Environmental Health Engineering and Management Journal 2022, 9(4), 409-418
http://ehemj.com
doi 10.34172/EHEM.2022.44
Environmental Health Engineering and Management Journal

Original Article

The assessment of groundwater vulnerability: A case study in the Doroud-Boroujerd aquifer, Iran

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Abstract

Background: Agricultural, industrial, and residential activities have caused the vulnerability of the groundwater of the Doroud-Boroujerd aquifer to pollution in Lorestan province, Iran. This study aimed to investigate the vulnerability of the Doroud-Boroujerd aquifer using a set of intrinsic (DRASTIC, IV) and specific (SI, LU-IV) vulnerability assessment methods.

Methods: The DRASTIC model with seven parameters of groundwater depth, net recharge, aquifer media, soil media, slope, the effect of the vadose zone, and hydraulic conductivity of the aquifer has the highest number of parameters. The total dissolved solids (TDS) index was used to compare the efficiency of different methods.

Results: The results showed two classes of medium and high vulnerability with an area of 73.71% and 26.3%, respectively, in the DRASTIC model. The SI model had two classes of low and medium vulnerability. The IV model had three classes of low to high vulnerability, of which the high class with an area of 75.94%, had the largest extent. The LU-IV model also included four classes of very low to very high (92.02%) vulnerability. The validation of DRASTIC, SI, IV, and LU-IV models with TDS index showed a weak correlation between vulnerability maps and TDS values, so it can be concluded that this index alone is not a good indicator for validation.

Conclusion: The results of vulnerability assessment of different methods generally showed that the groundwater of this area is highly vulnerable, so it is recommended to take the necessary measures to prevent, control, and manage these valuable water resources.

Keywords: Groundwater, Water pollution, Soil, Iran

Citation: Byeranvand L, Afzali A. The assessment of groundwater vulnerability: A case study in the Doroud-Boroujerd aquifer, Iran. Environmental Health Engineering and Management Journal 2022; 9(4): 409-418. doi: 10.34172/EHEM.2022.44.

Article History:
Received: 9 February 2022
Accepted: 15 May 2022
ePublished: 14 October 2022

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Introduction

Groundwater is the most crucial source of freshwater supply and water security buffer for humans. Approximately 2.5 billion people are entirely dependent on groundwater resources for their needs. Farmers need these resources to maintain their livelihoods and contribute to food security for others (1). Based on the results of general estimates of global water resources, groundwater accounts for about 1.7% of total water resources and about 30% of total freshwater resources in the world (2). Large populations, along with climate change, put significant pressure on the quantity and quality of groundwater resources (3).

Previous and current human activities can cause the spread of pollutants to the underground water reservoir (4). These pollutants may include organic chemicals, hydrocarbons, organic anions, inorganic cations, and pathogens (5).

Some pollutants are of agricultural origin, and some are of industrial origin. The presence of heavy metals in the groundwater is usually related to industrial activities. The vertical movement of these pollutants in the soil profile, which depends on several factors such as climate, soil texture, groundwater flow in various rocks, topography, saline infiltration to coastal areas, and human activities, reduces the quality of groundwater resources (6).

The release of these pollutants can threaten the exploitation of these resources for decades, thereby, threatening the environmental health of groundwater-dependent ecosystems. Due to the low velocity of groundwater depending on the environmental and geochemical conditions, the effects of human activities can be stable in aquifers for decades and even centuries (4).

A serious concern in many parts of the world is the degradation of water quality because of the high dependency on groundwater (7). As a general principle, protecting groundwater against contamination is more accessible than the subsequent removal of contamination, so the vulnerability assessment can serve as an early warning to authorities to take preventive measures, which subsequently, prevent further spread of pollution in these valuable resources (8). Intrinsic vulnerability is based on the function of hydrogeological factors, and particular vulnerability is based on the specific land uses and pollutants (4).

To protect and manage groundwater resources, groundwater vulnerability is estimated through spatial data and the use of GIS (9). Various methods for determining vulnerability include process-based methods, statistical methods, and index-overlay methods (9,10). Simulation models are used to estimate the movement of contaminants. Statistical methods are based on the correlation coefficients between spatial variables and the concentration of contaminants in groundwater. The factors controlling the movement of pollutants from the ground to the vadose areas of the aquifer are superposed using the index-overlay methods for obtaining the vulnerability index in different regions (11).

Overlay methods assign numerical scores or direct rankings to various physical properties to create a range of vulnerability categories (12). The purpose and scope of a particular study, the scale of the work, the availability of data, and most importantly, the researcher's time and cost are important in choosing the most appropriate method for determining vulnerability. The simplest and most widely used methods of vulnerability assessment are index-overlay methods, which assess vulnerability by combining physical factors associated with contamination potentials, such as soil texture, geological structure, aquifer depth as well as net recharge, and environmental factors (9).

