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Groundwater Vulnerability Assessment in Agricultural Areas Using a Modified DRASTIC Model

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Key points:

- Groundwater vulnerability was assessed using a modified DRASTIC model.
- The new rates were computed using the relationships between the parameters of the model and point data chloride concentrations in groundwater.
- The modification optimized the rating function of the DRASTIC model and resulted in a vulnerability map with higher accuracy.
- The proposed method is effective for evaluating groundwater vulnerability in plain lands where agricultural activities are dominant.

Abstract

Groundwater contamination is a major concern for groundwater resource managers worldwide. We evaluated groundwater pollution potential by producing a vulnerability map of an aquifer using a modified DRASTIC model with the help of Geographic Information System (GIS). This modification optimizes the rating function of DRASTIC parameters to obtain a more accurate vulnerability map. This method incorporated the use of statistical techniques for revising the rates of the DRASTIC parameters under a GIS environment. The new rates were computed using the relationships between the parameters and the point data chloride concentrations in groundwater. The model was applied on Saveh-Nobaran plain in central Iran and the results showed that the correlation coefficient (R^2) between the point data and the relevant vulnerability map increased significantly from 0.52 to 0.78 after modification. Single parameter and parameter removal sensitivity analyses were performed to evaluate the relative importance of each DRASTIC parameter. The results from both analyses show that the vadose zone is the most sensitive parameter influencing the variability of the aquifers vulnerability index. Based on these results for nonpoint source pollution in agricultural areas, using the modified DRASTIC model is efficient compared to the original model. The proposed method can be effective for future groundwater assessment and plains management where agricultural activities are dominant.

Keywords: Groundwater contamination, water resources management, parameter removal sensitivity analysis, single parameter sensitivity analysis, Saveh plain.

1. Introduction

Over the last few decades groundwater contamination has become one of the most serious problems in the world (Umar et al. 2009). In many regions, especially in arid and semi-arid areas, groundwater stored in aquifers is a substantial supply of freshwater, while the characters of groundwater aquifers makes groundwaters vulnerable. In the current being, increasing pollution due to factors like increased agricultural activity, sewage disposal and industrial wastewaters has rapidly increased this vulnerability. It is obvious that preventing groundwater from being polluted is indeed easier than the treatment processes used, as treating contaminated groundwater is very expensive (Nobre *et al.,* 2007). Therefore, a useful tool to help prevent groundwater contamination is very efficient and cost effective in comparison. Groundwater vulnerability assessment has been recognized for its ability to identify areas that are more likely to become contaminated as a result of the anthropogenic activities at/or near the earth's surface. Once these areas are identified, they can be targeted for correct land-use management and intensive monitoring, to prevent groundwater resources becoming contaminated (Babiker *et al.* 2005; Knodel *et al.* 2007). Groundwater resources are not only the most important resources for potable supply in Iran, but are also used extensively to satisfy agricultural, domestic and industrial water demands. Therefore, having a deep knowledge and insight on the groundwater systems seems necessary for optimum exploitation of the water (Sadat-Noori et al. 2013).

DRASTIC is a model often used to assess the vulnerability of groundwater to a wide range of potential contaminants (Rahman, 2007; Almasri, 2008; Samake *et al.,* 2011). This model was developed originally by the US Environmental Protection Agency (1985) and has been applied extensively for vulnerability analyses throughout the globe such as Slovenia (Ravbar and Goldscheider, 2007), USA (Gomezdelcampo and Dickerson, 2008); Mongolia (Hasiniaina and Zhou, 2010); Palestine (Baalousha, 2010a); New Zealand (Baalousha, 2010b) and Ethiopia (Tilahun and Merkel, 2010). Despite its popularity, the DRASTIC model may have some disadvantages. This model uses seven parameters in its calculation of a 'Vulnerability Index', with each parameter being assigned a specific weight and rating value. However, the influence of regional characteristics is not taken into account, therefore the same weights and rating values are used universally. In addition, there is no standard algorithm to test and validate the model for aquifers. Previous studies have correlated the vulnerability index with chemical or contaminant parameters such as nitrate (Kalinski et al., 1994; Rupert, 1999; Sener *et al.*, 2009; Srinivasamoorthy *et al.*, 2010; Yin et al., 2013). Others have correlated it with land use (Secunda, 1998; Worrall and Koplin, 2004; Bai *et al.,* 2012) or have attempted to optimize the calculation of different layers by using approaches such as fuzzy logic (Rezaei *et al.*, 2013).

On agricultural lands, among different nutrients found in fertilizers, nitrate and chloride have the most potential to deteriorate groundwater quality. Nitrate or chloride may be selected as good indicators of contaminant movement from surface to groundwater, especially in agricultural lands (Valle Junior *et al.*, 2014). Nitrate is not naturally present in groundwater and could serve as a better option for groundwater vulnerability studies. However chloride can be used as a calibrator, if it is not native in the area and the main source of chloride in groundwater is from human activities. Chloride originates partially from mineral fertilizers (KCl in the nitrogen, phosphorus and potassium mixture), and partially from technical salts used in road maintenance (Srinivasamoorthy, 2010).

Although DRASTIC has been applied in a large number of studies, only a limited numbers of the studies in the literature have focused on the vulnerability of groundwater from specific contamination sources. Here, we build on the literature by modifying the ratings of the DRASTIC model using groundwater chloride concentration point data combined with statistical and geostatistical methods. We hypothesize that by using a groundwater quality parameter for modification, the overall accuracy of the vulnerability map will improve. We show that chloride can be a suitable groundwater contaminant parameter for calibrating and validating the DRASTIC model in areas where agriculture activities are prevalent, fitting the DRASTIC model for assessing specific groundwater vulnerabilities. The Saveh-Nobaran aquifer system in central Iran is selected as a case study to apply the proposed approach. Additionally we applied two sensitivity analyses to distinguish the role of each parameter used in the model.

2. Materials and method

2.1. Study Area

Saveh-Nobaran plain is located in north of Markazi province, Iran and lies between longitude 50° 8' to 50° 50' E and latitude 34° 45' to 35° 3' N, with an area about 3,245 square kilometers. The mean altitude of Saveh-Nobaran plain is 1108 meters above the sea level. Figure 1 shows the location of the study area. The climate of the area is considered to be arid and semi-arid based on De Martonne (1955) and Emberger (1955) category, respectively, with an annual precipitation being approximately equal to 213 mm. The mean monthly temperatures vary between 5.7°C in February to 31.5°C in August, and the mean annual value is 18.2°C. The annual potential evaporation far exceeds the annual rainfall with a mean annual amount of 1505 mm (approximately estimated from 1975 to 2011) for Saveh city (Mosavi-Khansari, 1991).

The study area is located on the northwestern tectonics of central Iran. The pattern rocks are mainly limestone, sand stone and gravel. The major section of the study area is formed by Eocene remains and consists mostly of topical alluvium and conglomerate. Saveh-Nobaran alluvial aquifer consists mostly of gravel, sand and thick and thin layers of clay and marl. The thickness of the alluvial sediment is variable, ranging from 25 m on the sides to 250 m in the center of the plain. The transmissivity of the Saveh-Nobaran varies from 500 to 3450 m^2 day^{-1}, whereas the specific yield of the aquifer is about 3–7%. Saveh-Nobaran plain bed rock is clastic conglomerate (Pliocene), Miocene sandstones and evaporating clays (Mosavi-Khansari 1991). The average depth to groundwater table in the west and eastern sides of the region are 100 and 30 m, respectively.

Agriculture is a major industry and the principal land use in Saveh-Nobaran plain. In past few years, great amounts of chemical and animal fertilizers have been used to enhance crop production, the outcome of which is high chloride and nitrate concentration in the groundwater. The levels of chloride and nitrate concentration in Saveh-Nobaran groundwater are above the WHO standard (2004) restrictions (Serhal, 2009). The irrigation season in the area starts in April and ends in September with surface irrigation, sprinkler and drip irrigation methods being applied in the region. Saveh's irrigation network covers over 19300 hectares of land and the agricultural pattern of the area consists of 50% wheat and barley, 36% herbs and 16% gardens. The gardens produce pomegranates, walnuts, almonds, pistachios and cantaloupes with most of this development having occurred in the last 30 years. The population of Saveh-Nobaran is distributed in rural and urban areas and is about 280,000 inhabitants. 92% of people live in urban areas and 8% in rural areas (Mosavi-Khansari, 1991).

