Assessment of Groundwater Vulnerability in the Borazjan Aquifer of Bushehr, South of Iran, Using GIS Technique

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Introduction

Ground water is treated as an important source of water due to its large volumes and its low vulnerability to pollution when compared to surface waters (USEPA, 2006). Bushehr is an arid region with low rainfall (100 mm/year) and very high evapotranspiration (3000 mm/year). Like other arid countries, ground water is the main source of water for different purposes. Pollution vulnerability assessment requires in-depth knowledge of the hydrogeological, hydrodynamic and hydrochemical characteristics of aquifers. Several methods and simulation models have been developed since the 1970s. In the last 15 years, the advent of GIS, permitting the inventory, archival, retrieval and display of spatial data and the link to numerical rating systems, has resulted in the widespread use of parametric methods, based on the hydrogeological setting: e.g. DRASTIC (Aller et al., 1987) commonly used in the USA, and SINTACS (Civita and De Maio, 2000), an Italian modification.

The vulnerability of an aquifer, as the sensitivity to surface pollution, is based on the occurrence of natural attenuation process pollution of the soil. The degree of attenuation is defined by hydrogeological characteristics and geological intrinsic of an aquifer system and the medium overlying (Doerfliger et al., 1999; Leitao et al., 2003; Sinan and Razack, 2009). For the danger of pollution, this is defined as a potential source of contamination as a result of anthropogenic activities on the soil surface (Mimi and Assi, 2009). Risk pollution can therefore be estimated by an interaction between the contaminant load and vulnerability to pollution. With the

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knowledge of the behaviour of water quality and vulnerability factors associated with use, development scenarios can be generated that lead to the protection of the aquifer system.

This study addresses the influence of geological uncertainties in determining the SINTACS index (Civita and De Maio, 2000) and the method used to determine the intrinsic vulnerability of aquifers. It has as objective to apply this methodology to the area of the aquifer in the Borazjan, bounded by the River Basin Helleh, Dalaki and Shapour, Iran.

Hydrogeological Setting of the Study Area

The Borazjan Sampling Area

Borazjan study area is located in Helleh basin (Fig. 1). This area is restricted in longitudes 49° 29′ 84″ up to 53° 00′ 40″ East and latitudes 32° 22′ 10″ up to 32° 45′ 93″ and Genaveh study area in North, Ahram study area in the South and Shahpour and Dalaki watershed in the West. Climatically, this region is located in area with mean annual rainfall of 259.8 mm and mean temperature of 29.9°C and according to Emberger divisions is a desert district with middle warm climate.
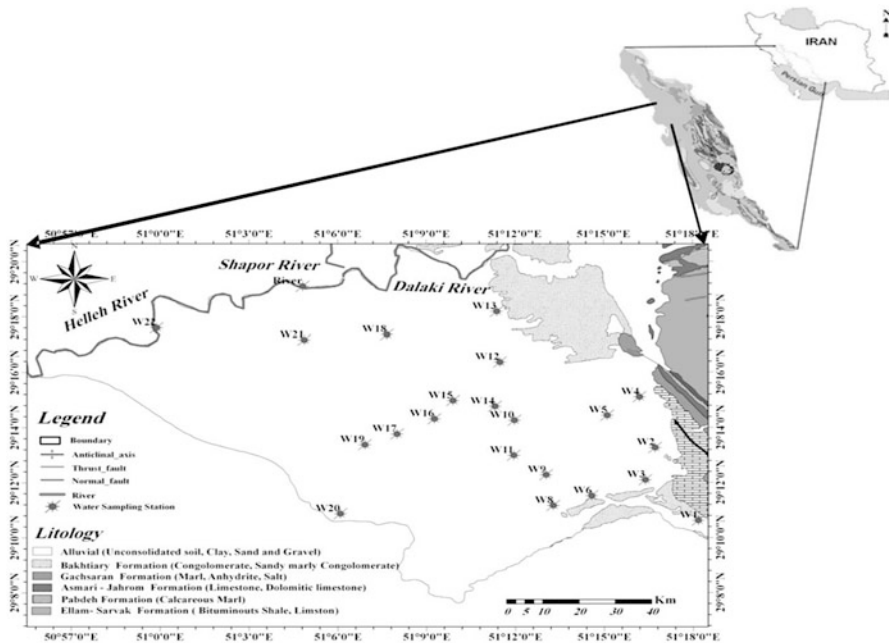

