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Research Article

ASSESSMENT OF GROUNDWATER VULNERABILITY IN THE BORAZJAN AQUIFER OF BUSHEHR, SOUTH OF IRAN, USING GIS TECHNIQUE

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ABSTRACT
Vulnerability assessment to delineate areas that are more susceptible to contamination from anthropogenic sources has become an important element for sensible resource management and land use planning. This contribution aims at estimating aquifer vulnerability by applying the SINTACS model as well as utilizing sensitivity analyses to evaluate the relative importance of the model parameters for aquifer vulnerability in Borazjan plain, in the south of Iran. An additional objective is to demonstrate the combined use of the SINTACS and geographical information system (GIS) as an effective method for groundwater pollution risk assessment. The SINTACS model uses seven environmental parameters to characterize the hydrogeological setting and evaluate aquifer vulnerability. The southern part of the Borazjan aquifer was dominated by high vulnerability classes while the central part was characterized by Moderate vulnerability classes. The elevated eastern and western parts of the study area displayed low aquifer vulnerability. The integrated vulnerability map shows the high risk imposed on the southern part of the Borazjan aquifer due to the high pollution potential of wells in different village's domestic wastewater, animal husbandry waste and non-organic fertilizers applied to agricultural land. In Borazjan, land use seems to be a better predictor of groundwater contamination by nitrate. Depth to water parameter inflicted the largest impact on the intrinsic vulnerability of the aquifer followed by vadose zone media, net recharge and soil media, aquifer media, topography and hydraulic conductivity. Sensitivity analyses indicated that the removal of net recharge, soil media and topography causes large variation in vulnerability index. Moreover, depth to water and vadose zone media were found to be more effective in assessing aquifer vulnerability than assumed by the SINTACS model. The GIS technique has provided efficient environment for analyses and high capabilities of handling large spatial data.

Keywords: *GIS, SINTACS Model, Aquifer Vulnerability, Groundwater, Borazjan, Pollution, Nitrate*

INTRODUCTION
Groundwater is treated as an important source of water due to it large volumes and its low vulnerability to pollution when compared to surface waters (USEPA, 1985). Boshehr is an arid region with low rainfall (100 mm/year) and very high evapotranspiration) 3000 mm/year). Like other arid countries, groundwater is the main source of water for different purposes.
Groundwater resources in Borazjan are especially important as they supply 99% of the demand for fresh water)Personal communication, Ministry of Regional Municipalities, Environment, and Water Resources, Muscat, Borazjan), and play a great role in the socio-economic development. In Borazjan, there are more than 128,000 wells tapping the major aquifers.
Of which originate from the groundwater. Groundwater resources are used practically for all purposes, ranging from domestic to agricultural, industrial and commercial. The high dependence on groundwater coupled with industrial and demographic expansion resulted in increasing pressures on available groundwater resources in terms of quantity and quality. The high withdrawal and low recharge reduced the amount of available groundwater especially in the coastal areas where seawater intrusion is another threat to groundwater recharge. Other changes such as industrial and agricultural activities that related to increase in population contribute significantly to the deterioration in groundwater quality through anthropogenic activities. Intrusion of pollutants from these different sources to groundwater alters the

