Application of a GIS-based DRASTIC model and groundwater quality index method for evaluation of groundwater vulnerability: a case study, Sefid-Dasht
Nastaran Khodabakhshi, Gholamreza Asadollahfardi and Nima Heidarzadeh

ABSTRACT
Pollution control and removal of pollutants from groundwater are a challenging and expensive task. The aims of this paper are to determine the aquifer vulnerability of Sefid-Dasht, in Chaharmahal and Bakhtiari province, Iran, using the DRASTIC model. In addition, the groundwater quality index (GQI) technique was applied to assess the groundwater quality and study the spatial variability of major ion concentrations using a geographic information system (GIS). The vulnerability index ranged from 65 to 132, classified into two classes: low and moderate vulnerability. In the southern part of the aquifer, the vulnerability was moderate. Furthermore, the results indicate that the magnitude of the GQI index varies from 92% to 95%. This means the water has a suitable quality. However, from the north to the south and southwest of the aquifer, the water quality has been deteriorating, and the highest concentration of major ions was found in the southwest of the Sefid-Dasht aquifer. A comparison of the vulnerability maps with the GQI index map indicated a poor relation between them. In the DRASTIC method, movement of groundwater is not considered and may be the reason for such inconsistency. However, the movement of groundwater can transport contaminants.

Key words | DRASTIC model, GQI, groundwater vulnerability assessment, Sefid-Dasht aquifer

INTRODUCTION
All human activities can decrease water quality in aquifers. Remediating the aquifer or removing the contaminants from the water before use will have enormous costs (Breaban & Paiu 2012). Agricultural activities, urbanization and industrial development threaten groundwater systems and exert enormous pressures on the available groundwater resources (Aljazzar 2010). Because of high population growth and industrialization, greater amounts of domestic and industrial effluents are discharged to aquifers, which cause increased groundwater pollution in shallow aquifers (Rahman 2008).

DRASTIC is one of the most widely used methods to determine groundwater vulnerability (Breaban & Paiu 2012). Seven factors are investigated in the method: the depth to water, net recharge, aquifer media, soil media, topography, the impact of the vadose zone, and hydraulic conductivity of the aquifer. The DRASTIC method is a quantitative model that was developed by Aller at the United States Environmental Protection Agency (US EPA) (Aller et al. 1987). The DRASTIC method has been used to make groundwater vulnerability maps in many parts of the world such as China (Lobo-Ferreira 2000), the state of Idaho (Rupert 2001), Turkey (Ersoy & Gultekin 2013), India (Umar et al. 2009), Germany (Aljazzar 2010) and Turkey (Buyukdemirci 2012).

The aims of this study are to determine aquifer vulnerability using the DRASTIC model with raster-based geographic information system (GIS) software and compare the results with groundwater quality index (GQI)-derived maps to assess the capabilities of the DRASTIC model in a real situation.
STUDY AREA: SEFID-DASHT PLAIN

The study area is the Sefid-Dasht aquifer, located near Borujen City, in the province of Chaharmahal and Bakhtiari, Iran. The study area is about 229 km². The aquifer lies between latitudes 51°5’ and 51°19’ N, and longitudes 32°1’ and 32°15’ E. The average height of the aquifer is 2150 metres above sea level. Figure 1 indicates the location of the Sefid-Dasht aquifer.

METHODOLOGY

All the necessary raw data were received from Chaharmahal and Bakhtiari Regional Water Authority (CBRWA). All of these data were point data. To convert point data into spatial raster data, we applied spatial interpolation. This technique allows us to allocate the variable values at unknown locations based on point data with known values at sampling locations. In this method the values of points close to sampled points are more likely to be similar than those that are farther apart. In this study, the Inverse Distance Weighting (IDW) method was used for spatial interpolation. IDW relies on the assumption that the value at an unsampled location is a distance-weighted average of the values of surrounding data points, within a specified window. If the number of observations is few, IDW is proposed as an optimization technique for interpolation (Habashi et al. 2006). The data needed for quality zoning were obtained from recorded information of eight monitoring wells in the study area during 2004–2007 by CBRWA. Table 1 indicates the average qualitative parameters of groundwater in the Sefid-Dasht aquifer.

HYDROGEOLOGICAL CHARACTERISTICS OF SEFID-DASHT

The water-table map (groundwater potential) and the flow direction map were prepared in ArcGIS10.1 using information on water level in monitoring wells that exist in the aquifer by transferring point data to spatial data. These maps gave useful information about the hydrogeological characteristics of groundwater in the Sefid-Dasht aquifer.