Fig. 1 Location map of the study area and sampling stations

The study area, with its almost flat morphology, covers approximately 418 km^2. The Borazjan Plain is crossed by the upper part of the Helleh, Dalaki and Shapour rivers. It is delimited by the Zagros mountains and by the Gisakan ridge to the east. The Borazjan Plain consists of alluvial deposits (thickness 0-80 m).

The aquifer in the plain can be considered a single continuous body. Water circulation takes place mainly in the permeable layers, with sand and gravel-sized grains. The aquifer is unconfined; locally, pyroclastic or clayey layers generate confined sectors. Borazjan area is located in one of the syncline of folded belt of Zagros mountain. The effect of tectonic forces on this region caused anticlines, tectonization formation and to form thrust faults and Qatar-Kazerun fault which with northern-southern direction passes through eastern part of plain. Qatar-Kazerun fault has divided study area into mountains and plain district; mountains district is located in eastern part of region. Surrounding heights of region in northern and southern areas include hills and high grounds of Bakhtiyari formation and in eastern area include Gisakan anticline with north western-south eastern direction and maximum height of 1785 metres from sea level with river water from Cretaceous to Pliocene. Stratigraphy of this study area has been shown in Fig. 1.

Methodology

The SINTACS procedure incorporates seven parameters relevant for the contaminant attenuation and vertical flow capacity (Table 1). In the vulnerability assessment procedure, the Borazjan plain was discretized with a regular mesh grid of 100×100 m. The grid square cell structure of the SINTACS input data has been designed in order to use several weight strings. The weight strings have been prepared in order to satisfactorily describe the effective hydrogeological and impacting situation as set up by the sum of data. The present release of SINTACS presents five weight strings for normal impact, relevant impact and drainage from the surface network. For each of the 7887 grid squares, element normalized SINTACS index was calculated and differently vulnerable areas were assessed using SINTACS R5 parametric methods (Civita and De Maio, 2000).

Results and Discussion

Soggiacenza as Depth to Water

Data from 22 water wells in the study area were used to prepare the depth to water table layer. The depth to water table was obtained by subtracting the water table level from the elevation of the piezometer wells and averaging over a three-year period (2009-2012). Generally, the depth to water in the centre part of study area is

Table 1 The SINTACS model parameters (Modified from Babiker et al., 2004)

Factor	Description	Relative weight
Soggiacenza as Depth to Water	Represents the depth from the ground surface to the water table, deeper water table levels imply lesser chance for contamination to occur.	5
Infiltrazione as Net Recharge	Represents the amount of water which penetrates the ground surface and reaches the water table, recharge water represents the vehicle for transporting pollutants.	4
Non Saturo as Impact of the Vadose Zone	Refers to the saturated zone material properties, which controls the pollutant attenuation processes.	3
TipologiaCopertura as Soil Media	Represents the uppermost weathered portion of the unsaturated zone and controls the amount of recharge that can infiltrate downward.	2
Caratteristiche Acquifero as Aquifer Media	Refers to the slope of the land surface, it dictates whether the runoff will remain on the surface to allow contaminant percolation to the saturated zone.	1
Conducibilita Idraulica as Hydraulic Conductivity	Is defined as the unsaturated zone material, it controls the passage and attenuation of the contaminated material to the saturated zone.	5
Acclivita Superficie Topografica as Slope	Indicates the ability of the aquifer to transmit water, hence determines the rate of flow of contaminant material within the groundwater system.	3

high (>30 m), and gradually decreases to boundaries. Even in the southwest of the study area depth to water table decreases to less than two metres. The depth to water layer was classified from 2 (least effect on vulnerability) to 10 (most effect on vulnerability) with regard to SINTACS classification (Fig. 2a).