water quality and reduces its value to consumers (Melloul and Collin, 1992). Groundwater vulnerability is considered an intrinsic property of groundwater that depends on its sensitivity to humans and natural impacts, and can be defined as the possibility of percolation and diffusion of contaminants from the ground surface into the groundwater system (Babiker *et al.,* 2005).Therefore, vulnerability deals with the hydrogeological settings and does not include attenuation of pollutants. Barbash and Resek (1996) reported that methods of evaluating groundwater vulnerability rely either on direct observations of contaminants in groundwater, or simulation and index methods. While the direct observation method yields most conclusive results, it requires large number of observations. Simulation and index methods predict vulnerability from field conditions and chemical properties of groundwater (Thapinta and Hudak 2003). Further, groundwater vulnerability studies are useful to evaluate land-use activity with respect to the development of pollution liability insurance and the assessment of economic impacts of disposal costs in highly vulnerable areas. Moreover, it is providing preliminary information and criteria for decision-making in such areas as: designation of land use controls, delineation of monitoring networks and management of water resources in the context of regional planning as related to protection of groundwater quality (Bachmat and Collin, 1990). Many different methods have been developed for assessing this vulnerability. It is classified into two major types: one is physical methods and the other is chemical methods. In the physical methods, the simplest method is GOD method that was developed by Foster (1987) and consists of only three parameters: Groundwater occurrence or aquifer condition (G), Overlying lithology (O) and Depth to groundwater (D). Another method is called DRASTIC, which is very familiar method developed in USEPA by Aller *et al.,* (1987). It is a rank/score based method and it includes seven hydrogeological parameters, Soggiacenza as Depth to Water (S), Infiltrazione as Net Recharge (I), Non Saturo as Impact of the Vadose Zone (N), TipologiaCopertura as Soil Media (T) , Caratteristiche Acquifero as Aquifer Media (A), Conducibilita Idraulica as Hydraulic Conductivity (C) and Acclivita Superficie Topografica as Slope (S). The SINTACS method assumes that: (1) any contaminant is introduced at the ground surface; (2) the contaminant is flushed into the groundwater by precipitation; (3) the contaminant has the mobility of water; (4) the areas evaluated using SINTACS are 0.4 km2 or larger. This method has been applied in several countries (Kim and Hamm 1999; Al-Zabet 2002; Lee 2003; Al-Adamat *et al.,* 2003). Similar index or score based systems were developed such as EPIK (Doerfliger *et al.,* 1999), German method (Von-Hoyer and Sofner 1998), ISIS (Civita and De-Regibus 1995), GIS based method (Faye *et al.,* 2004), SINTACS (Civita 1994), AVI rating system (Van-Stempvoort *et al.,* 1993), AQUIPRO (Pssero 1990; U.S. Environmental Protection Agency 1993), etc. Some of the researchers modified the DRASTIC method and extended using other parameters (Fritch *et al.,* 2000; Secunda *et al.,* 1998; Lee 2003). Secunda *et al.,* (1998) included the agricultural land use index as an additional parameter in the SINTACS method. Lee (2003) added lineament density to the SINTACS system to assess the groundwater pollution vulnerability in South Korea.

As mentioned earlier, information about vulnerability of groundwater to contamination is essential to facilitate groundwater planning and management. Additionally, such vulnerability information can aid in the choice of proper locations for certain activities so that the adverse effects on groundwater are minimized, and protection of groundwater is achieved.

Vulnerability map is one of the important tools that can be used for planning and decision making (Gogu and Dassargues 2000). In the present study, a detailed investigation was carried out to evaluate the potential for groundwater contamination through the construction of a vulnerability map for Barka groundwater aquifer system using DRASTIC method. Additionally, this research attempted to demonstrate the combined use of DRASTIC and geographical information system (GIS) as an effective method for groundwater pollution risk assessment and water resource management.

As the study region has been affected by saline water intrusion and anthropogenic activities, present study is necessary to identify the highly vulnerable zones and to protect valuable groundwater resources in the future.

The Remote Sensing and GIS tools have opened new paths in water resources studies. Remote sensing provides multi-spectral, multi-temporal and multi-sensor data of the earth's surface (Choudhury *et al.,*

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2003). One of the greatest advantages of using remote sensing and GIS for hydrological investigations and monitoring is its ability to generate information in spatial and temporal domain, which is very crucial for successful analysis, prediction and validation (Sarma and Saraf, 2002).

MATERIALS AND METHODS

Location of Study Area

Borazjan study area is located in Helleh basin. 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 South and Shahpoor and Dalaki watershed in West. Climatically, this region is located in area with mean annual rain fall of 259.8 mm and mean temperature of 29.9°C and according to Emberger divisions is a desert district with middle warm climate.

