Assessing the groundwater quality by applying fuzzy logic in GIS environment– A case study in Southwest Iran

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ABSTRACT

Water quality is a key environmental issue concerning the agricultural sector. Here, the application of fuzzy set theory for decision-making in the assessment of groundwater quality for agricultural purposes is being discussed. The experiments conducted in this study area located, Shahrekord plain that, lies in the Chaharmahal and Bakhtiari province, in the southwest Iran. Four groundwater parameters (EC, Mg, Na and Ca) are selected for water quality analysis and thematic maps are drawn for each of the parameters with the Kriging model. Different Fuzzy membership functions obtained from the related literature were employed and the weights for each parameter were calculated according to Analytic Hierarchy Process (AHP) that relies on pair wise comparisons. The Fuzzy theory showed 14.22% of the study area as having high groundwater quality, 19.86% as having moderate quality, 48.90% as having margin quality and 16.99% as having poor quality. In order to evaluate the accuracy of this method, eight different points were randomly selected. It is concluded that the Fuzzy method allows for obtaining results that correspond to the current conditions in the study area.

Keywords: Groundwater Quality, Fuzzy Theory, AHP.

1. Introduction

Very great volume of groundwater is pumped every day for industrial, agricultural, and commercial application. Therefore, information on the quality and quantity of ground water is important. The quality and availability of ground water is an important environmental issue for the Shahrekord plain. Long-term conservation, prudent development, and management of this natural resource are critical for preserving and protecting this priceless national asset (Samson et al., 2010). Surface and groundwater quality degradation due to agricultural practices and conversion of land to agriculture have been well described by Novotny (Novotny, 2002). Since the 1970s there has been a growing concern in Europe over the rise of nitrogen, phosphorus and pesticide residues rate in surface and groundwater table. Intense cultivation and “factory” livestock operations led to the conclusion, that agriculture is the significant non-point source contributor to surface and groundwater pollution (Heinz et al., 2002).

Agriculture is cited as a leading cause of groundwater pollution in the United States. In 1992, forty-nine out of fifty states identified as having nitrate as the principal groundwater contaminant, followed closely by the pesticide category. The US EPA (1994) concluded that “more than 75% of the states reported that agricultural activities posed a significant threat to groundwater quality”. It is becoming apparent that, it may take longer for the watersheds to recover after nutrient loads to surface and groundwater are reduced if remedial measures are
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gradually implemented (Novotny, 2005). Lessening of agricultural diffuse pollution sources can and must be conducted in the context of moving towards sustainable agriculture where agricultural best management practices are to be implemented (Novotny, 1999). Moreover, vulnerability of groundwater to agricultural chemicals has been studied to develop new strategies (Burkart and Stener, 2002). Various papers have already considered engineering applications of neural-fuzzy modeling in hydro-geological-based systems. In one of these studies, Chang et al., (2001) have shown that using ANFIS for real-time reservoir operation modeling is practicable and effective. Another articles presented by Lu and Lo (2004) have investigated reservoir water quality by applying self-organizing maps and fuzzy theory. Recently, neuron-fuzzy techniques have been applied to predict groundwater vulnerability using GIS (Dixon et al., 2002; Dixon, 2004, 2005), and for integrated water management (IHE, 2000).

Iran is the third unrestricted exploiter of groundwater recourses as a highly populated country, after china and India and with a 75% usage of restorable resource that is against the 40% UN standard, is in an unsuitable situation (http://www.gwea.ir). In light of the given statistics, a review of management strategies for water resources and a reconsideration of economic and social planning seem to be a serious necessity. The Chaharmahal & Bakhtiari province covering an approximate one percent of the country's surface and as the supplier of 10% (10.5 billion cubic meters) of the domestic fresh water supply (M.P.O, 2004) has a significant place in relation to the enhancement of the country's water resource status. In this province due to certain factors including severe shifts in altitude, economic underdevelopment the high cost of pumping water, the role of surface waters in water supply is approximately 15% (equivalent to 225 million cubic meters).

The remaining demand for water which is approximately 85% (10275 billion cubic meters) is supplied by the ground water recourses of the province. Over – exploitation of ground water resources in conjunction with the effect of recently occurring droughts has not only lowered the water level of the provincial water – beds with a rate of 2-12 meters annually, but has also lowered the quality such that the electric conduction amount of some water beds has Changed from a 300mm level to 900mm (Management and Planning Organization2005). Attentive to this area, the main purpose of this study is to prepare groundwater quality maps using Fuzzy method in the Shahrekord plain in the southwest of Iran in GIS environment.

