Assessment of Groundwater Nitrate Pollution and Determination of Groundwater Protection Zones Using DRASTIC and Composite DRASTIC (CD) Models: The Case of Shiraz Unconfined Aquifer

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Abstract

Background: Groundwater nitrate pollution is an important environmental problem in water resources management. In this regard, specific measures aiming at prevention of water pollution will be helpful to managers and decision-makers. Identification of aquifers' vulnerable areas and determination of groundwater protection zones using most widely used models, such as DRASTIC and CD, are one of the most useful approaches in water resources' hygiene.

Objective: The present study aimed to assess the vulnerability of Shiraz plain's unconfined aquifer using the above-mentioned models.

Methods: The main hydro-geologic factors affecting the transmission of pollution, including depth to water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone, aquifer hydraulic conductivity, and land use parameters were rated, weighted, and integrated using GIS 9.3. Finally, the maps of Shiraz plain's unconfined aquifer vulnerability were prepared.

Results: The vulnerability maps based on these two indexes showed very similar results, identifying the southeastern part of the aquifer, around Maharlu Lake, as the vulnerable zone. The observed nitrate concentrations from the wells in the underlying aquifer were in accordance with these findings. The results of sensitivity analyses indicated the depth parameter as the most effective parameter in vulnerability assessment of Shiraz plain.

Conclusion: As Shiraz plain has been covered with fine-grained sediments, except for some central and south-east regions which have moderate vulnerability and high nitrate concentration, its vulnerability is low. Given the intensive agricultural activities and also the rise in groundwater level in southeastern regions, more attention should be paid to these areas.

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Introduction

Groundwater is considered to be the most important and valuable water resource all over the world. These resources are the main sources of water supply among arid and semi-arid areas, including Iran, especially its southern areas.[1,2]

In the recent years, increase in the use of agricultural fertilizers, existence of no proper sewage systems, and indirect discharge of domestic, industrial, and agriculture effluents into the aquifers have caused groundwater contamination by several types of pollutants, especially nitrate, so that diffuse nitrate pollution is currently considered as one of the major causes of deteriorating water quality.[3,4]

In response to the environmental and health implications of this phenomenon, water resources managers apply groundwater vulnerability assessment and determine the protection zones.

The first term, "vulnerability", refers to the tendency or likelihood of contaminants to reach a specified position in the groundwater system after introduction at some locations above the uppermost aquifer.[5] This definition is based on the assumption that the physical environment may provide some degree of protection to groundwater against natural and human impacts, especially with respect to the contaminants entering the subsurface environment.[6,7]

The second concept, "groundwater protection zone", refers to the process of protecting a drinking water source by determining what area of land should be protected to minimize the potential of groundwater pollution by human activities and various land uses that occur on or below the land surface.[8] The relationship between the two concepts is that after determination of susceptible areas by vulnerability models, those areas will be considered as a protection zone which must be managed to prevent its water quality from deteriorating.

To achieve this aim, researchers apply two hydrogeological models, including DRASTIC and Composite DRASTIC (CD) models.

DRASTIC is among the most widely used methods to determine the vulnerability of aquifers. It was introduced by the United States Environmental Protection Agency (USEPA) and American Water Works Association (AWWA) for the first time.[9,10]

DRASTIC model is defined as "a composite description of all the major geologic and hydrologic factors that affect and control the groundwater movement into, through, and out of an area". The acronym DRASTIC is derived from the initials of the seven parameters used in the model, namely Depth to water (D), net Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of vadose zone (I), and hydraulic Conductivity (C).[11]

Some authors have incorporated land use parameter (L) into the DRASTIC model with the aim of designating nitrate vulnerable zones with a greater degree of accuracy. This model is known as "Composite DRASTIC" (CD index) and attempts to evaluate the potential effect of extensive land use upon groundwater quality resulting from alterations in the soil matrix and unsaturated zone media over time.[12]

Up to now, numerous studies have been conducted in the field of groundwater vulnerability using DARSTIC model, including the vulnerability assessment of shallow aquifer in Aligarh, India,[6] Senirkent-Uluborlu Basin, Turkey,[13] shallow aquifer of Kathmandu Valley, Nepal,[14] Khanyounis Governorate aquifer,[15] Zhangye Basin, China,[16] Southern Korea,[17] and coastal region of Oman, Barka.[18] The CD index was also applied by Al-Adamat (2003) to determine nitrate vulnerable zones for the basaltic aquifer of the Azraq basin of Jordan[19] and by Martinez-Bastida (2009) in central Spain.[12]

Objectives

In the recent years, immense Shiraz plain has been struggling with drought and water table decline, and now it is faced with the degradation of groundwater quality. Therefore, to identify the areas prone to nitrate contamination, the present study was conducted to investigate the vulnerability potential of Shiraz plain aquifer using DRASTIC and CD models in Geographic Information System (GIS) and to identify groundwater protection zones.

Materials and Methods

The Study Area

The current research was conducted in the first half of 2014 and the study area was Shiraz plain on which Shiraz, Fars province is located (figure 1). This plain with an area of about 300 km^2 is a part of Maharlu lake catchment. It lies between longitude 52^0 29′ to 52^0 36′ E and altitude 29^0 33′ to 29^0 36 N and is located in the south-west area of Iran. This plain is a closed basin and is similar to a Syncline. It is limited by Baba-Koohi and Kaftrak mountains to the north, by Derak mountain to the north-west, and by Fasa bridge and Maharlu Lake to the south. Studies have shown that Shiraz plain alluvial is layer by layer and clay layers are between the water-bearing layers in a way that alluvial deposits have uneven thickness and sand layers are located between the clay and silt layers. In addition, geophysical explorations in the plain have demonstrated that Shiraz plain's water-bearing layer was limited to a depth of 200 meters and if there is a water-bearing layer in greater depths, it suffers from inappropriate quality. According to previous studies, Shiraz plain's groundwater aquifer is classified into two categories, including shallow and deep aquifers. Shiraz has two seasonal rivers, Khoshkrud and Chenarrahdar. As figure 1 displays, the Asmari limestone formation has the most outcrops in the area. The average height of Shiraz plain is 1540 m above the sea level. Climatically,

