CIVIL ENGINEERING

Evaluation of vulnerability of aquifers by improved fuzzy drastic method: Case study: Aastane Kochesfahan plain in Iran

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Received 30 August 2015; revised 5 November 2015; accepted 29 November 2015
Available online 1 February 2016

KEYWORDS
Vulnerable locations; Fuzzy method; Membership function; Aastane Kochesfahan plain

Abstract In this study the vulnerability of aquifer is investigated by fuzziness of the different layers. The vulnerable potential of different location within the basin by most accuracy was traced. In this method by the use of max lambda the weights of parameters were become fuzzy and quantity weights parameters has been fuzzy by the use of membership function. The quality weights were done by the discrete functions became fuzzy. The final map showed that some parts of north and northeast parts of the aquifer were most vulnerable locations. The correlation coefficient of vulnerability and nitrate concentration by standard method was estimated 49 percent and in the fuzzy method 53 percent that showed fuzzy method is more realistic. In FAHP method 13.87% of the plain area was by the low vulnerability, 11.96% by low to moderate vulnerability, 41.24% by moderate to high vulnerability, and 32.92% by high vulnerability.

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1. Introduction

Vulnerability of an aquifer is known as easily getting of pollutant material from the soil surface to them [1]. In another words the vulnerability of an aquifer, is its absorption potential of it against pollutant. There are various methods of evaluation of vulnerability of aquifers classified into 3 categories such as Description, Statistic and panel data’s. The most important and usual methods of ranking are as follows: GOD, IRISH, AVI, DRASTIC [2–5], and the most practical and popular method among them is DRASTIC model, since...
the expenditure of its application is less and low information data were required for vulnerable location in the vast areas [5]. This method has very usage in various regions, but contains some limitations such as assuming a constant range and weight of parameters for each regions. To resolve this problem, the AHP method was used, but this method is recommended to apply in unfuzzy or crisp decision making, that unbalances scales of judges and also does not consider the uncertainties in the process in this model [6]. The modeling of these uncertainties in the FAHP is the ultimate method. To overcome the limitations of AHP methods Wenlarhon and Pedris applied fuzzy logics in analysis of hierarchal processes [7]. FAHP is as strong method in multi-objection decision making.

The application of the Analytical Hierarchy Process (AHP) has been involved in many fields, i.e. Sensitive Analysis of Optimized Infiltration Parameters in SWDC model [24], Optimize of all Effective Infiltration Parameters in Furrow Irrigation Using Visual Basic and Genetic Algorithm Programming [25], fuel blend in fish oil biodiesel for the IC engineering [8], resource allocation [9], alternative waste treatment policies [10], talent promotion [11], human migration

Figure 1  The situation of Astanea-Kochesfahan plain.
Although the AHP is to capture the expert’s knowledge, the traditional AHP still cannot really reflect the human thinking style. The traditional AHP method is problematic in that it uses an exact value to express the decision maker’s opinion in comparison of alternatives. And AHP method is often criticized due to its use of unbalanced scale of judgments and its inability to adequately handle the inherent uncertainty and imprecision in the pair-wise comparison process. To overcome all these shortcomings, FAHP was developed for solving hierarchical problems.

Decision makers usually find that it is more confident to give interval judgments than fixed value judgments.

Combination of this method and GIS technique in multi-objective decision making in vast dimension by a great accuracy is possible. Literature survey showed that some studies were conducted on fuzziness of DRASTIC method for accurate evaluation of pollution potential of groundwater. Diffraction of the present research and the past research works was as follows: fuzziness of the required maps and weight of parameters, use of membership functions according to trees of parameters, and combination of FAHP and GIS.

Table 1 The fuzzy membership functions [22].

<table>
<thead>
<tr>
<th>Membership function</th>
<th>Diagram of</th>
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<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Z shape</td>
<td></td>
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<td></td>
<td></td>
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<td>S shape</td>
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</table>

Table 2 The fuzzy values related to variables [23].

<table>
<thead>
<tr>
<th>Positive triangular values</th>
<th>Verbally variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1, 1, 1)</td>
<td>Equal importance</td>
</tr>
<tr>
<td>(3, 2, 1)</td>
<td>Medium importance</td>
</tr>
<tr>
<td>(4, 3, 2)</td>
<td>Moderate importance</td>
</tr>
<tr>
<td>(5, 4, 3)</td>
<td>Medium and moderate impotency</td>
</tr>
<tr>
<td>(6, 5, 4)</td>
<td>Strong importance</td>
</tr>
<tr>
<td>(7, 6, 5)</td>
<td>Medium importance</td>
</tr>
<tr>
<td>(8, 7, 6)</td>
<td>Very strong importance</td>
</tr>
<tr>
<td>(9, 8, 7)</td>
<td>Medium important</td>
</tr>
<tr>
<td>(9, 9, 9)</td>
<td>Very Very strong impotency</td>
</tr>
</tbody>
</table>

2. Materials and methodology

2.1. Presentation of case study region

The case study area was Astaneh Ashrafieh basin in Guilan province that is over the conglomerate of Sefid-rood river with the area of 1100 square kilometers in the east longitudes of 40°12’ till 50°25” and north latitude of 37°7” till 37°25” [19]. Fig. 1 shows the boundaries of selected areas of the basin.