Recently, the intrinsic vulnerability (IV) overlay method has been used to assess and map groundwater vulnerability, which is more effective than previous methods (13). This new method has several advantages over other methods; because it considers the vulnerability in the whole topographic surface of the aquifer, uses parameters that provide sufficient data to feed the model, and eliminates additional parameters. It can be implemented at different scales of an area, including local and regional scales, and in GIS, it has the flexibility to accept other parameters for vulnerability mapping (14).

Some studies have been conducted based on vulnerability assessments in Iran and other parts of the world. Odrago et al(15) and Ribeiro et al(16) have used only one model to assess groundwater vulnerability. But in many studies, several models have simultaneously been used to evaluate the vulnerability of an area. Poor Khosravani et al(17) evaluated the vulnerability of the aquifer based on the DRASTIC (Depth of water table, Recharge, Aquifer media, Soil, Topography, Impact of vadose zone, Hydraulic conductivity), composite DRASTIC models, and nitrate vulnerability index in Sirjan region of Kerman. They concluded that nitrate vulnerability models, composite DRASTIC and DRASTIC, are the most efficient methods, respectively. Asghari et al(18), in a region in Ardabil province, obtained vulnerability zoning using DRASTIC, SINTACS (Depth of water table, Recharge, Impact of vadose zone, Texture Soil, Aquifer media, Hydraulic conductivity, Slope), and SI models, and finally, based on the validation results, and concluded that the DRASTIC model in this region has higher accuracy than the others.

Rebolledo et al(19) prepared vulnerability maps of Aragon, Spain, using the new overlay method, VINAS-LSP (The Vulnerability Index to Nitrates from Agricultural Sources-Logic Scoring of Preferences), based on the Multi-Criteria Decision Analysis (MCDA). Grewal et al(20) assessed groundwater vulnerability using DRASTIC modified with land use/land cover parameter and determined the weight of parameters using Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP) in Nagpur region of India. Liang et al(10) modified the DRASTIC model based on the change of parameters, their ranking, and the weight calculation method. They used the new DRASTIC-LE model to assess the vulnerability of groundwater resources in the Datong Basin, China. They concluded that determining the weight of the parameters by the EW-AHP method increases the accuracy of the evaluation.

In the Doroud-Boroujerd aquifer, no research has been done to assess the groundwater vulnerability of this region as a result of human and agricultural activities. This area is exposed to high pollution due to the existence of extensive agricultural activities as well as sewage leakage from the rural areas. Therefore, this study aimed to apply a set of overlay methods, i.e. DRASTIC and SI, as well as the new methods, i.e. IV and LU-IV in the Doroud-Boroujerd aquifer, to identify vulnerable areas as a way to control, and subsequently, prevent the pollution of its underground water.

Materials and Methods

Study area

The Droud-Borujerd aquifer is located between 30° 48′ to 10° 49′ longitudes and 30° 33′ to 101° 34′ latitudes. This aquifer is the largest flat area in Lorestan province, which covers a large area of Boroujerd and Doroud cities and is one of the agricultural and horticultural hubs of the region. The study area of Doroud-Boroujerd is 2541 km^2, of which 819 km^2 are plains, and 1722 km^2 are elevations. The length of these plains is limited to Nahavand and Malayer plains from the north, to the mountain range between Lorestan province and the inner basin of Arak city from the east, to the Zagros mountains from the west, and Oshtrankuh mountains from the south. Figure 1 shows the location of the study area on the corresponding elevation map.

Groundwater vulnerability assessment

In this study, DRASTIC, SI, IV, and LU-IV overlay models were used to investigate the potential vulnerability of