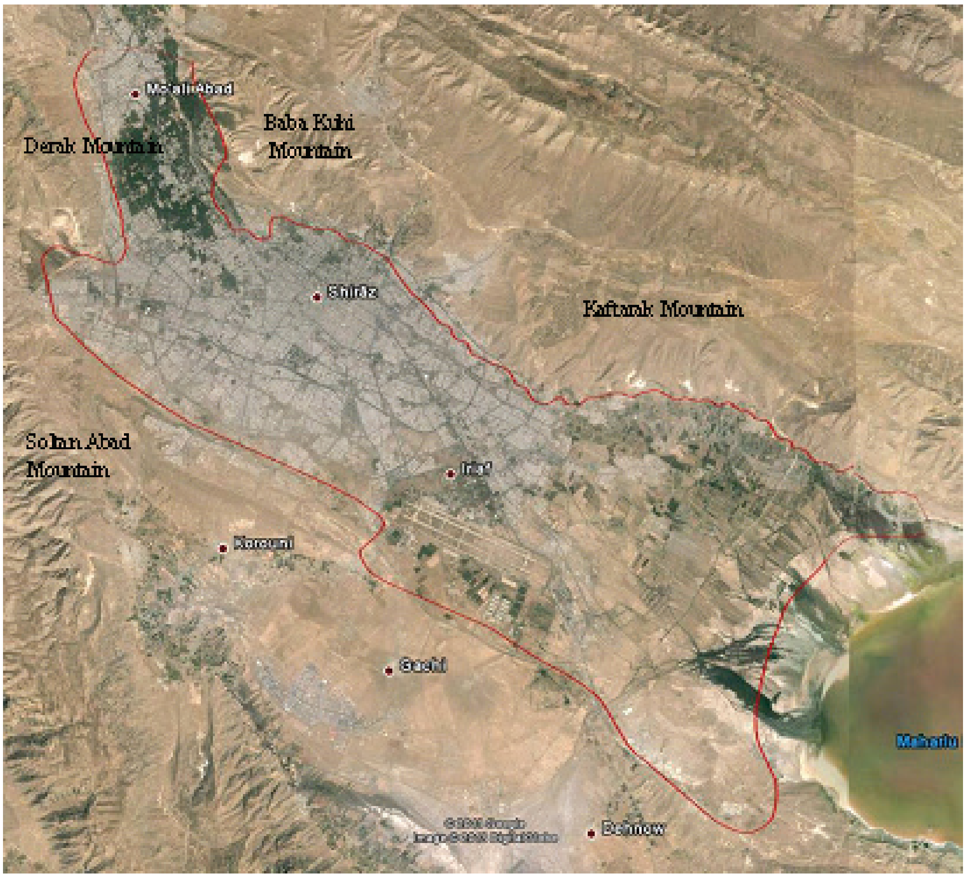

Figure 1: Satellite image of Shiraz plain

the study area belongs to semi-arid climate. The annual mean precipitation for the whole area is around 365.3 mm and its annual average temperature is 18.04°C.

DRASTIC Model

Each of the seven hydrogeological parameters is divided into ranges and then a number from 1 to 10 is assigned to them, according to their influence on vulnerability. In addition, a relative numerical weight from 1 to 5 is assigned to each parameter, with 5 and 1 representing the most effective and the least effective, respectively (table 1).

At the end, after collecting and digitizing the hydro-geological information using GIS, in order to prepare maps of vulnerability, the information is overlaid and integrated and the result is a new layer called DRASTIC index calculated using equation 1.

$$\text{DRASTIC Index}=D_r D_w+R_r R_w+A_r A_w+S_r S_w+T_r T_w+I_r I_w+C_r C_w \quad (1)$$

Where D, R, A, S, T, I, and C are the abbreviations of the seven effective hydro-geological parameters. Besides, subscripts r and w are the corresponding rates and weights presented in table 1.

The last output of DRASTIC model is a numerical index between 23 and 230. The greater the result (numerical index), the more vulnerable the aquifer would be.[12,20]

Preparation of the Needed Layers

Depth to water table layer (D): It represents the depth from the ground surface to the water table. In order to get the depth to water table layer, we used the most recent data regarding water level of 31 wells existing in the area of Shiraz plain. The information was obtained from Fars regional water organization during February 2012. The interpolation method was applied as an appropriate method for changing the mentioned point data into raster map of water level. Therefore, the map of depth to water table was prepared and classified according to table 1 in order to integrate with other layers.

Net Recharge layer (R): It is the amount of water which penetrates the ground surface and reaches the water table. In order to prepare the net recharge layer of Shiraz plain, Piscopo method was used.[20] Piscopo calculates the amount of net recharge by using rainfall, slope (%), and soil permeability, according to equation 2:

$$\text{Recharge Index}=\text{Soil permeability}+\text{rainfall}+\text{slope } (\%) \quad (2)$$

In order to calculate the slope (%), first a Digital Elevation Model (DEM) of the study area was generated from the topographic map. Then, the area's

Table 1: DRASTIC rating and weighting values for the various hydrogeological parameter settings (Source:Aller et al. 1987)