2.2.DRASTIC Model

DRASTIC is named for the seven factors considered in the model: depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone media and hydraulic conductivity of the aquifer (Aller *et al.*, 1987). Each of the above mentioned hydro-geological factors was assigned a rating from one to ten based on a range of values. The ratings were then multiplied by a relative weight ranging from one to five as summarized in Table 1. The most significant factors were assigned a weight of five while the least significant were assigned a weight of one. The equation for determining the DRASTIC index is as follows (Aller *et al.*, 1985):

$$DwDr + RwRr + AwAr + SwSr + TwTr + IwIr + CwCr \quad (1)$$

where D, R, A, S, T, I and C represent the seven hydro-geological factors, r and w designate the rating and weight, respectively. The resulting DRASTIC index represents a relative measure of groundwater vulnerability. A complete description of DRSATIC model including parameters weight and ratings can be found in Aller *et al.*, (1987). The intrinsic DRASTIC model gives groundwater vulnerability, against any pollution of surface origin, independent of land use or any actual occurrence of pollutants. In a modification, Secunda *et al.* (1998) added land use to the model and estimated the specific vulnerability as follows:

$$V_s = V_i + L_r L_w \quad (2)$$

where V_s is the specific vulnerability, V_i is the intrinsic vulnerability, and L_r and L_w are land use rate and weight, respectively. The recharge rates and weights used here were based on those proposed by Piscopo *et al.* (2001) and the land use rates and weights were based on those published by Secunda *et al.* (1998). The remaining parameter weights and rates were based on those suggested by Aller *et al.* (1987). The DRASTIC parameters were manipulated as raster maps in an ArcGIS environment (Ver. 9.3). The relevant GIS layers which were prepared to develop the model are described below:

2.2.1 Depth to Groundwater

In order to prepare the groundwater table depth map, the average groundwater table data of 5 years (2005-2009) from 65 wells in the study area was used. The data was collected from the Markazi Regional Water organization, Iran. The groundwater table depths were then classified into ranges as defined by the DRASTIC model and assigned rates ranging from 1 (minimum impact on vulnerability) to 10 (maximum impact on vulnerability). Deeper groundwater tables have a smaller rate in the DRASTIC model. The depth to groundwater layer was renewed to raster format with 100-m cell size (Akhavan, 2010). The created layer is shown in Figure 2. The depth of groundwater table from the surface, is mostly high (>30.4 m) in the region and decreases in the northeast and some western parts of the region.

2.2.2 Net Recharge

The net recharge layer was constructed using Piscopo method. The map incorporates available features like slope, soil permeability and rainfall which are important in the calculation of the recharge component (Piscopo, 2001). Equation (3) was used to generate a recharge value.

$$\text{Recharge value} = \text{Slope}\,(\%) + \text{Rainfall} + \text{Soil permeability} \qquad (3)$$

The rainfall map was obtained by interpolating a twenty year mean of annual precipitation (mm year^{-1}) from twelve representative rainfall stations in the region. For the soil permeability map, a hard copy of a soil map for the study area was collected from the Iranian Soil and Water Research Institute and then digitized. Based on the USDA (1994) classification, the soil map was classified into 5 classes and thereafter soil permeability was extrapolated and calculated from the soil type based on the size and the shape of the soil particles. A digital elevation model (DEM) of the study area was generated from the topographic map to identify the slope. After deriving all three maps (Slope, rainfall and soil permeability), they were reclassified according to the criteria given in Table 2 and the finalized values were calculated. Figure 3 shows the recharge map of the region. The most rechargeable region in the study area was located at the western part while central and eastern parts are less rechargeable due to soil type which is mostly clay.

2.2.3 Aquifer media

Well log data available for Saveh-Nobar plain and obtained from Regional Water Corporation of Markazi Province, Iran was used to provide this layer. The Aquifer media layer shows that most parts of the study area have a rate value equal to seven, the same value as sandstone (Fig. 4 and Table 3).

2.2.4 Soil media

This layer was prepared using characteristics of soil profiles such as soil classes, color, texture and structure from the available information in the archives of the Iranian Soil and Water Research Institution. The soil classes of the study area were arranged from 3 to 6 based on the classes proposed by the DRASTIC model (Fig. 5). Rate 3 is attributed to eastern parts of the study area, where soil has a low rate of infiltration and rate 6 to western parts for brown carbonate soil.

2.2.5 Topography

This layer has been created in the GIS environment, using the topography map of the study area in a format of a digital elevation model (DEM). The slope was categorized into five groups based on the DRASTIC classification. It was then assigned sensitivity rates of 10 for plain (<2%), 9 for gentle (2–6%), 5 for moderate (6–12%), 3 for steep (12–18%) and 1 for very steep (>18%) based on Aller *et al.* (1987). As shown in Figure 6, slope value in western parts of the study area was high and decreases towards eastern parts.

2.2.6 Impact of the vadose zone

Data of unsaturated zone lithology were extracted from the logs and boreholes, provided by the Markazi Regional Water Organization, Iran, and were used in construction of this layer. Five classes were identified based on Aller *et al.* (1987) classification as shown in Figure 7. Unsaturated zones from western to central areas consist of sand and gravel, while unsaturated zones in eastern parts of the study area are mostly clay deposits

2.2.7 Hydraulic conductivity

The hydraulic conductivity of the Saveh-Nobaran aquifer was calculated based on the following equation: $K = T\ b^{-1}$, where K is the hydraulic conductivity of the aquifer ($m\ s^{-1}$), T is the transmissivity ($m^2\ s^{-1}$), and b is the thickness of the aquifer expressed in m. This approach has been applied in similar geological settings (Saidi *et al.,* 2010). The hydraulic conductivity map obtained by interpolation was converted into a raster grid and multiplied by the weighting factor 3. Most parts of the study area have hydraulic conductivity values from 12 to 28 ($m\ day^{-1}$) with rating value of 4. In northeastern parts hydraulic conductivity varies between 4 to 12 ($m\ day^{-1}$) with a rating value of 2 (Fig. 8).

2.2.8 Land use

In order to introduce a land use factor into the DRASTIC index, the land use map was rated according to the Secunda *et al.* (1998) (Table 3). This map was converted into a raster grid and then multiplied by the weight factor of the parameter ($L_w = 5$) (Fig. 9). The resultant grid coverage was then added to the DRASTIC index based on Equation (2) (Secunda *et al.,* 1998). Finally, the vulnerability map of the study area was created by overlaying all the eight parameters which were created in raster formation using GIS environment.

2.3.Correlation between vulnerability map and chloride pollutant

Chloride concentration data collected in the wet and dry seasons from fifty eight monitoring wells in the region for the year 2011 was obtained from the Regional Water Corporation of Markazi Province, Iran, and used for calibration. The correlation between the polluted areas and the results of the DRASTIC model was based on Pearson's (r) correlation factor (Pearson, 1896). To have a better assessment of annual chloride concentration fluctuation due to different rainfall conditions, an average of two chloride samples collected in the wet and dry seasons was used for each well.

The rates of DRASTIC model were initially modified using the Wilcoxon Rank-Sum Non-Parametric Statistical Test (Wilcoxon 1945). Using this test it was ascertained that the average of two neighboring classes did not vary significantly. Classes were grouped in such categories, while for non-continuous parameters (parameters with discrete classes, e.g. aquifer type, vadose zone type and soil type) all of the classes existing in the area were maintained, regardless of their statistical diversity. In the proposed method to modify the rates, in the first step, the data was ranked from high to low values, with the highest amount being assigned to the largest rate, and the remaining rates being calculated based on the highest rate.

In the second step, the average chloride concentration in each range for each parameter was calculated. For example, for the depth to groundwater table parameter, the average concentration of chloride in the range within 0 – 1.5 m on the map was calculated to be 1117.83 mg l^{-1}. Thereafter, the highest rate is assigned to the range with the highest amount of average chloride concentration which is the basic rate and the remaining rates for that parameter are modified according to that basic rate with a linear relationship. For instance, considering soil media parameter, its second class with the original rate of 4 had the highest amount of chloride concentration (928.03 mg l^{-1}). Therefore, it was modified as receiving the biggest rate which is 10 and the rest of the ranges are assigned to a rate based on this relation linearly. In this modification method, for the highest chloride concentration range, the biggest rate (10) was assigned even if there were no 10 rating for that parameter. After modification the model was validated with an independent data set comprised of fifty eight wells sampled in wet and dry season of 2012.

3. Results and discussion

3.1. The DRASTIC vulnerability index

The results of DRASTIC values in this application lay between 47 and 194. Therefore, according to Aller *et al.,* (1987) categorization, the area is classified into four classes (Table 5). Within the four classes, 10% of the study area is recognized as very high potential pollution, 8% as high pollution potential, 61.5% as moderate pollution potential and 20.5% as low pollution potential. The groundwater vulnerability map (Fig. 11) shows that the eastern and central parts of Saveh-Nobaran aquifer are recognized as very high vulnerability. Towards the western parts of the study area the vulnerability decreases, whereas in the far western part (Nobaran region), potential pollution increases again. It should be mentioned that most parts of the study area are in the moderate vulnerability classification while in some parts of the study area potential pollution is low. The reason for this can be found within three factors; high depth to groundwater table, vadose zone low permeability and aquifer media.

To get a better understanding of the parameters involved in the model, each input parameter of different layers (including chloride layer) was correlated with the final output of DRASTIC model using GIS, as shown in Table 6. The results of the correlation matrix suggest that among DRASTIC layers the impact of the vadose zone, recharge, and land usage show a high correlation (R^2 = 0.73, R^2 = 0.71, and R^2 = 0.65, respectively). Less correlation was observed in the remaining parameters. Also it is observed that the DRASTIC model and chloride level factors have a positive correlation of R^2 = 0.52 with each other.

