Assessment of groundwater vulnerability to nitrate pollution caused by agricultural practices

Shabnam Goudarzi, Seyed Ali Jozi, Seyed Masoud Monavari, Abdoreza Karbasi and Amir Hesam Hasani

ABSTRACT

Environmental risk assessment is a step towards identification, analysis, and classification of risk factors and thus reduction of the possibility of adverse consequences. In this research, a novel approach for environmental risk assessment on groundwater pollution is applied. By combination of aquifer vulnerability DRASTIC map, pollution severity and prioritizing of the plain regions by the TOPSIS method, more sensitive regions of Qazvin aquifer in Iran are identified. In the first step, seven hydro-geological characteristics of the aquifer are overlaid to produce the potential vulnerability map. Nitrate is used as the pollution parameter and its value in monitoring wells is measured by sampling. Spatial distribution of nitrate concentration is investigated by ordinary kriging method. TOPSIS ranking method is also applied to estimate the probability of occurrence of pollution based on five affecting criteria defined and quantified in regions of the aquifer. By production of these three layers, the risk map of the aquifer is generated. Results indicate that 9% of the area of the aquifer is categorized in the high risk level which needs an emergency recovery action plan. Also, sensitivity analysis on the parameters of the aquifer vulnerability shows the effect of the soil media more than other parameters.

Key words | DRASTIC, environmental risk assessment, groundwater, nitrate pollution, TOPSIS

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INTRODUCTION

Groundwater contamination by nitrate and other nutrients is a major problem throughout the world, often occurring as the result of anthropogenic activities, lack of management, and over-exploitation of groundwater resources (Addiscott *et al.* 1991; Pisciotta *et al.* 2015). Groundwater resources are under intense anthropogenic pressures and constant threat of pollution. Human activities such as agriculture, urbanization, and industry have caused irreversible degradation of groundwater quality; therefore, prevention is the most appropriate strategy in the fight against groundwater pollution (Kazakis & Voudouris 2015). Groundwater, as one of the most important water resources, is confronted by various challenges such as natural and non-natural contaminants. In arid and semi-arid countries like Iran, a major part of water uses are supplied from groundwater resources, especially in areas which suffer from insufficient surface water resources. Ths main important pollutants in water resources generally are due to human activities (Freeze & Cherry 1979). Population growth, increased use of fertilizers, and conversion of agricultural lands to intensive cultivated areas have caused major environmental problems. Agricultural activities are named as the main cause of groundwater nitrate pollution (Hailin *et al.* 2011).

Nitrates and pesticides are the most common non-point source contaminants detected in shallow alluvial aquifers in agricultural areas (Güler *et al.* 2012; Nisi *et al.* 2013; Bartzas *et al.* 2015). In relation to this subject, many studies have been performed on nitrate pollution in groundwater resources (Rutkoviene *et al.* 2005, 2009; Wick *et al.* 2012;

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Zhang et al. 2013; Chica-Olmo et al. 2014; Espejo-Herrera et al. 2015; Han et al. 2015; Matiatos 2016; Menció et al. 2016; Ouedraogo et al. 2016). Also, many studies have been done on nitrate regarding human health risk assessment, such as cancer risk, and other critical phenomena on groundwater (Yong et al. 1992; Weyer et al. 2001; Gulis et al. 2002; Gao et al. 2012; Fabro et al. 2015; Wheeler et al. 2015; Wongsanit et al. 2015). The World Health Organization's guideline has indicated that the ingestion of more than 50 mgL^{-1} nitrate in potable water can be harmful to human health (WHO 2008).

Groundwater pollution is one of the major environmental threats caused by human activities, such as the use of fertilizers on agricultural land. Agricultural activities have been developed from traditional methods to modern applications, resulting in an overuse of chemical fertilizers that increase the amount of pollutants, particularly when farmers are unaware of the adverse effects of fertilizer use. Some fertilizers, including nitrate, pollute water at a greater extent than other fertilizers. The frequent use of fertilizers on agricultural land induces an increase in nitrate-N pollution in groundwater. To evaluate the effects of pollution in water resources, researchers should identify and assess the extent of pollution by constructing a risk map.

Antonakos & Lambrakis (2007) used a DRASTIC model to explore potential nitrate polluted groundwater zones. They also compared a DRASTIC vulnerability index with groundwater nitrate distributions mapped by geo-statistical approaches (Antonakos & Lambrakis 2007; Assaf & Saadeh 2009; Baalousha 2010). During the past decades, several methods for assessing groundwater vulnerability using different evaluation factors and approaches have been developed. Apart from all these methods, the DRASTIC method, developed by the US Environmental Protection Agency (US EPA), remains one of the most frequently used approaches to assess vulnerability to groundwater contamination in porous aquifers (Aller et al. 1987; Panagopoulos et al. 2006).

In spite of its age, the DRASTIC method has been used for vulnerability assessment in many recent studies. One of the main reasons for the frequent use of DRASTIC is the availability of the data which are needed. In central Japan, a GIS-based DRASTIC model was used to assess aquifer vulnerability (Babiker et al. 2005). To study the risks and vulnerability of agricultural potential nitrogen pollution, Leone et al. (2009) adopted the DRASTIC model. Geo-statistical techniques, such as indicator kriging (IK) and ordinary kriging (OK) are commonly applied in various applications, including iso-concentration maps showing groundwater contaminants (Stigter et al. 2006) and iso-probability maps revealing the concentration of a specific contaminant exceeding a particular threshold (Pulido-Leboeuf et al. 2002; Ribeiro & Paralta 2002; Hu et al. 2005; Stigter et al. 2005; Chen et al. 2013).

