines the rate of flow of contaminant material in the groundwater system (Al-Rawabdeh et al., 2013). Well logs available for the study area were used to prepare the aquifer media layer (Awawdeh and Jaradat, 2010). First, the aquifer media rating was calculated for each well based on the criteria. Next, the aquifer media layer was prepared and converted to grid coverage using the ratings and well locations.

Soil media: Soil media represents the uppermost weathered portion of the unsaturated zone and controls the amount of recharge that can infiltrate downward. Soil infiltration can be affected by the structure of the soil surface. Fine soil media with the texture of silt-clayey loam, for instance, have lower permeability rates than coarse soil media such as sand dunes (Javadi et al., 2011). The resource and soil fertility map of the study area prepared by the Environmental Resource Office of Zanjan province was used to prepare the soil media layer. A hardcopy of this map was scanned and the polygons were assigned ratings using GIS.

Topography: This is the slope and slope variability of the land surface that dictates whether or not runoff will remain on the surface to allow contaminant percolation into the saturated zone. The topography of the land affects groundwater vulnerability because the slope of the land helps determine whether the contaminant released will become runoff or infiltrate the aquifer. A mild slope means that contaminant is less likely to become runoff and more likely to infiltrate the aquifer; areas with mild slopes receive a higher vulnerability rating. The topography layer was prepared based on the slope map of the study area and was then classified according to the criteria.

Effect of vadose zone: The vadose zone is a zone above the water table which is unsaturated or discontinuously saturated. The effect of the vadose zone on aquifer vulnerability is the same as that of soil media and depends on the soil permeability and the properties of the unsaturated zone. Preparation of the effect of vadose zone layer is the same as for the aquifer media layer. This layer was prepared based on the texture of interbedded deposits from the land surface to the water table.

Hydraulic conductivity: This refers to the ability of the aquifer materials to transmit water; hence, it controls the passage and attenuation of the contaminant material to the saturated zone. Hydraulic conductivity is affected by the fractures, bedding planes, and inter-granular voids in the aquifer. These components become pathways for fluid movement and for contaminant movement once a contaminant enters the aquifer. The hydraulic conductivity is positively correlated with the vulnerability rating. Pump- test data was used to derive hydraulic conductivity data and to prepare the conductivity layer. The transmission coefficient values were calculated for all wells with regard to the thickness of the saturated zone and then the hydraulic conductivity map of the study area was developed using DRASTIC classification.

Preparation of vulnerability map: Once the necessary data was collected to prepare the vulnerability map, the DRASTIC vulnerability index was computed by applying a linear combination of all seven model parameters. Data analysis and model implementation included assigning sensitivity ratings to mapped attributes and combining or overlaying individual characteristic maps to create the final cumulative vulnerability map using GIS(Aller et al., 1987).

Application of the model yielded a numerical index derived from the ratings and weights assigned to the model parameters. The significant media types or classes of each parameter represent the ranges. The parameters were then assigned weights reflecting their relative importance. GIS coverage is in Raster format and values for each overlay are summed according to the pixel value of each area that results from multiplying the ratings with the appropriate DRASTIC weight.

RESULTS AND DISCUSSIONS

Regarding to increased correlation coefficient of modified DRASTIC index and nitrate concentration compared to the normal DRASTIC model, it can be concluded that results of the modified model was in more compliance with real conditions of the area.

With increasing contamination and urbanization, increasing agricultural and industrial activities and as a result increased pollution due to urban wastewater, agricultural and industrial waste against the increased demand for drinking water, there should be decisive environmental monitoring and management in the study area, which of course will only be achieved by the participation of people, experts, officials and managers. This study is a very important tool for management and development, because consider full details of the groundwater vulnerability and now it's time that shareholders in the water and environment sectors and local authorities use this method of vulnerability as a tool for making decisions and developing sustainable solutions to protect these resources.

Fig.1: groundwater vulnerability to pollution m

Table 1: Vulnerability Index, Class and Corresponding Area.

Vulnerability Class	DRASTIC Index	Area in km2	Percentage of area
Moderate	101-140	1121.07	49.03
High	141-186	1067.99	46.71
Low	82-100	97.29	4.25

Validation of DRASTIC Vulnerability Index: Nitrate ion concentrations in 14 groundwater samples were used to validate the results of DRASTIC. Simple linear regression was used by running the model in Excel to determine the correlation between groundwater nitrate concentrations (nitrate layer) and the aquifer vulnerability maps. The correlation coefficient for the vulnerability index and nitrate concentrations was determined to be 0.81 (Figure 2). This value confirms the necessity of validating the DRASTIC vulnerability index using nitrate ion concentrations.

Modification of weights in DRASTIC index and reassignment of optimal weights for each parameter: Every parameter in the model has a fixed weight that denotes the relative influence of that parameter in transporting contaminants to the groundwater. Applying similar parameters and indices to different areas produced mixed vulnerability results. The parameter weights in DRASTIC may be indefinite; thus, it was necessary to modify their relative significance in DRASTIC. In the present study, the analytic hierarchy process (AHP) was used to determine the optimal weight of each parameter. The parameter weights were reviewed and modified using AHP and by correlation analysis between DRASTIC parameters and nitrate ion concentrations in location samples. AHP involves structuring the multiple choice criteria on to a hierarchy, assessing the relative importance of these criteria, Comparing alternatives for each criterion and determining an overall ranking of the alternatives (Saaty, 1980). It is based on the well-defined mathematical structure of consistent matrices and the associated ability of the right eigenvector to generate true or approximate weights. AHP compares criteria, or alternatives, with respect to a criterion in binary pairwise mode. To do so, AHP uses a fundamental scale of absolute numbers that have been proven in practice and has been shown to capture individual preferences with respect to quantitative and qualitative attributes just as well as or better than other scales. It converts individual preferences into ratio scale weights that can be combined into a linear additive weight for each alternative. The resultant weight can be used to compare and rank the alternatives. The seven parameters of the DRASTIC model were prioritized based on their individual influence in transporting contaminants to the groundwater and their individual significance in determining the vulnerability index. A pair-wise comparison matrix was then generated by author expertise using the Saaty scale. Next, the thematic layers based on the AHP were combined and the correlation coefficient between the DRASTIC vulnerability index and nitrate ion concentration were calculated (Figure 2). The correlation coefficient between nitrate ion concentration and pollution risk reached was 0.92 using the modified weights of the parameters (a.b).