3.2. DRASTIC index calibration and validation

The correlation between the polluted areas and the results of the DRASTIC model before modification was R^2 = 0.52. In other words, the relationship rate between chloride concentration and the vulnerability values was low. This situation demonstrated that in determining groundwater vulnerability, a pollutant parameter must be considered to demonstrate realistic assessment of pollution potential in the area. The effect of this parameter along with the intrinsic vulnerability of an aquifer could lead to results close to reality. In our case, due to not having access to nitrate data, calibration was based on chloride concentration data to obtain specific results. This should be feasible if chloride sources in the area are anthropogenic.

Furthermore, it has been suggested that the following three conditions should be satisfied when using a contamination parameter to calibrate the rates (Panagopoulos *et al.*, 2006), (1) Agricultural activities should be the main source of contamination (chloride) at the surface of the land, (2) the distribution area should be relatively uniform and (3) leaching of contamination (chloride) should be due to recharges from the surface over a long period of time. Agricultural practices are the main activity in the area, therefore ensuring that these basic conditions are met (Javadi *et al.*, 2011). Moreover, the background chloride concentration in groundwater in the study area was reported as 10 mg l^{-1} (Saveh-Nobaran Water Quality Report, 2011). Comparing this value to the annual average chloride concentration (of 400 mg l^{-1} in the dry season and 410 mg l^{-1} in the wet season) shows a significant difference, which refers to the influence of agricultural activities in the area. As Figure 12 shows the north-eastern parts of the study area have the highest amount of chloride concentration at 1682 mg l^{-1}, which is significantly higher than the background value.

With a large amount of agricultural activities in the region being associated with a high usage of chemical fertilizers, it can be mentioned that the main source of chloride in the groundwater is the irrigated agriculture in the region. Additionally, the irrigated return flow which moves towards the east due to flow direction and area topography contributes to increased chloride concentration in the east of Saveh-Naboran. Based on this it can be suggested that chloride contamination in the study area's groundwater is related to human activities. In the proposed method, rates of seven attribute layers of the DRASTIC model, depth to groundwater table, net recharge, hydraulic conductivity, vadose zone, aquifer media, topography and soil media, were changed according to the mean chloride concentration as presented in Table 7.

After modifications, the new DRASTIC map (Fig. 13) was calculated using the new rating system. For validation we used the fifty eight chloride samples for the year 2012 to evaluate the performance of the model. Chloride concentration in those wells ranged from 31 to 1775 mg l^{-1} with an average of 903 mg l^{-1}. Table 4 represents average chloride concentration (wet and dry) of monitoring wells used for validation. Figure 10 illustrates the sample locations and the spatial distribution map of chloride concentration, according to WHO standards (2004). It is found that chloride is beyond its permissible limits by over 70%, which has also been reported by Sadat-Noori et al., (2014). A correlation between the vulnerability map (DRASTIC values) and contamination in the study area was calculated using the Pearson correlation factor and the results revealed a significantly higher positive correlation of R^2 = 0.78. In other words, regions which have a high amount of chloride concentration are associated with high DRASTIC values. Therefore, the specific vulnerability which has been calculated based on the intersection of vulnerability and a pollutant parameter, raises the overall accuracy of the results. Thus, this confirms that the created vulnerability map has a significant correlation with real contaminations existing in the study area.

Based on the new DRASTIC map involving the new rates, statistical analyses were carried out which showed that 14% of the area falls into the very high vulnerability classification. It was 10% before the modification. The calculated area for the high vulnerability classification was 8% before modification and 20 % thereafter, and in the moderate vulnerability class, 61.5% before modification and 36% after modification. These results show a clear effect resulting from the modification, making DRASTIC values more normalized. In order to show the spatial distribution of the index both before and after the modification, the two maps were compared. The result shows 31% similarity and 69% difference in one class or more, demonstrating the effectiveness of the applied method once more. Figure 13 shows parts of the study area having high chloride concentration, marked as high and very high pollution potential zones.

3.3.Sensitivity analysis

Sensitivity analysis provides valuable information on the influence of rating values and weights assigned to each parameter and helps in judging the significance of subjective elements (Gogu and Dassargues, 2000). The effectiveness of the parameters used for vulnerability assessment was analyzed by two sensitivity analysis methods of map removal (Lodwick *et al.* 1990) and single parameter (Napolitano *et al.,* 1996). Lodwick *et al.* (1990) introduced the map removal sensitivity analysis which determines the sensitivity of a parameter by removing a map in, according to Equation (5):

$$S_i = \left| \frac{V_i}{N} - \frac{V_{xi}}{n} \right| \tag{5}$$

where S_i is sensitivity (for *i*th unique condition subarea) associated with the removal of one map (of parameter *X*), V_i is vulnerability index computed using Equation (1) on the *i*th sub area, V_{xi}, vulnerability index of the *i*th subarea excluding one map layer, N number of map layers used to compute vulnerability index in Eq. (1) and n, number of map layers used for sensitivity analysis. In order to assess the magnitude of the variation created by removing one parameter, the variation index can be computed by Eq. (6) (Pathak *et al.,* 2009):

$$VAR_i = \left(\frac{V_i - V_{xi}}{V_i} \right) \times 100 \qquad (6)$$

where VAR_i is variation index of the removal parameter and V_i and V_{xi} are vulnerability index computed using Eq. (1) on the *i*th subarea and vulnerability index of the *i*th subarea excluding one map layer, respectively.

As presented in Table 8, the most sensitive parameter influencing variation in the aquifers vulnerability index is the impact of vadose zone with a 2.9% average sensitivity value. This is mainly due to the high weight associated with this parameter. It is clear that a high variation in the vulnerability index is also expected upon the removal of the land use parameter from computation (average variation index=1.9%). The net recharge parameter has a 1.7% average variation value to vulnerability index in the third place. The vulnerability index also seems to be sensitive to the removal of the depth to groundwater parameter (average variation index value equal to 1.5%). The importance of the parameters to vulnerability variation is followed by topography, soil type and hydraulic conductivity with 1.3%, 1% and 0.8% of average variation index values, respectively. The lowest effect (0.5%) on the vulnerability index variation was obtained after the removal of aquifer media parameter. From the results it can be stated that the weight associated to each parameter in the DRASTIC model is satisfying and acceptable for this region. Although it was found that in the study area, the depth to groundwater table parameter which is theoretically more important than a net recharge, which had a lower effect on the vulnerability index variation compared to the net recharge parameter. This could be due to the groundwater table being low in most of the region.

The results of the sensitivity analysis of the simultaneous removal of multiple parameters for the DRASTIC model are presented in Table 9. In this sensitivity analysis, two or more layers were omitted, the vulnerability index was calculated and then the related statistical differences of the variation index were computed. The results show that in vulnerability assessments, the impact of the vadose zone, followed by net recharge are the most important parameters. The most insignificant parameter is aquifer media, which is similar to the results found by Samake (2011). In general, the complex nature, uniqueness and inconsistency of each aquifer causes different results in employing the DRASTIC model in different regions.

A single-parameter sensitivity measure was developed to evaluate the impact of each DRASTIC parameter on the vulnerability index. It was made to compare the “effective”, or "real" weight of each input parameter in each polygon, with the "theoretical" weight assigned by the analytical method. The "effective" weight of each polygon is obtained using Equation (7) (Babiker *et al.* 2005):

$$W_{xi} = \frac{x_{ri} \times x_{wi}}{V_i} \times 100 \tag{7}$$

Table 10 shows that the impact of the vadose zone and net recharge parameters are the most effective parameters in the vulnerability assessment, by having a higher average effective weight (23.51% and 22.12% respectively), compared to their theoretical weight. These findings match the results found by Neshat *et al.* (2014) which applied the model in a similar geological setting. Hydraulic conductivity also had a high effective weight (14.61%) compared to its theoretical weight (13%), and furthermore, the effective weight of the soil type and topography parameters (10.31 and 6.91%) also exceeded their theoretical weight. Other parameters had a lower effective weight compared to the assigned weight in the DRASTIC model. The results obtained from the single map sensitivity analysis emphasize the importance of net recharge (R), vadose zone (I) and hydraulic conductivity parameters in assessing vulnerability using the DRASTIC model. Therefore, preparing accurate, detailed, and representative data about these parameters can improve the outcome of the DRASTIC model.

4. Conclusion

Based on the research outcome, it can be concluded that although in the central parts of the study area, groundwater table is near the surface and infiltration rate is high, due to low thickness of surficial clay, groundwater is being contaminated by chloride due to agricultural activities. Therefore, extreme monitoring and management strategies must be applied in central parts of the region. Moreover, potential pollution around the western parts of the study area is high, thus, to prevent this area from falling in the "very high" class of vulnerability, special monitoring and attention is required. A modified version of the DRASTIC is applied and proposed in this paper in order to determine the vulnerability maps of groundwater more accurately based on the specific land use of the region. Although the DRASTIC model usually gives satisfactory results, it should not be used for assessing groundwater pollution risk in its origin form in different plains with different activities. Therefore, it is necessary to calibrate and modify the original algorithm in order to obtain accurate results. We perform this modification using statistical techniques with the help of GIS.