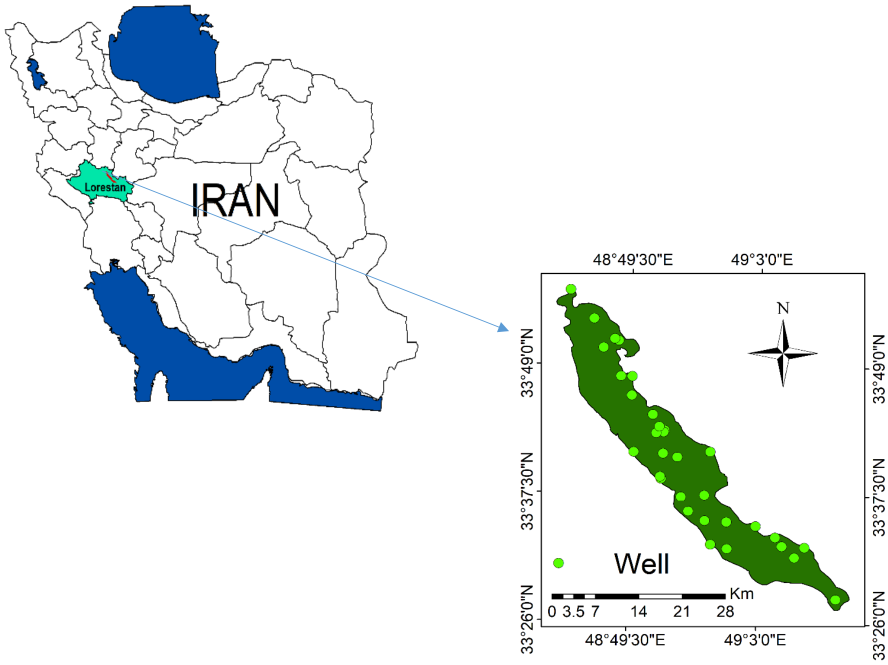

Figure 1. The location of the study area

groundwater resources in the Doroud-Boroujerd aquifer. Index and overlay methods rely mainly on the quantitative and semi-quantitative formulation and the interpretation of mapped parameters. The number and definition of these parameters vary from one method to another. In general, vulnerability assessment is based on the three main parameters including soil conditions, the vadose zone of subsoil and bedrock, and transport in the vadose zone. Combining these parameters leads to the creation of the final vulnerability index, which shows the degree of contamination sensitivity (5).

The DRASTIC model uses seven hydrogeological parameters to calculate the inherent vulnerability of an area. Intrinsic vulnerability includes only the hydrological and geological characteristics of an area independent of the nature of the pollutants and the conditions of the area in which they are released (20). Geographic Information Systems (GIS)-based DRASTIC model is used to assess groundwater vulnerability by considering water depth, net recharge, aquifer media, soil media, topography, the impact of the vadose zone, and hydraulic conductivity. The weight and rank of the parameters are predetermined, with a rating of 1 to 10 based on the relative impact of each parameter on aquifer vulnerability and a weight of 1 to 5 based on their relative importance for assessing groundwater vulnerability.

The SI index is adapted from the DRASTIC method by inserting additional parameter of land use and removing parameters of soil texture, the impact of the vadose zone, and hydraulic conductivity. The land use parameter considers the impact of agricultural activities (use of fertilizers and pesticides) on groundwater quality. Stigter (21) notes that even if soil type can significantly affect the attenuation potential of some pollutants, its impact on groundwater vulnerability can be indirectly assessed by land use. In SI index, the parameters are ranked from 10 to 100, and after the final combination of parameters, the final index is obtained.

The Land use-IV (LU-IV) index is a new approach for assessing the specific vulnerability of groundwater, which consists of two stages. First, the intrinsic vulnerability IV index based on four environmental parameters of the vadose zone, groundwater depth, topography, and rainfall is obtained from Eq. (1). In the next step, after calculating the ranking map of the IV index into two categories of 0 and 1 (non-vulnerable areas and vulnerable areas), the specific vulnerability map of LU-IV is obtained by its overlaying with the land use map in the GIS environment (14). Table 1 lists the vulnerability classes and the vulnerability range of different models.

$$IV = (L+D+T+P)/4 \qquad (1)$$

Effective parameters in vulnerability assessment

To model the vulnerability potential of the Doroud-Boroujerd aquifer, first, the required data and information were collected from relevant organizations. These data include geological information, soil texture, land use, altitude and slope, meteorology, water table, pumping test, and water quality. As shown in Figure 1, statistics for 32 wells were obtained from Lorestan Regional Water Authority. Then, the collected data and criteria maps were entered into Arc GIS 10.4 software environment for processing, preparation, integration, and finally, preparation of vulnerability zoning maps. All criteria maps were prepared within 30×30 m pixel size.

Table 1. Vulnerability classes and values of DRASTIC, SI, IV, and LU-IV

	Vulnerability classes	Values
DRASTIC INDEX	Negligible	23-46
	Low	47-92
	Moderate	93-137
	High	138-184
	Extreme	184-230
SI INDEX	Low	<45
	Moderate	45-64
	High	65-84
	Extreme	85-100
IV, LU-IV INDEX	Negligible	1,2
	Low	3,4
	Moderate	5,6
	High	7,8
	Extreme	9,10

Groundwater depth
The depth of the groundwater indicates the vertical distance between the ground level and the water level. This parameter determines the time required for water-soluble pollutants to penetrate from the ground to the aquifer. Thus, near-surface aquifers are likely to become contaminated faster than deeper aquifers (14). The groundwater layer was made based on the water level data of 32 wells from 2012 to 2016 and based on the classification criteria of Aller et al(22).

