Improvement in GIS-based DRASTIC Model Using Statistical Methods and Analytical Hierarchy Process (AHP)

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ABSTRACT

The assessment of groundwater vulnerability to nitrate pollution has been done through modifying weights of DRASTIC parameters using simple statistical methods in Hamedan-Bahar plain, west of Iran. The weights of parameters assigned based on Analytical Hierarchy Process (AHP) under a Geographical Information System (GIS) environment. In addition to usual rating of DRASTIC method, this study has also proposed a fuzzy method for scaling criterion maps as well as their preparations for integration. Spearman's rho coefficient and Kendall's tau coefficient have been employed in order to determine suitable weights in DRASTIC model. It was distinguished that soil media, aquifer media and depth to groundwater with the weights of 5, 4, and 3.5, respectively, indicate highest correlation with the nitrate concentrations. Thus the new equation has been named as DAS which substituted with DRASTIC for assessment of groundwater vulnerability in Hamedan-Bahar plain. On the basis of the weights resulted from AHP method, both the deterministic and fuzzy layers of DRASTIC are integrated with each other, separately. After determining the correlation coefficients in different models, it was found that the DAS model with deterministic rating layers has the highest correlation (0.70) of nitrate concentrations. For preparing pollution risk map, land use was considered as an additional parameter. The correlation coefficient between nitrate concentrations and the pollution risk map reached to 0.78. The risk map shows that 5% of study area is completely risky while 10%, 29.95%, 26%, 21.3%, 9%, and 7% of it has very high, high, high to moderate, moderate to low, low, and the least pollution risk, respectively. Only 0.75% of study area is without any pollution risk.

INTRODUCTION

The groundwater vulnerability is the possibility of percolation and diffusion of contaminants from the ground surface into the groundwater system (Vrba and Zoporozec, 1994). Vulnerability is also a function of pollutant type. Pollution type dependent vulnerability, or vulnerability to specific land uses, is sometimes referred to as "specific vulnerability" or "integrated vulnerability". The simplest to apply, and for that reason the most widely used, is DRASTIC method. This method is the most widespread PCSM method of evaluation of the intrinsic vulnerability (Aller et al.1987), that taking into account seven parameters of the geological and hydrological environment, was developed in the USA where it has been applied several times (Fritch et al. 2000; Shukla et al. 2000), but also in many other regions of the world (Johansson et al. 1999; Kim and Hamm, 1999; Zabet, 2002). The seven elements that are combined in the model are Depth to Water (D), Net Recharge (R), Aquifer Media (A), Soil Media (S), Topography (T), Impact of the Vadose Zone (I), and Hydraulic Conductivity (C). These parameters are imported in a simple linear equation after they have been reduced from the physical range scale to a ten-grade relative scale. Each parameter is multiplied by a weighting coefficient which has been determined with qualitative, not with quantitative criteria, based on the judgment of the authors of this method. The reduction of the physical range scale to the relative ten-grade scale is conducted with the same philosophy. The major drawback of this method is the subjectivity of the determination of the rating scale and the weighting coefficients. The selection of many parameters and their interrelationship decrease the probability of ignoring some important parameters, restrict the effect of an incidental error in the calculation of a parameter and so enhance the statistical accuracy of the model (Rosen, 1994). Improvements of the DRASTIC model have been proposed by several researchers. Most of them propose the subtraction of factors included in the model (Evans and Myers, 1990; Rupert, 2001) or the inclusion of additional factors like land use or irrigation type and intensity (Secunda et al. 1998; Rupert, 1999; McLay et al. 2001).

Fuzzy rule-based techniques are particularly useful when modeling fuzzy inputs common to hydrogeologic parameters because they tolerate imprecision and uncertainty (Burrough & McDonnell, 1998; Burrough et al.1992; Sui, 1992; Wang et al.1990). In fact, there exists a transition from the easiest to be polluted to the most difficult to be polluted so that vulnerability of groundwater is of a fuzzy nature and therefore fuzzy sets theory can be used to assess the vulnerability of groundwater (Chen, 1994).

Analytical Hierarchy Process (AHP) was developed by Saaty (Saaty, 1980), in which the hierarchy of components of the decisions was used in Multi-Criteria Decision Making. The AHP is based upon the construction of a series of pair- wise comparison matrices which compares all the criteria to one another. This is done to estimate a weighting of each of the criteria that describes the importance of each of these criteria in contributing to the overall objective.