Stratigraphy

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 from 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 which 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 of Gisakan anticline with north western – south eastern direction and maximum height of 1785 meters from sea level with river water from Cretaceous to Pliocene. Stratigraphy of this study area has been shown in figure 1

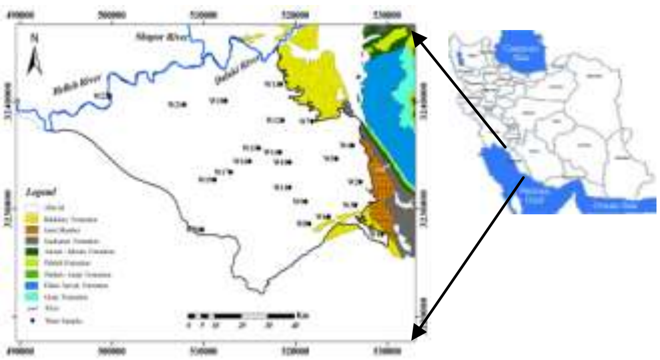

Figure 1: Location map of the study area and sampling stations

Methods

Model Description

A SINTACS method applied in GIS environment was used to evaluate the vulnerability of Barka aquifer (Sovita *et al.*, 1990). The method yielded a numerical index that was derived from ratings and weights associated with the seven parameters. The significant media types or classes of each parameter represent the ranges, which were rated from 1 to 10 based on their relative effect on the aquifer vulnerability. The seven parameters were then assigned weights ranging from 1 to 5 to reflect their relative importance. The SINTACS Index was computed by applying a linear combination of all factors according to the following equation:

$$I_v = \sum P_{(1,7)} \times W_{(1,n)}$$

This model was selected based on the following considerations. SINTACS uses a relatively large number of parameters (seven parameters) to compute the vulnerability index, which ensures the best representation of the hydrogeological setting. The numerical ratings and weights, which were established using the Delphi technique (Aller *et al.*, 1987), are well defined and are used worldwide. This makes the model suitable for producing comparable vulnerability maps on a regional scale. The necessary information needed to build up the several model parameters was available in the study area or could easily be inferred. Data analyses and model implementation were performed using the GIS software of the International Institute for Geo-Information Science and Earth Observation (ITC), Netherlands, bIntegrated Land and Water Information SystemQ (ILWIS 3.1).

The acronym SINTACS stands for the seven parameters used in the model which are: Soggiacenza as Depth to Water, Infiltrazione as Net Recharge, Non Saturo as Impact of the Vadose Zone, TipologiaCopertura as Soil Media, Caratteristiche Acquifero as Aquifer Media ,

Conducibilita Idraulica as Hydraulic Conductivity and Acclivita Superficie Topografica as Slope (Table 1). The model yields a numerical index that is derived from ratings and weights assigned to the seven model parameters. The significant media types or classes of each parameter represent the ranges, which are rated from 1 to 10 based on their relative effect on the aquifer vulnerability. The seven parameters are then assigned weights ranging from 1 to 5 reflecting their relative importance. The SINTACS Index is then computed applying a linear combination of all factors according to the following equation:

The aquifer sensitivity and groundwater vulnerability mapping procedures carried out in this study incorporated the use of a Geographic Information System (GIS). A GIS is a computerized mapping and spatial data analysis system, which enables the manipulation and analysis of spatially referenced information to describe the relationship between landscape features.

Though not originally designed as a GIS-based tool, the SINTACS model lends itself to such an implementation (Merchant, 1994). GIS applications of the DRASTIC model (Trent, 1993) and its variations (Lusch *et al.*, 1992) have been widely documented in the literature.

Also in this study the GIS was used in a number of procedures, including: (i) converting hard copy map information into a digital format, (ii) creating a map of groundwater depth from well log, water depth records and well location information, (iii) creating a map of the saturated hydraulic conductivity from well log pumping data and well location information, (iv) assigning sensitivity rating values to mapped attribute values, and (v) combining or overlaying individual characteristic maps to create the final cumulative vulnerability maps.

Table 1: The drastic model parameters (modified from Babiker *et al.*)

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

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Development of the SINTACS Vulnerability Index
The SINTACS index was calculated in the GIS environment to map the groundwater vulnerability of the study area and eqn (1) was used to produce the SINTACS index. Several types of data were used to construct thematic layers of the seven model parameters.

Soggiacenza as Depth to Water
Data from 12 water wells in 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 tree-year period (2009-2012). Generally, the depth to water in the center part of study area is high (>30 m), and gradually decrease to boundaries. Even in the southwest of the study area depth to water table decreases to less than 2 meters. The depth to water layer was classified from 2 (least effect on vulnerability) to 10 (most effect on vulnerability) with regard to SINTACS classification (figure 2a and table 3).