Infiltrazione as Net Recharge

To prepare net recharge layer Piscopo (2001) method was used. In order to calculate the recharge value, a digital elevation model (DEM) of the study area was generated from the topographic map. The slopes in the study area were then derived from the DEM and classified according to the criteria given in Table 2a. The resulting slope map was converted into a grid coverage taking into consideration that the pixel values in this grid coverage are based on the slope ratings. The soil map was classified into two classes based on the criteria given in Table 2c and was then converted into grid coverage. This process was essential in order to perform arithmetic operations within the GIS. Finally, both grids were added together
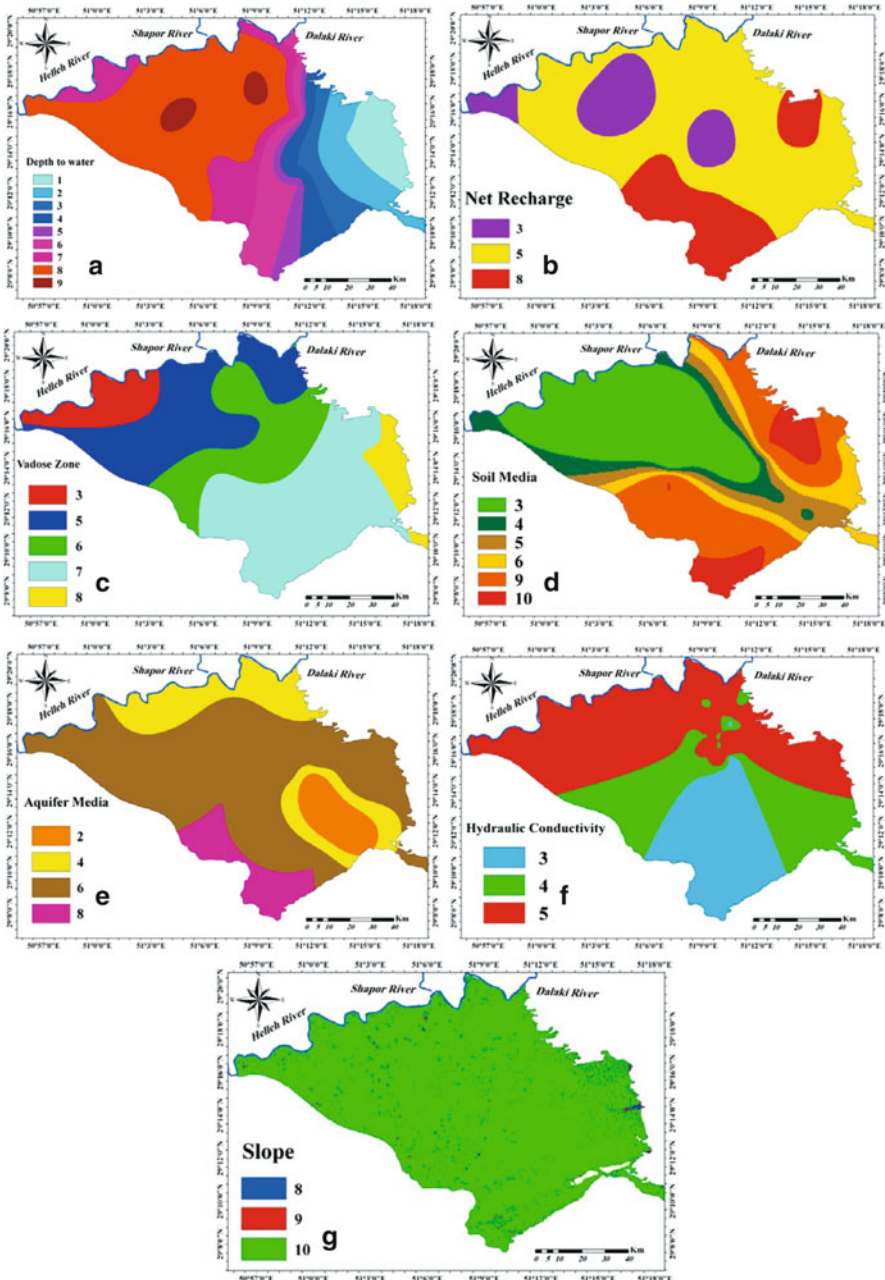
Fig. 2 Parametric maps of SINTACS groundwater vulnerability model for the Borazjan aquifer

