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ORIGINAL PAPER

Assessing groundwater vulnerability to contamination in an arid environment using DRASTIC and GOD models

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Abstract Groundwater is vulnerable to contamination by anthropological activities. Vulnerability mapping is considered as a fundamental aspect of groundwater management. The aim of this study was to estimate aquifer vulnerability by applying the DRASTIC and GOD models in Abarkooh plain, Yazd province, center of Iran. The DRASTIC model uses seven environmental parameters (depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity) to characterize the hydrogeological setting and evaluate aquifer vulnerability. GOD is an overlay and index method designed to map groundwater vulnerability over large regions based on three parameters (groundwater confinement, overlying strata, and depth to groundwater). The information layers for models were provided via geographic information system. The overlap techniques were used to provide and produce the vulnerability map of the study areas considering weight coefficients of each layer. Accuracy of the models was evaluated using linear regression between observations values of nitrate and estimated vulnerability to pollution in the measured wells. A significant correlation was observed between measured nitrate and pollution potential evaluated by DRASTIC model ($P < 0.01$), but no significant correlation was observed for GOD model ($P < 0.05$). The results showed that the DRASTIC model is better than GOD model to estimate groundwater vulnerability to pollution in the measured wells. For DRASTIC model, the correlation coefficient between vulnerability index and nitrate concentration was 68 % that was substantially higher than 28 % obtained for the GOD model. We can conclude that nitrate concentration should be a suitable parameter to investigate the accuracy of the DRASTIC and GOD models.

Keywords Abarkooh plain · DRASTIC · GOD · Groundwater contamination · Nitrate

Introduction

In the arid and semiarid regions of the world, water resources are limited and are under pressure due to pollution, population growth, increasing per capita water use, and irrigation. The management of water resources, especially groundwater, has become an increasingly pressing issue in these areas (Ghazavi et al. 2010).

In these regions, groundwater is a valuable resource. It is the vital local water source for industry, agriculture, as well as wildlife. Groundwater is also the main source of drinking water in arid and semiarid area, and hence its vulnerability assessment in delineate areas that are more susceptible to contamination is very important (Ighbal et al. 2014). The groundwater dynamics reflects the response of the groundwater system to external factors such as climate condition, water storage, groundwater consumption, and other human activities (Minville et al. 2010; Ghazavi et al. 2011, 2012). Infiltration of industrial and urban wastewater can recharge groundwater, but can also pollute aquifers used for potable supply (Oişte 2014; Odukoya and

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Abimbola 2010). Groundwater is vulnerable to contamination by anthropological activities. The nitrate pollution of groundwater caused by agricultural activity and a substantial increase in fertilizer utilization are also becoming an increasing problem. Groundwater vulnerability mapping is an important key to improving planning and decision-making processes in order to prevent groundwater contamination (Farjad et al. 2012; Mahvi et al. 2005).

Groundwater vulnerability (the degree of protection that the natural environment provides against the spread of pollution in groundwater) is classified into intrinsic and specific vulnerability (National Research Council 1993). Intrinsic vulnerability can be defined as the ease with which a contaminant introduced into the ground surface can reach and diffuse in groundwater (Vrba and Zoporozec 1994). Specific vulnerability is used to define the vulnerability of groundwater to particular contaminants (Gogu and Dassargues 2000). At present, groundwater-specific vulnerability is regarded as more meaningful than intrinsic vulnerability, because some affecting factors of intrinsic vulnerability, such as groundwater depth, net recharge, soil media, have been changed due to increasing effect of human activities. Different methods have been introduced to estimate groundwater vulnerability. These methods may be divided into three general categories: process-based simulation models, statistical methods, and overlay and index methods (Harbaugh et al. 2001). Overlay and index methods are based on combining different maps of the region. The more popular types of the overlay and index methods are GOD (Foster 1987), IRISH (Daly and Drew 1999), AVI (Van Stemproot et al. 1993), and DRASTIC (Aller et al. 1987). DRASTIC and GOD have been used in several places including the USA (Fritch et al. 2000; Shukla et al. 2000), Morocco (Ettazarini 2006), China (Wen et al. 2008; Houan et al. 2012), Jordan (Naqa et al. 2006), and Iran (Niknam et al. 2007; Saatsaz and Sulaiman 2011; Akbari and Rahimi 2011). GOD and DRASTIC models take benefit of a GIS-based cartography. This methodology took advantage of using available data, which had already been collected for other purposes. The DRASTIC model uses seven environmental parameters (depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity). GOD model is based on three parameters (groundwater confinement, overlying strata, and depth to groundwater). These parameters had been already measured by regional water authority. The objectives of this study were: (1) assessing groundwater vulnerability of Abarkooh plain to contamination using DRASTIC and GOD models and (2) performance comparison of DRASTIC and GOD models for the evaluation of groundwater contamination.