Results from the study show that before modification the correlation coefficient between the point measured contamination data and the relevant vulnerability map was R^2=0.52 while after the modification the same test showed a significantly higher R^2 value of 0.78. Results of this study also show that chloride concentration can be used as a modifying parameter with considerable improvement in the resulting index that could lead to a better understanding of groundwater quality management in agricultural areas. The results of the sensitivity analysis showed that the impact of the vadose zone, land use, net recharge, depth to groundwater table, topography, soil type and hydraulic conductivity are the most sensitive to groundwater contamination. Furthermore, the most effective parameters in the vulnerability assessment of the Saveh-Nobaran aquifer are the impacts of the vadose zone and net recharge, whereas the additional land use parameter had great influence on the development of the final vulnerability map. The modified DRASTIC model proposed here could be used as a valuable tool for managers to make better informed decisions in landuse change and aquifer management for groundwater assessments in plains where agricultural activities are dominant.

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Table 1. The DRASTIC model parameters and weights (Aller et. al, 1987) (Secunda et. al, 1998)

The DRASTIC model parameters	Parameter description	Original weight
Depth to water (D)	Represents the depth from the ground surface to the water table. Deeper water table levels imply lesser contamination chances.	5
Net recharge (R)	Represents the amount of water that penetrates the ground surface and reaches the water table. Recharge water represents the mean for transporting pollutants.	4
Aquifer media (A)	Refers to the material property of the saturated zone, which controls the pollutant attenuation processes.	3
Soil media (S)	Represents the uppermost weathered portion of the unsaturated zone and controls the amount of recharge that can infiltrate downward.	2
Topography (T)	Refers to the slope of the land surface. It indicates the potential for runoff as opposed to infiltration.	1
Impact of vadose zone (I)	Defines the material in the unsaturated zone. It controls the passage and attenuation of the contaminant to the saturated zone.	5
Hydraulic conductivity (C)	Indicates the ability of the aquifer to transmit water.	3
Landuse (L)	Represents the effect of landuse activity on the aquifer.	5

Table 2. Net recharge rates assigned to the study area based on Piscopo (2001) method

Slope (%)		Rainfall		Soil Permeability		Net Recharge	
Slope (%)	Rating	Rainfall (mm year-1)	Rating	Range	Rating	Range	Rating
< 2	4	< 500	1	Very Low	1	11- 13	10
2 - 10	2	500 – 700	2	low	2	9 -11	8
10 - 33	3	700 – 850	3	Moderate	3	7 - 9	5
> 33	1	> 850	4	High	4	5 - 7	3
				Very High	5	3 - 5	1

Table 3. DRASTIC rating and weighting values for the various hydrogeological parameters (Aller *et al.* 1987)

parameter	Rating	parameter	Rating
Depth to water table (meter)		**Recharge (mm)**	
0 - 1.5	9	0 - 5	1
1.5 - 4.6	8	5 - 10	3
4.6 - 9.1	7	10 - 18	6
9.1 - 15.2	5	18 - 25	8
15.2 - 22.8	3	> 25	9
22.8 - 30.4	2		
> 30.4	1		
Weight :5		Weight : 4	
Aqufier media	Rating	**Soil type**	Rating
Clay	5	Gravel	10
Sand with silt and caly	6	Sand	9
Limestone, Gravel, sand	7	Peat	8
Gravel and sand	8	Aggregated clay	7
Gravel	9	Sandy loam	6
		Loam	5
		Silty loam	4
		Clay loam	3
		Muck	2
		Nonaggregated clay	1
Weight : 3		Weight : 2	
Impact of vadose zone	Rating	**Topography (%)**	Rating
Clay and silt	4	0 - 2	10
Clay and sand	5	2 - 6	9
Clay, silt with gravel	6	6 - 12	5
Sand, gravel with clay and silt	7	12 - 18	3
sand and gravel	8	> 18	1
Weight :5		Weight : 1	
Hydrualic conductivity (m day^{-1})	Rating	**Landuse**	Rating
< 4	1	Salin lands	9
4 - 12	2	Irrigated farming	8
12 - 24	4	Urban	8
24 - 40	6	Range	5
		Dry farming	3
Weight : 4		Weight :5	

Table 4. Average chloride concentration (wet and dry) in monitoring wells

Well no.	UTMX	UTMY	Cl ($mg\ l^{-1}$)	Well no.	UTMX	UTMY	Cl ($mg\ l^{-1}$)	Well no.	UTMX	UTMY	Cl ($mg\ l^{-1}$)
1	458206	3865220	534.6	21	429250	3881500	487.4	41	403508	3885470	121.7
2	454500	3840000	268.7	22	439055	3877014	736.2	42	401590	3880713	255.9
3	446141	3873780	1241	23	434010	3881275	493.4	43	408970	3881030	532.5
4	467288	3867613	1775	24	445300	3881700	467.1	44	382200	3890300	62.8
5	456000	3849500	159.7	25	447846	3877813	913.4	45	416350	3879700	572.9
6	442250	3878500	683.7	26	435500	3882850	46.8	46	419645	3881628	223.2
7	461555	3874583	998.2	27	444042	3890582	35.8	47	421300	3878300	999.3
8	449000	3873600	1184.2	28	446813	3850722	90.8	48	384450	3892000	140.5
9	443500	3842300	182.1	29	436647	3863633	636.8	49	402950	3900300	31.5
10	442760	3874520	993.2	30	440231	3868520	599.9	50	425500	3871000	388.3
11	449750	3862600	116.4	31	446700	3890200	46.8	51	419000	3891400	117.5
12	451130	3849230	65.3	32	440130	3874200	976.6	52	414210	3883534	276.9
13	446850	3861264	535.6	33	442200	3888050	53.2	53	364800	3899400	30.8
14	468520	3858760	234.3	34	432850	3882000	79.8	54	370400	3895400	68.8
15	462435	3862923	1098.3	35	430500	3871000	301.7	55	370250	3895600	32.3
16	472336	3861660	429.0	36	391250	3882050	103.3	56	362350	3901750	118.4
17	441850	3879200	718.1	37	413065	3880692	710	57	365500	3905150	25.5
18	442470	3853020	140.9	38	422458	3873889	603.5	58	360300	3903950	119.1
19	442630	3844280	79.5	39	405467	3885038	278.6				
20	446550	3883400	634.0	40	397900	3882250	131.3				

Table 5. DRASTIC vulnerable index classification, (Aller *et al.* 1987)

DRASTIC Index	Range	Area (%) before modification	Area (%) after modification
Low	47 - 92	20.5	30
Moderate	93 - 136	61.5	36
High	137 - 184	8	20
Very High	> 184	10	14

Table 6. Correlation coefficient of measured chloride and DRASTIC parameters before modification

Parameter	Model	D	R	A	S	T	I	C	L	Chloride
Model	1									
D	0.61	1								
R	0.71	0.3	1							
A	0.28	-0.2	0.05	1						
S	0.41	-0.12	0.12	0.2	1					
T	0.38	-0.15	-0.1	-0.04	0.01	1				
I	0.73	0.23	0.13	0.09	0.05	0.12	1			
C	0.28	-0.17	-0.1	-0.05	0.17	0.067	0.21	1		
L	0.65	0.1	0.2	0.03	0.21	0.11	0.3	0.24	1	
Chloride	0.52	0.35	0.53	0.29	0.45	0.36	0.61	0.32	0.54	1

Table 7. The Original and modified rates based on chloride concentrations

parameter	Range	Original Rate	Average chloride concentration (mg l^{-1})	Modified rate
Depth to water (meter)	0 -1.5	10	1117.8	10
	1.5 - 4.6	9	728.3	6.5
	4.6 - 9.1	7	445.5	3.9
	9.1 - 15.2	5		
	15.2 - 22.8	3	366.8	3.2
	22.8 - 30.4	2	221.9	1
	> 30.4	1		
Recharge (millimeter $year^{-1}$)	0 - 50.8	1	78.3	1.8
	50.8 - 101.6	3		
	101.6 - 177.8	6	313.7	4.7
	177.8 - 254	8		
	> 254	9	663.5	10
Topography	0 -2	10	602.5	10
	2 - 6	9	426.1	7
	4 - 12	5	322.6	5.3
	12 - 18	3	216.7	3.5
	> 18	1	276.8	4.5
Soil media	Clay loam	3	684.3	7.3
	Silty loam	4	928.0	10
	Loam	5	146.4	1.5
	Sandy loam	6	301.6	3.2
Aquifer Media	Sand with silt and clay	6	121.8	3.5
	Limestone and gravel	7	301.5	8.8
	Gravel and sand	8	342.4	10
Vadose Zone	Metamophic	4	32.5	1
	limestone	5	314.6	2.1
	Sandstone	6	437.2	3.4
	Sand, gravel with clay	7	698.2	4.6
	Sand and gravel	8	2645.6	10
Hydraulic conductivity	0.04 - 4.1	1	112.2	1.3
	4.1 - 12.3	2	264.3	3
	12.3 - 28.7	4	867.3	10

Table 8. Statistics results of the map removal sensitivity analysis

Variation index (%)	Removed Parameter							
	D	R	A	S	T	I	C	L
Min.	0	0.3	0.1	0	0.0	0	0	0.1
Max.	3	3.4	1	2	2.8	5.8	1.9	5.8
Avg.	1.5	1.7	0.5	1	1.3	2.9	0.8	1.9
S.D.	0.8	0.7	0.3	0.6	0.5	1.6	0.6	0.8

S.D. refers to the standard deviation.