Depth to water table (m)				**Topography slope (%)**		**Hydraulic conductivity (m day $^{-1}$)**	
Range	**Rating**			**Range**	**Rating**	**Range**	**Rating**
0.0-1.5	10			0-2	10	0-4.1	1
1.5-4.6	9			2-6	9	4.1-12.2	2
4.6-9.1	7			6-12	5	12.2-28.5	4
9.1-15.2	5			12-18	3	28.5-40.7	6
15.2-22.9	3			>18	1	40.7-81.5	8
22.9-30.5	2	**Aquifer media**		**Impact of the vadose zone**			
>30.5	1	Range	Rating[a]	Range			Rating
Soil media		Massive shale	1-3 (2)	Confining layer			1
Range	Rating	Metamorphic/igneous	2-5 (3)	Silt/clay			2-6 (3)
Thin or absent	10	Weathered metamorphic/igneous	3-5 (4)	Shale			2-6 (3)
Gravel	10	Glacial till	4-6 (5)	Limestone			2-5 (3)
Sand	9	Bedded sandstone, limestone and shale sequence	5-9 (6)	Sandstone			2-7 (6)
Peat	8	Massive sandstone	4-9 (6)	Bedded limestone, sandstone and shale			4-8 (6)
Shiniking and/or aggregated clay	7	Massive limestone	4-9 (8)	Sand and gravel with significant silt and clay			4-8 (6)
Loam	5	Sand and gravel	4-9 (8)	Sand and gravel			4-8 (8)
Silty loam	4	Basalt	2-10 (9)	Basalt			2-10 (9)
Clay loam	3	Karst limestone	9-10 (10)	Karst limestone			8-10 (10)
Muck	2						
Non-shrinking and non-aggregated clay	1						
Weights of Parameters according to Aller et al. (1987)							
Parameters		Relative weight					
Depth to water table		5					
Impact of the vadose zone		5					
Net recharge		4					
Aquifer media		3					
Hydraulic conductivity		3					
Soil media		2					
Topography slope		1					

slope map was extracted from DEM. Moreover, soil permeability map was prepared by using the soil map of Shiraz plain (with scale 1:250000) and log of observation and exploration wells. Finally, the map of the area’s rainfall rate was prepared according to the annual mean precipitation of Shiraz plain. All the maps were rated and added using table 2. The resulting map that represented the net recharge was then classified.

Aquifer media layer (A): It refers to the saturated zone’s material properties which control the pollutant attenuation processes. Aquifer media describe consolidated and unconsolidated rocks where water is contained. Based on the logs of 20 wells available in the study area obtained from the reports of Fars regional water organization, the aquifer media rating layer of Shiraz plain was prepared.

Soil media layer (S): It represents the uppermost weathered portion of the unsaturated zone which continues to the penetration area of plant roots and organic creature activities.

Topography layer (T): It refers to the change in the slope of the land surface. The soil layer and slope map of Shiraz plain were prepared by the same method used in provision of net recharge layer and classified

Table 2: rating of Net Recharge (source: Piscopo.G,2001)

a: Slope		**b: Percipitation**		**c: Soil permeability**		**d: Recharge**	
Range (%)	**Factor**	**Range (mm)**	**Factor**	**Range**	**Factor**	**Range**	**Rating**
2>	4	850<	4	High	5	13-11	10
2-10	3	700-850	3	Moderate to high	4	11-9	8
10-33	2	500-700	2	Moderate	3	9-7	5
>33	1	500>	1	Low	2	7-5	3
				Very low	1	5-3	1

according to the DRASTIC model criteria.

Impact of Vadose Zone layer (I): Vadose zone lies above the aquifer and below the soil zone. The type of vadose zone media determines the attenuation characteristics of the material below the typical soil horizon and above the water table. The vadose zone media of Shiraz plain was achieved from litologic data of 20 observation and exploration wells. Finally, using this map and regarding table 1, the raster map of Shiraz plain's impact of vadose zone was designed.

Hydraulic conductivity layer (C): The ability of the aquifer to transmit water is called hydraulic conductivity. In order to prepare the hydraulic conductivity layer of Shiraz plain, the pumping tests data of 23 exploration wells prepared by Fars regional water organization were used. Finally, this layer was rated according to table 1.

Specific vulnerability to Nitrate Pollution: Composite DRASTIC

The CD index is an adaptation of the DRASTIC index based on the addition of a new parameter defining the potential risk associated with land use (L). The specific vulnerability to nitrate pollution ranges from 28 to 280 according to this index and is calculated using the following equation:

$$\text{CD Index}=D_r D_w+R_r R_w+A_r A_w+S_r S_w+T_r T_w+I_r I_w+C_r C_w+L_r L_w \quad (3)$$

Where, Lw is the relative weight of the potential risk associated with land use, the rating of the potential risk associated with land use, and the rest of the parameters are the same as those in equation.[1]

Land use map of Shiraz plain was prepared using IRS satellite data of 2009. It was then rated to the values given in table 3. Afterwards, this map was converted into a raster grid and multiplied by the weight of the parameter (L_w=5). The resultant grid coverage was then added to the DRASTIC index based on equation 3.

Table 3: Ranges and ratings applied to the potential risk associated with land use (L) according to the CD index (Source: Secunda et al. 1998)

Range	Rating
Urban areas	8
Irrigated field crops	8
Orchards	6
Uncultivated land	5

Sensitivity Analysis

One of the major advantages of DRASTIC model is implementation of assessment using a large number of input data which can limit the impacts of errors or uncertainties of the individual parameters on the final output. However, some researchers, like Barber and Merchant, believed that we could gain similar results using fewer data and lower costs.[11,21,22] The unavoidable subjectivity associated with selection of the seven parameters, ratings, and weights used to compute the vulnerability index has also been criticized.[23] Hence, in order to eliminate the aforementioned criticisms, two sensitivity analyses were done as follows.