2.2. DRASTIC method

US-EPA the United States environmental protection agency selected the DRASTIC method for determination of pollution potential of aquifers [5]. The DRASTIC method though with its vast applications contains some limitations such as assumption of equal values for range and weight of parameters for the entire region of a field studies, and to overcome this problem AHP method can be used, but the latest method is along with some deficits; this method was basically used on applications of unfuzzies decision making (crisp), and does not take into account uncertainties of individual judgments. The judgment and behavior of decision makers get huge difference in the output results. Hence the classical AHP method is unable to reach accurate results [6] for the modeling of uncertainties, and fuzzy theory by comparisons of pair elements adjoins the analytical hierarchal processes, so that more accurate results for decision makers are prepared. By use of the facilities of both methods of AHP and FAHP for the first time Villarhoon and Pideriz applied the principals of fuzzy logics in analysis of AHP [7]. FAHP is a strong method in multivariable decision making, that by combination of this method and GIS, the multi-decision making in a vast area is possible. The literature showed that only a few studies were conducted on the subject of fuzzy-DRASTIC method for accurate evaluation of
vulnerable potential of aquifers. The difference of present paper with the past studies was that fussiness of maps, the weights of parameters, fuzziness of quality parameters, and use of membership elements according to the trends of variations of parameters adjoin FAHP and GIS methods.

The US-EPA was used in this method for evaluation of pollution potential of groundwaters aquifer [5] and this index is dimensionless and depended on aquifer characteristics. The vulnerability index in this method was calculated from the sum of multiplication of weighs and ranks of 7 parameters according to Eq. (1). The ranks of each parameter vary between 1 and 10 and the weight of parameters with respect to its importance varies between 1 and 5.

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Figure 3  Fuzzy indexes maps.
where 

\[ D_i = \sum_{j=1}^{7} W_j \times R_j \] (1)

where \( D_i \) – final amount of index, \( W_j \) – weight of \( j \) factor, \( R_j \) – rank of \( j \) factor.

After calculation of index, one can say which location is most vulnerable to pollution hazard, and this method was based on 7 parameters of groundwater table, pure recharge of the aquifer, environment of the water catchment, soil texture, topography, effects of unsaturated layer and hydraulic conductivity of aquifer.

### 2.3. Preparation of fuzzy layers

After classification and preparation of raster layers according to DRASTIC method indexes, the quality layers by the use of membership functions, are converted to the fuzzy layers, Table 1. These function to any of the members of the functions gives a value between 0 to 1 by the use of increase or decrease of trend of each indexes of the suitable fuzzy function. For fuzziness of that indexes was used. For the factors with the discrete data the fuzziness conducted in discrete form. The used fuzzy functions are nonlinear and symmetrical, and that values of each factor are in the range \( a-b \). The critical ranges of the values of these factors, can be selected as an index for the rate of influence of that factor in groundwater pollution.

### 2.4. Calculation of fuzzy weight by the use of FAHP processes

By preparation of pairs of variables table and filling the ideas of expert people about the rate of impotency of each index variables in reaching the target function, these values are imported to the EXPERT choice software and adaptation coefficients applied to the suggestions of expert persons by the software, if these coefficients were less than or equal to 0.1; then, the guides are adaptable and acceptable otherwise these guides must be revised. [20]. By the use of Table 2 the values of paired comparisons matrix prepared from the suggestions of expert persons are converted to triangular fuzzy values, and each of them was assigned a variable. By the use of lambda maximum method the values of comprised pairs matrix were converted to the triple number values and the values of these 3 matrices imported to the EXPERT-CHIOCE software; from each matrix a weight was found for each index and by the use of Chen method the values of triangular matrices became defuzzy and were converted to the classic values. The weighted fuzzy values multiplied into fuzzy layers and for overlying the layers the fuzzy summation function was used in the Chen method and the coming equation was used;

\[ C_{Ci} = d_i(w_i, 0)/(d_i(w_i, 1) + d_i(w_i, 0)) \] (2)

where \( i = 1, 2, \ldots, n \).

\[ d(w_i, 0) = \sqrt{0.33((w_{ia} - 0)^2 + (w_{ib} - 0)^2 + (w_{ic} - 0)^2)} \] (3)

\[ d(w_i, 1) = \sqrt{0.33((w_{ia} - 1)^2 + (w_{ib} - 1)^2 + (w_{ic} - 1)^2)} \] (4)

\( d(w_i, 0) \) and \( d(w_i, 1) \) are the measured distance of two known fuzzy numbers.
2.5. The final classification of maps comes out of FAHP

After preparation of the map, its accumulated frequency of pixel values is plotted and the turning points are chosen as class boundaries [21].