Table 9. Statistics results of the multiple map removal sensitivity analysis

Parameters used	Variation index (%)		
	Mean	Minimum	Maximum
D, R, A, S, T, C	1.9	0	2.94
D, A, S, T, C	4.14	0.05	4.22
A, S, T, C	4.88	0.4	4.88
A, S, C	5.35	0.92	6.1
A, C	5.94	1.2	7.43
A	6.3	1.5	8.21

Table 10. Statistics results of the single map sensitivity analysis

Parameter	Theatrical weight	Theoretical weight (%)	Effective weight			
			Avg.	Min.	Max.	S.D.
D	5	21.7	12.2	3.05	38.4	6
R	4	17.4	23.51	1.5	32.5	5.2
A	3	13	11.9	8.2	21.8	2
S	2	8.7	10.31	6.1	15.4	1.9
T	1	4.3	6.91	0.4	12.3	2.4
I	5	21.7	22.12	8.3	38.3	4.8
C	3	13	14.61	3.1	22.1	4.2

S.D. refers to the standard deviation.

Figure Captions

Fig. 1 Location of the study area and monitoring wells

Fig. 2 Depth to groundwater rating map

Fig. 3 Net recharge rating map

Fig. 4 Aquifer media rating map

Fig. 5 Soil type rating map

Fig. 6 Topography rating map

Fig. 7 Vadose zone rating map

Fig. 8 Hydraulic conductivity rating map

Fig. 9 Saveh-Nobaran plain land use map

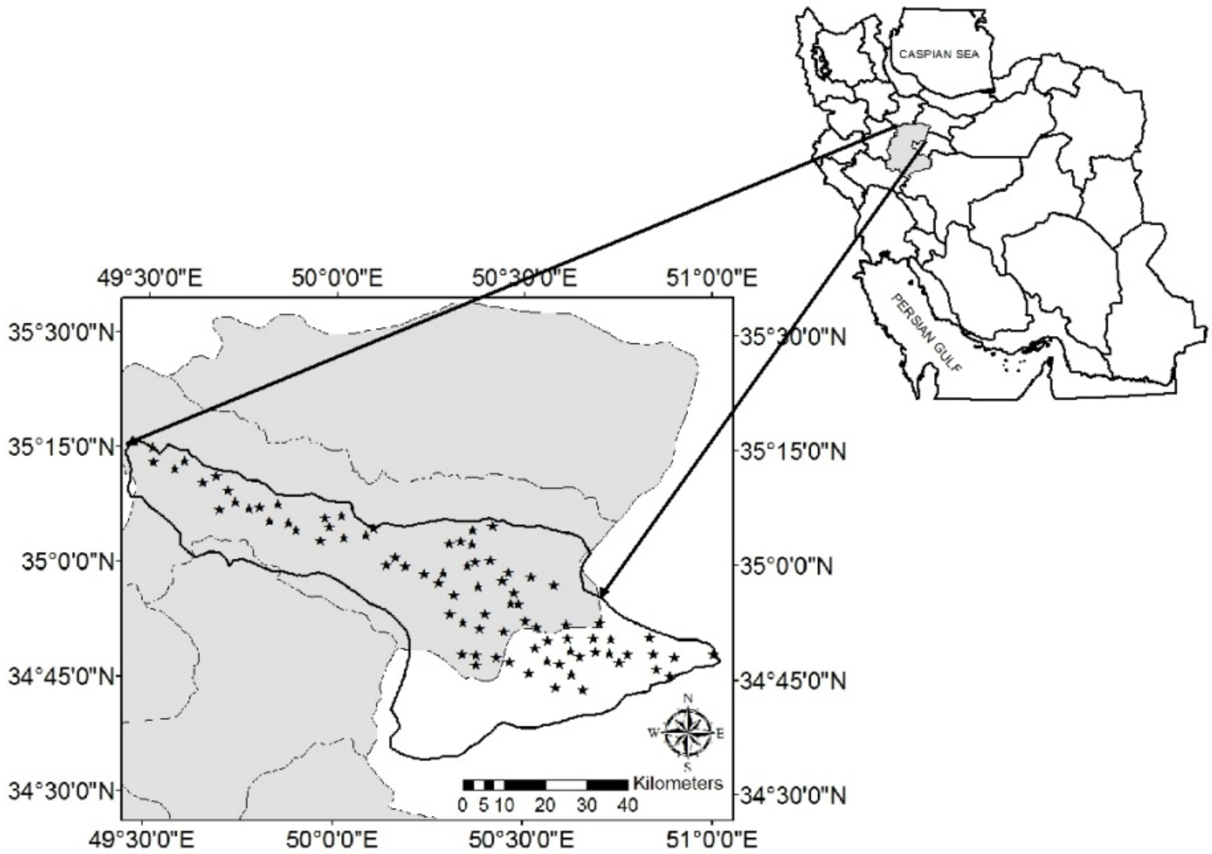
Fig. 10 Spatial distribution map of chloride according to WHO standards (2004) and sampling locations

Fig. 11 Groundwater vulnerability map

Fig. 12 Original vulnerability map and chloride concentrations for study area

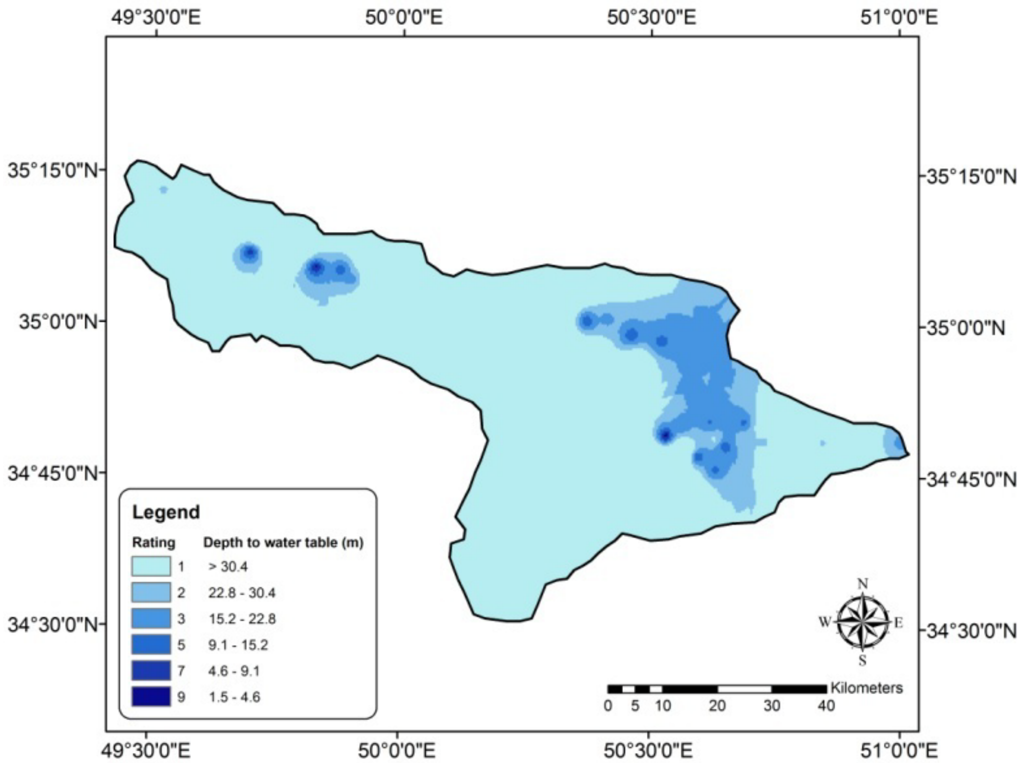
Fig. 13 Modified vulnerability map and chloride concentrations

Fig. 1



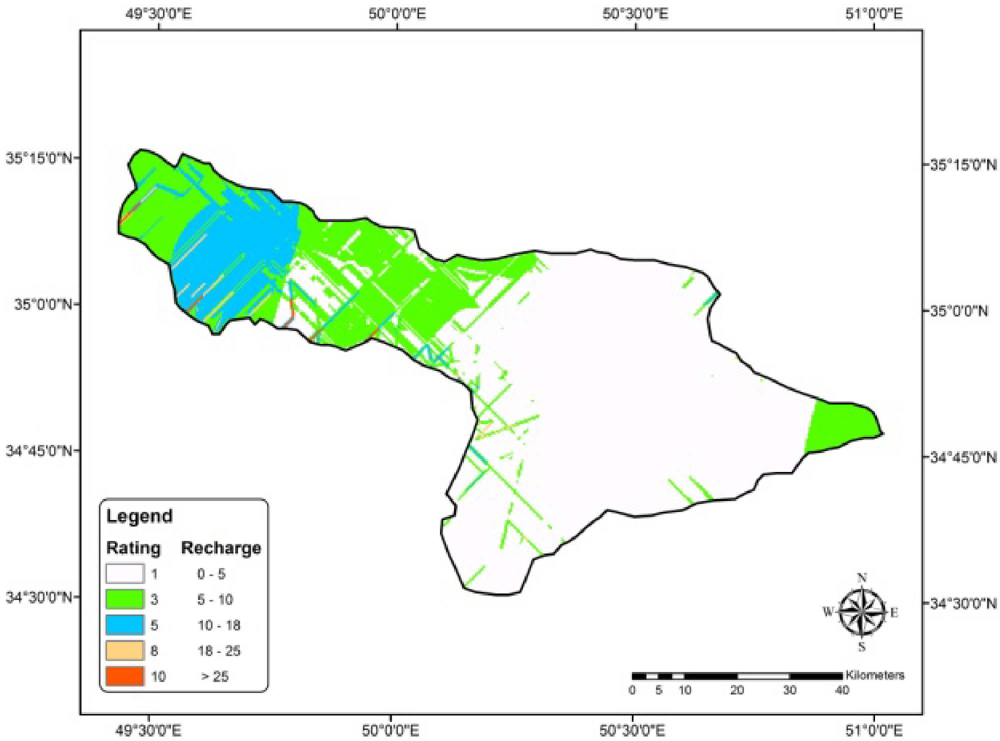
CASPIAN SEA
PERSIAN GULF
49°30'0"E
50°0'0"E
50°30'0"E
51°0'0"E
35°30'0"N
35°15'0"N
35°0'0"N
34°45'0"N
34°30'0"N
N
S
W
E
Kilometers
0 5 10 20 30 40