Map Removal Sensitivity Analysis: Map removal sensitivity measure identifies the sensitivity of the suitability map (vulnerability map) towards removing one or more maps from the suitability analysis and is computed using the following formula:

$$S=\left(\frac{\left| V/N-V'/n \right|}{N}\right)\times 100 \quad (4)$$

Where S is the sensitivity measure expressed in terms of variation index, V and V′ are the unperturbed and perturbed vulnerability indices respectively, and N and n are respectively the number of data layers used to compute V and V′. The actual vulnerability index obtained using all the seven parameters was considered as unperturbed vulnerability, while that computed using a lower number of data layers was considered as perturbed vulnerability.

Single Parameter Sensitivity Analysis: It was introduced by Napolitano and Fabbri for the first time in 1996.[23] This analysis evaluates the influence of each of DRASTIC parameters in the final vulnerability index. Using this method derived from equation 5, the actual and effective weight of each parameter can be determined and it will be compared to its theoretical weight in the primitive DRASTIC model.

$$W=\left(\frac{P_r P_w}{V}\right)\times 100 \quad (5)$$

Where W refers to the effective weight of each parameter, Pr and Pw are the rating value and weight of each parameter respectively, and V is the overall vulnerability index.[12]

Results

Depth to water table (D): The depth to water layer (figure 2a) and the rating table of DRASTIC model's parameters corresponding to the study area showed that the depth to the water table varied from a few meters to more than 30.5 m (about 55 m). Additionally, the rating values varied from 1 for depths greater than 30.5 m (least effect on vulnerability) in the north-west part of the plain to 10 for shallow depths (2.03 m) (most effect on vulnerability)

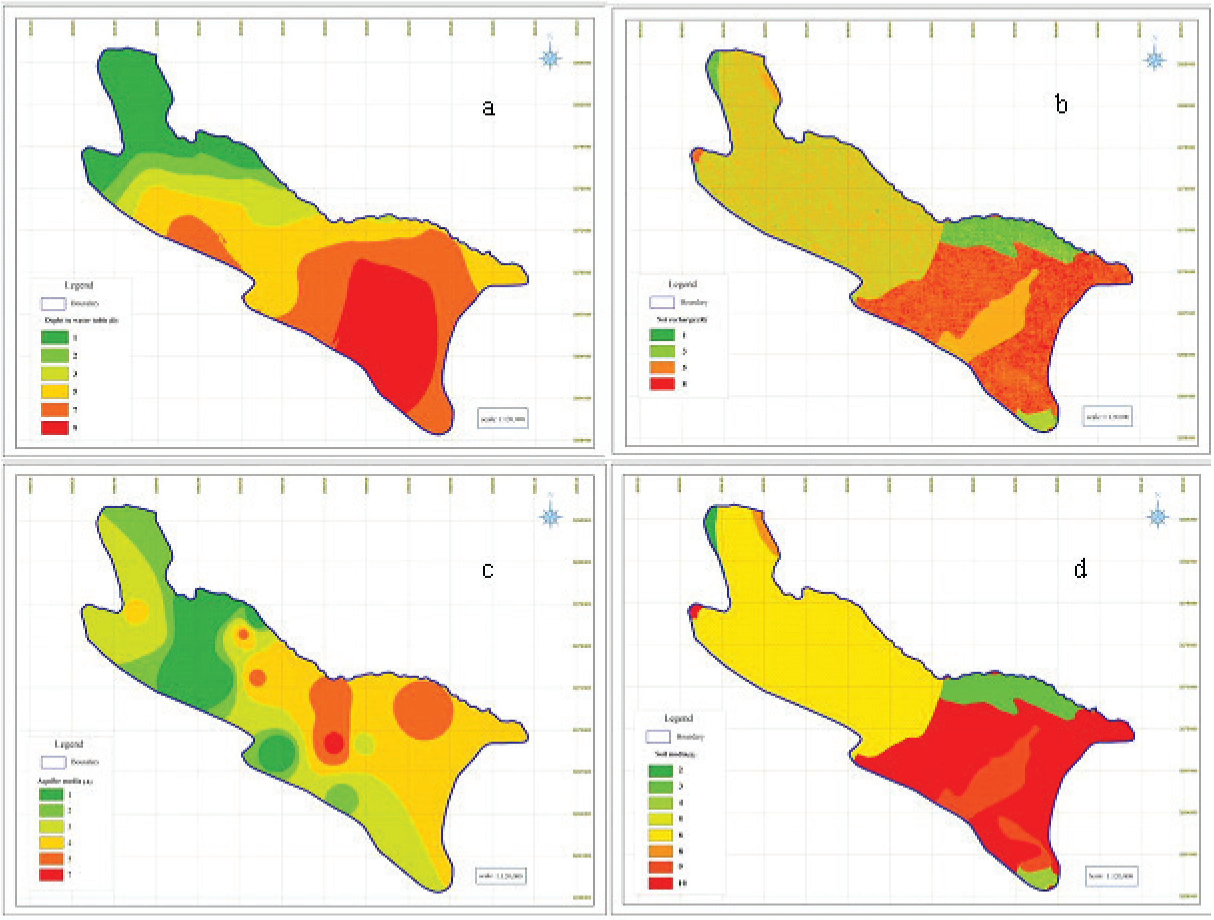

Figure 2: Shiraz plain's rated maps of a) depth to water table, b) net recharge, c) aquifer media, and d) soil media

in the south-east area of Shiraz aquifer.

Net Recharge (R): According to figure 2b, the net recharge in Shiraz plain was divided into 4 categories based on Piscopo's method.

Aquifer media (A): According to the aquifer media layer (figure 2c), most parts of the study were composed of clay and silt. However, the size of the deposits became coarser around Kaftrak Mountain.

Soil media(S): According to figure 2d, an area extending from northwest to the center of the plain was mainly composed of sandy loam. From the center to the south-eastern regions, the soil layer got thinner in such a way that there was no soil in some parts.