Materials and methods

Study site

The study site named Abarkooh (53°00′–53°3′00″E and 30°50′30″–31°12′30″N) was located in the southeast of Yazd Province, Iran (Fig. 1). The total area of the Abarkooh basin is about 1200.9 km^2. The area has a mean annual rainfall of 120 mm, a mean annual potential evapotranspiration (PET) of 2600 mm, and a mean annual air temperature of 20 °C. The average elevation of the study area is 1035.2 m above sea level. Low annual rainfall and an extremely hot weather during spring and summer make the study area as an arid area.

The direction of the regional groundwater flow over the whole basin is from the highlands toward the lowland in the middle and south parts (Fig. 1). Groundwater aquifers are located in structures belonging to the Quaternary formations. Pleistocene deposits consist of rough sand with gravel in the base, sheltering underground terrace aquifers and Holocene alluvial deposits shelter floodplain aquifers (Arzani 2007).

Methodology

In order to assess the aquifer vulnerability to pollution in Abarkooh plain, two models were used: GOD and DRASTIC. The information about the layers for each model was provided via geographic information system (GIS). ArcGIS 10 software was used to create an interactive geodatabase, compile the geospatial data, compute the GOD and DRASTIC indexes, and to generate the final vulnerability maps.

DRASTIC method

DRASTIC has been applied to a number of groundwater basins. The name stands for depth to groundwater, recharge rate, aquifer media, soil media, topography, impact of vadose zone media, and hydraulic conductivity of the aquifer (Aller et al. 1987). Each parameter is subdivided into ranges with different ratings assigned in a scale of 1–10. A higher DRASTIC index shows greater groundwater pollution vulnerability (Aller et al. 1987). Weight multipliers are then used for each factor to balance and enhance its importance. The final vertical vulnerability using the DRASTIC index is computed as the weighted sum overlay of the seven layers.

The seven maps are then overlaid. DRASTIC vulnerability score at each point of the map is obtained via