Fig. 2



49°30'0"E
50°0'0"E
50°30'0"E
51°0'0"E
35°15'0"N
35°0'0"N
34°45'0"N
34°30'0"N
Legend
Rating
Depth to water table (m)
1 > 30.4
2 22.8 - 30.4
3 15.2 - 22.8
5 9.1 - 15.2
7 4.6 - 9.1
9 1.5 - 4.6
N
W
E
S
0 5 10 20 30 40
Kilometers

Fig. 3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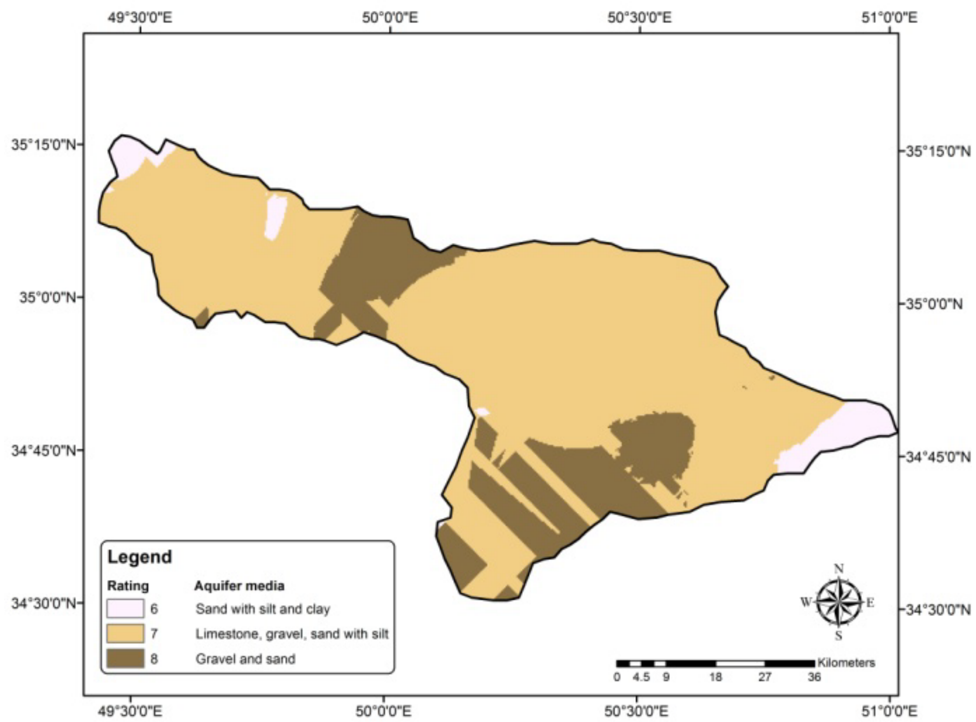
50°0'0"E
50°30'0"E
51°0'0"E
35°15'0"N
35°0'0"N
34°45'0"N
34°30'0"N
Legend
Rating Recharge
1 0 - 5
3 5 - 10
5 10 - 18
8 18 - 25
10 > 25
N
W
E
S
Kilometers
0 5 10 20 30 40

Fig. 4



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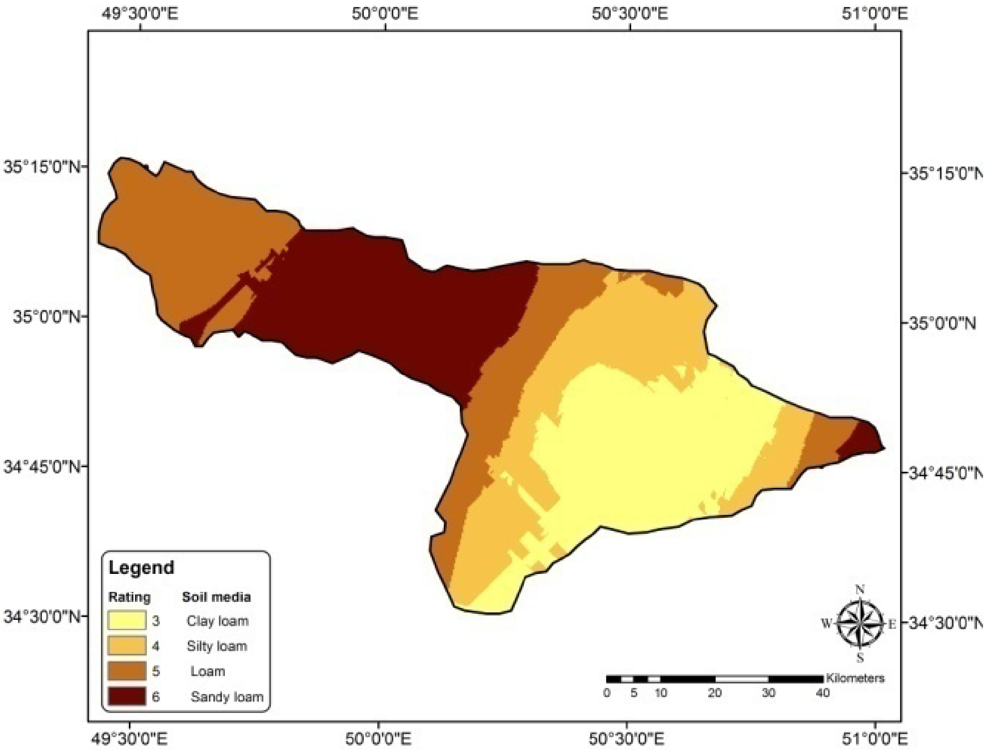
50°0'0"E
50°30'0"E
51°0'0"E
35°15'0"N
35°0'0"N
34°45'0"N
34°30'0"N
Legend
Rating
Aquifer media
6
Sand with silt and clay
7
Limestone, gravel, sand with silt
8
Gravel and sand
N
W
E
S
0 4.5 9 18 27 36
Kilometers

Fig.5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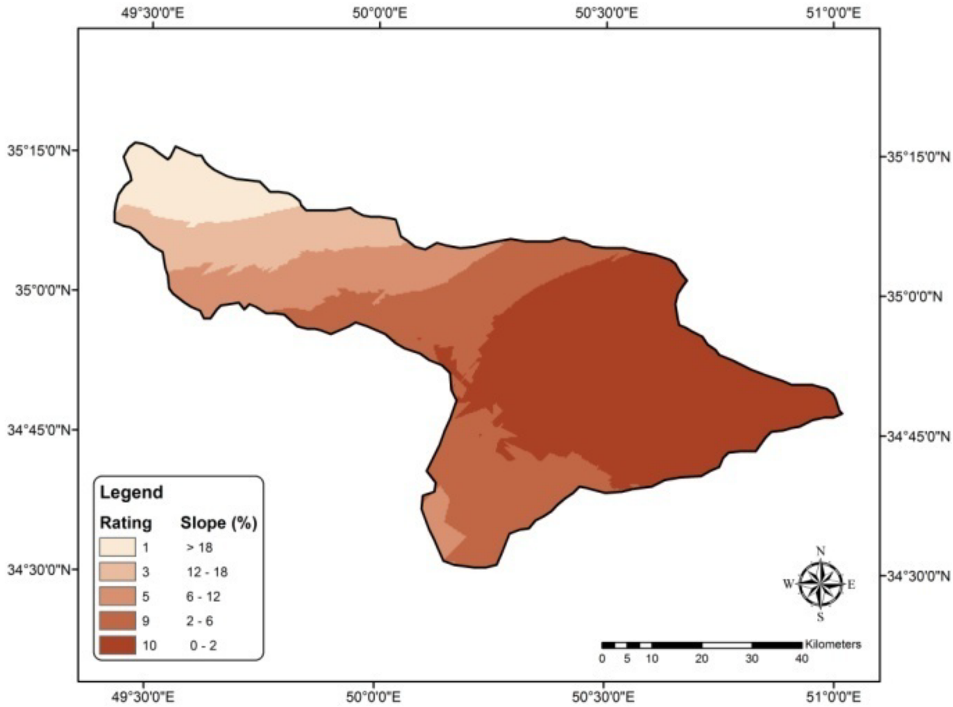
51°0'0"E
35°15'0"N
35°0'0"N
34°45'0"N
34°30'0"N
Legend
Rating
Soil media
3 Clay loam
4 Silty loam
5 Loam
6 Sandy loam
N
W
E
S
0 5 10 20 30 40
Kilometers