Table 2 The recharge ratings and weightings for the study area

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

with the rating value of the rainfall, which is equal to 1 in the study area (Table 2b). Recharge index was then calculated as:

$$\text{Recharge Index} = \text{Slope } (\%) + \text{Rainfall} + \text{Soil permeability}$$

The resulting map was then classified according to the criteria given in Table 2d. With regard to the net recharge layer, the most rechargeable zone belongs to sand dunes area (175-250 mm/year, with rating of 8), while the central part of the study area has moderate recharge (100-175 mm/year, with rating of 5) and the area with low recharge (50-100 mm/year, with rating of 3) (Fig. 2b) surround the moderate zone.

Non Saturo as Impact of the Vadose Zone

Based on the 22 well logs available in the study area, the aquifer media layer was prepared.

First, the aquifer media rating was calculated for each well and then using these ratings and well locations, the aquifer media layer was prepared and finally converted to grid coverage. Aquifer media layer exhibits that most parts of the study area have the rating value equal 6 (clay and silt) and some small areas have 3 and 8 rating values (Fig. 2c and Table 3).

Tipologia Copertura as Soil Media

Soil map of the study area (1/50,000) that had been prepared by Environmental Source Office of Bushehr Province was used to prepare the soil media layer. First the hard copy of this map was scanned and was digitized using ENVI software and then the vector file of soil map was prepared in Arc View GIS software. The soil media types were then assigned ratings from 3 to 9 according to their permeability. Coarse soil media have high rates in comparison to fine soil media. The vector layer of soil was converted to a raster grid which has produced the map as presented in

Table 3 The SINTACS index for the study area

Parameter	Rating
Soggiacenza as Depth to Water (m)	
7-10	6
10-13	5
13-20	4
<56	1
Infiltrazione as Net Recharge (mm/year)	
175-250	8
100-175	5
50-100	3
Non Saturo as Impact of the Vadose Zone	
Sand and gravel	9
Sand with some clay/silt	7
Clay and silt with some sand/gravel	5
Clay and silt	2
Tipologia Copertura as Soil Media	
Silty Sand	7
Clayey sand	6
Clay with high sand	5
Clay with low sand	4
Clay and silt	3
Confined aquifer or compact clay	1
Caratteristiche Acquifero as Aquifer Media	
Sand dunes	9
Loamy sand to sandy loam	6
Silty-clayey loam to clay loam	3
Conducibilita Idraulica as Hydraulic Conductivity (m/day)	
28-40	6
12-28	4
4-12	2
<4	1
Acclivita Superficie Topografica as Slope	
0-2	10
2-6	9
6-12	5
12-18	3
>18	1

Fig. 2d. According to the soil media layer, sand dunes with high permeability are located in hydrologic group of A, the central part of the study area with texture of loamy sand to sandy loam is located in hydrologic group of B and other parts of the study area with texture of silty-clayey loam are located in hydrologic group of C.

Caratteristiche Acquifero as Aquifer Media

The preparation of the impact of vadose zone layer was exactly the same as the aquifer media layer. Moreover, this layer was prepared based on logs of 22 piezometers (Fig. 2e). According to this layer deposits of unsaturated zone in the north and northeast of the study area are highly discontinuous and have many interbeds of sand and clay. Existence of clay interbeds has high impact on decreasing of vulnerability. Conversely the unsaturated zone in most parts of south and southwest part of the study area have formed from continuous sandy deposits.