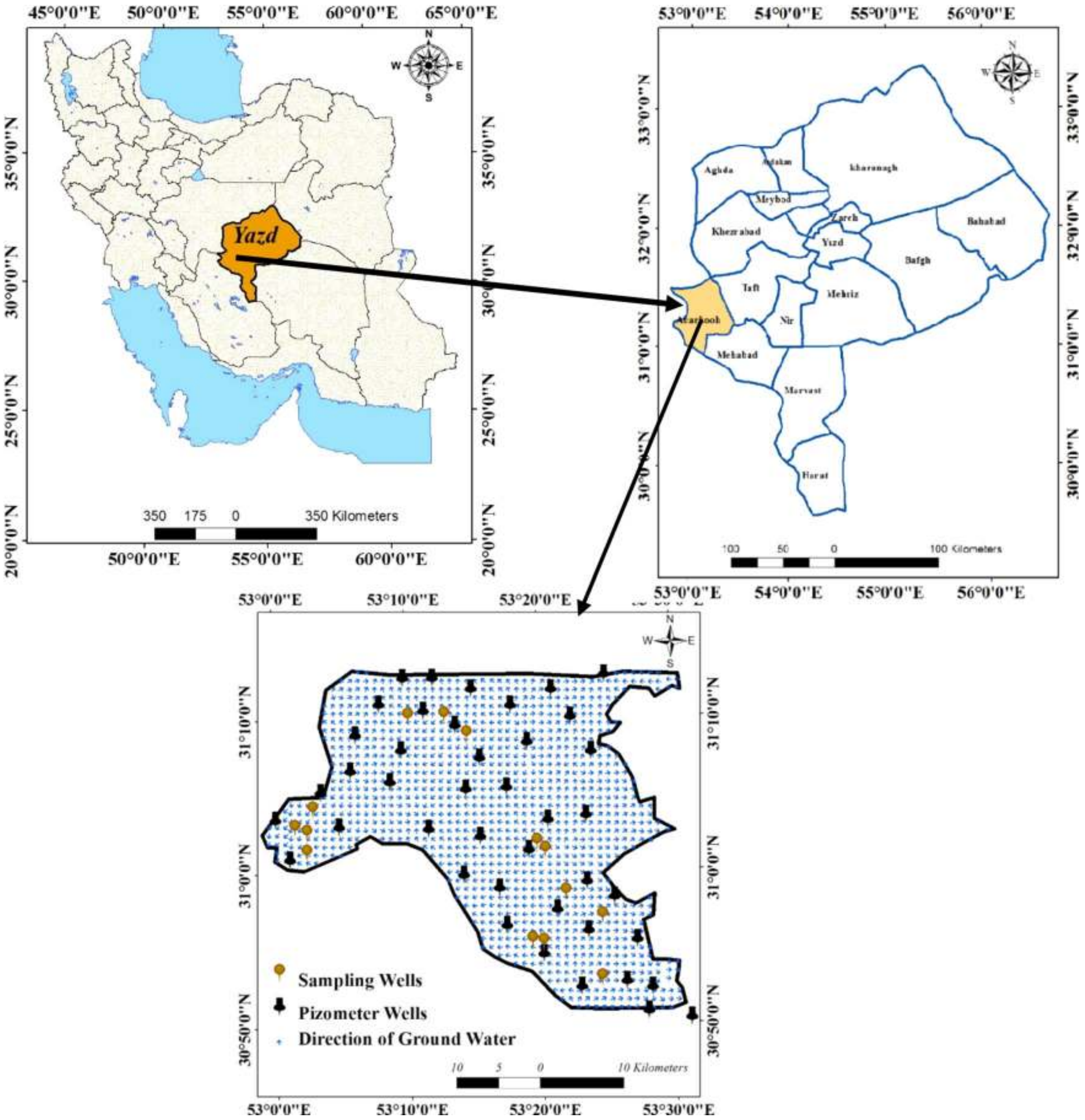

Fig. 1 Geographical location of the study area and the study wells in Abarkooh plain—Iran

computing the score from the seven parameters valid at that location of the map. A GIS system makes this task extremely simple. DRASTIC index does not account directly for contaminating activities or groundwater contamination already present in the area of interest. It also does not account for the travel time within the aquifer.

The DRASTIC index is finally computed by implying linear combinations of the products of rating and weights for each factor as follows (Aller et al. 1987):

$$\text{DRASTIC index (DI)} = \sum_{i=1}^{i=7} W_i \times R_i \qquad (1)$$

where DI is the vulnerability index based on the DRASTIC index and W_i is the weighting coefficient for parameter i with an associated rating value of R_i.

Table 1 indicates DRASTIC rating and weighting values for the various hydrogeological settings in the study area. In this study, each parameters of the DRASTIC model has been expressed as a thematic layer using ArcGIS 10 software in raster format. The Geostatistical Analyst extension with Kriging interpolation algorithm in ArcGIS was used to interpolate the points and create the raster map. Kriging has shown great success for interpolation in groundwater studies (Kumar 2007; Gundogdu and Guney 2007). Some information such as geological cross sections and drilled well logs data, soil texture, soil permeability, and rainfall were obtained from Yazd regional water authority. All produced layers were used to assess intrinsic groundwater vulnerability to pollution. The layer of depth to groundwater table (*D*) was generated based on the 43

Table 1 Drastic rating and weighting values for the various hydrogeological settings in the study area