Efficient preventive programs, including risk management, should be implemented to monitor the risks of groundwater pollution. In many countries, vulnerability maps are used to assess groundwater pollution risk. Inherent and natural characteristics are considered in traditional methods of vulnerability mapping. Other researchers also applied risk map in their studies. For instance, Ducci et al. (2008) explained that risks not only include the inherent vulnerability of an aquifer called static factor but also consider human activities as important dynamic factors. To prevent the drawbacks encountered in previous studies focusing on risk mapping, researchers should consider the pollution occurrence probability factor in risk maps (Neshat et al. 2015). Pusatli surveyed the risk of aquifer pollution in Küçük River in the western part of Turkey by combining a vulnerability index and quality index (Pusatli et al. 2009).

TOPSIS, one of the classical multi-criteria decision-making methods was developed by Hwang & Yoon (1981). It is based on the concept that the chosen alternative should have the shortest distance from the positive ideal solution and the farthest from the negative ideal solution. TOPSIS also provides an easily understandable and programmable calculation procedure. It has the ability to take various criteria with different units into account simultaneously (Ekmekcioglu et al. 2010). Previous applications include a business model comparison (Zhou et al. 2012), evaluating transportation systems (Awasthi et al. 2011), competition in the tourism industry (Zhang et al. 2011), a product adoption process for the automobile market (Kim et al. 2011) and performance measurement for aviation firms (Aydogan 2011). TOPSIS has not been applied in the assessment of the probability of occurrence and most probable regions in the aquifer to have nitrate pollution are ranked by this method based on the quantified criteria, in this research.

The British Standards Institute recognizes risk as the combination of occurrence and results of a hazardous event (Wright 2003; Jozi *et al.* 2012). Risk assessment determines the qualitative analysis of risk potential regarding the sensitivity or vulnerability of the surrounding environment. Environmental risk assessment is the qualitative analysis process of hazard forces and potential risks in a project as well as the sensitivity or vulnerability of the environment.

In this research, to assess the risk of pollution resulting from agricultural fertilizers, the DRASTIC map of the Qazvin aquifer is prepared to show the vulnerability potential. Then, the pollution severity in the aquifer is extracted from the observed data of nitrate pollution obtained from selected pumping wells by kriging method. The TOPSIS method is then used to evaluate the probability of occurrence of pollution in various zones of the aquifer. Finally, the risk assessment approach is applied to estimate the risk priority number (RPN) of each cell of the aquifer in a GIS environment. Based on the classification of RPN values, the areas with high, moderate, and low pollution risks are identified and required solutions are proposed to be considered for further studies.

MATERIALS AND METHODS

Description of the study area

Qazvin aquifer is located in Qazvin Province in the northwest of Iran. Qazvin aquifer, with an area of $15{,}559.45 \times 106\ m^2$, annual mean temperature of 13 °C, annual precipitation about 0.320 m, and a cold, dry climate is selected as the case study (Figure 1). Average groundwater depth varies from 28 to 35 m from the ground level. Qazvin plain, with an area of 8,830 km^2, has a large agricultural area of about 350,000 ha, divided into two parts depending on sources of water. In the northern Qazvin plain, Qazvin irrigation system has been in operation for more than 30 years providing water from the Taleghan River through the diversion tunnel and supplemented by groundwater. About 76,000 ha of farmland are covered by this irrigation system. The rest of the plain remains under rain-fed conditions with water supplied partly from natural streams and groundwater.

Figure 1 | Location of the Qazvin aquifer.

The plain is one of the most important agricultural regions in the country. Because of the high rate of production, farmers are willing to use chemical fertilizers in order to increase agricultural productivity. Thus, by infiltration of the excess fertilizers to the groundwater of the plain, many pollution problems may arise in the region. Therefore, it is necessary to evaluate the pollution risk of nitrate in groundwater resources of Qazvin plain. Groundwater flow in the aquifer is from west to east, but it changes in northern areas towards southeast and in southern and southwest areas is towards the center of the plain and then towards the northeast. Finally, all groundwater flows are directed to the eastern marsh and flow out of the region by natural drainage. Based on the latest collected data, 51% of the wells, 90% of the springs, and 56% of the aqueducts are dedicated to agricultural uses in the plain. Accordingly, 90% of the groundwater withdrawal, which is about 1.6 billion cubic meters per year, is used for agricultural consumption. About 7% of the total groundwater withdrawal is used for drinking water and 3% is used for industrial uses. Figure 1 shows the location of Qazvin aquifer.

Most areas of the Qazvin plain are dedicated to agricultural concerns and Qazvin aquifer is the main water resource which supplies the required water. In recent years, use of chemical fertilizers has been increased by the famers in order to produce more products. Therefore, by infiltration of the drainage water to the aquifer, the concentration of nitrate has increased in the aquifer which has raised worries about health problems. Hence, it is necessary to define the risk of pollution in the aquifer and identify which parts need emergency action plans. Based on country divisions, Qazvin plain is composed of five regions: Qazvin, Alborz, Abyek, Takestan, and Boeenzahra.

Risk assessment method

In this research, a novel method is applied to identify all areas of the Qazvin aquifer that are at risk from agricultural activities. The method involves the combination of a vulnerability map (obtained by DRASTIC method), groundwater pollution map (obtained by measuring nitrate concentration in monitoring wells and interpolation by Kriging method), and pollution occurrence probability map (obtained by TOPSIS method), as shown in Figure 2. The final risk map is divided into risk categories which show risk levels in the zones of Qazvin aquifer. Zones with high and very high risk levels warrant serious attention and emergency action plans for reclamation of the aquifer.