Topography (T): The slope of the whole plain was very gentle between 0 and 2% (figure 3a)

Impact of vadose zone (I): According to figure 3b, deposits of unsaturated zone in the northwest toward the southeast of the study area were clay. The unsaturated media in the north and northeast parts and around Kaftrak Mountain became a bit coarser and gradually got smaller toward the central and southeastern parts.

Hydraulic conductivity (C): Although the hydraulic conductivity of most parts of the study area was less than 12 m/day, it varied from a minimum of 0.34 m/day to a maximum of 37 m/day around Kaftarak Mountain. The hydraulic conductivity was high only in some parts located on the east (figure 3c).

Land Uses

Overall, four main land uses were observed in Shiraz plain, (figure 4 and table 4).

Table 4: Classes of land use in Shiraz plain

Range	Percentage
Uncultivated land	45.67
Urban areas	38.29
Irrigated field crops	11.32
Orchards	4.72

DRASTIC Index of Shiraz Aquifer

The final DRASTIC index was calculated using equation 1, multiplying the rated layers by their weights (table 1), and integrating them in GIS. Then, zoning of Shiraz plain's vulnerability map was done (figure 5). The results demonstrated that the DRASTIC

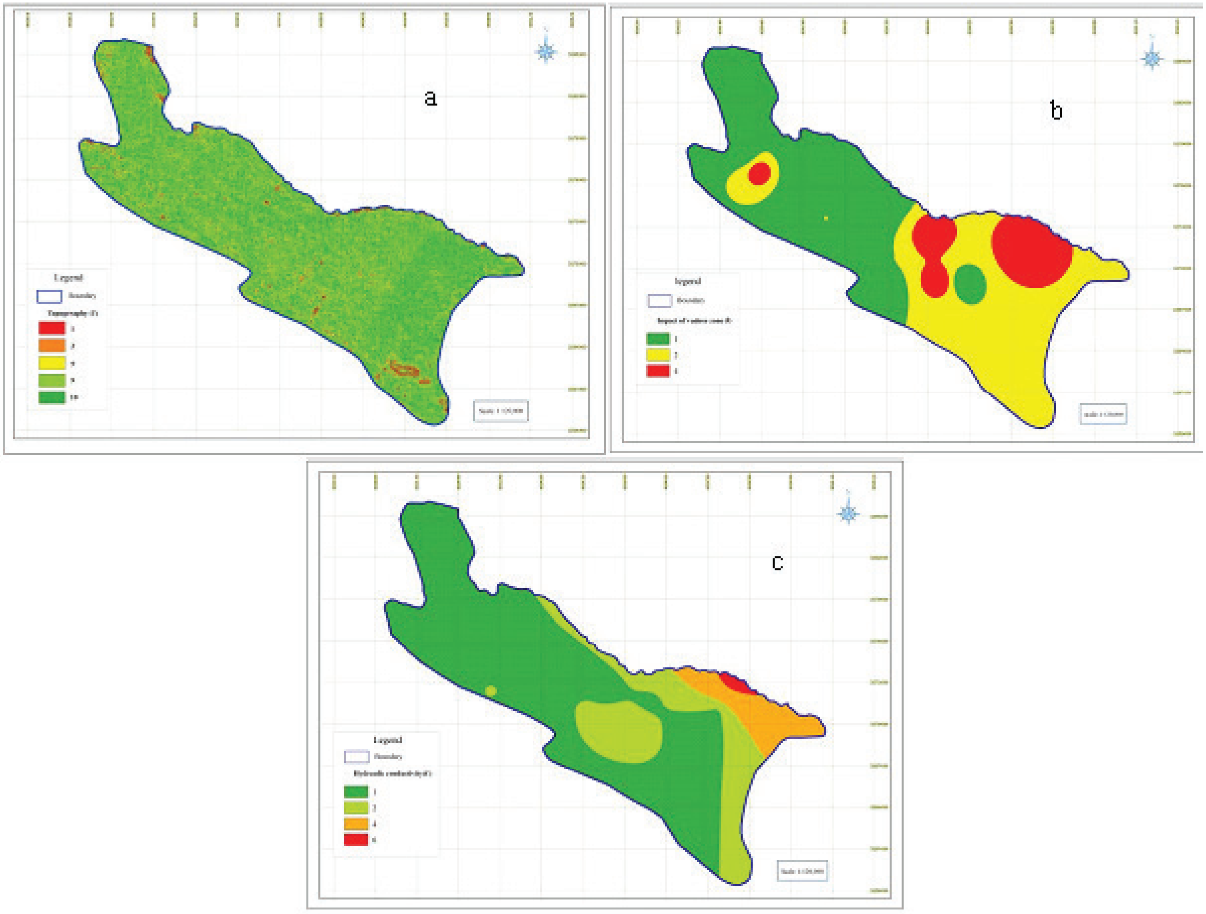

Figure 3: Shiraz plain's rated maps of a) topography, b) vadose zone, and c) hydraulic conductivity

