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Evaluation of Aquifer Vulnerability by GIS Application: Case study from Asadabad, Hamadan (Western Iran)

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Study Area: Asadabad aquifer, Hamadan, Iran
Coordinates: 37° 07 to 37° 25 N; 48° 07 to 34° 47 E

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Abstract

DRASTIC model has been used to map groundwater vulnerability due to pollution in various areas. This method needs to be calibrated and reformed for a specific aquifer and pollution. The suggested methodology was applied to Asadabad aquifer located in western Iran. In the present research, the rates of DRASTIC parameters have been reformed so that the vulnerability potential to pollution can be determined more exactly. The new rates were calculated using the relationships between each parameter and the nitrate concentration in the groundwater. The measured nitrate concentration values were used to correlate the pollution potential in the aquifer to DRASTIC index. The results showed that the modified DRASTIC is better than the original method for the nonpoint source of pollutions in agricultural zones. Application of the new rates, a new DRASTIC map was expanded that shows that 2.1% of the area fall in high vulnerability class. The assessed area was 34.2% and 58.19% for moderate class and, for low vulnerability class, 63.7% and 31.39% respectively, before and after using the new rates.

Introduction:

The term vulnerability is used to explain the degree to which human or environmental systems are likely to get harm due to perturbation or stress, and can be known for a determined system, hazard, or group of hazards (Popescu *et al.*, 2008). In hydrogeology, vulnerability evaluation typically describes the effectiveness of a specific aquifer to contamination that could decrease the Groundwater quality. The idea was first of all imposed in France by the end of the 1960s to create awareness about groundwater contamination (Vrba & Zaporozec, 1994).

No single standardized description for Groundwater vulnerability exists; although, the concept describes the relative ease with which the Groundwater resource could be contaminated. The National Research Council (1993) determined it as the tendency or likelihood for contaminants to reach a specified position in the Groundwater system after introduction at some location above the uppermost aquifer. Two idioms are used to describe Groundwater vulnerability: essential and specific. The essential vulnerability is the natural susceptibility to contamination based on the physical characteristics of the environment while specific

vulnerability is determined as an accounting for the transport properties of a particular contaminant or group of contaminants through the subsurface (Jessica & Sonia, 2009). The assessment of vulnerability gathering complex, the hydrogeological data must be handled in such a way so that it can be used by a non-specialist people such as decision-makers. Vulnerability evaluation of Groundwater aquifer provides a basis for initial protective measurement for important groundwater resources and would normally be the first step in a groundwater pollution hazard assessment and quality when its interest (Foster, 1987).

Many approaches have been expanded for assessing groundwater vulnerability and could be grouped into three major categories (Tesoriero *et al.*, 1998): a. overlay and index methods; b. methods using process-based simulation models; c. statistical methods. In overlay and index methods, factors which are controlling the movement of pollutants from the ground surface into the saturate zone (e.g., geology, soil, impact of vadose zone, etc.) are mapped depending on existing and/or derived data. Subjective numerical values (rating) are then assigned to each factor based on its importance on

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controlling pollutants circulation. The rate maps are linear to produce final vulnerability map of a region. The groundwater vulnerability assessment by such methods is qualitative and relative. The main benefit of such methods is that some of the factors controlling the movement of pollutants can be assessment over the large area, which makes them appropriate for regional scale evaluation (Thapinta & Hudak, 2003). Fortunately, with the development of GIS digital technology, adoption of such methods for creating vulnerability maps is an easy task. Several overlay and index methods have been expanded. The most common one are: the DRASTIC system (Aller *et al.*, 1987), the GOD system (Foster, 1987), the AVI rating system (Stempvoort *et al.*, 1993), the SINTACS method (Civita, 1994), the German method (Von Hoyer & Sofner, 1998), the EPIK (Doerflinger *et al.*, 1999), and the Irish perspective (Daly *et al.*, 2002). Process-based method and statistical methods are not generally used for vulnerability evaluation because they are constrained by data shortage, computational hardness, and experience required for implementing them.