2. Materials and Methods

2.1 Study area and Data used

The study area, Chaharmahal & Bakhtiari plain, is located in the southwest of the province, in the southwest of Iran (Figure 1). Data used for the case study consist of: EC, Mg, Na and Ca in 214 points that were selected in the total zone of study area randomly. A summary of the data used for this study is shown in Table 1 [WRCCB, 2005].

This plain (water – bed) with an altitude of 2000 meters from sea level and a surface area of 125000 hectares, 21 rural settlements and one urban settlement are situated in the Shahrekord plain (Iran data center –2006). From a hydrological perspective the plain is a part of the Karoon basin (North Karoon basin) where the Jahanbin River flows (CRWCB, 2001). The Shahrekord plain is, speaking a descended plain formed by quarts sediments with an alluvial depth of 60 – 110 meters geologically (M.P.O 2004).
Table 1: Summary of effective parameters for groundwater in the study area [WRCCB, 2005]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg</td>
<td>4.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Ca</td>
<td>6.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Na</td>
<td>4.3</td>
<td>0.007</td>
</tr>
<tr>
<td>EC</td>
<td>279</td>
<td>120</td>
</tr>
<tr>
<td>SAR*</td>
<td>1.86</td>
<td>0.0056</td>
</tr>
</tbody>
</table>

\[
*SAR = \frac{[\text{Na}^+]}{\sqrt{[\text{Ca}^{++}/2 + \text{Mg}^{++}/2]}}
\]

2.2 Methods

Fuzzy logic was initially developed by Lotfi Zadeh in 1965 as a generalization of classic logic. He has defined the Fuzzy set as “a class of objects with a continuum of grades of memberships”; the value 0 means that \( \chi \) is not a member of the fuzzy set; the value 1 means that \( \chi \) is fully a member of the fuzzy set. The values between 0 and 1 characterize fuzzy members that belong to the fuzzy set only partially. Traditionally thematic maps are represented with discrete attributes based on Boolean memberships, such as polygons, lines and points. These types of entities either have a value or do not have it; an intermediate option is not possible. With the Fuzzy theory, the spatial entities are associated with membership grades that indicate to which extent the entities belong to a class (Hall et al, 1992). Mathematically, a fuzzy set can be defined as (Mc Bratney A. B. and Odeh I. O. A. 1997):

\[
A = \{x, \mu_A(x)\} \quad \text{For each } x \in X
\]
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where, $\mu_A$ is the function (membership function MF) that defines the grade of membership of $x$ in $A$. The MF $\mu_A(x)$ takes values between and including 1 and 0 for all $A$. If $X = \{x_1, x_2, ..., x_n\}$ the previous equation can be written as:

$$A = \{[x_1, \mu_A(x_1)] + [x_2, \mu_A(x_2)] + ... + [x_n, \mu_A(x_n)]\}$$

(2)

In simple terms, equations 1 and 2 mean that for every $x$ that belongs to the set $X$, there is a membership function that describes the degree of belonging of $x$ in $A$.

Mc Bratney and Odeh (1997) expressed the fuzzy membership function $\mu_A$ as $(x) \rightarrow [0,1]$ with each element $X$ belonging to $X$ with a grade of membership $\mu_A(x) \in [0,1]$. Here $\mu_A = 0$ indicates that the value of $x$ does not belong to $A$ and $\mu_A = 1$ means that the value belongs completely to $A$. Alternatively $0 < \mu_A(x) < 1$ implies that $x$ to a certain degree belongs to $A$.

The membership function can take any shape and can be symmetrical or asymmetrical. The simplest function is of triangular form but Trapezoidal, Gaussian, and Parabolic among others are also possible. Given the non-discrete characteristics of soils and land use, fuzzy theory suits well to the analysis of groundwater quality. With fuzzy representation, the boundaries between suitability classes are not so strict and map units that are more or less suitable, that is they are in an intermediate condition, can be described properly. The development of GIS has contributed to facilitate the mapping the groundwater quality results, both Boolean and fuzzy, but the topological rules implied in GIS software are based on Crisp theory.

In this study first, interpolation using of 214 sampling point are developed for each of the parameters with Kriging method for production of map for each one of parameters model. Second, the calculation of the fuzzy memberships for the EC, Mg, Na and Ca was evaluated using a linear function as given in Eq.3 (Hydroinformatics, 2000).

$$\mu_A(x) = f(x) = \begin{cases} 
1 & x \leq a \\
b - x / b - a & a \pi x \pi b \\
0 & x \geq b 
\end{cases} \mu_A$$

(3)

where, $x$ is the input data and $a$, $b$ are the limit values.