DRASTIC MODEL

The DRASTIC method was designed to provide an evaluation of groundwater pollution potential. In this study, ArcGIS10.1 software was used to create hydrogeological characteristic maps and vulnerability maps of the aquifer. This model is based on seven parameters, corresponding to seven map layers to be used as input parameters to the model. To prepare these layers, hydrological and hydrogeological data such as depth to water, net recharge, precipitation, soil media, aquifer media, topography, hydraulic conductivity and permeability were obtained from CBRWA and transferred to spatial data as explained above. Map layers of depth to water, precipitation, soil...
media, aquifer media, impact of the vadose zone, hydraulic conductivity and permeability were prepared by applying the IDW interpolation technique for the available point data. To prepare slope (topography) map layer, a Digital Elevation Model (DEM) raster layer was converted to the slope map using the SLOPE module in the ArcGIS 10.1 software.

To create the net recharge map, Piscopo’s method was applied from Equation (1) (Piscopo 2001):

\[
\text{Net recharge} = \text{slopes (\%)} + \text{precipitation} + \text{permeability} \tag{1}
\]

where the weight, ranges and rating of Piscopo’s equation are given in Table 2.

The DRASTIC methodology is based on a weighting and rating method that assesses vulnerability by means of the seven map layers mentioned above. Each of these parameters has an individual impact on pollution potential with its subjective rating. The weight multipliers are then used for each factor to balance and enhance its importance. The final DRASTIC vulnerability index map (Di) can be computed as the weighted sum overlay of the seven layers using Equation (2) below (Aller et al. 1987):

\[
\text{DRASTIC Index} = D_wD_r + R_wR_r + A_wA_r + S_wS_r + T_wT_r + I_wI_r + C_wC_r \tag{2}
\]

where \(D\) is the depth to water; \(R\) is recharge rate; \(A\) is aquifer media; \(S\) is soil media; \(T\) is topography; \(I\) is impact of the vadose zone and \(C\) is the hydraulic conductivity. The subscript ‘\(r\)’ is the rating value, and ‘\(w\)’ is the weight assigned to each parameter.

The rates and weights of each parameter of the DRASTIC model are given in Tables 3 and 4. The \(D\), \(R\), \(S\), \(T\), and \(C\) factors are assigned one value per range. The parameters vary from 1 to 10, with the higher values describing higher pollution potential.

GROUNDWATER QUALITY INDEX METHOD

To compare the groundwater vulnerability and the existing quality of the Sefid-Dasht aquifer, the GQI method in

Table 1 | The average of the groundwater quality parameters in the Sefid-Dasht aquifer received from CBRWA (2004–2007)

<table>
<thead>
<tr>
<th>Well no.</th>
<th>Na (mg/lit)</th>
<th>Mg (mg/lit)</th>
<th>Ca (mg/lit)</th>
<th>SO₄²⁻ (mg/lit)</th>
<th>Cl (mg/lit)</th>
<th>TDS (mg/lit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68.16</td>
<td>23.20</td>
<td>84.00</td>
<td>38.40</td>
<td>194.07</td>
<td>622.67</td>
</tr>
<tr>
<td>2</td>
<td>13.57</td>
<td>23.40</td>
<td>48.00</td>
<td>40.80</td>
<td>37.28</td>
<td>305.00</td>
</tr>
<tr>
<td>3</td>
<td>32.28</td>
<td>21.60</td>
<td>66.67</td>
<td>72.00</td>
<td>37.87</td>
<td>491.33</td>
</tr>
<tr>
<td>4</td>
<td>12.96</td>
<td>25.60</td>
<td>50.67</td>
<td>54.40</td>
<td>26.03</td>
<td>324.67</td>
</tr>
<tr>
<td>5</td>
<td>54.97</td>
<td>41.60</td>
<td>96.67</td>
<td>67.20</td>
<td>195.25</td>
<td>698.67</td>
</tr>
<tr>
<td>6</td>
<td>46.08</td>
<td>21.20</td>
<td>66.00</td>
<td>84.80</td>
<td>61.53</td>
<td>470.00</td>
</tr>
<tr>
<td>7</td>
<td>34.12</td>
<td>20.80</td>
<td>59.33</td>
<td>78.40</td>
<td>59.17</td>
<td>402.33</td>
</tr>
<tr>
<td>8</td>
<td>27.60</td>
<td>31.20</td>
<td>58.00</td>
<td>62.40</td>
<td>85.20</td>
<td>447.00</td>
</tr>
</tbody>
</table>

Table 2 | Weight, ranges and rates of Piscopo’s equation (Piscopo 2001)