DRASTIC parameters	Range	Rating	Weight	Total weight (rating × weight)	Area %	Area km^2
Depth to water table (m)	5					
	>30.4	1		5	76.8	922.83
	22.8–30.4	2		10	14.4	172.51
	15.2–22.8	3		15	7.3	88.01
	9.1–15.2	5		25	1.5	17.74
Recharge (mm)	4					
	3–5	1		4	96.1	1154.56
	5–7	2		8	3.9	46.53
Aquifer media	3					
	Clay–silt	1		3	1.8	22.11
	Silt	2		6	43.5	522.01
	Clay–silt–sand	3		9	13.9	167.21
	Silt–gravel	4		12	10.4	124.99
	Sandstone	5		15	9.1	109.51
	Sand clay	6		18	19.4	232.78
	Sand–gravel	7		21	1.9	22.48
Soil media	2					
	Clay	1		2	2.8	33.22
	Clay loam	2		4	74.3	892.83
	Silty loam	3		6	13.2	158.83
	Sandy loam	6		12	5.6	67.48
	Sand	9		18	4.1	48.73
Topography (slope%)	1					
	>18	1		1	0.4	4.39
	12–18	3		3	0.4	4.74
	6–11.99	5		5	1.2	13.91
	2–5.99	9		9	7.6	91.35
	0–1.99	10		10	90.5	1086.7
Saturated zone (vadose)	5					
	Clay/silt	2		10	2.7	31.95
	Silt/clay	3		15	34.7	416.63
	Clay/sand/conglomerate	4		20	42.2	506.79
	Sandstone	5		25	13.7	164.33
		6		30	6.8	81.39
Hydraulic conductivity (m/day)	3					
	<4	1		3	96.5	1158.45
	4–11.9	2		6	3.5	42.64

observation wells (Fig. 2). Groundwater depths were interpolated using Kriging algorithm. A raster map was generated and categorized into ranges defined by DRASTIC model. Three raster layers includes rainfall (mm), slope (%), and soil permeability (mm) were classified (Table 2). Net recharge value was estimated using net recharge range variables estimation method modified by Piscopo (2001). Net recharge map was created via combination of these layers (Table 2; Fig. 1). The aquifer and soil media maps were created based on the available geological cross sections and drilled well logs data obtained from Yazd regional water authority (Fig. 1).

Using the topographic map of the study area prepared by the National Cartographic Center, a digital elevation model (DEM) with a pixel size of 100 m was created. Slope map (Fig. 1) was extracted based on DEM and slope rating chart