The DRASTIC system is the widest method used in the assessment of the intrinsic vulnerability for a wide range of potential contaminants. It is an overlay and index model deliberate to product vulnerability scores by combining several thematic maps. It was originally developed in the USA under a cooperative agreement between the National Water Well Association (NWWA) and the US Environmental Protection Agency (EPA) for detail hydrogeology assessment of pollution potential (Rundquist *et al.*, 1991). The word DRASTIC is an acronym for most main factors within the hydrogeological settings which control groundwater pollution. The hydrogeological setting is a compound description of all major hydrogeological and geologic factors which affect the groundwater movement into through, and out of the area. These factors are depth to water, aquifer media, net recharge, topography (slope), soil media, hydraulic conductivity and impact of the vadose zone. The DRASTIC numeric ranking system contains three major parts: ratings, weights, and ranges. Groundwater vulnerability was appraised using hydrogeological factor that can influence the pollutant transport by the vadose zone to the water bearing strata using GIS-based DRASTIC method (Aller *et al.*, 1987). The flowchart shows the general overview of the research methodology. Figure-1 shows methodology flowcharts for groundwater vulnerability analysis using DRASTIC model in GIS.

Weights in each DRASTIC factor is appraised with respect to each other to determine the relative importance of each factor. Table-1 shows each factor is specified a relative weight range of 1–5 (1). The most substantial factor is allocated five; the least substantial is assign one. DRASTIC has two weight classifications, one for normal

conditions (standard) and the other for conditions with intense agricultural activity. The last is called pesticide DRASTIC index and represent a special case of DRASTIC index. The difference between the two versions of DRASTIC is in the assignment of relative weights for the seven DRASTIC factors. All the other parts of the two indices are identical. The application of the pesticides when mixed with sensitive groundwater, it can impose a substantial impact on the water quality. Agricultural contaminants i.e., when pesticides get dissolve in the irrigated water and permeate through the soil profile.

Despite its amicability, the DRASTIC method does have some disadvantages. This method uses seven parameters in its calculation of “Vulnerability Index” with each parameter being specified a special weight and rating value as shown in Table 2 (Aller *et al.*, 1987). The influence of zonal characteristics is not calculated for in the method and so the same weights and rating values are used all over. In addition, there is no standard algorithm to test and validate the method for an aquifer. Some researchers have tried to correlate the vulnerability index with contaminant or chemical parameters (Kalinski *et al.*, 1994; Rupert, 1999; Maclay *et al.*, 2001). Some other researchers have correlated land use to vulnerability (Secunda, 1998; Worrall & Koplin, 2004), but, they did not use it to right or weights of the DRASTIC model.

The final vulnerability index is a weighted sum of the seven factors and can be calculated using the following formula:

$$VI = DrDw + RrRw + ArAw + SrSw + TrTw + Irlw + CrCw. \text{ ---(1)}$$

Where D, R, A, S, T, I and C are the seven factors of the DRASTIC method, (w) the weight of the factor, and (r) the rating associated. Values of DRASTIC index very from 26 to 256 in the case of the DRASTIC pesticides and from 23 to 226 in the case of the DRASTIC standard version. Aller *et al.* (1987) did not suggest any classification for their DRASTIC results, thus the vulnerability ranges of the DRASTIC index used in this study generally to the most commonly used reference in the literature. Table-3 shows criteria of the evaluation of the degrees of vulnerability (Civita & De Regibus, 1995; Corniello *et al.*, 1997).

The objective of this study is to evaluate the intrinsic vulnerability of the principal aquifer in Asadabad city, Iran for both general and pesticides contaminants using the most popular DRASTIC overlay and index method. Vulnerability assessments are a key component of the integrated management of water resources. These assessments can help to guide the decision making about future development and the options available to protect and monitor the groundwater resource. In linking water planning and land use planning together, decision makers can consider a set of scenarios and select a path that is most in line with the desired future of their community.

Materials and methods:

Based on the collected data and required information, a database in the GIS environment was prepared for calculation of final vulnerability index in the methods. The main hydro-geologic factors affecting the transmission of pollution, including depth to water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone, aquifer hydraulic conductivity, and land use parameters were rated, weighted, and integrated using GIS 9.3. Finally, the maps of Asadabad plain's unconfined aquifer vulnerability were prepared. In order to calibrate the DRASTIC model, the concentration was chosen as the primary contamination parameter. Twenty agricultural wells were chosen for sampling and analysis. Two sets of samples in June and September of 2014 were taken. Figure- 2 shows the location of the samples in the study area. The precise position of each well was determined using Global Positioning System techniques. The Asadabad aquifer with an area of 962 square kilometers is situated in western Iran (Fig.-2) in Asadabad basin. In the region under study, almost 1.5 percent of the irrigation water that is about 4 million cubic meters (MCM) infiltrates into the groundwater per year. In addition part of the municipal wastewater i.e. about 4 MCM, from the cities of Chardoli, and Asadabad, percolates into the groundwater annually (Anonymous, 2014). These factors have resulted in the groundwater in some parts of the aquifer being polluted, making it necessary to have an precise plan to prevent more damage to the groundwater resources (Anonymous, 2014). In the present study, rates of DRASTIC parameters were calibrated for the specific area. Using nitrate measurements in the groundwater, statistical analysis was applied to correlate nitrate concentration with vulnerability index and calibrate parameters rates.