Groundwater vulnerability map

During the past decades, several methods for assessing groundwater vulnerability using different evaluation factors and approaches have been developed, including GOD (Foster 1987), SINTACS (Civita 1999), AVI (Van Stempvoort *et al.* 1993), and the PI method (Goldscheider *et al.* 2000). Apart from these methods, the DRASTIC method, developed by the US Environmental Protection Agency (US EPA), remains one of the most frequently used approaches to assess vulnerability to groundwater contamination in porous aquifers. DRASTIC uses seven parameters, 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*) as weighted layers to enable a reliable assessment of vulnerability (Fijani *et al.* 2013; Rajasooriyar *et al.* 2013).

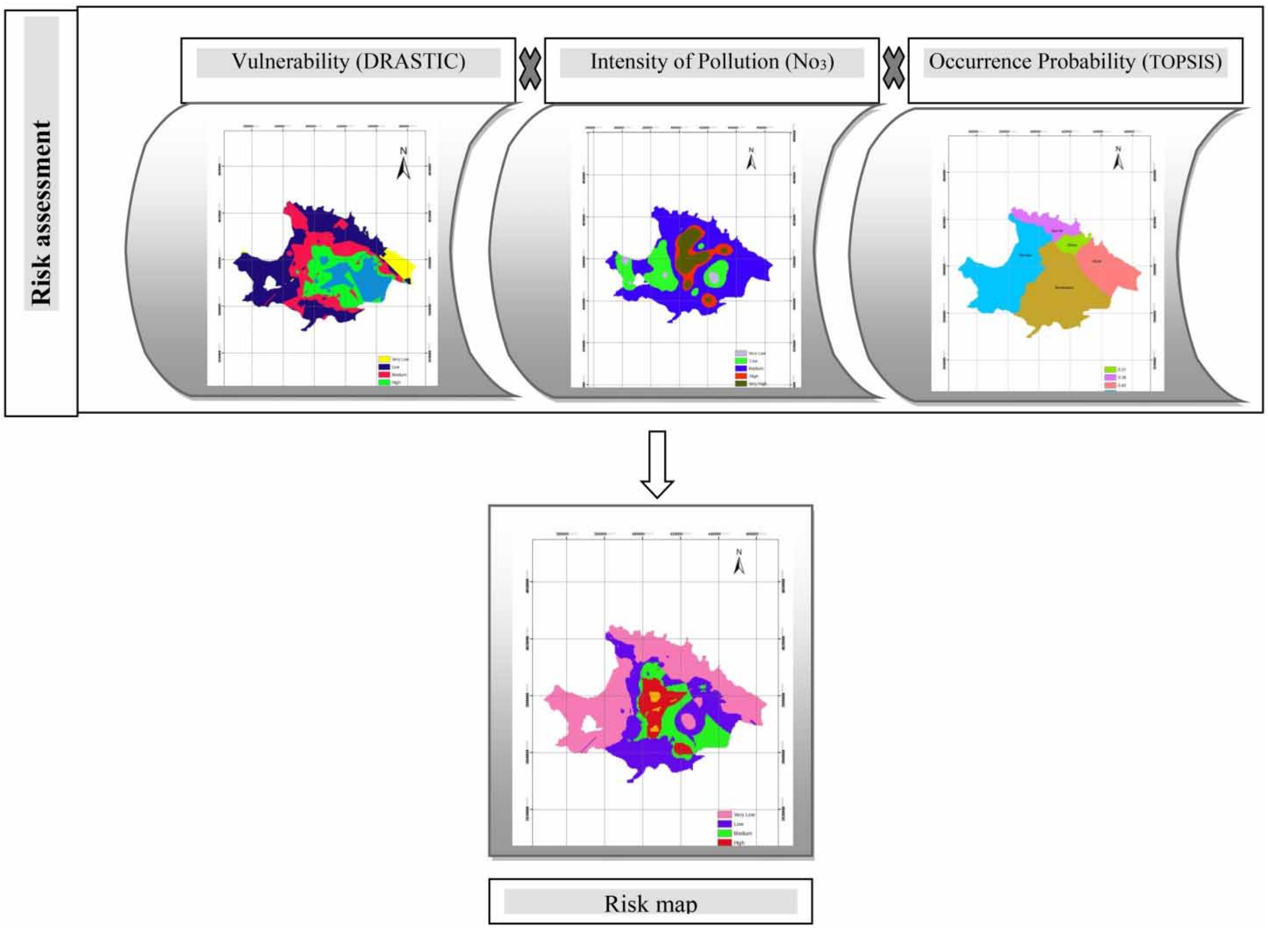

Figure 2 | Methodology overview.

In order to integrate spatial and descriptive data and analyses of vulnerability in Qazvin plain's aquifer, the DRASTIC method was applied. A map of each characteristic was prepared and classified into ranges based on Table 1. Each parameter has its weight regarding the vulnerability potential. Weighting multipliers are then used for each factor to balance and enhance their importance. The final vulnerability index is a weighted sum of the seven characteristics presented in Table 1. The DRASTIC index (D_i) can be computed using Equation (1):

$$D_i = D_r \times D_w + R_r \times R_w + A_r \times A_w + S_r \times S_w + T_r \times T_w + I_r \times I_w + C_r \times C_w \quad (1)$$

where D_i is DRASTIC index, w is weighting factor for each parameter, r is rate of each parameter and $D, R, A, S, T, I,$ and C are the seven parameters mentioned above, with their weights and boundary values presented in Table 1.