Finally, for groundwater quality, it is required to calculate the convex combination of the raster values containing the different fuzzy parameters. The convex combination means that “if $A_1, ..., A_k$ are fuzzy subclasses of the defined universe of objects $X$ and $w_1, ..., w_k$ are non-negative weights summing up to unity, then the convex combination of $A_1, ..., A_k$ is a fuzzy class $A$ the membership function of which is the weighted sum” (Burrough, 1989). Here the weights $w_1, ..., w_k$ were calculated through AHP and the fuzzy parameters $\mu_A$ were calculated with the membership functions and using conditional statements in ArcGIS. Equations 5 to 7 present the convex combination.

$$\mu_A = \sum_{j=1}^{k} w_j \cdot \mu_{A_j(x)}$$
3. Results

In this study first, the interpolation using of 214 sampling points are developed for each of the parameters with Kriging method for production map for each one of parameters model (Figure 2). Second, the fuzzy maps were prepared for each of the parameters through Eq.3 as shown in Figure 3. AHP relies on Pair wise Comparison Matrices which relate to different components and are assigned values according to their relative importance. These values are given on a scale from 1 to 9, where 1 means that the two elements being compared having the same importance and 9 indicates that from the two elements one is more important than the other (Saaty and Vargas 2001).

\[ \sum_{j=1}^{k} w_j = 1 \quad \text{for} \quad x \in X \quad \text{and} \quad w_j > 0 \]
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Figure 3: Fuzzy maps for each parameter

(a) SAR, (b) Ec

Ground water quality based on the Fuzzy logic is shown in Figure 4.

Figure 4: Groundwater quality map with Fuzzy method

According to Table 3, the study area was classified in four parts shown in Figure 5.

Table 3: Numerical values of index for the various classes

<table>
<thead>
<tr>
<th>Groundwater quality</th>
<th>class</th>
<th>Fuzzy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly quality</td>
<td>1</td>
<td>0-0.25</td>
</tr>
<tr>
<td>Moderate quality</td>
<td>2</td>
<td>0.25-0.5</td>
</tr>
<tr>
<td>Margin quality</td>
<td>3</td>
<td>0.5-0.75</td>
</tr>
<tr>
<td>Non</td>
<td>4</td>
<td>0.75-1</td>
</tr>
</tbody>
</table>
The Fuzzy theory showed 14.22% of the study area as having high groundwater quality, 19.86% as having moderate quality, 48.90% as having margin quality and 16.99% as having poor quality. In order to evaluate and present a better method, eight different points were randomly chosen and Mg, Na, Ca and EC were measured (Figure 6). The points are plotted on the comparison map and are shown in Figure 6 and their information is given in Table 6.

Table 4: Information of the sampling points for comparison of the results of Fuzzy and Wilcox methods

<table>
<thead>
<tr>
<th>point</th>
<th>X</th>
<th>Y</th>
<th>SAR</th>
<th>EC</th>
<th>Class</th>
<th>Classification by Wilcox</th>
<th>Classification by fuzzy method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>469130</td>
<td>3596899</td>
<td>8.3</td>
<td>354</td>
<td>C2S1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>483685</td>
<td>3584467</td>
<td>91</td>
<td>540</td>
<td>C2S4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>488840</td>
<td>3568699</td>
<td>64.6</td>
<td>543</td>
<td>C2S4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>521891</td>
<td>3545957</td>
<td>5.7</td>
<td>375</td>
<td>C2S1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>456092</td>
<td>3569912</td>
<td>12.3</td>
<td>508</td>
<td>C2S2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>469130</td>
<td>3556570</td>
<td>26.9</td>
<td>530</td>
<td>C2S4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>4858082</td>
<td>3538983</td>
<td>104.7</td>
<td>600</td>
<td>C2S4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>508246</td>
<td>3518970</td>
<td>13.9</td>
<td>589</td>
<td>C2S2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
This Table shows the corresponding classes of the locations for different methods together with SAR and EC measured in the plain. In this Table the two methods of Fuzzy and Wilcoxon are compared. As shown in Table, there exists an agreement between the methods.

4. Conclusion

As shown in Table 6, there is not any limitation for EC in this area. But SAR generates limitation for agricultural applications in the study area. Furthermore, because of sedimentation of salts in low part of areas (Figure 6), in the higher mentioned parts of the plain, groundwater quality is better than that of the lower parts. Applying different GIS functions to the model for land evaluation were one of the main objectives of this article. Furthermore, since the groundwater quality properties have continuous spatial change, the Fuzzy method which is based on the continuous changes of the parameters applied in the fitness of groundwater quality can be applied for determining groundwater quality.

5. References


3. Center of Researches Water sheet of Chaharmahal and Bakhtiari province (2001), The identify of watershed basins of CHB Province, Center of Research of Natural Resource.