Vadose zone
The vadose zone contains sediments in the surface soil layer to the depth of the water table. The vadose zone controls the infiltration and downward movement of the feed, traps contaminants, and determines the time it takes for pollutants to reach the aquifer. This is an essential parameter in estimating vulnerability. It affects the stopping time of pollutants based on the lithological characteristics and degree of composition (consolidation), and thus, determines the capacity to reduce pollution (14). To prepare this layer, the geological map of the region was used according to the ranking of Aller et al(22) (in the DRASTIC model) and Foster et al(23) (in the IV model).

Net recharge
Net recharge indicates the amount of water that penetrates the ground surface and reaches the water table. The recharge transports the contaminants vertically, reaches the hydrostatic surface, and then, moves horizontally. Further recharge increases the potential for aquifer contamination (24). The net recharge map was prepared based on the Piscopo method (25).

Hydraulic conductivity
The ability of the aquifer media (rock and soil) to transfer water through pores or fractures is called hydraulic conductivity, which controls the flow of groundwater under a specific hydraulic slope. This parameter plays an essential role in the rate of dispersal and migration of pollution (26). Higher levels of hydraulic conductivity indicate more significant infiltration and movement of water and contaminants into the aquifer, resulting in higher pollution potential. The hydraulic conductivity layer was obtained based on the method used by Khosravi et al (26).

Aquifer media
The aquifer media reflects the characteristics of the constituents of the aquifer vadose zone that affect the water flow inside the aquifer and control the processes of pollutant attenuation (7). Larger grain size and more porosity in the vadose zone cause higher permeability, lower neutralization capacity, and, as a result, more vulnerability to groundwater (26). To prepare this layer using the geological map of the region, the geological structure of the aquifer was determined and ranked according to the criteria of Aller et al (22).

Soil media
Soil is the first medium through which pollution can penetrate the ground. Soil has a significant effect on the amount of recharge; therefore, it affects the ability of a pollutant to move vertically in the vadose area. Fine-grained materials such as clay and silt reduce soil permeability, and thus, limit the movement of contaminants. To create the soil media map, the soil map of the study area was used and ranked according to the type of soil texture of each class and the amount of pollution potential based on the criteria of Aller et al (22).

Topography
The land slope is a critical factor that determines the amount of surface runoff. As a result, low-slope areas tend to retain water for a more extended period, leading to more significant infiltration, and thus, higher pollution potential (28). The final topographic map was prepared according to the Arauzo method and ranked according to the criteria of Aller et al (22).

Land use
Infiltration of pollutants into groundwater depends on the land use types. This parameter is used only in specific vulnerability assessment methods (SI, LU-IV). To prepare the land use map, the desired area was cut using the clip command, and its raster map was created by the Polygon to raster command according to the type of different land

uses and criteria (29).

Rainfall

As the amount of rainfall increases, the infiltration of water into the deeper layers of the soil increases. If the two regions are similar in hereditary characteristics, soil moisture, agricultural activities, and vegetation, the region with higher rainfall, and consequently, more recharge and infiltration has a higher potential for vulnerability (18). In the IV model, the final rainfall parameter map was prepared based on the precipitation data for 2008-2017 and Arauzo criteria (14).

Validation with TDS index

In general, the concentration of TDS in polluted and potable groundwater is high and relatively low, respectively (30). Therefore, in this study, the TDS index was used to validate different vulnerability models. For this purpose, information about TDS values was obtained from Lorestan Regional Water Authority. To determine the correlation between different models and quantitative data, first, the vulnerability maps and TDS values were overlaid, and the extent of vulnerability changes at different sampling points was determined. Finally, the Pearson's correlation coefficient was used for validation.

Results

The results of the assessment of groundwater resources vulnerability in the Doroud-Boroujerd aquifer using different methods, i.e. DRASTIC, SI, IV, and LU-IV, and their validation using the TDS index are presented in the following section.

Assessment of groundwater vulnerability using the DRASTIC method

Seven effective parameters in the DRASTIC method for the Droud-Borujerd aquifer were investigated. The groundwater depth in the Doroud-Boroujerd aquifer ranges from 1 to 59 m. The range of 15.2-9.1 m occupies the largest area. According to the map of the impact of the vadose zone, a high percentage of the aquifer area has a sand structure, which is ranked eighth in terms of vulnerability in the DRASTIC model.

The net recharge map was obtained based on the Piscopo method by combining the maps of three parameters such as soil permeability, slope, and rainfall. In general, this aquifer is located in the lower slope range. Due to the soil texture of the region, a large part of the aquifer soil has moderate permeability. The degree of permeability and potential vulnerability is directly related. This aquifer has two rainfall ranges of <500 and 500-700 mm, of which the range of 500-700 mm is observed only in the southern parts of the region. The final net recharge map created by overlapping the three parameters has two ranges of medium and high vulnerability.