Severity of pollution

Nitrate concentration was chosen as the most problematic contamination in the Qazvin aquifer because of the intensive agricultural activities and widespread use of fertilizer in the region. Nitrate normally penetrates the surface and proceeds into groundwater. Sampling and analysis were carried out on 48 agricultural wells with a range of 87–113 m deep and widespread over the aquifer to cover the area. Locations of the sampling points (wells) were chosen based on overlying of the locations of the withdrawal wells on the aquifer and the land use layers' data prepared in GIS. Wells near to agricultural lands and farms were selected to measure the nitrate concentration in them. Sampling from the wells was performed in July of 2014 when the use of fertilizers had the highest rate in the region as the worst case scenario. This time was selected in order to observe the critical situation in the aquifer. The 48 samples were sent to and analyzed in the laboratory by the spectrophotometric method and NO_3 concentrations in the wells were obtained. Afterward, it was necessary to expand the point data over the aquifer. The ordinary interpolation kriging was applied for collected nitrate samples to obtain nitrate concentrations in all pixels in the area to create a pollution parameter for risk assessment of the Qazvin aquifer. OK has better predictive capability due to larger correlation coefficients and lower error in predictions, as is indicated by the root mean squared error of predictions. The minimum estimation error variance was determined from the kriging method to achieve better spatial estimation from the sampling points (Baalousha 2010). Before applying OK, we checked the spatial autocorrelation using Pearson coefficient and spatial stratification using PD value in geographical detector (Wang & Hu 2012) in order to ensure that the employed OK was a good choice. Using the kriging, variance of estimate is independent of actual measurements from the field, which is the best linear unbiased estimator of an unknown field. The OK interpolation equation is as follows:

$$Z*(x_0) = \sum_{i=1}^{n} n\lambda_i Z(x_i) \quad (2)$$

where $Z^*(x_0)$ is the estimated value, n is the number of points, $Z(x_i)$ is the measured value at point x_i, and λ_i is the kriging weight (Neshat *et al.* 2015).

Probability of occurrence

The risk rating is based on the probability of occurrence. This probability could be obtained by evaluating and ranking possible alternatives based on the affecting criteria. In this research, as a new idea, the TOPSIS method was used to calculate the probability of occurrence of nitrate pollution in the

Table 1 | Drastic weighting factors (Aller *et al.* 1987)

		Rate		Weighted Rate	
Parameter	**Weight**	**Min.**	**Max.**	**Min.**	**Max.**
Depth to water (*D*)	5	1	10	5	50
Net recharge (*R*)	4	1	9	4	36
Aquifer media (*A*)	3	2	10	6	30
Soil media (*S*)	2	1	10	2	20
Topography (*T*)	1	1	10	1	10
Impact of vadose zone (*I*)	5	1	10	5	50
Hydraulic conductivity (*C*)	3	1	10	3	30
DRASTIC index	–	–	–	26	226

area of the Qazvin aquifer. By defining the main criteria which could cause nitrate pollution in the aquifer, weighting them by aggregation of regional experts' opinions, and quantifying them by use of the data available in the region, most risk-prone regions of Qazvin plain to have high nitrate pollution were ranked. This rank is based on a distance index which is calculated by the TOPSIS method by defining ideal positive and negative solutions. According to this definition, the TOPSIS index could be used to show the probability of the occurrence of pollution. Regions which are more risk-prone and likely to introduce more nitrates into the groundwater are ranked first; therefore, the value of the TOPSIS index is used as the probability of occurrence.

TOPSIS is a multi-attribute decision-making methodology based on the measurement of the Euclidean distance of an alternative from an ideal goal. The technique has been specifically adapted to simplify the risk-assessment procedure and to allow a correct evaluation of pertinent data. Based on index properties and data collected about alternatives, this method selects a group of the best indicators as the virtual positive ideal solution and a group of the worst indicators as the virtual negative ideal solution. Accordingly, comparison of the solutions can be done by calculation of the Euclidean distance between the alternative and the positive and negative ideal points. The resulting Euclidean distance may then be used to evaluate whether a solution is good or more probable. As the TOPSIS method is based on a simple working theory and is easily understood and applied, it soon attracted the attention of relevant economic and management departments and has been widely applied. The TOPSIS method was initially presented by Yoon & Hwang (1981) and is a process of finding the highest rank among all alternatives. The TOPSIS method is expressed in a succession of six steps as follows.

Step 1: Calculate the normalized decision matrix. The normalized value r_{ij} is calculated as follows:

$$r_{ij} = x_{ij}\sqrt{\sum_{i=1}^{m} x_{ij}^2}, i = 1,\ 2,\ \ldots,\ m \text{ and } j = 1,\ 2,\ \ldots,\ n \tag{3}$$

where x_{ij} is the performance of alternative i for criterion j, m is the number of alternatives, and n is the number of criteria or indicators.

Step 2: Calculate the weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as follows:

$$v_{ij} = w_j \times r_{ij}, i = 1,\ 2,\ \ldots,\ m \text{ and } j = 1,\ 2,\ \ldots,\ n \tag{4}$$

where w_j is the weight of criterion j and $\sum_{j=1}^{n} w_j = 1$.

Step 3: Determine the positive ideal (A^*) and negative ideal (A^-) solutions for each criterion:

$$A^* = \{(\max_i v_{ij}\,|j \in C_b),\ (\min_i v_{ij}\,|j \in C_c)\} = \{v_j^*\,|i = 1, 2,\ \ldots, m\} \tag{5}$$

$$A^- = \{(\min_i v_{ij}\,|j \in C_b),\ (\max_i v_{ij}\,|j \in C_c)\} = \{v_j^-\,|i = 1, 2,\ \ldots, m\} \tag{6}$$

v_j^* and v_j^- are positive ideal and negative ideal solutions for criterion j, and C_b and C_c are sets of desirable and undesirable criteria.