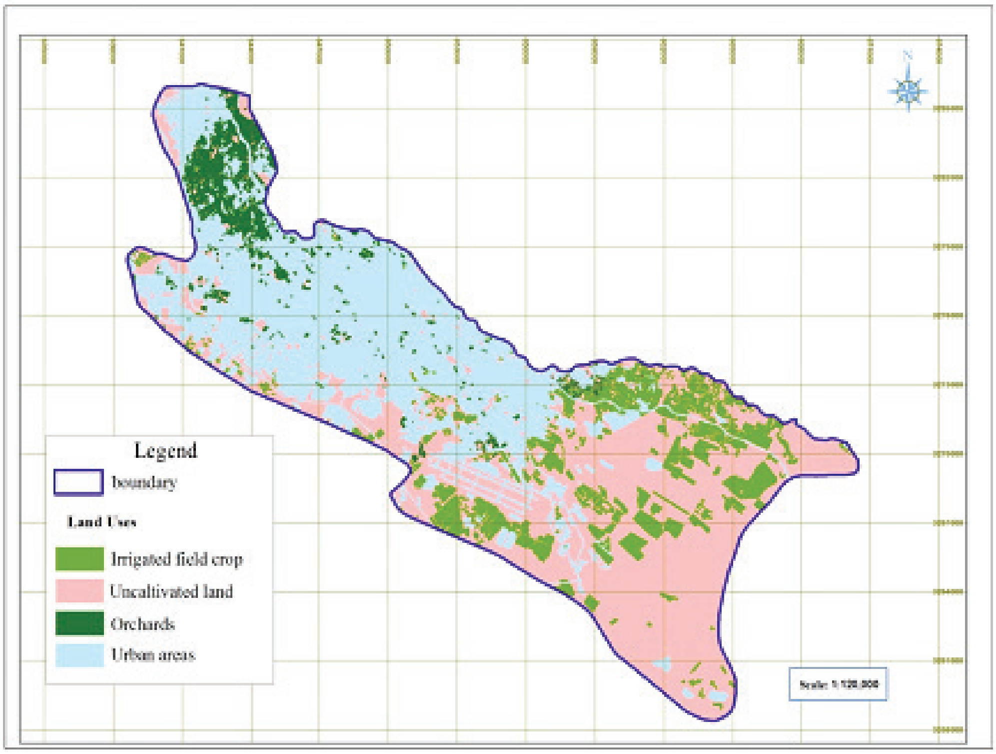

Figure 4: The major land use classes in the study area

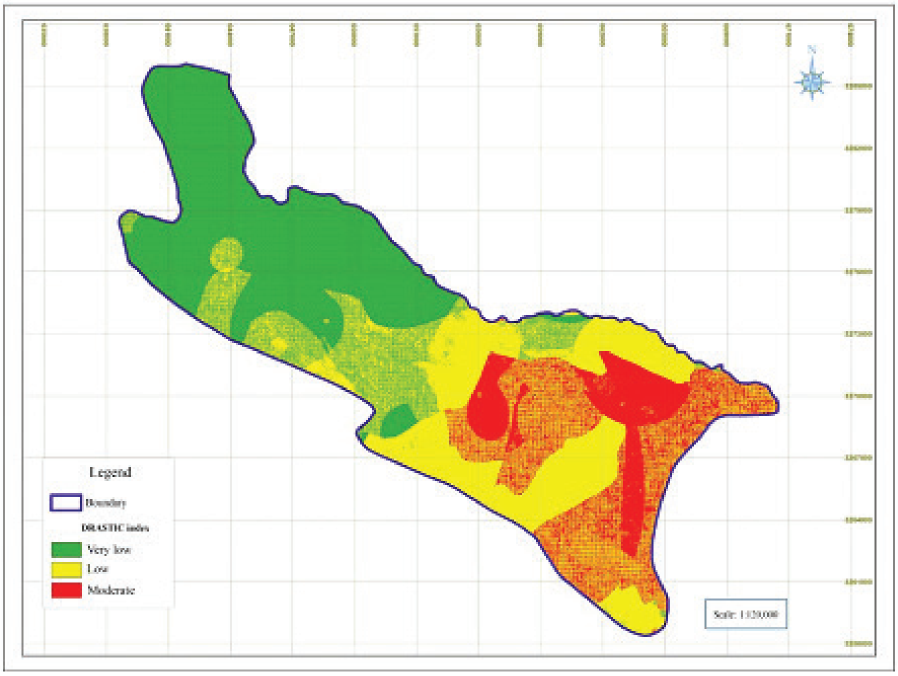

Figure 5: Groundwater vulnerability map of Shiraz's unconfined aquifer using DRASTIC model

index of Shiraz plain ranged from 28 to 148, and was divided into three classes (table 5).

Table 5: Classification of DRASTIC index in Shiraz plain

Range of Vulnerability	Location	Percentage
Very low (28-80)	Northwest	41.6
Low (80-120)	Center and North	39.1
Moderate (120-148)	Southeast	19.3

CD Index: Vulnerability of Groundwater to Nitrate Pollution

The map of specific vulnerability to nitrate pollution according to the CD index is presented in figure 6. Accordingly, CD index for Shiraz aquifer varied from 53 (very low) to 185 (medium) and was divided into three classes (table 6).

Map Removal Sensitivity Analysis

The results showed the importance of each of the DRASTIC parameters in the vulnerability index of Shiraz aquifer. According to these findings, the highest variation of the vulnerability index was related to removal of the depth of the groundwater (mean variation index: 34.05%). Thus, depth

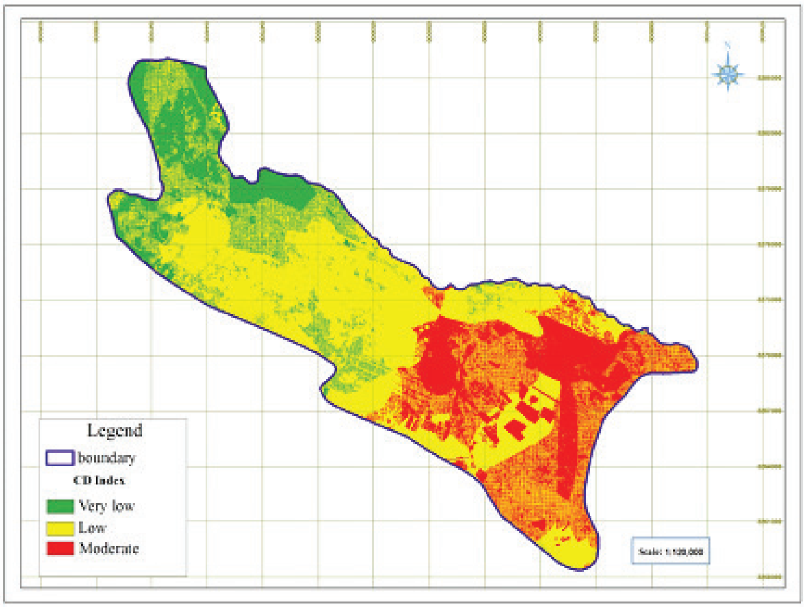

Figure 6: Map of specific vulnerability to nitrate pollution for groundwater in Shiraz aquifer according to CD index