According to the results, the category 0.04 to 4.1 m/day has the largest area, with a low rank on the aquifer hydraulic conductivity map. Therefore, the amount of hydraulic conductivity is low, and since the potential for vulnerability is directly related to this parameter, the amount of vulnerability is low. The geological structure of the sand of the aquifer media contains most of the region, which is graded eighth in the aquifer media ranking. A large percentage of the study area is composed of sandy loam texture, which according to the soil texture rankings, is ranked sixth and has a moderate vulnerability.

The slope map of the area was divided into five classes. Most area of the aquifer is located in two classes of 0-2% and 2-6%, and the other classes include the lower percentage. Finally, the final vulnerability map of the aquifer in the DRASTIC method was prepared by overlapping the seven parameters and was divided into two categories of medium and high vulnerability. Medium and high vulnerability classes occupy 73.71% and 26.3% of the aquifer, respectively (Figure 2).

Assessment of groundwater vulnerability using the SI method

The groundwater vulnerability assessment was performed based on the SI model by overlapping the five parameters of groundwater depth, aquifer media, net recharge, slope, and land use. Due to the existence of 4 common parameters with the DRASTIC model and their almost similar ranking system, and as a result of their similar maps, in this section, only the land use parameter is explained. According to the land use map, agricultural land use occupies the most area, and urban area land use

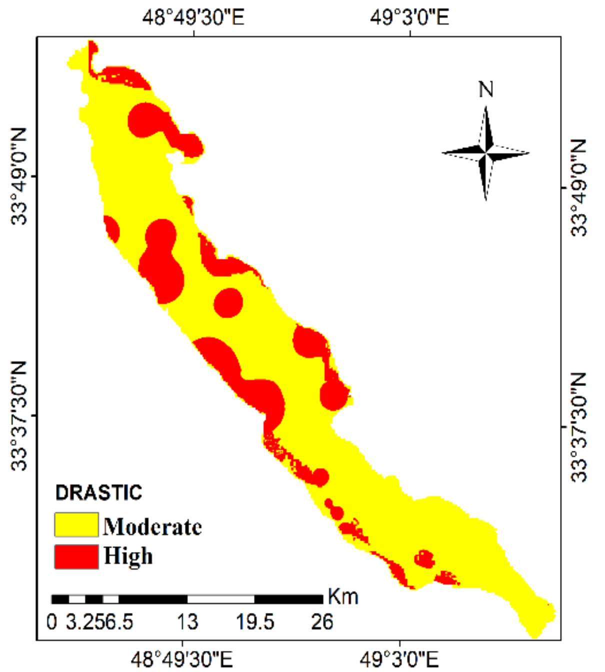

Figure 2. Intrinsic groundwater vulnerability map based on the DRASTIC method

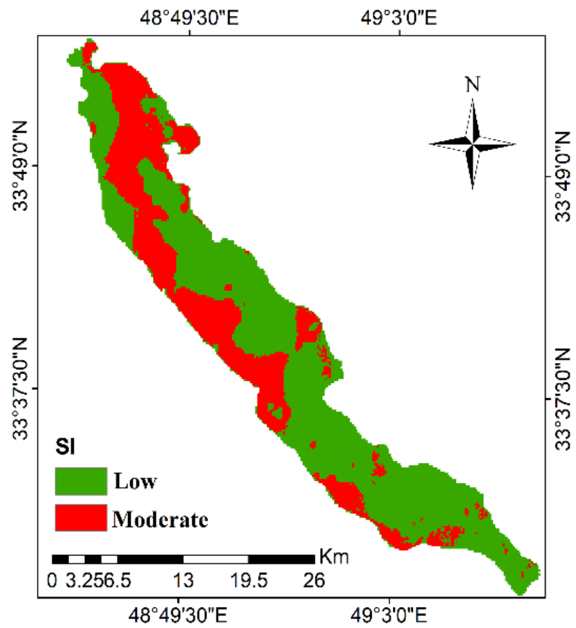

Figure 3. Specific groundwater vulnerability map based on the SI method

with an area of 3.01 km² occupies the least area. Based on the results obtained from the overlap of baseline maps, the SI vulnerability index includes two classes of low and medium vulnerability with an area of 63.84% and 36.16%, respectively (Figure 3). According to this index, this aquifer does not have a high potential for vulnerability.

Assessment of groundwater vulnerability using the IV method

The final vulnerability map using the IV method was obtained based on the four parameters of groundwater depth, the impact of the vadose zone, rainfall, and slope of the area. The groundwater depth map was divided into five classes of 0-50 m, the class 10-20 m of which had the largest area, which is almost average in terms of vulnerability (Figure 4). The rainfall map was divided into three rainfall classes from 300 to 600 mm with a rank of four to six; due to the high rainfall in the aquifer, the vulnerability is almost high. The slope map was prepared and ranked similar to the DRASTIC method (Figure 4).