Step 4: Calculate the distance using the n-dimensional Euclidean distance. The distance of each alternative from the positive ideal solution and the negative ideal solution, respectively, is as follows:

$$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2}, i = 1, 2,\ \ldots, m \tag{7}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}, i = 1, 2,\ \ldots, m \tag{8}$$

Step 5: Calculate the relative closeness to the ideal solution. The relative closeness of the alternative i to the ideal solution is defined as follows:

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-}, i = 1, 2,\ \ldots, m \tag{9}$$

Step 6: Rank the preference order for alternatives. Each alternative that has a bigger relative closeness has a higher priority among the other options.

Groundwater pollution risk

Probability mapping performed using parameter uncertainty is the most important factor in preparing a risk map while carrying out an uncertainty survey and analysis to estimate the pollution risk. A risk map of pollution in an area can be obtained if the amount of damage and its probability can be determined. A pollution model would always be prone to a level of uncertainty and it can always be used to obtain its probability map. Morris & Foster (2000) defined the risk of aquifer pollution as probability values of groundwater pollution exceeding the tolerable level caused by activities above the plain surface. In other words, risk analysis of an aquifer can be conducted when pollution occurrence probability is considered (Zaporozec 2004). The risk can be calculated by the following equation:

$$\text{Risk} = \sum_{i=1}^{R} \text{Probability of event i} \times \text{Consequence of event i} \tag{10}$$

Equation (11) indicates damage denoted by D_i and probability of occurrence denoted by P_i. This phenomenon occurs R times during its life cycle as given below:

$$\text{Risk} = \sum_{i=1}^{R} \mathrm{P_i} \times \mathrm{D_i} \tag{11}$$

In the case of groundwater, damage can be either natural or unnatural. Natural factors, such as geological, hydrological, and hydrogeological characteristics, influence groundwater vulnerability. Groundwater pollution can be considered as human impact, specifically if pollution parameters originate from human activities, such as nitrate in this study. Nitrates were selected in this research because agricultural activities in Qazvin plain were considered. The groundwater risk assessment depended on three factors: groundwater vulnerability; pollution; and probability of pollution occurrence. The risk map was then calculated as follows:

$$\text{Risk} = \text{Vulnerability} \times \text{Pollution} \times \text{Occurrence probability} \tag{12}$$

These factors are directly related to the risk; as one of these factors is increased, the risk is also increased, and vice versa.

RESULTS AND DISCUSSION

Groundwater vulnerability assessment

A validated groundwater vulnerability detection map of the Qazvin aquifer is shown in Figure 2. It was created using the DRASTIC method through summation of the seven previously mentioned DRASTIC parameters after multiplying each parameter with modified rates and weights, respectively. The vulnerability index is divided into five classes, ranging from very low to very high, and is shown in Table 2. In Table 3, definitions of the classes of potential vulnerability are presented. As seen in Figure 2, the central and eastern parts of the aquifer represent the highest vulnerability class, indicating that they are the most vulnerable regions to pollution. The northeastern area of the plain is assigned the lowest classification. Based on Table 2, about 45% of the aquifer area lies in low-vulnerable regions, 24%

Table 2 | Variation of the DRASTIC index in the Qazvin aquifer

Rank	DRASTIC index	Class of vulnerability	Area (%)
1	76–102	Very low	4.4
2	102–120	Low	40.6
3	120–133	Moderate	23.9
4	133–146	High	17.5
5	164–146	Very high	13.4

Table 3 | Classes of potential vulnerability

No.	Class of vulnerability	Definition
1	Very low	Ignorable potential of loss of natural resources
2	Low	Low potential of loss of natural resources
3	Moderate	Relatively harmful to natural resources
4	High	Harmful but not potentially destructive
5	Very high	Very harmful and potentially destructive, high loss of natural resources

Table 4 | Variation of nitrate pollution in Qazvin aquifer

Rank	Nitrate concentration (ppm)	Intensity of pollution	Area (%)
1	0–25	Very low	1.9
2	25–50	Low	19.3
3	50–75	Moderate	61.5
4	75–100	High	7.8
5	100–125	Very high	9.5

in moderate-vulnerable regions, and 31% is classified as highly vulnerable.

Risk mapping

Figure 4 shows the nitrate concentration measured in July 2014 and interpolated by kriging method in the Qazvin aquifer. The range of pollution variation is reported in Table 4.

As seen in Figure 4, dispersion of the pollution has a higher intensity in central and southeastern regions of Qazvin aquifer than the other parts. Comparing the maps of potential vulnerability (Figure 3) and severity of pollution (Figure 4) shows a reasonable match between these two maps. Central and eastern regions of the aquifer have the highest potential to be vulnerable while central and southeastern regions have the highest intensity of nitrate concentration. This issue may result in a high risk of damage in these regions.

In order to rank probability of pollution occurrence in regions of Qazvin aquifer, it is necessary to define and weight the affecting criteria. By filling in prepared questionnaires by some local experts on the subject and aggregation of the proposed suggestions, five criteria and their weighting factors were determined as the main causes of the introduction of nitrate pollution into the aquifer. Based on the available data, these criteria are quantified in five regions of the aquifer: Qazvin, Abyek, Boeenzahra, Takestan, and Alborz. In Table 5, the main causes of nitrate pollution in Qazvin aquifer regions are presented with their weights, and are quantified based on the existing data in the reports. In fact, regions are alternatives to be ranked in the TOPSIS method based on the probable causes of nitrate pollution.

By use of the TOPSIS method, the probability of pollution occurrence in regions of the aquifer is obtained and ranked. In Table 6 and Figure 5, ranks and values of the probability of occurrence of pollution in the regions of Qazvin aquifer are reported.