Figure-1: Methodology flowcharts for groundwater vulnerability analysis using DARSTIC model in GIS.

Figure-2: Location map of the study area in Asadabad basin

Asadabad aquifer located in the west of Iran selected as a case study to show the applicability of the proposed method. The chosen study region is mostly included of agricultural lands and the use of fertilizers and pesticides are common in practices.

For the purposes of this investigation, nitrate was chosen as the primary (contaminant) control parameter used to modify the DRASTIC rates. Nitrate is not generally present in groundwater under natural conditions, it usually permeates from the surface layer. It can, so, be used as an indicator to show whether the vulnerability index correctly represents the actual situation in the study region. To use nitrate for optimizing the weights, indicate that the following conditions should be satisfied (Panagopoulos *et al.*, 2006). The source of nitrate must be due to agricultural activities at the surface. The area distribution must be relatively uniform leaching of nitrate must be due to recharges from the surface over a long period of time to ensure the correlation between human and contamination activities the combination of a relatively shallow depth of groundwater i.e. high water table elevation in the study area with agriculture being the main activity satisfies the necessary condition to use nitrate as a calibration parameter. Nitrate concentrations measured in June 2014 were used to calibrate the index and measurements in September 2014 were used to compute the correlation factor. The nitrate concentrations were divided into 5 classes and the mean of every class was used to compute the modified rate of each DRASTIC parameter based on the Wilcoxon rank-sum nonparametric statistical test (SAS Institute Inc., 1999).

Results and Discussion:

The DRASTIC index is generally built into Geographic Information Systems (GIS)-based maps to facilitate planning and management of groundwater protection, where each hydrogeological setting is a mappable unit with common hydrogeological factors. This practice, aimed to indicate areas at low, moderate or high risk of groundwater contamination, was applied in Japan,

Jordan, and New Zealand. The DRASTIC method has been criticized in the past due to its subjectivity as well as the lack of some important hydrogeological characteristics and specific properties of contaminants. For example, Dixon (2004) indicated that groundwater contamination potential maps were more consistent with field data when soil structure was taken into consideration in a study conducted in Woodruff County in the Mississippi Delta region of Arkansas. Sandersen & Jorgensen (2003) explained that, even when aquifers are deep-seated and appear to be well protected, preferential flow paths for downward transport of contaminated water from shallow aquifers may occur. Melloul & Collin (1998) suggested that both vertical and lateral flow play an important role in groundwater contamination.

Worrall & Kolpin (2004) found that interaction between site and chemical factors represents the most important process in the occurrence of pesticides in groundwater, based on multi-annual monitoring datasets from the United Kingdom and Mid-Western United States. They indicated that the best-fit model to predict the occurrence of herbicides in groundwater of the Mid-West United States combined organic carbon content, percentage sand content and depth to the water table with molecular descriptors representing molecular size, molecular branching and functional group composition of the herbicides.

The attribute layers for the seven DRASTIC parameters were assembled within a Geographic Information System format, the commercially available ArcGIS 9.3 software being used to perform the necessary calculations in raster format. The depths to water table were measured at 30 observation wells in June 2014. Figure-2 also showing the location of the sampled wells. Using the measurements at these points, the two-dimensional variation in water table elevation was constructed. The geostatistical analyst extension with Kriging interpolation algorithm in ArcGIS was used to interpolate the points and create the raster map with a pixel size of 100 m. Kriging has shown a great success for incorporation in groundwater studies (Gundogdu & Guney, 2007; Kumar, 2007; Theodossiou, 1999).

Figure-3 shows depth to water table in Asadabad aquifer. Using the created maps and based on the rating system recommended in the original DRASTIC model, the depths were divided into different classes. Net recharge in the study area is the result of rainfall influence, river flow, irrigation return flow and absorption wells. Based on a water balance calculation, the net recharge for the study area was noted a 272 MCM per year. Table 4 shows the water balance in the study area compute by Hamadan Water Authorities (Anonymous, 2014). Dispensation of hydraulic conductivity in the study area was used to compute the spatial distribution of the net recharge.