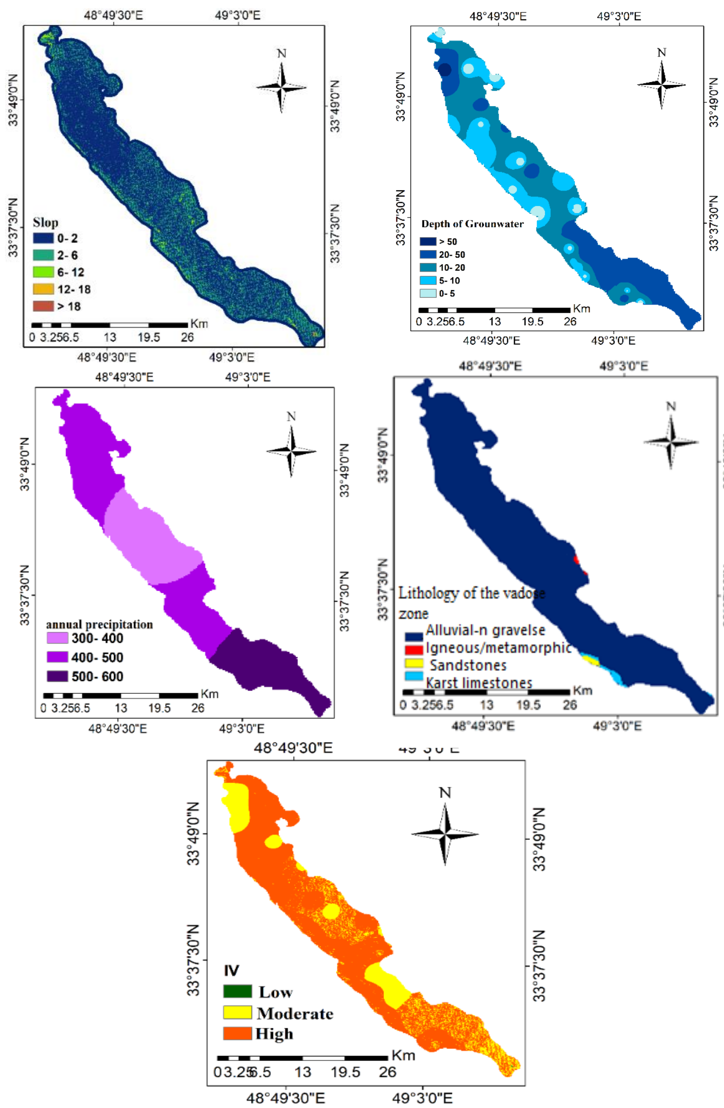

Figure 4. Intrinsic vulnerability map of groundwater based on the IV method and its constituent parameters

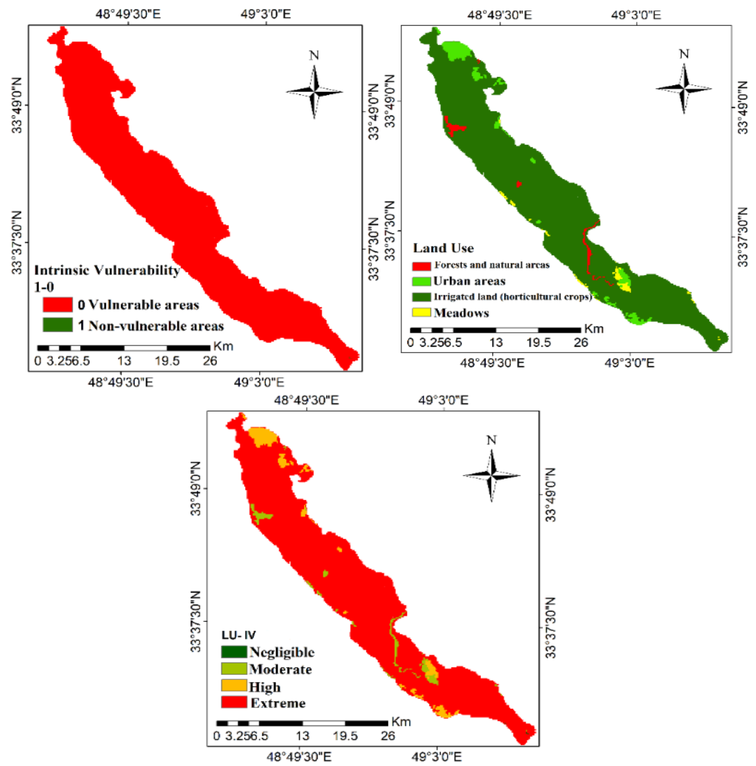

Figure 5. Specific groundwater vulnerability map based on the LU-IV method and intrinsic vulnerability (0-1) and land use maps

According to Figure 4, the vulnerability map based on the IV method is composed of three vulnerability categories of low, medium, and high, with an area of 0.01%, 24.03%, and 75.94%, indicating the high vulnerability of the aquifer to pollution.