Fig. 6



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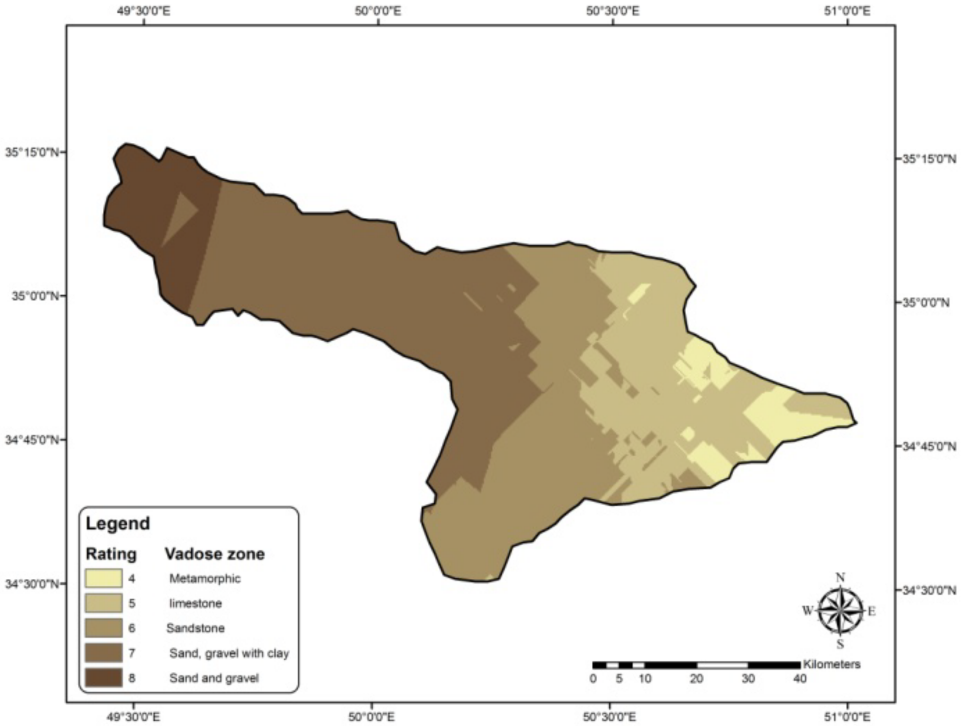
50°30'0"E
51°0'0"E
35°15'0"N
35°0'0"N
34°45'0"N
34°30'0"N
Legend
Rating
Slope (%)
1
> 18
3
12 - 18
5
6 - 12
9
2 - 6
10
0 - 2
N
W
E
S
0
5
10
20
30
40
Kilometers

Fig. 7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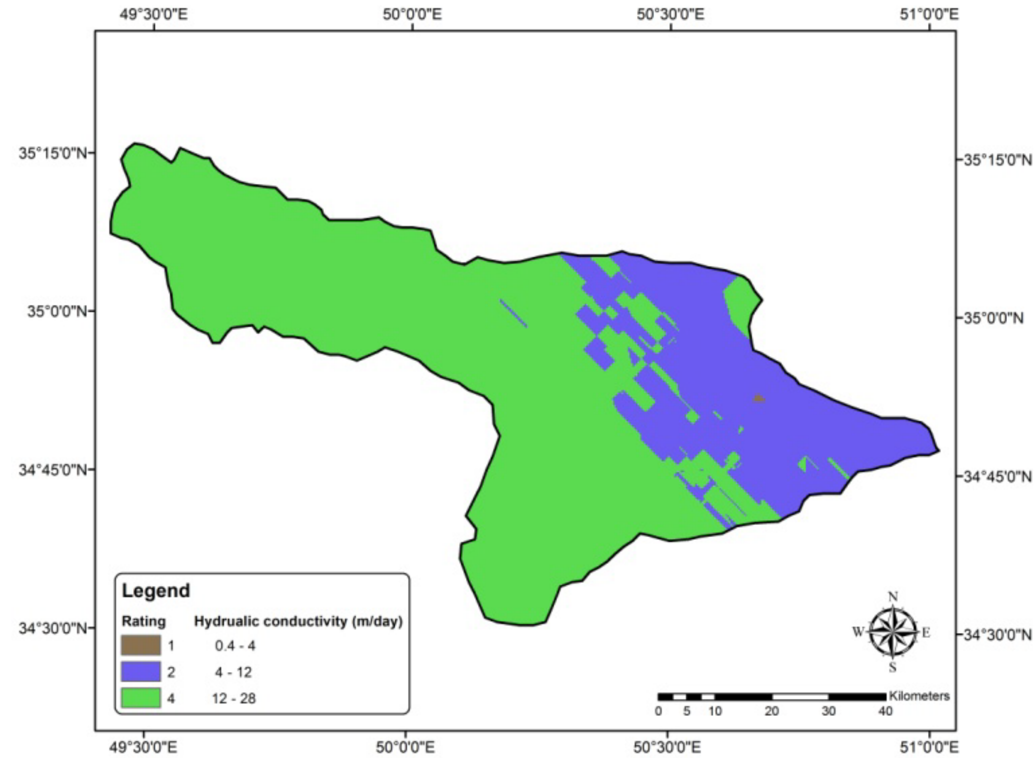
50°0'0"E
50°30'0"E
51°0'0"E
35°15'0"N
35°0'0"N
34°45'0"N
34°30'0"N
Legend
Rating Vadose zone
4 Metamorphic
5 limestone
6 Sandstone
7 Sand, gravel with clay
8 Sand and gravel
N
W
E
S
0 5 10 20 30 40
Kilometers

Fig. 8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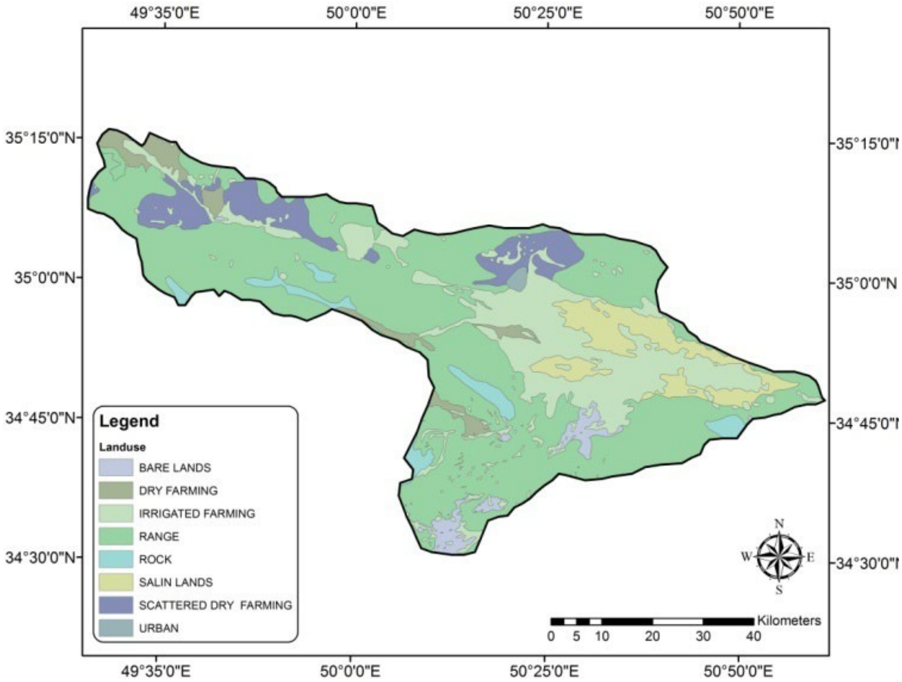
50°0'0"E
50°30'0"E
51°0'0"E
35°15'0"N
35°0'0"N
34°45'0"N
34°30'0"N
Legend
Rating
Hydrualic conductivity (m/day)
1 0.4 - 4
2 4 - 12
4 12 - 28
N
W
E
S
0 5 10 20 30 40
Kilometers

Fig. 9



49°35'0"E
50°0'0"E
50°25'0"E
50°50'0"E
35°15'0"N
35°0'0"N
34°45'0"N
34°30'0"N
Legend
Landuse
BARE LANDS
DRY FARMING
IRRIGATED FARMING
RANGE
ROCK
SALIN LANDS
SCATTERED DRY FARMING
URBAN
N
W
E
S
Kilometers
0 5 10 20 30 40