Table 6: Classification of CD index in Shiraz plain

Range of Vulnerability	Location	Percentage
Very low (53-100)	Northwest	19
Low (100-145)	Center and North	56
Moderate (145-185)	Southeast	25

parameter was the most effective factor in the vulnerability assessment of Shiraz plain. Also, the vulnerability index seemed to be sensitive to removal of hydraulic conductivity and net recharge. In addition, the results revealed aquifer media to be the least effective parameter.

Single Parameter Sensitivity Analysis

According to the study findings, the "effective" weights of the DRASTIC parameters obtained in this study exhibited some deviation from the "theoretical" weights, and in some cases noticeable differences were observed between effective and theoretical weights. Based on the results obtained from the map removal sensitivity analysis, water table depth was the most effective parameter in vulnerability of Shiraz aquifer. The mean effective weight for this parameter (26.90%) was higher compared to its theoretical weight in DRASTIC model (21.74%). The effective weights of net recharge, soil media, and topography parameters were also higher than their theoretical weights in DRASTIC assumptions. On the other hand, the aquifer media, vadose zone, and hydraulic conductivity parameters exhibited lower effective weights compared to the theoretical weights and, consequently, they had less impact on the aquifer vulnerability in comparison to the theoretical DRASTIC model.

Validation of the Intrinsic and Specific Vulnerability Maps

Aquifer vulnerability methods require validation to reduce subjectivity in selection of rating and to increase reliability in field conditions. To this end, 70 groundwater samples were collected from 35 piezometers and observation wells placed in the study area and their nitrate concentration, as the most common pollutant, was measured. These samples were taken during two sampling events in one year, in August and January. The nitrate pollution map was prepared based on average values for all the measurements of nitrate concentration recorded for each sampling point. Then, ArcGIS 9.3 was applied to interpolate the nitrate concentration used to generate the nitrate pollution map. The groundwater nitrate pollution map for Shiraz aquifer has been presented in figure 7. Accordingly, the most polluted areas could be observed in the southeast part of the study area, around Maharlu lake, where agricultural activities were concentrated. However, the lowest values corresponded to the western areas. Moreover, nitrate concentrations were higher at the south and southeast parts that had moderate vulnerability compared to low or very low risk areas. Hence, the results obtained using DRASTIC and CD indices were confirmed.

Protection Zones

The concept of a 'zone of protection' for areas containing groundwater has been developed and adopted to help in land use planning, with the aim of preventing groundwater resources degradation.

Very low and low vulnerability class areas are

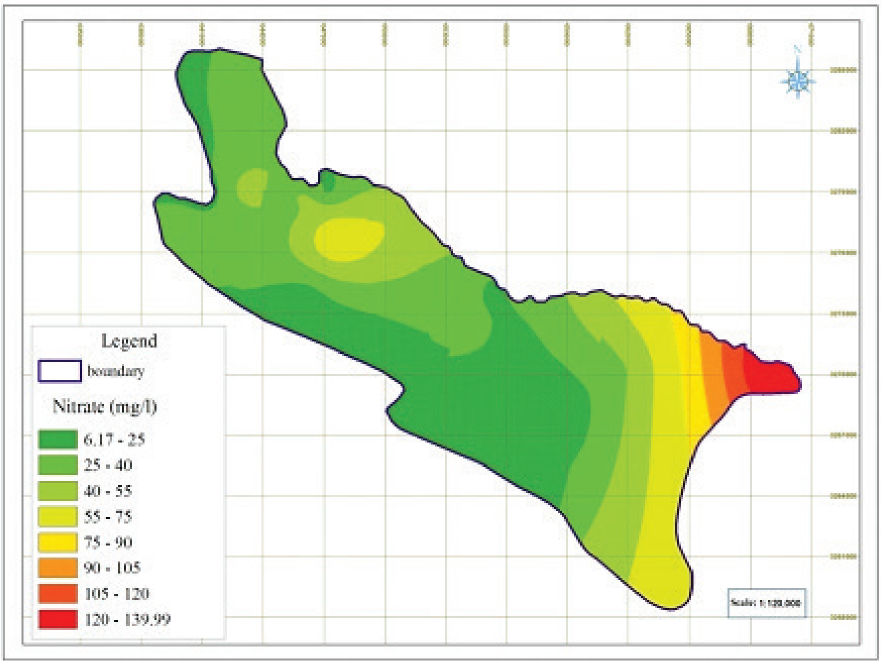

Figure 7: Map of nitrate pollution of groundwater in Shiraz aquifer

considered as protection zone 1, where all agricultural, industrial, and urban activities are convenient with low conditions of groundwater protection. Wastewater treatment plants and waste disposal sites are compatible to be constructed here with high conditions of groundwater protection. Nevertheless, due to the existence of some orchards in the northwestern parts of Shiraz plain, relatively high concentrations of nitrate have been found in groundwater of these regions and in spite of very low vulnerability, full attention must be given to these areas.

Moderate vulnerability class areas should be considered as protection zone 2, where agricultural activities and urban areas without wastewater treatment plants or waste disposals are valid to be constructed. Suitable condition of groundwater protection must be considered in this zone. In the moderate vulnerability zone of Shiraz, near Maharlu Lake, considerable application of nitrogen fertilizers has led to pollution of this part of the aquifer. Thus, development of agricultural activities should be made with more discretion.