Conducibilita Idraulica as Hydraulic Conductivity

Pumping test data of 22 deep wells in the study area were used for preparation of this layer. Transmissivity values were calculated for all wells by using Mace method (Mace, 1996). Then with regard to the thickness of saturated zone, hydraulic conductivity was calculated for all wells and according to SINTACS model classification, rating values were obtained for the total of the study area. Figure 2f shows that most parts of the study area have hydraulic conductivity value between 4 and 12 (m/day) with rating value of 2. In the southern part of the study area there is a small part with hydraulic conductivity of less than 4 (m/day) and its rating value is 1.

Acclivita Superficie Topografica as Slope

In order to prepare the topography layer, a digital elevation model (DEM) of the study area was generated from the topographic map. The slopes in the study area were then derived from the DEM and classified according to the criteria of SINTACS model (Fig. 2g). Figure 2e shows that the slope value in most parts of the study area is less than 2 % (rating value = 10) and only a small part between 2 and 6 % (rating value = 9). Generally slope in the study area is low and therefore increases the groundwater vulnerability.

The SINTACS Vulnerability Index

The GIS coverage were all in raster format and values for each overlay were summed in ArcView GIS according to the pixel value of each area that resulted from multiplying the ratings with its appropriate SINTACS weight (Table 3).

Since the minimum possible SINTACS index for using these parameters is 63 and the maximum is 180, this range was divided into eight classes. These classes were (Civita and De Maio, 2000):

(a) Less than 63 (No risk)
(b) 64–77 (Very low)
(c) 78–99 (Low)
(d) 100-119 (Moderate)
(e) 120-139 (Moderate-High)
(f) 140-159 (High)
(g) 160-179 (Very high)
(h) More than 180 (Completely vulnerable)

The resulting SINTACS values in this application lay between 97 and 171. This range was classified on the basis of the above classification as: (c) 97-110, which was assigned a low vulnerability, (d) 111–126, which was assigned a moderate vulnerability, (e) 126–141, which was assigned a moderate to high vulnerability, (f) 141-156, which was assigned a high vulnerability, and (g) 156-171 which was assigned a complete vulnerability as shown in Table 4. Table 4 shows that 12.4 % of the study area has low vulnerability to contamination, 31 % of the study area has moderate vulnerability groundwater, 38.9 % of the study area has moderate to high vulnerability groundwater, 9.2 % of the study area has high vulnerability to contamination and the remainder of the study area (less than 8.5 %) has a very high vulnerability.

The SINTACS aquifer vulnerability map clearly shows the dominance of "Moderate-High" vulnerability classes in most parts of the study area, particularly in the centre, east and northeast of the study area. The western and southwestern parts are characterized by "moderate" vulnerability (Fig. 3). This pattern is mainly dictated by the variation in impact of vadose zone media from east to west. Also the soil media and depth to water table have high impact, but their importance are less than impact of vadose zone media. The parts at south of the study area display "High risk to pollution". This is due to the combination of deep water table, low permeability of vadose and aquifer media.

Table 4 The SINTACS index for the study area (Civita and De Maio, 2000)