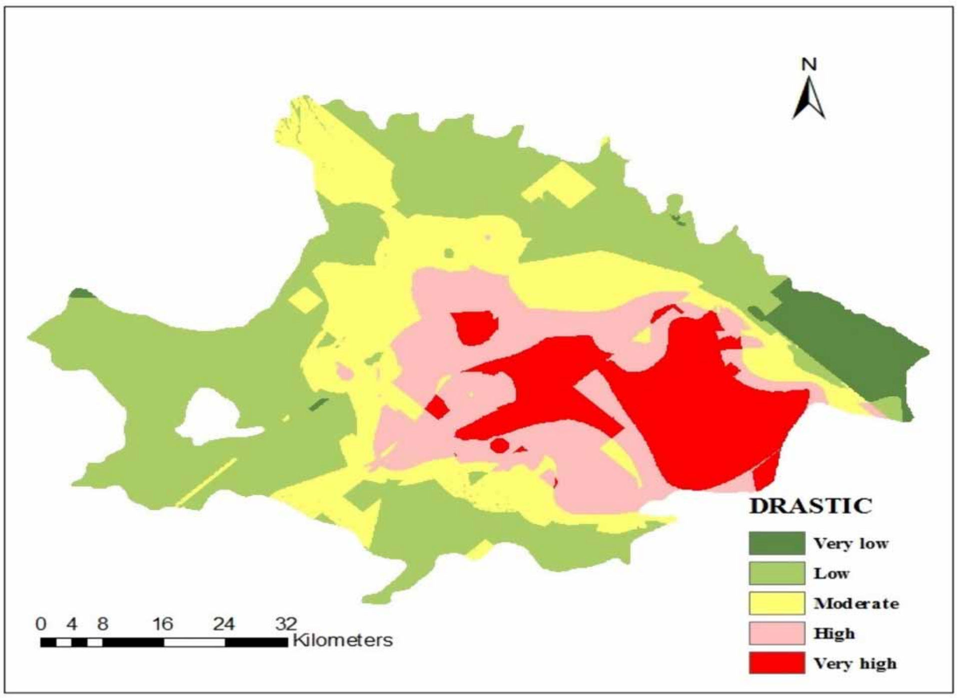

Figure 3 | Vulnerability map of the Qazvin aquifer.

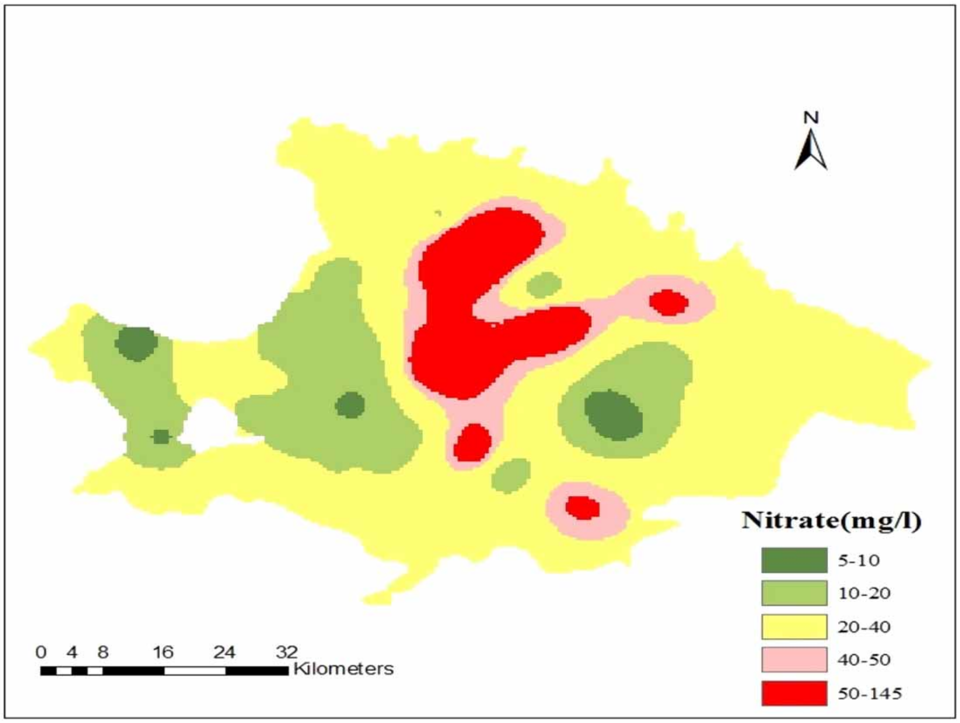

Figure 4 | Severity of nitrate pollution in Qazvin aquifer.

Table 5 | Weight and dimensionless rate of criteria of pollution occurrence in regions of Qazvin aquifer

			Region				
No.	**Criteria (cause)**	**Weight**	**Qazvin**	**Abyek**	**Boeenzahra**	**Takestan**	**Alborz**
1	Use of agricultural fertilizers	0.3	0.16	0.16	0.39	0.19	0.09
2	Cultivated area	0.3	0.24	0.1	0.34	0.25	0.08
3	Irrigated area	0.2	0.1	0.18	0.08	0.09	0.12
4	Farmers' literacy level	0.1	1.28	2.11	1.39	1.93	2.11
5	Drainage area	0.1	0	0.7	0.15	0.1	0.15

According to Equation (12), by production of the vulnerability detection map (Figure 3), groundwater pollution map (Figure 4), and pollution occurrence probability map (Figure 5), the risk map which shows the RPN in each cell of the aquifer in GIS is obtained according to the process shown in Figure 2. Degree of risk based on the values obtained for RPNs are specified. Table 7 and Figure 6 show the values obtained for RPN and the risk map for the Qazvin aquifer.