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

Recharge Index = Slope (%)+Rainfall+Soil permeability (2)

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) (Figure 2b) surround the moderate zone.

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

Non Saturo as Impact of the Vadose Zone
Based on the 32 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 exhibit 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 (Figure 2c and table 3).

Tipologia Copertura as Soil Media
Soil map of the study area (1/50000) that had been prepared by Environmental Source Office of Boshehr 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 soft ware. 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 Figure 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 is 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 32 piezometers (figure 2f). According to this layer deposits of unsaturated zone in the north and northeast of the study area is highly discontinuous and have many interbedded of sand and clay. Existence of clay interbeds has high impact on decreasing of vulnerability. Conversely the unsaturated zone in the most part of south and southwest part of the study area has formed from continuous sandy deposits.

Conducibilita Idraulica as Hydraulic Conductivity

Pumping test data of 140 deep wells in the study area were used for preparation of this layer. Transmissivity values were calculated for all wells by using Mace method (Lusch *et al.*, 1992). Then with regard to the thickness of saturated zone, hydraulic conductivity was calculated for all wells and according to DRASTIC model classification, rating values were obtained for the total of the study area. Figure 2g shows that the most part of the study area has hydraulic conductivity value between 4-12 (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.

Table 3: The drastic index for the study area

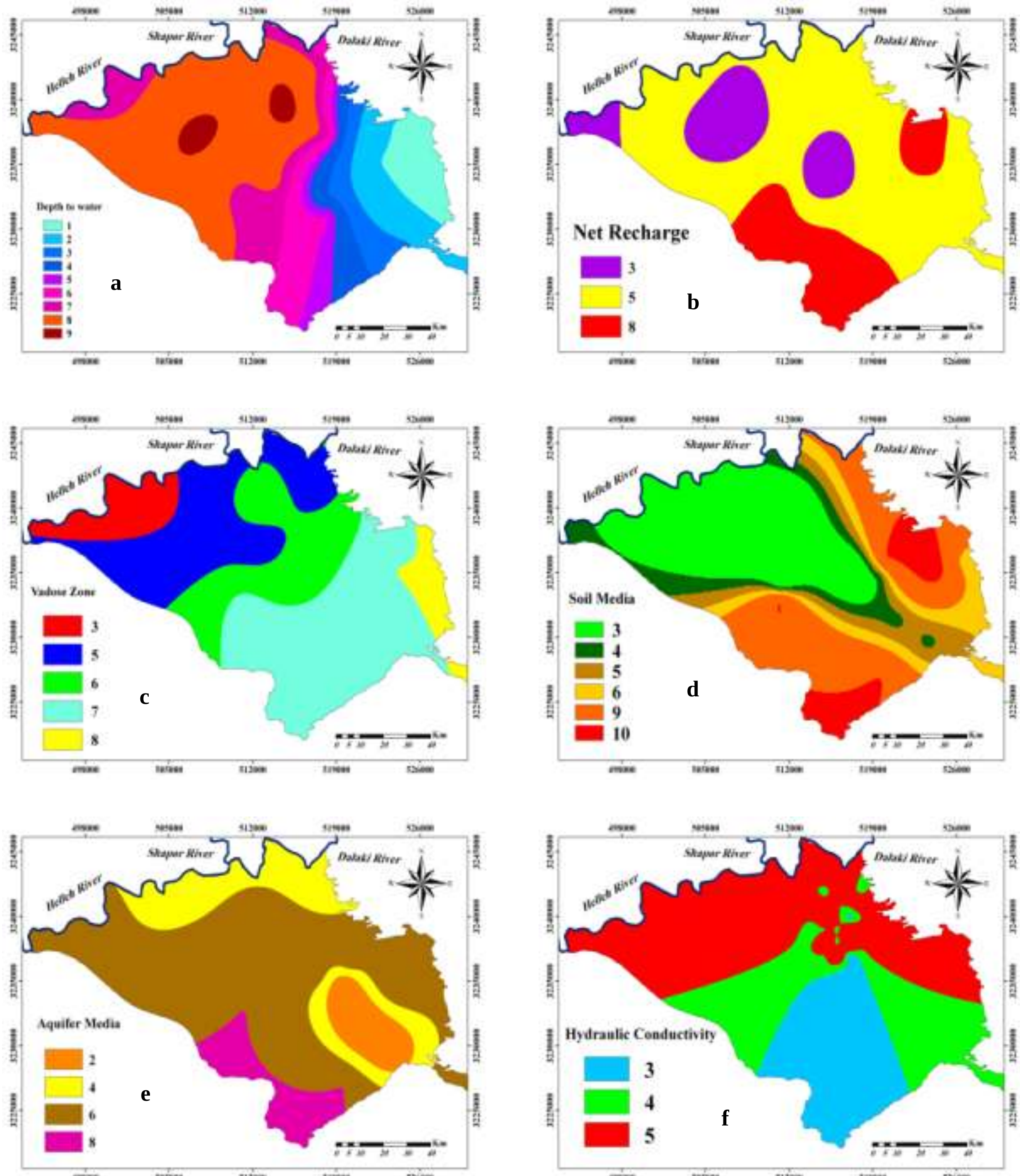
Parameter	Rating	Parameter	Rating
Soggiacenza as Depth to Water (m)		Caratteristiche **A**cquifero as Aquifer Media	
10-7	6	sand dunes	9
13-10	5	loamy sand to sandy loam	6
20-13	4	silty-clayey loam to clay loam	3
56<	1	**C**onducibilita Idraulica as Hydraulic Conductivity(m/day)	
Infiltrazione as Net Recharge (mm/year)		28-40	6
175-250	8	12-28	4
100-175	5	4-12	2
50-100	3	<4	1
sand and gravel	9	Acclivita Superficie Topografica as Slope	
sand with some clay/silt	7	0-2	10
clay and silt with some sand/gravel	5	2-6	9
clay and silt	2	6-12	5
Tipologia Copertura as Soil Media		12-18	3
silty sand	7	>18	1
clayey sand	6		
clay with high sand	5		
clay with low sand	4		
clay and silt	3		
confined aquifer or compact clay	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 (Figure 2e). Figure 2e shows that the slope value in the most part of the study area is less than 2% (rating value=10) and only small part between 2-6 % (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 Arc View GIS according to the pixel value of each area that resulted from multiplying the ratings with its appropriate SINTACS weight (Table 3).