Fig. 10

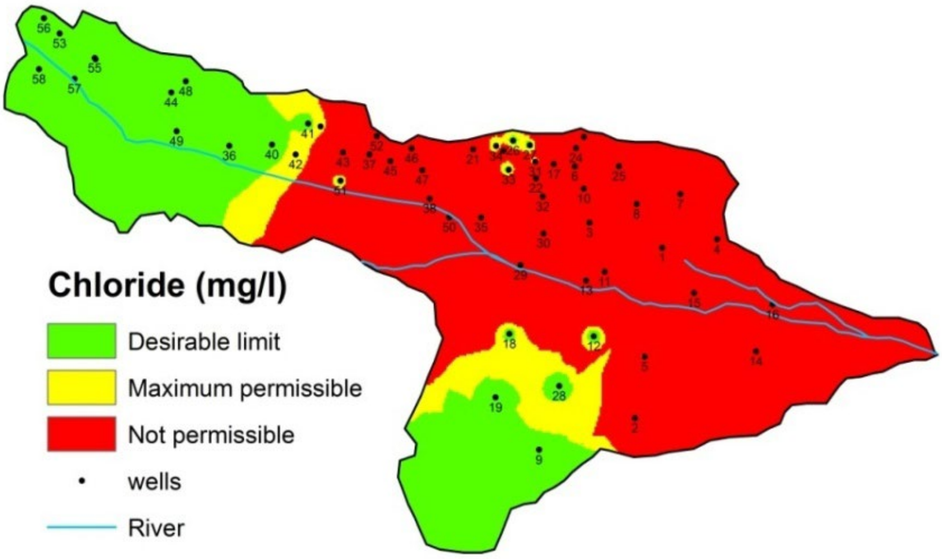

Chloride (mg/l)
Desirable limit
Maximum permissible
Not permissible
wells
River

Fig.11

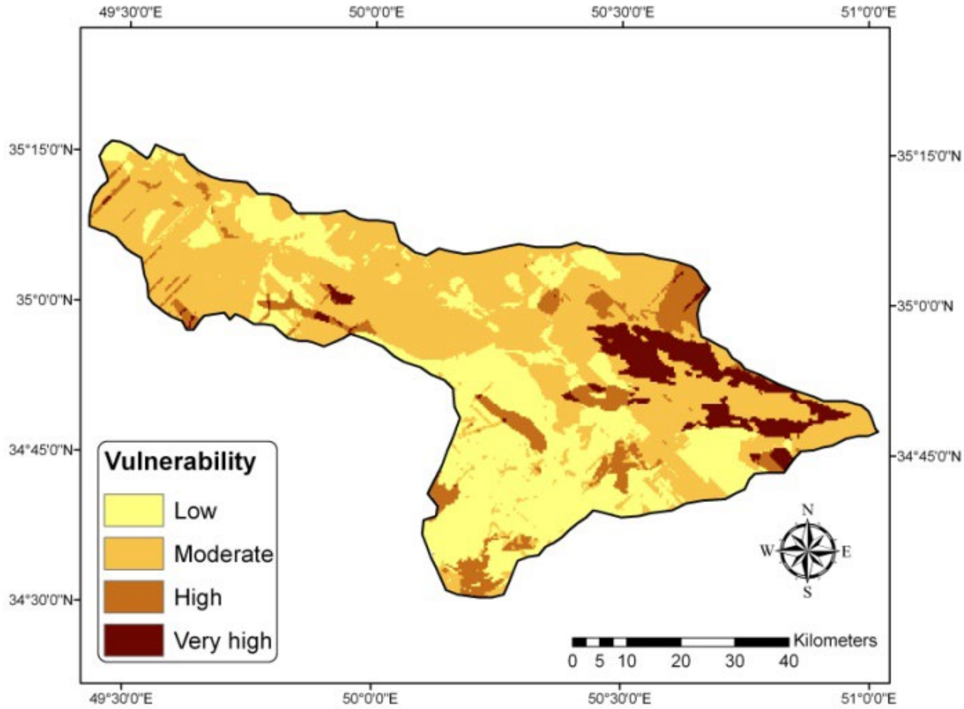

49°30'0"E
50°0'0"E
50°30'0"E
51°0'0"E
35°15'0"N
35°0'0"N
34°45'0"N
34°30'0"N
Vulnerability
Low
Moderate
High
Very high
N
W
E
S
Kilometers
0 5 10 20 30 40

Fig. 12

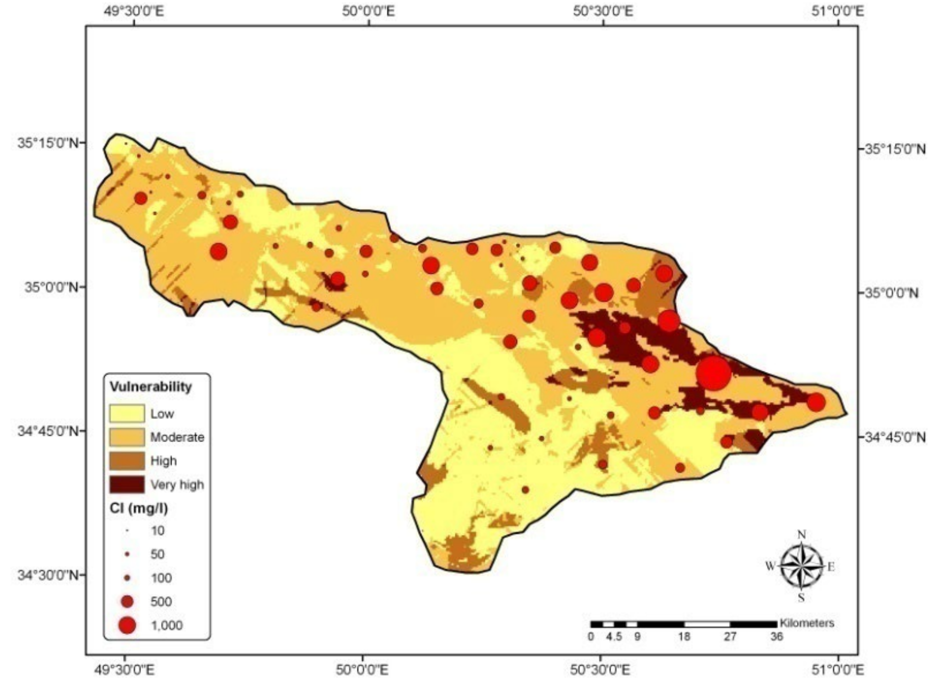
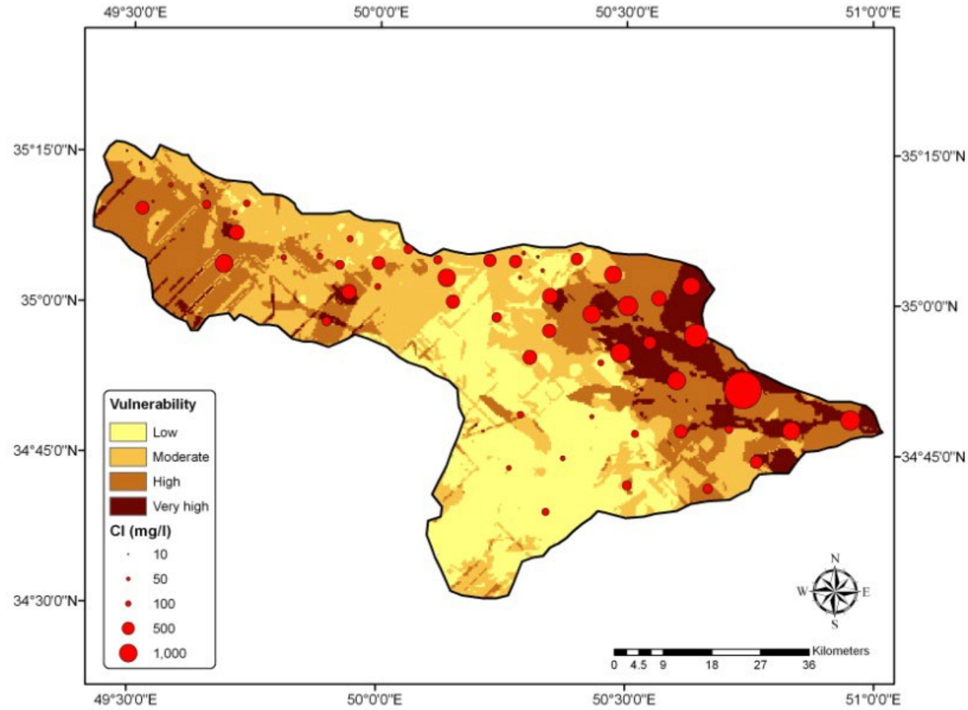

49°30'0"E
50°0'0"E
50°30'0"E
51°0'0"E
35°15'0"N
35°0'0"N
34°45'0"N
34°30'0"N
Vulnerability
Low
Moderate
High
Very high
Cl (mg/l)
10
50
100
500
1,000
N
S
E
W
0 4.5 9 18 27 36
Kilometers

Fig. 13


49°30'0"E
50°0'0"E
50°30'0"E
51°0'0"E
35°15'0"N
35°0'0"N
34°45'0"N
34°30'0"N
Vulnerability
Low
Moderate
High
Very high
Cl (mg/l)
10
50
100
500
1,000
N
W
E
S
0 4.5 9 18 27 36
Kilometers