Residential, municipal, commercial, industrial, and agricultural activities could be all affect groundwater quality. High levels of nitrate in the groundwater originating mainly from agriculture activities are encountered in the Hamedan-Bahar plain. To ensure that this aquifer can remain as a source of water for the Hamedan-Bahar plain, it is necessary to estimate whether certain locations in this aquifer are more susceptible to receive and transmit pollution. The main objective of this study is to evaluate the aquifer vulnerability to nitrate pollution using DRASTIC method. An optimization of the DRASTIC method was attempted based on the revision of the factor weights via the use of statistical methods and the weighting based on analytical hierarchy process (AHP). The final goal is the development of an integrated method which could successfully predict the specific vulnerability or the pollution risk of the Hamedan-Bahar aquifer under intense environmental stress.

STUDY AREA

Study area is located in the northern part of Hamedan city, west of Iran. The Hamedan-Bahar alluvial aquifer is approximately 520 km^2 in area (Fig. 1). Groundwater is the main source of drinking water, industrial plants, and agricultural irrigation in study area. The area is strongly vulnerable to pollution due to the presence of intensive agricultural activities.

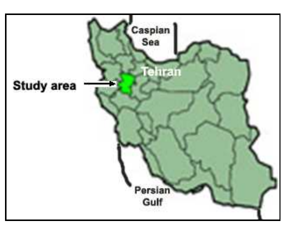

Figure 1. Location map of study area

The main rock types in the Hamedan-Bahar area are sedimentary, igneous, and metamorphic rocks. The oldest deposits are containing slate and schist of Jurassic age that outcrop in the eastern and southern parts of the basin. The Cretaceous deposits consist of the carbonate series. The main portion of the study area is covered by Quaternary sediments and consists mainly of recent alluvium and conglomerate. Hamedan-Bahar alluvial aquifer consist mainly of gravel, sand, silt and clay. The thickness of alluvial aquifer ranges from 25 m in the border to more than 75 m in the middle parts of the plain. The recharge aquifer from precipitation is ranges from 5 to higher than 90 mm/year. The transmissivity of the aquifer ranges from 100 to 2000 m^2/day.

MATERIAL and METHODS

In this study DRASTIC model was used to evaluate the intrinsic vulnerability of the Hamedan-Bahar aquifer in a GIS environment. Several types of data were used to construct thematic layers of the seven model parameters. The depth to water table was obtained by subtracting the water table level from the elevation. The net recharge map was constructed from the multiplying storativity by the water table changes in the wet season. The piezometer and exploitation well logs have been encode to the geological units according to the DRASTIC model rating system for prepare Aquifer media and Impact of vadose zone layers. The topography layer (slope map) was extracted from the DEM. The hydraulic conductivity map was obtained based on the transmissivity and aquifer thickness data. Afterwards kriging interpolation technique was used to generating surface representation of the seven layers. The thematic maps was then classified into ranges defined by the DRASTIC model and assigned rates ranging from 1 (minimum impact on vulnerability) to 10 (maximum impact on vulnerability). In addition to usual ratings of DRASTIC method, this study has also used a fuzzy method for scaling criterion maps as well as their preparations for integration. The fuzzy layers have been calculated by linear membership functions. Membership degree of 1 represents that the section is mostly vulnerable to pollution, while membership degree of 0 is least.

An optimization of the DRASTIC method was attempted based on the revision of the factor weights via the use of statistical methods and the weighting based on analytical hierarchy process (AHP). The criterion for this optimization was the correlation coefficient of each parameter with the nitrate concentrations in groundwater. On the basis of their statistical significance, some parameters were subtracted from the DRASTIC equation, while land use was considered as an additional DRASTIC parameter.

AQUIFER VULNERABILITY ASSESSMENT

The methodology developed in this study for the evaluation of pollution risk attempts to utilize all of the aforementioned advantages, maintaining the basic structure of the DRASTIC model, while, at the same time, with various transformations and additions, aiming to improve it. The criterion for the effectiveness of these transformations is the value of the correlation coefficient of the "aquifer vulnerability" and "nitrates concentration" parameters. This correlation is expressed by the Pearson's (r) correlation factor (Pearson, 1896). The application of Pearson's (r) correlation factor presupposes a normal distribution of the nitrates concentration values, a condition which is not satisfied for the data of the research area. By a logarithmic transformation the nitrates concentrations can be normalized. In this study the nitrates concentration of 25 sampling wells were used. After normalizing the nitrates concentrations, the intrinsic vulnerability (Fig. 2) was computed according to DRASTIC equation. The Pearson's (r) correlation coefficient between vulnerability and nitrates concentration is 0.61. The weighting factors have been revised based statistical and AHP methods to improvements of the vulnerability indices and nitrate concentrations.