The risk map (Figure 6), resulting from overlaying the probability map (Figure 5) and the severity map (Figure 4) and the vulnerability detection map (Figure 3), splits the study area into five classes according to their degree of risk: very low, low, moderate, high, and very high risk zones. A comparison between the vulnerability map, nitrate concentration, and the probability map shows the possibility of pollution occurrence in central areas with high nitrate concentration. It appears that the high and very high risk areas in Figure 6 coincide with the highest nitrate regions in Figure 4. Accordingly, the risk level shows high and very high risk of hazard in some parts of the center and southeast of the aquifer. Thus, in high risk

Table 6 | Probability of occurrence of pollution in regions of Qazvin aquifer

Rank	Region	TOPSIS index	Probability of occurrence
1	Alborz	0.21	Very low
2	Qazvin	0.38	Low
3	Abyek	0.42	Moderate
4	Takestan	0.43	Moderate
5	Boeenzahra	0.65	High

areas of the plain, the probability of pollution occurrence should be reduced by performing specific proceedings. Based on the range of RPNs and the degree of risk, a classification of required plans to be considered is described in Table 8.

It is concluded that about 9% of Qazvin aquifer's area which lies in the central and southeastern regions of the plain is at high and very high risk of pollution and needs immediate action plans, such as restricting the use of chemical fertilizers for agricultural purposes. Also, it is seen that there is a logical relation between the degree of risk and the potential vulnerability map of the aquifer. In regions where it is more probable for damage, a higher degree of risk is also obtained. According to results, it is vital that some proper actions be taken by the agricultural sector for the aquifer's recovery in the central and southeastern regions of the plain. These actions could be restriction of usage of chemical fertilizers by farmers, change of the agricultural crop pattern and cultivation of crops which need less fertilizer for yield production, and encouraging farmers to use less fertilizer on their land.

Map removal sensitivity analysis

The sensitivity analysis carried out in this study helped to validate and evaluate the consistency of the analytical results and is the basis for proper evaluation of the vulnerability maps. Using sensitivity analysis, a more efficient interpretation of the vulnerability index can be achieved (Pathak *et al.* 2008). Table 9 illustrates the variation of the vulnerability index as a result of removing one layer from the assessment.

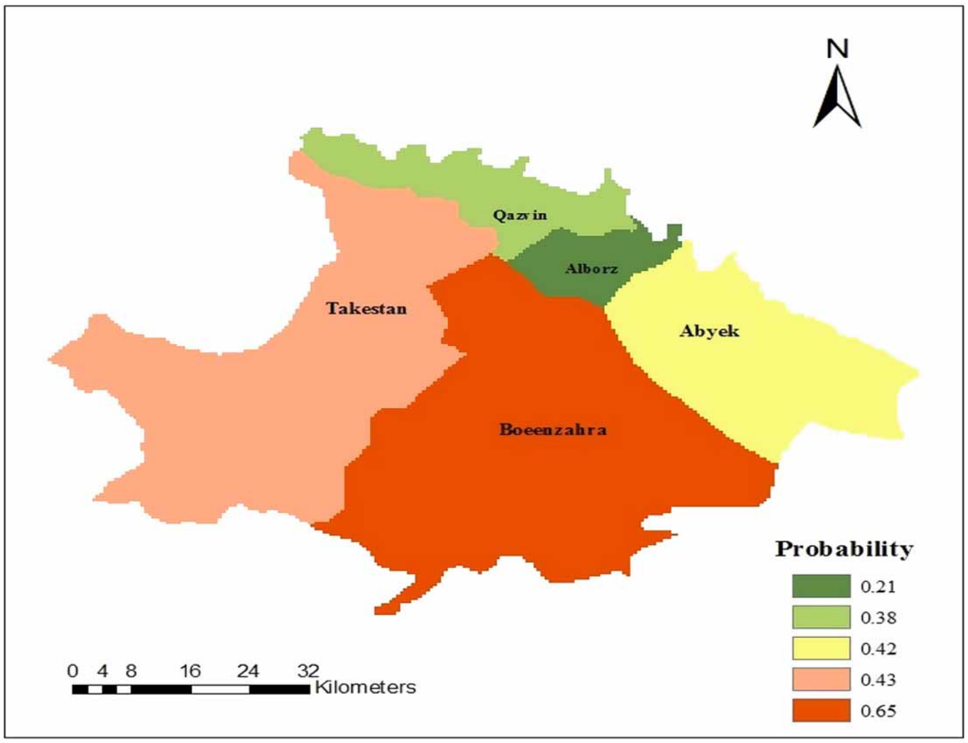

Figure 5 | Probability of occurrence of pollution in regions of Qazvin aquifer.

Table 7 | RPN and risk level in the Qazvin aquifer

No.	RPN	Degree of risk	Area (%)
1	1–27	Very low	47
2	27–52	Low	30
3	52–76	Moderate	14
4	76–100	High	8
5	100–125	Very high	1

The vulnerability index appears to be sensitive to the removal of aquifer media (*A*) as the mean variation index is 32%. Although having a low theoretical weight, removing the depth of groundwater (*D*) caused a variation of 25%. The least sensitive parameter is the impact of the vadose zone (21%), in spite of the high theoretical weight assigned to it. The hydraulic conductivity and the impact of the vadose zone impose a low risk of aquifer contamination (6% and 21%, respectively). However, the interpretation of some average variation indices needs further investigation, but through this sensitivity analysis it is clear that considerable variation in the vulnerability assessment is expected if a few parameters have been integrated. Sensitivity analysis results indicate that aquifer media have the biggest impact on the vulnerability index of the aquifer; accordingly, in the central region of the plain where the soil type consists of permeable gravel and sand, the risk level obtained is high and very high, respectively.