Figure-3: Depth to water table in Asadabad aquifer

Figure-4: Original vulnerability maps and nitrates concentration for study area

Figure-5: Modified (factor rating) vulnerability maps and nitrates concentrations

Hydraulic conductivity distribution map was developed using the pumping test results and geo-electrical study in the area. Areas with a higher hydraulic conductivity have the higher potential for influence. Three other layers, namely, the soil the vadose zone and the aquifer-media were classified based on the drilling logs for each well and Table 3. 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 meters was created.

Transmissivity was measured in the pumping wells and, based on these measurements, hydraulic conductivity was computed. Geostatistical algorithms were used to interpolate the hydraulic conductivity and create the raster layer. After creating all the necessary layers, each pixel was classified and rated, then, reproduced by its weighting factor and the DRASTIC index calculated. The resulted index was divided into 5 equal groups (Aller *et al.*, 1987). Small numbers indicate low vulnerability potential and large numbers are related to those regions that have high pollution potential. Figure-4 shows original vulnerability maps and nitrates concentration for the study area.

Table 1. Weights of the factors in the DARSTIC (Standard and Pesticides) (after Aller et al., 1987).

Factor	Description	DRASTIC version	
		RW (St.)	Pesti.
Depth to water	D ■ Show the depth from the ground surface to the water table; deeper water table levels imply lesser chance for contamination to occur.	5	5
Net Recharge	R ■ Show the amount of water which penetrates the ground surface and reaches the water table, recharge water represents the vehicle for transporting pollutants.	4	4
Aquifer media	A ■ Refers to the saturated zone material properties, which controls the pollutant attenuation processes.	3	3
Soil media	S ■ Show the uppermost weathered portion of the unsaturated zone and control the amount of recharge that can infiltrate downward.	2	5
Topography	T ■ Mention 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	3
Impact of vadose zone	I ■ Is specific as the unsaturated zone material, it controls the passage and attenuation of the contaminated material to the saturated zone.	5	4
Hydraulic Conductivity	C ■ Presentation the ability of the aquifer to transmit water, hence determines the rate of flow of contaminant material within the groundwater system.	3	2

RW (St.)- Relative Weight (Standard); Pesti.- Pesticide

Table 2. The original DRASTIC rating and weights systems (Aller et al., 1987).

(a)							
Depth to Water (m)	Recharge (mm)	Topography (m/D)	Conductivity (Slope %)				
Range	R*	Range	R*	Range	R*	Range	R*
0-1.5	10	0-50.8	1	0-2	10	0.04-4.1	1
1.5-4.6	9	50.8-101.6	3	2-6	9	4.1-12.3	2
4.6-9.1	7	101.6-177.8	6	6-12	5	12.3-28.7	4
9.1-15.2	5	177.8-254	8	12-18	3	28.7-41	6
15.2-22.8	3					41-82	8
22.8-30.4	2	>254	9	>18	1	>82	10
>30.4	1						

DRASTIC Weight: 5 DRASTIC Weight: 4 DRASTIC Weight: 1 DRASTIC Weight: 3
Pesticide Weight: 5 Pesticide Weight: 4 Pesticide Weight: 3 Pesticide Weight: 2
R*- Rating

(b)					
Aquifer Media	Vadose Zone Material		Soil Media		
Range	R*	Range	R*	Range	R*
Massive Shale	2	Confining Layer	1	Thin or Absent	10
Metamorphic/Igneous	3	Silt/Clay	3	Gravel	10
Weathered Metamorphic Igneous	4	Shale	3	Sand	9
Glacial Till	5	Limestone	3	Peat	8
Bedded Sandstone, Limestone	6	Sandstone	6	Shrinking Clay	7
Massive Sandstone	6	Bedded Limestone, Sandstone	6	Sandy Loam	6
Massive Limestone	8	Sand and Gravel, W. Silt	6	Loam	5
Sand and Gravel	8	Sand and Gravel	8	Silty Loam	4
Basalt	9	Basalt	9	Clay Loam	3
Karst Limestone	10	Karst Limestone	10	Muck	2
				No shrinking Clay	1

DRASTIC Weight: 3 DRASTIC Weight: 5 DRASTIC Weight: 2
Pesticide Weight: 3 Pesticide Weight: 3 Pesticide Weight: 5
R*- Rating

Table 3. Criteria of the evaluation of the degrees of vulnerability (Civita and De Regibus, 1995; Corniello et al., 1997).