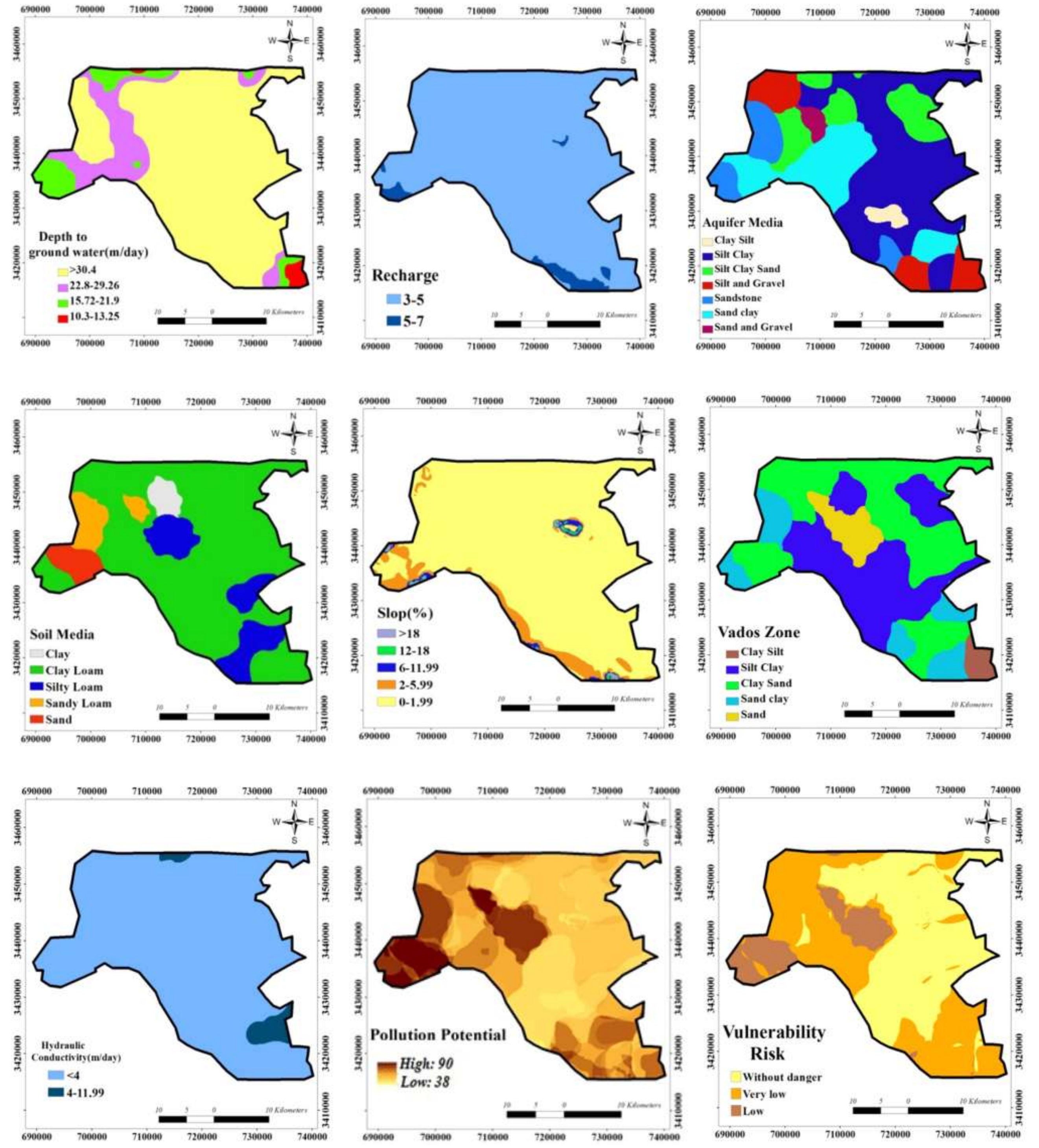

Fig. 2 Depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone, hydraulic conductivity, DRASTIC intrinsic vulnerability, and DRASTIC rating maps of the study area

(Tables 1, 2). The vadose zone map was created using the type and material forming of the saturated zone based on the means of drilled well log data and geoelectrical cross section (Fig. 1).

The hydraulic conductivity values were obtained based on the Table 3. Estimated values were interpolated using Kriging method. The hydraulic conductivity map was created using interpolated value (Fig. 1).

Table 2 Net recharge range variables and factors [modified from Piscopo (2001)]

Slope		Rainfall		Soil permeability[a]		Recharge value	
Slope (%)	Factor	Rainfall (mm)	Factor	Range	Factor	Range	Rating
>18	1	0–5	1	Very slow	1	3–5	1
12–18	2	5–10	2	Slow	2	5–7	3
6–12	3	10–17.5	3	Moderately slow	3	7–9	5
2–6	4	17.5–25	4	Moderately	4	9–11	7
0–2	5	>25	5	Moderately rapid	5	11–13	8
				Very rapid	6	13–15	9
				Rapid	7	15–17	10

[a] Soil permeability is based on USDA (1994)

Table 3 Range of hydraulic conductivity values by soil texture (Smedema and Rycroft 1983)

Texture	Hydraulic conductivity (m/day)
Gravelly course sand	10–50
Medium sand	1–5
Sandy loam, fine sand	1–3
Loam, well-structured clay loam and clay	0.5–2
Very fine sandy loam	0.2–0.5
Poorly structured clay loam and clay	0.002–0.2
Dense clay (no cracks, no pores)	<0.002

GOD method

GOD is a vulnerability assessment method developed in Great Britain. Like DRASTIC, GOD is an overlay and index method designed to map groundwater vulnerability over large regions based on three parameters: (1) *G*, groundwater confinement, (2) *O*, overlying strata, and (3) *D*, depth to groundwater. The lowest level for aquifer pollution vulnerability is attributed to values <0.1 (negligible), while the highest level is ascribed to values >0.7 (extreme). Scores are assigned to each of the three categories and then multiplied to yield a final score.