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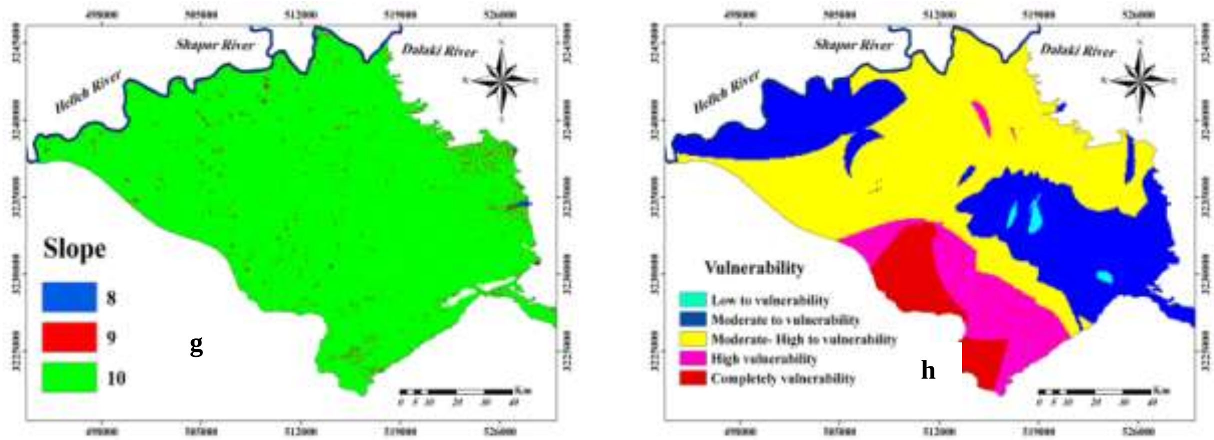