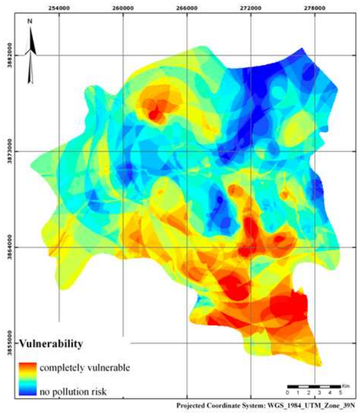

Figure 2. Aquifer vulnerability map of Hamedan- Bahar plain

Revision of the weighting factors

The revision of the weighting factors is achieved by the study of the correlation of each parameter with nitrate concentrations of the sampling points. Due to the fact that the factor scores vary with an interval scale, the correlation was calculated using the Spearman's rho (Spearman, 1904) and Kendall's tau correlation coefficients (Kendall, 1975), which are advisable for such type parameters. Based on these coefficients and after their values were reduced to a scale with a maximum value of 5, as defined by the DRASTIC model, the new weighting factors were calculated. In the case where one of the coefficients is not statistically significant, the corresponding parameter will be excluded from the equation of the vulnerability. Table.1 shows the correlation coefficients values and the revised weighting factors, where it becomes evident that the recharge net (R), Aquifer media (A), topography (T), Impact of vadose zone (I) and hydraulic conductivity (C) parameters are not statistically significant and should be excluded. It is also seen that the largest modified weighting factor is attributed to the soil media parameter (5), while the depth to groundwater is degraded.

Table.1. Original and modified weights of the DRASTIC parameters and correlation coefficients between DRASTIC parameters and nitrates concentration

Parameters of DRASTIC	Original weight	Spearman's rho coefficient	Kendall's tau coefficient	Modified factor weight
D	5	0.4	0.28	3.5
R	4	0.32	0.27	—
A	3	0.44	0.34	4
S	2	0.55	0.42	5
T	1	-0.07	-0.05	—
I	5	0.07	0.04	—
C	3	-0.15	-0.081	—

After the application of the revised weighting factors and the removal of the four non-correlated, intrinsic vulnerability can be formulated as follows:

$$\textbf{(1)} \qquad V(\text{intrinsic}) = 3.5 \cdot D + 4 \cdot A + 5 \cdot S$$

Where Vintrinsic is the intrinsic vulnerability, D is the depth to groundwater, A is the aquifer type and S is the soil media.

With the application of the above equation, the correlation between vulnerability and nitrates concentration values (using deterministic layers) is further increased, since the correlation coefficient is now $r = 0.70$. Once more using fuzzy layers the intrinsic vulnerability was computed according to Eq. 1 that is shown in Fig. 3. The correlation between vulnerability and nitrates concentration has been recalculated. The Pearson's (r) correlation coefficient is 0.65.

Weighting based on AHP

In this study AHP method has been used to derive weights of parameters in the DRASTIC model (Table 2). On the basis of the weights extracted from AHP method, both the deterministic and fuzzy layers of DRASTIC are integrated with each other, separately (Fig. 3). The correlation between vulnerability indices and nitrate concentrations using AHP with deterministic and fuzzy layers is 0.65 and 0.59, respectively. According to the correlation between vulnerability indices resulted from the four applied methods and nitrate concentrations, the DAS model with deterministic layers was selected as best model and it is used to estimate pollution risk of the aquifer.