CONCLUSION

In this research, a risk map for the Qazvin aquifer in Iran was developed using a novel risk assessment method. Nitrate was considered as the pollutant factor for assessing the risk of pollution in the aquifer. *RPN* for the aquifer was calculated by production of the three parameters of potential vulnerability, severity of pollution, and probability of occurrence of pollution. Potential vulnerability was extracted from the DRASTIC map of the aquifer. Severity of pollution was obtained by preparing a map of intensity

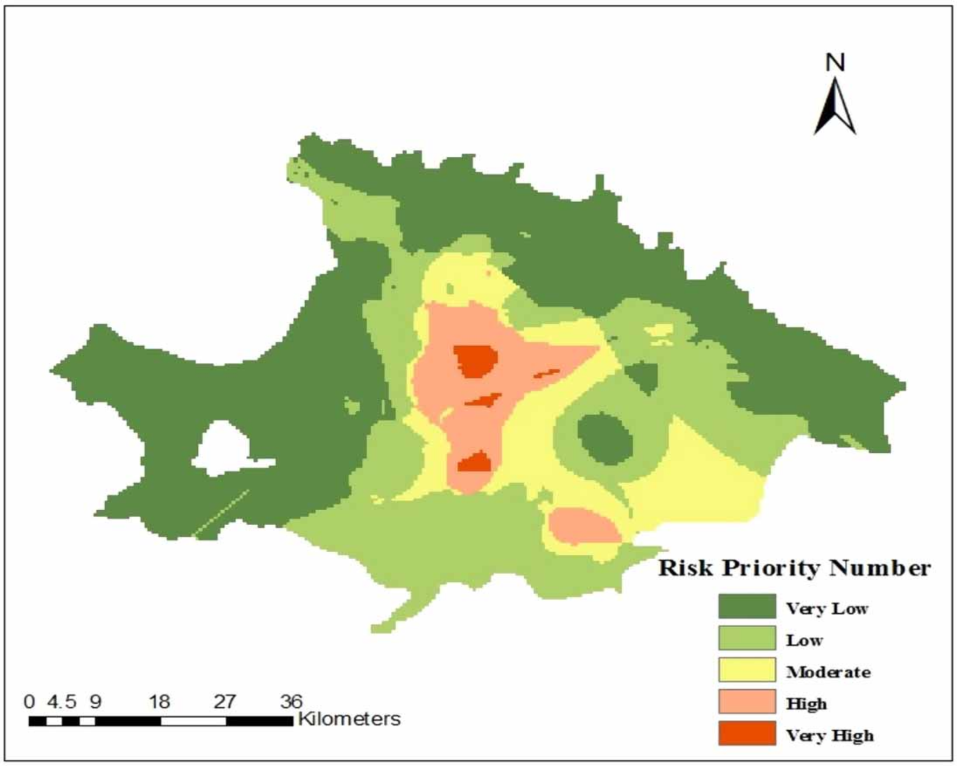

Figure 6 | Environmental risk map of the Qazvin aquifer.

Table 8 | Classification of required plans according to the degree of risk

No.	RPN	Risk level	Plan
1	1–27	Very low	Damage not detectable
2	27–52	Low	Damage needs consideration
3	52–76	Moderate	Almost sensible and needs recovery plan
4	76–100	High	Sensible and needs effective action plan
5	100–125	Very high	Highly susceptible to damage and needs immediate action plan

Table 9 | Results of the sensitivity analysis by map removal

No.	Layer	Mean coefficient of variation
1	Aquifer	0.32
2	Depth	0.25
3	Hydraulic conductivity	0.06
4	Recharge	0.28
5	Soil	0.06
6	Topography	0.08
7	Impact vadose zone	0.21

of nitrate concentration in the aquifer. Probability of occurrence was obtained by use of the TOPSIS method, where definition of the main affecting criteria and weighting them were done based on the opinions of the experts and quantified based on the existing data. Results show that 77% of the aquifer area is placed in the low risk zone, 14% is placed in the medium risk zone, and 9%, mostly in central and southeastern parts, poses high and very high risk levels. It is seen that in these regions, nitrate concentration is high and also the DRASTIC map shows a higher vulnerability index for the central area of the aquifer. In addition, the probability of occurrence of pollution gained the highest rate in Boeenzahra sub-basin, located in the central and southern part of the plain. Therefore, aggregation of these three characteristics resulted in the highest risk degree in central and southeastern regions of the aquifer. Sensitivity analysis shows the impact of aquifer media as the most effective parameter on the vulnerability map. Thus it is seen that the vulnerability index is high in central parts of the aquifer that are mainly composed of highly permeable sand and gravel soil type which increases the potential for nitrate to enter the aquifer.

Our results indicated that the development of risk assessment, based on vulnerability, severity of pollution, and probability of occurrence is possible. Comparison of the method used in this research and the previous studies on risk assessment show the ability of the model to predict logically the high risk zones of pollution in an aquifer. This ability is based on common available data in most watersheds and the opinion of local experts who have a broad knowledge about the case; these facts can be named as the advantages of the present method. Thus, governments could provide solid guidelines for establishing a groundwater conservation region and agricultural management policies. For example, areas of medium, high, and very high risk of pollution potential should be considered as groundwater protection regions, where fertilizer application is significantly minimized or completely restricted on agricultural land. Results obtained by the model are dependent on the limited pollution dataset measured in July 2014 in the region. Therefore, for a more generalized conclusion, the model could be tested more rigorously by using a more extensive dataset over a longer period of sampling. The dependency of the probability map on the defined criteria and the criteria weights relying on regional experts' opinions, which may cause bias in the results in the case of using a few experts, may be named as the potential weaknesses of the method applied in the research. The authors of this paper recommend applying this methodology to achieve risk mapping, specifically in agricultural regions. In addition, the pollution source in each region can be detected and used for groundwater pollution risk assessment. This factor highlights the necessity of identifying other alternative sources of pollution.

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