Assessment of groundwater vulnerability using the LU-IV method

According to Figure 5, the large area of the aquifer is vulnerable with a rank value of 0, and only a small part of the region is not vulnerable with a rank value of 1. According to the LU-IV map, there are four vulnerability classes in the Doroud-Boroujerd aquifer, while the most vulnerable class occupies 92.02% of the area (Figure 5). Vulnerability classes and their area for the DRASTIC, SI, IV, and LU-IV methods are shown in Table 2.

Validation of the methods with TDS

Based on the results, the correlation between TDS values and DRASTIC, SI, IV, and LU-IV vulnerability assessment methods was weak (less than 0.2) or not observed in the study area.

Discussion

Vulnerability assessment by DRASTIC, SI, IV, and LU-IV methods

In this study, the vulnerability of groundwater resources of the Doroud-Boroujerd aquifer was evaluated using DRASTIC, SI, IV, and LU-IV methods. The DRASTIC method with the highest number of parameters is considered as the basic method for assessing groundwater vulnerability. In Iran, the DRASTIC method has been widely used, which has provided more acceptable results compared to other methods.

In the Doroud-Boroujerd aquifer, two classes of moderate vulnerability (73.71%) and high vulnerability (26.3%) were observed in the DRASTIC model, in which the average vulnerability class has the highest area. The conditions that have caused high vulnerability in these areas are sandy soil texture, shallow water, geological structure, and high recharge. Rahman et al (31) identified the vulnerable areas of south-central Bangladesh using a GIS-based DRASTIC model. According to the results,

Table 2. Vulnerability classes and their area in the Doroud-Boroujerd

	Vulnerability classes	Index values	Area (km²)	Area (%)
DRASTIC INDEX	Moderate	93-137	340/60	73/71
	High	138-184	121/51	26/3
SI INDEX	Low	<45	299/7	63/84
	Moderate	45-64	169/83	36/16
IV INDEX	Low	4	0/07	0/01
	Moderate	5,6	114/34	24/03
	High	7,8	361/25	75/94
LU-IV INDEX	Negligible	1	0/07	0/01
	Moderate	5	13/98	2/93
	High	7	23/9	5/02
	Extrem	9	437/72	92/02

57% of the region was in the middle vulnerability category. They also examined the groundwater quality index (GWQI), and based on the 13 effective elements in water quality, concluded that the region's water is not of good quality for drinking.

In the SI model, aquifer vulnerability was divided into two low and medium classes, with the lowest vulnerability class having an area of 63.84%. Due to the land use parameter in the SI model, areas with urban land use have moderate vulnerability in the final map. This model has four parameters in common with the DRASTIC model and has some similarities in terms of vulnerability classes and their limits. Daoui et al(32) identified the vulnerable areas of Habib region in south-eastern Tunisia based on the four models including DRASTIC, DRASTIC Pesticide, SI, and SINTACS. Based on the results, the low to medium vulnerability class had the highest area. On the other hand, the highest vulnerability was observed in the western part of the region due to the reduced groundwater depth and water evaporation processes. In this study, water pollution indices in 25 samples were studied. The validation was performed between different methods of vulnerability and water pollution indices.

According to the study of Arauzo (14), the significant obstacle to the implementation of environmental policies to control groundwater pollution is the lack of consensus on the type of methods and criteria used to determine vulnerable areas. One of these methods is the DRASTIC model, which despite having the largest number of parameters and considering a basic model for vulnerability assessment, has weaknesses. According to the study of Hamza et al(33), all DRASTIC parameters, regardless of their specific weight, are equally important. As a result, sometimes, there are discrepancies between the vulnerability maps and the nitrate pollution map, which casts doubt on the validity of the groundwater vulnerability estimation. In addition, the DRASTIC model has two main weaknesses including an overemphasis on the attenuation capacity of the vadose zone and the difficulty in accurately estimating aquifer recharge and hydraulic conductivity (21). The hydraulic conductivity parameter, which increases with increasing groundwater velocity, reflects the system's ability to transport contaminants through the vadose zone, but does not assess vulnerability (Arauzo, 14).