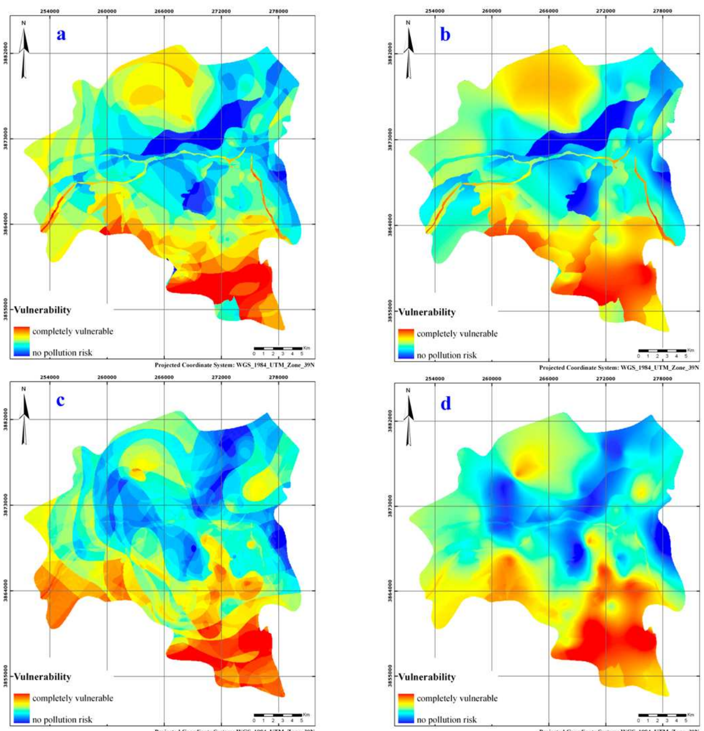

Figure 3. Aquifer vulnerability map of Hamedan- Bahar plain obtained by (a) DAS with deterministic layers, (b) DAS with fuzzy layers, (c) AHP with deterministic layers and (d) AHP with fuzzy layers

Table 2. Modified weights of DRASTIC parameters based on AHP

Parameters of DRASTIC	Weights based on AHP
D	0.3739
R	0.2445
A	0.1487
S	0.0664
T	0.0254
I	0.0384
C	0.1027

Pollution Risk of Ground Water

After determining the correlation coefficients in different models, it is found that the DAS model with deterministic rating layers has the highest correlation with about 70 percent of nitrate concentrations. For preparing pollution risk map, land use was considered as an additional parameter. A statistical method resemble to modification of the weighting factors is used to calculation of the weight of land use parameter. The weight of land use parameter was calculated equal to 3. The new specific vulnerability or pollution risk map is shown in Fig. 4. The correlation between specific vulnerability and nitrates concentration with a correlation coefficient r = 0.78. The improvement of the correlation, induced by the addition of the contaminant loading factor, is in the order of 0.018, which is lower than expected, based on the assumed importance of this parameter. This can be attributed to the fact that in the study area, the points with a high intrinsic vulnerability also have high contaminant loadings. The risk map shows that 5% of study area is completely risky while 10%, 29.95%, 26%, 21.3%, 9%, and 7% of it has very high, high, high to moderate, moderate to low, low, and the least pollution risk, respectively. Only 0.75% of study area is without any pollution risk.

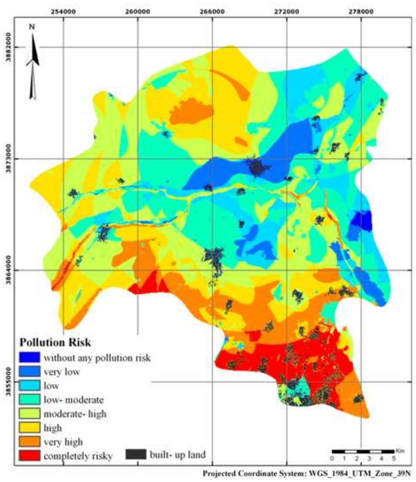

Figure 4. Groundwater pollution risk map to nitrate in Hamedan- Bahar plain

CONCLOSION

By modifying and optimizing the well known and widely used DRASTIC model it was possible to predict the intrinsic vulnerability to pollution as well as the groundwater pollution risk more accurately. For the optimization procedure we can use nitrates concentration data. Some of the factors that are taken into account for the vulnerability evaluation by the DRASTIC method, such as net recharge, topography, impact of vadose zone and hydraulic conductivity, do not seem to be related to the nitrates concentration. Spearman's rho and Kendall's tau coefficients have been employed in order to determine suitable weights in DRASTIC model. It was distinguished that soil media, aquifer media and depth to groundwater with the weights of 5, 4, and 3.5, respectively, indicate highest correlation with the nitrate concentrations. Thus the new equation has been named as DAS which substituted with DRASTIC for assessment of groundwater vulnerability in Hamedan-Bahar plain. After determining the correlation coefficients in different models (using statistical methods and AHP), it was found that the DAS model with deterministic rating layers has the highest correlation (0.70) of nitrate concentrations. For preparing pollution risk map, land use was considered as an additional parameter. The correlation coefficient between nitrate concentrations and the pollution risk map reached to 0.78. The risk map shows that 5% of study area is completely risky while 10%, 29.95%, 26%, 21.3%, 9%, and 7% of it has very high, high, high to moderate, moderate to low, low, and the least pollution risk, respectively. Only 0.75% of study area is without any pollution risk.