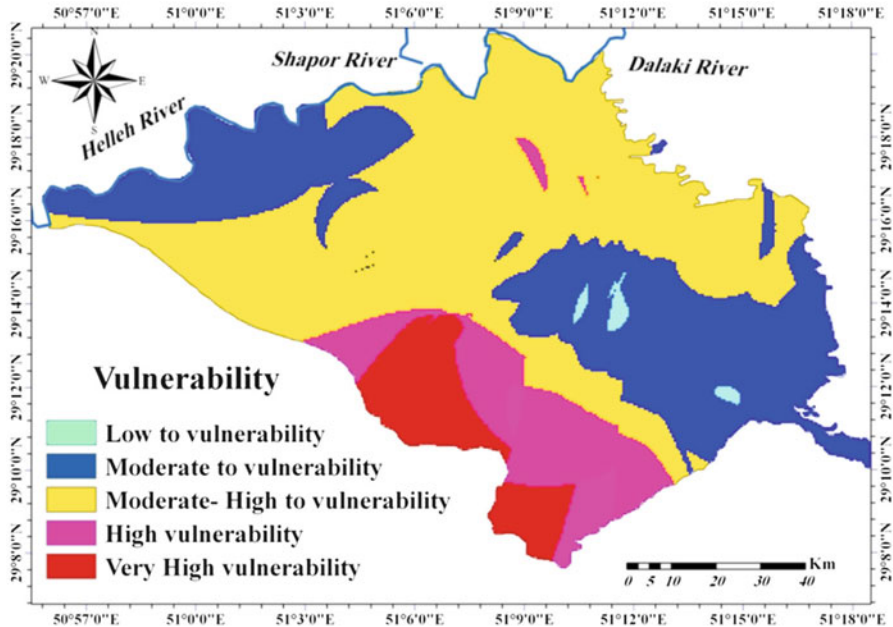| SINTACS index	SINTACS range	Area (km^2)	% of the total area
Low vulnerability	97-110	52	12.4
Moderate vulnerability	111-126	129.9	31
Moderate to high vulnerability	126-141	162.6	38.9
High vulnerability	141-156	38.3	9.2
Very high vulnerability	156-171	35.6	8.5
	Total	418.4	100

Fig. 3 Distribution of the groundwater vulnerability index in the Borazjan aquifer

SINTACS Model Validation

Twelve water samples were collected from agriculture wells and analyzed to validate the result of SINTACS model. With regard to the fact that the most-used fertilizers at the study area are animal or nitrate mucks, the nitrate anion was analyzed (Table 5). Chemical analysis was performed at laboratory of Zagros Abshenase Fars Company, Iran, using Metrohm 761 apparatus. It is a sophisticated and careful water analysis machine. Wells location and iso-nitrate map are shown in Fig. 4. According to Fig. 4 nitrate concentrations at the south parts of study area that have high vulnerability is more than nitrate concentration at the north, east and west parts that have moderate to high vulnerability; therefore the results of vulnerability assessment using SINTACS model are confirmed.

Correlation coefficient between SINTACS model parameters and nitrate layer was calculated using Arc GIS 9.3 software to identify the most effective parameter on groundwater vulnerability at the study area. The results of this calculation are presented in Table 6. These results show that the most correlation is between Non Saturo as Impact of the vadose zone and Caratteristiche Acquifero as Aquifer media parameters and nitrate layer. This means that impact of vadose zone and Aquifer media parameters have the most impact on groundwater vulnerability to pollution in comparison to other SINTACS parameters in the study area.