The GOD index can be divided into five categories: negligible (0–0.1), low (0.1–0.3), moderate (0.3–0.5), high (0.5–0.7), and very high (0.7–1) (Foster et al. 2002). The higher number shows the greater relative pollution potential risk to another one. The groundwater confinement, overlying strata, type of soil, and depth to groundwater maps were created as described for DRASTIC model, but these maps were rated from 0 to 1 based on Table 4.

Models validation

Validation refers to some independent procedure that can verify the results of the vulnerability analysis. Verification of vulnerability assessments can be done in many different ways. The most common approach, particularly for verification of assessments done with overlay and index methods, is to compare the vulnerability map with the actual occurrence of some common pollutant in groundwater. Typical pollutants used are nitrate and pesticides (Javadi et al. 2011). For validation DRASTIC and GOD models in the study area, nitrate concentration was selected as the primary contamination parameter. Fourteen agricultural wells were selected for sampling and analysis in June 2011 (Fig. 1). The exact position of each well was determined using GPS techniques. Accuracy of the models was evaluated using liner regression between observations values of nitrate and estimated vulnerability to pollution in the measured wells.

Results and discussion

DRASTIC vulnerability map

The sums of seven DRASTIC thematic parameters were used to estimate the final DRASTIC index (Fig. 1). According to the DRASTIC index, 12.2 and 42.2 % of the study area classified in the very low and low vulnerability, respectively, while 46.6 % of the study area was classified as without-risk area. Aquifer pollution vulnerability map represents that west parts of the studied area are more vulnerable to groundwater contamination than others part due to the low slope, high hydraulic conductivity, and clay loam soil type.

Table 4 GOD rating and weighting values for the various hydrogeological settings in the study area

GOD parameters	Range	Rating	Weight	Total weight (rating × weight)
Depth to water table (m)	1			
	5–10	0.8		0.8
	10–20	0.7		0.7
	20–50	0.6		0.6
Aquifer type	1			
	Unconfined	1		1
Lithology	1			
	Residual soil	0.4		0.4
	Limon alluvial, loess, shale, fine limestone	0.5		0.5
	Aeolian sand, siltite, tuf, igneous rock	0.6		0.6
	Sand and gravel, sandstone, tufa	0.7		0.7
	Gravel	0.8		0.8
Soil media	1			
	Clay	0.5		0.5
	Clay–silt	0.6		0.6
	Silt	0.8		0.8
	Silt–sand	0.9		0.9

GOD vulnerability map

GOD index vulnerability map was created via overlapping of groundwater confinement, overlying strata, depth to groundwater, and soil type maps. Table 4 indicates GOD rating and weighting values for the various hydrogeological settings in the study area. The study aquifer was classified into three classes: low (89.2 %), moderate (6.5 %), and high (4.5 %) vulnerable zones (Fig. 3). According to results, the major part of the study aquifers is located in the low-vulnerability risk category, but the west part of the study area is located in the high and moderate category.

Model validation

A significant correlation was observed between measured nitrate and pollution potential evaluated by DRASTIC ($P < 0.01$), but no significant correlation was observed for GOD model ($P < 0.05$). The regression line between observations and estimated values in the validation data is shown in Fig. 4. According to results, DRASTIC model is more suitable model for classifying of the pollution potential in the study area than GOD model.

The groundwater contamination risk map, created via DRASTIC model, shows three classes of vulnerability (2). According to results, 46.6 % of the study area in the east part, classified as without risk. The depth to water table in this area is more than 30 m. This makes the east part of the study area less susceptible to contamination according to DRASTIC assumptions (Fig. 5).

The low hydraulic conductivity, low permeability, and the vadose zone cause very low- and low-vulnerability area according to DRASTIC parameters.