REFERENCES

Aller, L. T., Bennett, H. J. R., Lehr, R., Petty, J. and Hackett, G., 1987. "DRASTIC: A standardized system for evaluating ground water pollution potential using geo- hydrogeologic settings" US Environmental Protection Agency Report. EPA600/2–EP87/036.

Burrough, P.A. and McDonnell, R., 1998. Principles of Geographical Information Systems. Oxford University Press, New York, p. 346.

Burrough, P.A., Macmillan, R.A. and Van Deursen, W., 1992. Fuzzy classification methods for determining land suitability from soil profile observations and topography. Jounal of Soil Science, 43 (2), pp. 193–210.
Chen, S.Y., 1994. Systematic Fuzzy Decision-Making Theory and Application. Publishing House of Dalian University of Technology, Dalian (in Chinese).
Evans, B. M. and Mayers, W.L., 1990. A GIS-based approach to evaluating regional groundwater pollution potential with DRASTIC. Journal of Soil and Water Conservation, 45, pp. 242–245.
Fritch, T. G., McKnight, C. L., Yelderman, J. C., and Arnold, J. G., 2000. An aquifer vulnerability assessment of the Paluxy aquifer, central Texas, USA, using GIS and a modified DRASTIC approach. Environmental Management, 25, pp. 337–345.
Johansson, PO., Scharp, C., Alveteg, T. and Choza, A., 1999. Framework for ground-water protection-the Managua Ground Water System as an example. Ground Water, 37(2), pp.204–213**.**
Kendall, M., 1938. A New Measure of Rank Correlation. Biometrika. 30, pp. 81-89.
Kim, YJ. and Hamm, S., 1999. Assessment of the potential for ground water contamination using the DRASTIC/ EGIS technique, Cheongju area, South Korea. Hydrogeology Journal, 7(2), pp.227– 235.
McLay, C. D. A., Dragten, R., Sparling, G. and Selvarajah, N., 2001. Predicting groundwater nitrate concentrations in a region of mixed agricultural land use: a comparison of three approaches. Environmental Pollutants, 115, pp. 191-204.
Pearson, K., 1896. Regression, Heredity, and panmixia. Philosoph Trans Royal Society London Ser A 187, pp. 253–318.
Rosen, L.A., 1994. A study of the DRASTIC methodology with emphasis on Swedish conditions. Groundwater, 32(2), pp. 278-85.
Rupert, M.G., 2001. Calibration of the DRASTIC groundwater vulnerability mapping method. Ground Water, 39(4), pp.625-630.
Saaty, T. L., 1980. The Analytic Hierarchy Process. McGraw-Hill, Inc.
Secunda, S., Collin, M. L. and Melloul, A. J., 1998. Groundwater vulnerability assessment using a composite model combining DRASTIC with extensive agricultural land use in Israel's Sharon region. Journal of Environmental Management, 54, pp. 39-57.
Shukla, S., Mostaghimi, S., Shanholt, VO., Collins, MC. and Ross, BB., 2000. A county-level assessment of ground water contamination by pesticides. Ground Water Monitor, 20(1), pp104–119.
Spearman, C., 1904. The proof and measurement of association between two things. American Journal of Psychology, 6, pp. 72–101.
Sui, D.Z., 1992. A fuzzy GIS modeling approach for urban land evaluation. Computers, Environment and Urban Systems, 16(2), pp. 101–115.
Vrba, J. and Zoporozec, A., 1994. Guidebook on mapping groundwater vulnerability. IAH International Contribution for Hydrogeology, p.131.
Wang, F., Hall, B. and Subaryono, G., 1990. Fuzzy information representation and processing in conventional GIS software: Database design and application. International Journal of Geographical Information Systems, 4(3), pp. 261–283.
Zabet, TA., 2002. Evaluation of aquifer vulnerability to contamination potential using the DRASTIC method. Environmental Geology, 43, pp, 203–208.