Discussion

Generally, the main aquifer of Shiraz plain is divided into two aquifers, shallow and deep aquifer. In the present study, two different models, i.e. DRASTIC and CD indexes, were used for assessment of vulnerability and determination of groundwater protection zones of Shiraz plain unconfined (shallow) aquifer. The study results highlighted the usefulness of these models to evaluate groundwater nitrate pollution and the models' outcomes were consistent with the actual conditions in the field as observed by nitrate concentrations in the study area.

Although the study aquifer was shallow, a vast part of the plain contained fine-grained sediments which cause a decrease in the surface recharge, and also the possibility of increase in the attenuation process occurrence including chemical degradation, absorption, and dispersion.[24] This can be noticed from the rated maps of the aquifer media, vadose zone, and hydraulic conductivity (figures 2 and 3). So, most parts of Shiraz plain were placed in very low and low vulnerability classes. The main land use in these parts was urban areas with maximum (worst) rating of 8. However, as mentioned above, fine-grained sediments are considered an advantage and have protected these areas against pollution by nitrate. On the other hand, DRASTIC and CD indexes determined the southeastern parts of the study area, from center toward Maharlu Lake, as the most vulnerable areas. This can be justified by two reasons. Firstly, these parts have shallow groundwater depth and low thickness of unsaturated media; they lack the soil layer, and the general slope of Shiraz plain is toward this area. In the second place, the dominant land use in these areas is agricultural activities in which nitrogen fertilization and poorly optimized irrigation techniques encourage development of nitrate leaching processes. These are the main reasons why the southeastern parts of Shiraz plain are at the highest risk of nitrate pollution of groundwater. Therefore, these areas must be considered as protection zone 2.

The nitrate pollution map indicated that groundwater nitrate concentration increased by moving from the west to the east of the plain, so that the eastern and southeastern parts were the most polluted areas (figure 7). This confirmed the results obtained in the two models.

The results of both map removal sensitivity analysis and single parameter sensitivity analysis revealed that the highest risk of groundwater pollution in the study area originated from the depth to water table parameter. This is due to the high theoretical weight assigned to this factor as well as to the shallowness of water table throughout the plain, especially in the southern parts. Also, net recharge, soil media, and topography parameters showed great influence on the potential nitrate pollution due to the lack of soil layer in some parts of the plain and the gentle slope all through the study area. Yet, their impacts were not as important as that of depth to water table. On the other hand, aquifer media, vadose zone, and hydraulic conductivity parameters were the least effective parameters in assessment of groundwater nitrate pollution. This was expectable because the sediments and constitutive layers of aquifer media and unsaturated zone were fine in most parts of the plain.

Based on the rated map of water table depth and the results of sensitivity analysis, the main cause of moderate vulnerability in the southern and southeastern parts of the plain was elevated groundwater level. Although three drainage lines are being constructed in the southern and southeastern parts of Shiraz plain during the recent years to overcome this problem, the change of soil contexture into fine-grain near Maharlu Lake and the final part of the drainage has declined the hydraulic conductivity and drainage efficiency in this area. Also, the closeness of the drainage line to the surface can be effective in decreasing the water table decline in this part of Shiraz plain.

As previously mentioned, another reason for the vulnerability of eastern areas was agricultural activities and irrigated field crops which resulted in a higher risk of diffuse nitrate pollution affecting the underlying aquifer. Therefore, it is necessary to manage the amount, form, and timing of nitrogen fertilizer application in order to minimize groundwater contamination resulting from their use.[25]

Based on nitrate pollution map, concentration of nitrate was noticeable in some points located in the northeast of the study area. This can be attributed to the urban areas as the dominant land use in which nitrate can easily reach and pollute groundwater due to the absence of sanitation network.

It is necessary to point out a restriction of the used models which is the lack of attention to groundwater flow direction. In fact, none of the parameters of the DRASTIC and CD indexes considers the influence of this factor on the vulnerable areas. The groundwater flow direction implies that some points of a given aquifer receive groundwater (and its corresponding pollutants) from a larger area in comparison to other points within the same aquifer. This tends to favor an increase in the concentration of these pollutants in stagnant areas, where there are convergences of groundwater flows (accumulation process) or a reduction in the concentration of these pollutants (dilution process) depending on the quality of the received groundwater. Despite such a limitation, the results of this study supported the great usability of vulnerability indexes as very useful instruments for decision making to promote sustainable management of different land uses and identification of nitrate vulnerable zones at the regional scale. Proper implementation of groundwater protection zoning will ensure water quality benefits in long run. Subsequently, unpolluted water sources will aid in improvement of the people's health , animals, and ecosystems, and healthier workforce and living environment can significantly enhance the economic benefits of an area and even a country.

Conclusion

In this study, we attempted to assess the vulnerability of Shiraz aquifer and to identify and classify vulnerable and non-vulnerable areas to groundwater contamination in order to provide zoning of the groundwater protection and implementation of effective groundwater management strategies. This was accomplished using DRASTIC and CD models. Based on the results, about two-thirds of Shiraz aquifer had very low and low vulnerability and were considered as protection zone 1. In contrast, both models showed the most vulnerable zone in the study area to involve 25% of the region corresponding to the southeastern parts of the aquifer where intensive agricultural activities were the dominant land use and water table was shallow. Therefore, this part of Shiraz aquifer was considered as protection zone 2 and more attention is recommended to be paid to this area. In doing so, optimized irrigation techniques and a lower rate of pesticides are suggested to be used in these regions. The results of statistical analyses indicated that the depth to water table was the most effective parameter in the vulnerability assessment due to the shallowness of the aquifer. It should be noted that all the findings were consistent with groundwater nitrate pollution map of Shiraz plain.

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