Table 5 Concentration of nitrate in groundwater

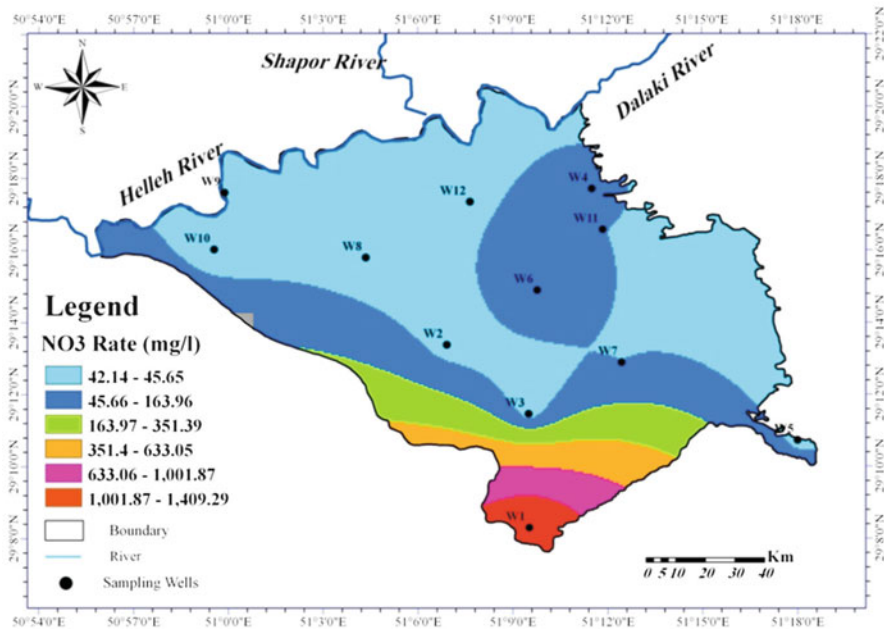| Well	NO_3 (mg/l)	Well	NO_3 (mg/l)
W_1	1400	W_7	51.7
W_2	5.17	W_8	1.64
W_3	3.29	W_9	2.88
W_4	94.8	W_{10}	4.15
W_5	17.31	W_{11}	49.9
W_6	162.4	W_{12}	22.34

Fig. 4 Wells location and nitrate rate in groundwater at the study area

Table 6 Correlation coefficient between nitrate layer and SINTACS model parameters

Layer	S	I	N	T	A	C	S
Nitrate	-0/05259	0/53770	0/30323	0/46755	0/54989	-0/53895	0/022170

The reasons for this high correlation is that the most sediment at south part of study area are sandy and therefore surficial pollutants; especially nitrate ion can easily pass from sand filter and reach groundwater. While there are fine grain sediments silt and clay at the other parts of study area and therefore pollutants cannot easily pass from these fine grain filters and generally are removed from infiltrating water before reaching groundwater.

Aquifer media parameter also has high correlation with nitrate layer that can be explained by the fact that at low water table areas, pollutants have less time to be removed by physical (filtering), chemical (reaction with existing material at vadose zone) and biological (biodegradation) processes and hence reach groundwater rapidly. But at high water table areas, the mentioned processes have more time for removing the pollutants and therefore aquifer is subjected to less pollution risk. Superposition of nitrate layer on depth to water table layer at the study area confirms the results of SINTACS model clearly.

Conclusions

In this paper, we have attempted to assess the aquifer vulnerability of the Borazjan groundwater basin employing the empirical index SINTACS model of the U.S. Environmental Protection Agency (EPA). Borazjan Basin, located in the middle reaches of the Helleh, Dalaki and Shapour rivers, is an important agricultural and industrial centre. Ground water is a major water source for these activities. Due to excessive abstraction of ground water, the quality of ground water has been deteriorated. In this paper, the empirical index SINTACS model and GIS technique were employed to assess the aquifer vulnerability of the shallow aquifer of Borazjan Basin. Seven environmental parameters including depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity were used to represent the natural hydrogeological setting of the Borazjan Basin. According to the results of the groundwater vulnerability assessment, the study area can be divided into five zones. The results show that 8.5 % of Borazjan aquifer area has very high contamination potential, 9.2 % high, 38.9 % moderate to high, 31 % moderate and 12.4 % has very low potential to be polluted. Southern areas of this plain has the higher contamination potential than other parts of it located in the groundwater recharge zones. Correlation analysis between SINTACS parameters and nitrate ion layers showed that nitrate layer has the best correlation with impact of vadose zone parameter followed by Acquifero as Aquifer Media parameter. This shows that most effective parameters on groundwater vulnerability to pollution at the study area are impact of vadose zone and depth to water table. According to the results, if current trends of contamination due to leaching of inorganic fertilizers which applied to agricultural land, domestic sewage and livestock and poultry wastewater are continued, the plain will reach the worst condition of pollution. The results of this study indicate that groundwater vulnerability and risk mapping is an efficient tool to assist with planning and decision-making processes.

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