The GOD model application indicates higher vulnerable zones to be contaminated by pollutants (Fig. 3), but DRASTIC model indicates more accuracy in this study area. DRASTIC, GOD, and AVI models were compared in an alluvial aquifer of Florina basin in Greece using linear regression analysis (Kazakis and Voudouris 2011). To obtain comparable value, a quantitative comparison of vulnerability methods was involved. The results of this study indicate that the GOD method has a stronger correlation with the other two methods, and the three models produced comparable vulnerability maps. Ighbal et al. (2014) compared a GIS-based fuzzy pattern recognition model (modified DRASTIC model) with a standard DRASTIC model in Ranchi district, Jharkhand, India. The results of this study indicated that GIS-based fuzzy pattern recognition model had better performance than the standard DRASTIC model. Polemio et al. (2009) indicate that the GOD method is useful for mapping large areas with high vulnerability contrasts, whereas DRASTIC are useful for any type of aquifer.

The nitrate concentration in groundwater in the west part of the study area was more than 30 mg/l in June 2011. Also the maximum acceptable nitrate concentration for human

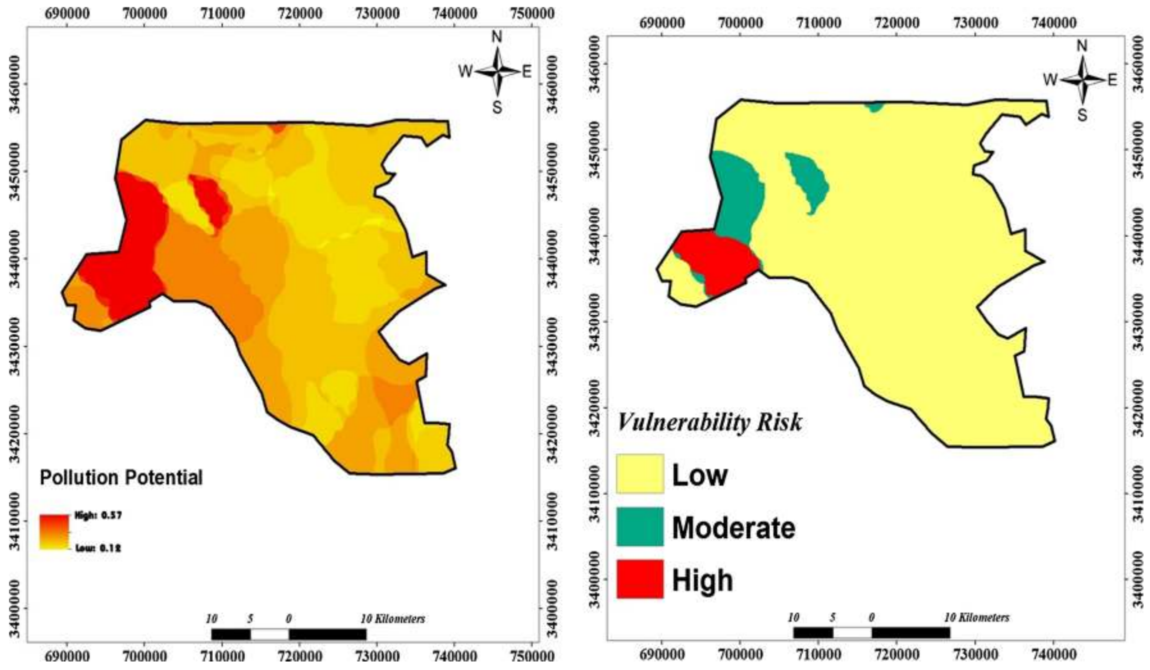

Fig. 3 GOD intrinsic vulnerability and rating maps of the study area

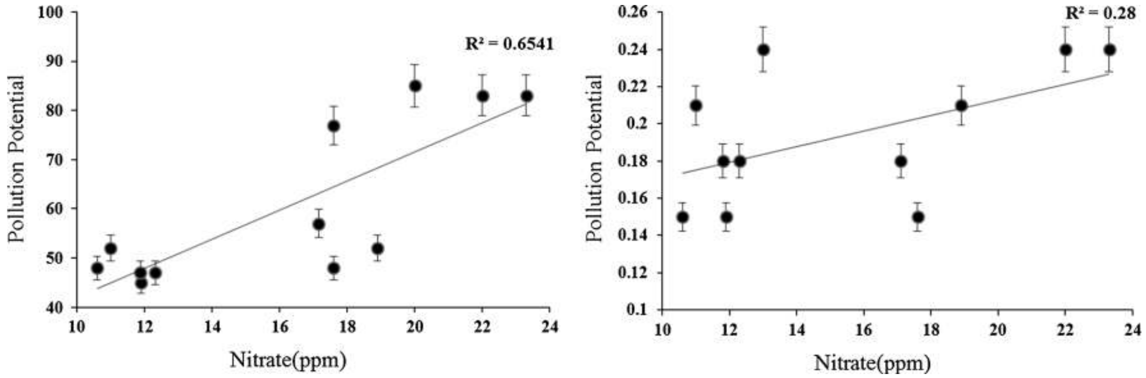

Fig. 4 Linear regression between measured nitrate and pollution potential evaluated by DRASTIC (*left side*) and GOD (*right side*) models