Degree of vulnerability	DRASTIC index
< 80	Very low
80-120	Low
120-160	Moderate
160-200	High
> 200	Very high

Table 4. Groundwater balance of Asadabad aquifer in 2014.

Inflow	Value (MCM/year)	Outflow	Value (MCN/year)
Recharge from river	69	Drainage from groundwater	257
Recharge from rainfall	58	Discharge from wells	8
Underground inflow	43	Underground outflow	3
Return flow from domestic Wastewater	4	Evaporation from groundwater	4
Return flow from agriculture well	98		
Total	272	Total	272

Table 5. Correlation factors between nitrate concentration and original vulnerability index.

Pearson's Corr. Coef.	Number of Data	Factor
100%	20	Nitrate Concentration
63%	20	DRASTIC index

Table 6. The original and modified weighting rates based on nitrate concentration for the various hydrogeological parameter settings (Al-Zabet, 2002 and Aller et al., 1987).

(I)				
Factor	Range	Original rating	Mean NO ₃ (mg/l)	Modified rating
Depth to ground water (m)	0-1.5	10	5.31	10
	1.5-4.75	9	1.51	2.3
	4.75-9.14	7	2.19	5
	9.14-15.24	5	1.87	6.1
	15.24-22.86	3	2.03	2.9
	22.86-30.48	2	2	1.4
	>30.48	1	1.65	1.1

(II)

Factor	Range	Original rating	Mean NO ₃ (mg/l-1) concentration	Modified rating
Hydraulic conductivity (m/day)	0.4 4.1 4.1 12.3 12.3 28.7 28.7 - 41	1 2 4 6	1.7 3.2 4.21 4.9	1.23 3.5 6.3 6

(III)

Factor	Range	Original rating	Mean NO ₃ (mg/l-1) concentration	Modified rating
Recharge (mm)	0 58.8 50.8 101.6 101.6 177.8 177.8 254 >254	1 3 6 8 9	2 2.81 3.2 3.51 4.7	3.1 2.5 6.5 8.1 9

(IV)

Factor	Range	Original rating	Mean NO ₃ (mg/l-1) concentration	Modified rating
Soil type	Clay loam Silty loam loam Sandy loam Shrinking Peat	3 4 5 6 7 8	2.9 5 3.1 2.8 2.2 9.41	3 4.3 5.2 5.4 3.1 10

(V)

Factor	Range	Original rating	Mean NO ₃ (mg/l-1) concentration	Modified rating
Impact of vadose zone	Silt/clay Silty sand clay Sandstone Sand & gravel w. silt coarse	3 4 5 6 8	4 6.1 3.2 3.9 9.3	3.1 4.9 2.8 4.1 8

Table 7. Correlation factors between nitrate concentration and modified vulnerability index.

Pearson's corr. coeff.	Number of data	Factor
100%	20	Nitrate index
70%	20	DRASTIC index

Conclusion:

The presented method would be useful for regional scale evaluation though it suffers from few flaws. The results represent that there is a major need to manage groundwater resources in a sustainable way to avoid overexploitation and contamination of groundwater. Also, allowing sufficient recharge to prevent draft exceeding the recharge. This study highlighted areas of high vulnerability and medium vulnerability; where special measures should be taken to improve the condition of the groundwater resources. The sites for artificial rainwater harvesting to restore the discharged resource must be encouraged. In addition, the sites where contamination can cause unrepairable damages, that can be prevented. The highlighted areas must be monitored

extensively for further analysis. The purpose of this research was to assess the vulnerability potential of the Asadabad aquifer using the original and modified DRASTIC index. However the DRASTIC method usually gives satisfactory results in the assessment of groundwater intrinsic vulnerability to pollution, it cannot be used for accurate assessment of the groundwater pollution risk. Hence, it is necessary to calibrate and modify the original algorithm in order to obtain more precise results. Results of this study represent that nitrate concentration could be used as a modifying parameter with substantial improvement in the resulting index that could lead to more realistic management of groundwater quality. The proposed method could be suggested for the agricultural areas where the extensive use of nitrates is common, where an accumulation of nitrates in the groundwater is a routine phenomenon due to its leaching from the soil surface layers.

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