Thus, the sum of the weight age of the pollutants obtained as $\sum_{i=1}^{7} w_i = 1$. Where, CI=0.034 , CR=0.026. Since, CR < 0.1, the judgments are acceptable.

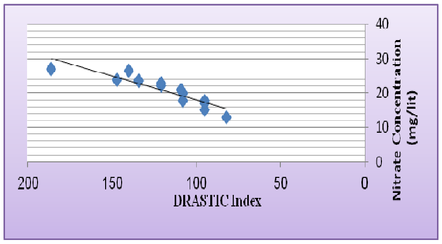

Fig.2 Relative Drastic Index and Nitrate Concentration

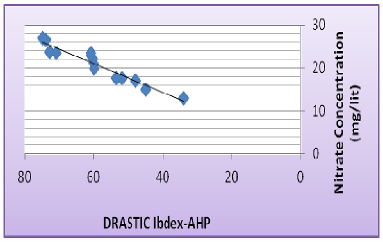

Fig.3 Relative Drastic Index- AHP and Nitrate Concentration

Sensitivity of DRASTIC: Table 2 summarizes the data for the seven parameters used to calculate the DRASTIC index for Zanjan plain. Analysis shows that the greatest risk of groundwater contamination was from depth-to-water table, impact of vadose zone and hydraulic conductivity (respective averages of 1.36, 1.31 and 1.09). The net recharge and aquifer media were of moderate risk (respective averages: 0.967 and 0.714) and soil media and topography were low risk (respective averages: 0.357 and 0.224). The greatest contribution to variation in the index of vulnerability was for topography (CV: 68.6%). The net recharge, impact of vadose zone, depth-to-groundwater and aquifer media showed an average contribution (respective CV: 67.58%, 57.6%, 53.1% and 51.8%) and hydraulic conductivity and soil media showed medium to low vulnerability (respective CV: 15.7 and 12. 8).

Table 2: The summary statistics of drastic parameters

	D	R	A	S	T	I	C
Min	0.504	0.179	0.238	0.32	0.04	0.236	0.872
Max	2.52	1.79	1.19	0.39	0.4	2.36	1.09
Average	1.36	0.967	0.71	0.357	0.224	1.31	0.981
SD	0.72	0.652	0.369	0.046	0.154	0.757	0.154
CV%	53	67.5	51.8	12.8	68.6	57.6	15.7

Analysis of the DRASTIC aquifer vulnerability map indicated the dominance of moderate and low vulnerability to contamination in most of the study area (53.28%) (Table 1).

This resulted from a combination of type of soil media (fine-grained soils and thick shale), a deep water table, and low permeability. The western and northwestern parts of the study aquifer and small areas in the northeastern study area were characterized by high vulnerability. This pattern was mainly dictated by the variation in slope (relatively steeper slope), the existence of coarse-grained soils produced mainly from the deterioration of granite and basalt rock and limestone layers with high permeability. The higher correlation coefficient for the modified DRASTIC index and nitrate layer than for that of the standard DRASTIC model suggests that the actual conditions in the study area can be better explained by the modified version of DRASTIC model than by the standard model.

*Conclusion***:** Seven hydrogeological parameters were used to show the aquifer vulnerability in the study area. These parameters include Depth to water table, net nutrition, aquifer environment, Soil environment, topography, effect of non-saturated environment and hydraulic conductivity of aquifer. The generated maps for each parameter were classified according to the rankings of DRASTIC method. Then, the layers were combined using the weights provided by DRASTIC model and the vulnerability map was prepared based on DRASTIC index (Figure 8). Drastic model determines various vulnerability districts more accurately. The reason is more characteristics and different weightings based on their role in determining the contamination. In this method, due to large number of characteristics, the uncertainty effect of some characteristics is somewhat eliminated. So that, when uncertainty of one characteristic is high in Drastic method, its effect is partially covered by other characteristics.

The overall results of the study showed that a large part of the area (53.28%) had low and moderate vulnerability (Table 5). This area showed reduced vulnerability severity due to the presence of fine grained soils, thick shale and high water table depth. Other parts with potential vulnerabilities were found in the west and northwest directions as well as a part of the northeast aquifer area, which was because of steep slopes and coarse grained soil mainly due to the destruction of granite and basalt stones and calcareous masses with a high hydraulic conductivity and It was found that it has a high potential for contamination.

*Suggestions***:** According to the results of this study, the method used in this here is a suitable method for assessing the potential of groundwater contamination. This method can be used for all aquifers in the country to manage and maintain the quality of groundwater resources. Because removal of contamination in groundwater resources is costly, the zonings can be used as a valuable tool for custodians and authorities to help them make the necessary decisions for managing Zanjan aquifer. Now that, different areas of the plain have been investigated in terms of potential contamination, it is suggested that to determine contamination values in each area and then compare these values with standard values for drinking and agricultural use.

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