As a result, he assessed the vulnerability of 46 large aquifers in northern Spain by the IV method using four parameters of the vadose zone, rainfall, slope, and groundwater depth. Since the intrinsic vulnerability of IV is calculated only based on the hydrogeological, natural, and geological characteristics, he added the land use parameter to the IV model, and thus, the LU-IV specific vulnerability model for the evaluation of vulnerability to human activities was developed. The map of parameters and the final vulnerability of the IV index are shown in Figure 4. The IV Index in the Doroud-Boroujerd region includes five classes of low to high vulnerability, of which the fourth class, with an area of 73.19%, has the highest area. In the LU-IV method, four categories of very low to very high vulnerability were observed. Since, in this region, the use of irrigated agriculture has the largest area, it increases the possibility of increased consumption of fertilizers and pesticides and pollution of groundwater resources. On the other hand, due to the high rank of irrigated agriculture, according to the ranking criteria of land use parameter in the LU-IV index, the level of vulnerability was very high. In a study by Abu Bakr (34) in three regions of Egypt, 34groundwater vulnerability was assessed based on the eight environmental parameters. The parameters were ranked based on the hydrogeological characteristics of each region, and the weights of the parameters were measured by the AHP method. In all three areas, the average vulnerability class had the largest area.

In the Doroud-Boroujerd aquifer, in almost all models, medium and high vulnerability classes have the largest area, but in the SI model, which has two low and medium vulnerability classes, the low vulnerability class has the largest area. Different vulnerability assessment methods have different types and number of parameters, weights, and rankings, so their final vulnerability map is different. Therefore, perhaps it is more accurate to compare the intrinsic and specific vulnerability methods, separately.

Validation with the TDS index

In this study, the validation results of vulnerability indices showed a weak correlation with TDS values. In general, the validation results showed a weak correlation of TDS values with different models, so it can be concluded that this index does not have a good performance for validation in this study, and it is better to use other indicators such as nitrate values. Although correlation analysis is widely used to validate vulnerability models, it is still a relatively limited approach (35). In general, many researchers believe that validation of vulnerability maps of different models is not the correct method, because such maps show the potential vulnerability of an aquifer, and an area may be potentially vulnerable. Still, there are no sources of groundwater pollution in the area.

Nokhostin Rohi et al(30) used the TDS quality index to validate both SI and DRASTIC models. Their results showed that the SI model with a correlation coefficient of 0.76 has a higher correlation than the DRASTIC model. Therefore, they concluded that the SI model has a higher accuracy for assessing the vulnerability of the region. In a study by Mafakheri and Arasteh (6), the electrical conductivity index (EC) was used to validate the three models of DRASTIC, SINTACS, and GODS. The results showed that the DRASTIC model was more compatible with salinity distribution in the region, indicating the superiority of this model over the other two models for zoning the vulnerability of the region.

In the Doroud-Boroujerd aquifer, the medium and high vulnerability classes had the greatest extent. Among the natural conditions that have caused high vulnerability in this area, low slope, the geological structure of sand and the presence of karst limestone, rainfall of 300-500 mm, shallow groundwater depth in a wide range, and high recharge could be mentioned. Therefore, it is suggested to monitor groundwater resources in this area continuously to prevent vulnerability, and consequently, pollution of these essential resources.

Conclusion

In this study, the groundwater vulnerability of the Doroud-Boroujerd aquifer was evaluated based on the DRASTIC, SI, IV, and LU-IV methods. Comparing different models in an area with unique hydrogeological features can lead to the selection of the appropriate vulnerability assessment model in that area. The TDS index was used to compare the performance of different vulnerability models and their validation. The results showed that although correlation analysis is widely used to validate vulnerability models, it is still a relatively limited approach.

As it was observed, in general, based on the results of various methods of vulnerability assessment, this aquifer is exposed to high vulnerability, which can be a valid reason for implementing pollution control programs for these resources. Therefore, it is suggested that to design water quality protection programs in different areas, first, the risk factors or quality reducers, and then, the vulnerable areas should be identified. In this study, there are some data constraints. However, the vulnerability of the study area can be investigated using some other indices and models, which can be supplemented in future studies through more comprehensive studies.

Acknowledgments

The authors would like to thank the anonymous reviewers for their careful reading of the manuscript and their insightful comments and suggestions.

Ethical issues

The authors certify that all data collected during the study are as stated in the manuscript, and no data from the study has been or will be published elsewhere separately.

Competing interests

The authors declare that they have no conflict of interests.

Authors' contributions

Conceptualization: Leila Byeranvand, Afsaneh Afzali.
Data curation: Leila Byeranvand.
Formal Analysis: Leila Byeranvand , Afsaneh Afzali.
Funding acquisition: Leila Byeranvand , Afsaneh Afzali.
Investigation: Leila Byeranvand, Afsaneh Afzali.
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Resources: Leila Byeranvand, Afsaneh Afzali.
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Supervision: Leila Byeranvand, Afsaneh Afzali.
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Writing – original draft: Leila Byeranvand, Afsaneh Afzali.
Writing – review & editing: Leila Byeranvand, Afsaneh Afzali.

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