Figure 2: Maps related to SINTACS model parameters and vulnerability map in the study area

Since the minimum possible SINTACS index for using these parameters is 63 and the maximum is 180, this range was divided into four classes. These classes were (Al-Adamat *et al.*, 2003):
(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) and (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: (i) 97-110, which was assigned a low vulnerability, (ii) 111–126, which was assigned a moderate vulnerability (iii) 126–141, which was assigned a moderate until high vulnerability,(iv) 141-156, which was assigned a high vulnerability, and (v)156- 171 which was assigned a Completely vulnerability as shown in Table 4 and Figure 2h. 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 until high vulnerability groundwater, 9.2% of the study area has high vulnerability, vulnerability to contamination and the remainder of the study area (less than 8.5%) has a completely vulnerability.

Table 4: The SINTACS index for the study area

SINTACS Index	SINTACS Range	Area (Km^2)	% of the total area
Low to vulnerability	97-111	52	12.4
Moderate to vulnerability	111-126	129.9	31
Moderate- High to vulnerability	126-141	162.6	38.9
High vulnerability	141-156	38.3	9.2
Completely vulnerability	156-171	35.6	8.5
	Total	418. 4	100

The SINTACS aquifer vulnerability map clearly shows the dominance of “low” vulnerability classes in the most part of the study area, particularly in the center, east and northeast of the study area. The western and southwestern parts are characterized by “Moderate” vulnerability (Figure 2h). 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 is less than impact of vadose zone media. Small parts at northwest and southeast part of the study area display “no risk to pollution”. This is due to the combination of deep water table, low permeability of vadose and aquifer media.

SINTACS Model Validation

12 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, therefore the nitrate anion was analyzed. Chemical analysis 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 showed in figure 3. According to figure 3 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 until high vulnerability; therefore the results of vulnerability assessment using SINTACS model are confirmed.

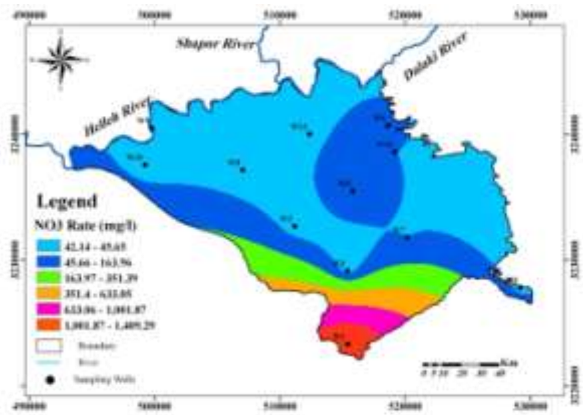

Figure 3: Wells location and nitrate rate in groundwater at the study area

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 5. 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.

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 to 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 reach to 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 to 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.

Table 5: Correlation coefficient between nitrate layer and water table layer

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

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). Seven environmental parameters were used to represent the natural hydrogeological setting of the Borazjan aquifer; Soggiacenza as Depth to Water, Infiltrazione as Net Recharge, Non Saturo as Impact of the Vadose Zone, TipologiaCopertura as Soil Media, Caratteristiche Acquifero as Aquifer Media, Conducibilita Idraulica as Hydraulic Conductivity and Acclivita Superficie Topografica as Slope. The

SINTACS aquifer vulnerability map indicated that the south part of the study area is dominated by "completely" vulnerability classes while the north and eastern parts were characterized by "low" vulnerability classes. Small parts at northwestern and southeastern part of the study area display "moderate and low to contamination". This is due to the combination of deep water table, less-porous ness of vadose and aquifer media.

Results of chemical analysis of water samples showed that nitrate concentration in the groundwater at south part of study area is more than nitrate concentration at north and northeast parts. These results confirm the vulnerability assessment. 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 respectively.

The GIS technique has provided an efficient environment for analyses and high capabilities in handling a large quantity of spatial data. The seven model parameters were constructed, classified and encoded employing various map and attribute GIS functions. The SINTACS vulnerability index, which is defined as a linear combination of factors, was easily computed in GIS environment.

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