health is 45–50 mg/l (WHO 2008), but it is well know that nitrate concentration higher than 10 mg/l in groundwater indicates anthropogenic contamination. Hence, it can be concluded that increasing of the nitrate concentration in this area, especially in the west part, should be related to input of agricultural fertilizers and industrial contamination located in this area.

Correlation coefficient between DRASTIC index and nitrate concentration was 68 % compared with 28 % for GOD index. Comparative analysis between DRASTIC results and nitrate levels has been used in several studies (Assaf and Saadeh 2009). Javadi et al. (2011) modified DRASTIC model using nitrate measurements. They showed that correlation coefficient between DRASTIC index and nitrate concentration was 68 % in modified model that was substantially higher than 23 % obtained for the original model. Houan et al. (2012) indicated that mapping of groundwater vulnerability to nitrate can be applied for sensible groundwater resource management and land-use planning.

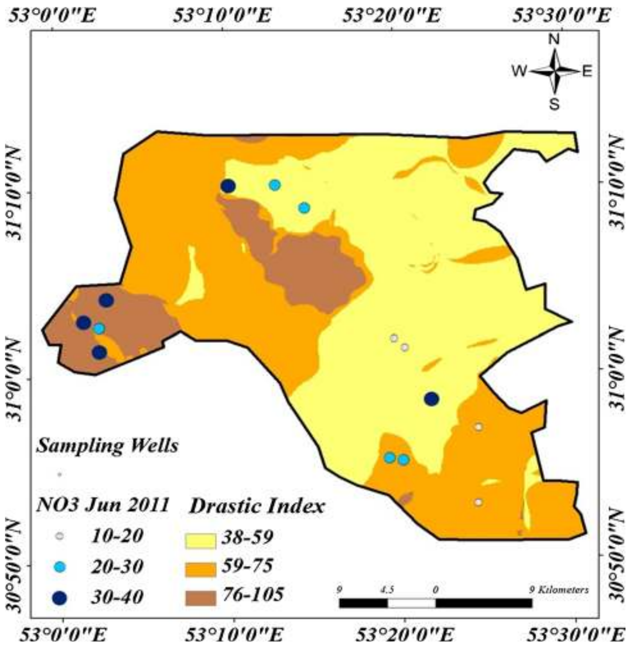

Fig. 5 Spatial distribution of groundwater vulnerability score

Conclusion

The purpose of this research was to assess the vulnerability potential of the Abarkooh aquifer using the DRASTIC and GOD indexes. We also investigate the performance of DRASTIC and GOD models for the evaluation of groundwater contamination. Results of this study showed that DRASTIC model is more suitable for evaluation of groundwater contamination in the study area. According to the results, a significant relationship was observed between nitrate concentration and aquifer vulnerability evaluated via DRASTIC model. Results of this study showed that nitrate concentration should be a suitable parameter to investigate the accuracy of DRASTIC and GOD models.

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