A comparison of 2 methods of standard DRASTIC and fuzzy DRASTIC for the nitrate concentration and \( R \) calculation is done; for evaluation of validation of results that came out of two methods of standard DRASTIC and fuzzy DRASTIC, the correlation coefficient of nitrate concentration of the observed data and estimated ones, through the mentioned methods was used.

3. The results and discussion

By calculating of DRASTIC method in the region, and combined together the vulnerable location maps were prepared the amount of vulnerability index varied between 107 and 180 and this map in 4 vulnerable classes of low vulnerable, low to moderate, moderate to high, and very high vulnerable were classified. Fig. 2 and Table 3 show the vulnerability of the aquifer by the standard DRASTIC method.

After preparation of raster layers, the decision parameters in ARC GIS configuration and by MATLAB software were converted to fuzzy base. The water table depth and topography indexes were since reducible, by increasing distance toward them, and the optimization of the rest of parameters will reduce, and therefore by the use of membership function and \( z \) shape became fuzzy. The hydraulic conductivity and the recharge indexes were increasable parameters and \( s \) shape membership function was used to become fuzzy. Unsaturated soil layers and aquifer boundaries were discrete indexes and therefore fuzzy values of them were also discrete. The critical points of fuzzy membership functions indexes were shown in Table 4. In Fig. 3 fuzzy layers indexes were presented.

By the use of FAHP method and the fuzzy weight the indexes were calculated and then these weights based on Chen formulae, Eq. (3) were defuzzied; the calculated weight ages showed that the depth of groundwater table index has the most effects in
reaching the final object. After introducing the calculated weights in the concerned layers and combining them together the result is shown in Fig. 5. To classify the resulted map out of this method the accumulated frequency values were changed to classic values.

The fuzzy and unfuzzy values are presented in Tables 5 and 6 respectively.

The figure of used pixel is shown in Fig. 4 and by the use of this figure the points 0.2000, 0.485, and 0.6078 were selected as class boundary layers. The area percentage of each class is reported in Table 7. Fig. 5 shows classification by FAHP methods.

For evaluation of groundwater quality of selected locations and certainty of accurate results its correlations by the collected sample of nitrate concentration that was collected from 20 wells of aquifer of Kochesfahan-Astane plain in May 2014, we compared the measured nitrate concentration was varied in the range of 0.39–28.64. The permitted range of nitrate in drinking water is 45 milligram per liter. By the respect of this standard level at present there is no alarm of

Table 8 The correlations coefficient for DRASTIC models and fuzzy DRASTIC.

<table>
<thead>
<tr>
<th>DRASTIC models</th>
<th>$R$ in percentages (%)</th>
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<tbody>
<tr>
<td>Standard DRASTIC</td>
<td>49</td>
</tr>
<tr>
<td>Fuzzy DRASTIC</td>
<td>52</td>
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</tbody>
</table>
danger for this aquifer. The values of locations of measured nitrate are reported in Fig. 6. Table 8 shows the correlation coefficient for DRASTIC and fuzzy DRASTIC models. Results showed that correlation coefficient of Fuzzy DRASTIC is 0.53 and DRASTIC standard method is 0.49. Due to the result, FAHP method is more accurate than the standard method.

4. Conclusion

In this research work 2 DRASTIC models of fuzzy and standard and also GIS 9.3 software capabilities are used on the vulnerable groundwater quality locations in Kochesfahan-Astane plain. In standard DRASTIC model 18.56 percent of the areas of the plain was low vulnerable and 51.29 percent was low to moderate vulnerable; 1.67 percent was high vulnerable in FAHP model also, and by the use of maximum lambda the weighted indexes were prepared and then converted to unfuzzy weight. The raster layers of decision indexes by the use of suitable membership functions proportional to the trends of efficiency of each index were converted to fuzzy raster, and by multiplications of these layers into the concern calculated weight s, by the use of algebraic operator became fuzzy overlaid. In FAHP method 13.87% of the plain area was by the low vulnerability, 11.96% by low to moderate vulnerability, 41.24% by moderate to high, and 32.92% by high vulnerability. In fuzzy DRASTIC model most of the northern regions of the plain were marked by moderate to high vulnerability, and in southern region the vulnerability was low to moderate. In standard DRASTIC model only the small location in the northern region was calculated by high vulnerability to the pollutants, and most of the rest of the basin area were by low to moderate vulnerability. Fuzzy DRASTIC model compared to standard DRASTIC model showed more adaptability to this plain.

References


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