<table>
<thead>
<tr>
<th>Slope (%)</th>
<th>Precipitation (mm)</th>
<th>Permeability</th>
<th>Recharge (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight Rate</td>
<td>1</td>
<td>4</td>
<td>&gt;850</td>
</tr>
<tr>
<td>2–10</td>
<td>5</td>
<td>700–850</td>
<td>3</td>
</tr>
<tr>
<td>10–33</td>
<td>2</td>
<td>500–700</td>
<td>2</td>
</tr>
<tr>
<td>&lt;33</td>
<td>1</td>
<td>&lt;500</td>
<td>1</td>
</tr>
</tbody>
</table>

\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
\textbf{Depth to water (D)} & \textbf{Net recharge (R)} & \textbf{Topography (slope) (T)} & \textbf{Hydraulic conductivity (C)} \\
\textbf{(m)} & \textbf{(mm)} & \textbf{(%)} & \textbf{(m/day)} \\
\hline
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 \\
9.1–15.1 & 5 & 177.8–254 & 8 & 12–18 & 3 & 28.7–41 & 6 \\
15.2–22.8 & 3 & >254 & 9 & >18 & 1 & 41–82 & 8 \\
22.8–30.4 & 2 & >254 & 9 & >18 & 1 & 41–82 & 8 \\
>30.4 & 1 & >254 & 9 & >18 & 1 & >82 & 10 \\
\hline
\end{tabular}
ArcGIS10.1 was used. The GQI is used to determine the overall quality of groundwater \((\text{Babiker et al. 2007})\). To evaluate the quality of groundwater, the average concentrations of Mg, Ca, Cl, SO\(_4\), total dissolved solids (TDS) and Na, which are shown in Table 1, were compared with the standard amounts of major ions, according to the World Health Organization (WHO), for drinking water \((\text{WHO 2008})\). Therefore, raster layers of the concentration of each parameter were provided using interpolation tools in ArcGIS10.1, as explained above. Additionally, in this study, the IDW interpolation method was used to prepare the quality map layers. After creating raster layers for each parameter in GIS, the new maps of concentration for each parameter were created by using Equation (3), which compares the average concentration and maximum allowable concentration of WHO, and then the classified maps were prepared by using Equation (4) \((\text{Babiker et al. 2007})\):

\[
C_{\text{new}} = \frac{C_i - C(\text{WHO})_i}{C_i + C(\text{WHO})_i}
\]  
(3)

\[
R = 0.5C^2 + 4.5C + 5
\]
(4)

where \(C_i\) is the concentration of the parameter and \(C(\text{WHO})_i\) is the maximum allowable concentration provided by the World Health Organization. \(C\) is the concentration obtained from Equation (3) and \(R\) is the rating assigned to each of these concentrations.

In ArcGIS10.1, the Map Algebra expression was used to aggregate several input raster layers and create a raster output. First, the raster layers of the concentration of each parameter were applied to create six new maps using Equation (3), with their new pixel values varying from \(-1\) to \(1\). Then, the maps were reclassified using Equation (4) to achieve the new values of \(1\) to \(10\). Finally, to create the final map that indicates the status of the GQI, the six reclassified layers were combined using the Map Algebra expression and Equation (5) \((\text{Babiker et al. 2007})\):

\[
\text{GQI} = 100 - \left[ \frac{\sum_{i=1}^{n} W_i R_i}{n} \right]
\]
(5)

where \(R_i\) is the rating of each ion obtained from Equation (3) on the basis of the raster layer; \(W_i\) is the relative weight of each of these parameters, which is equal to the average concentration of each of the rated parameters, and \(n\) is the number of raster layers that should be combined in this method (here it is \(6\)). The GQI is expressed as a percentage. Values of GQI less than \(60\%\), \(60\%\) to \(80\%\), and more than \(80\%\), represent the poor, average, and good quality water, respectively \((\text{Rahmani et al. 2011})\).
RESULTS AND DISCUSSION

Flow direction of the aquifer

The map for evaluating groundwater potential indicates that the groundwater level is high in the north and south of the aquifer. In the central part of the aquifer, the water table is about 40–45 metres below the ground surface. In this aquifer, the flow direction of groundwater is from the north and south to the center and southwest of the region. Figure 2 shows the groundwater potential and flow direction map. As this figure has been derived from the observed existing point data of the studied wells, it can show the reality of groundwater flow direction. However, there are no further investigations that can confirm it. The flow direction is important because the movement of groundwater can transfer contaminants in aquifers. The effect of this factor will be discussed in the next sections.

DRASTIC indices

Depth to water

The depth to water of the study area is from about 4.6 to 47 metres. The rating map of this parameter was prepared using the reclassify tool in ArcGIS10.1 and in accordance with...
Table 3 the rates in it varied from 1 to 7. The depth to water in the southern and northern parts of the study area is low and in the central part it is very high. Therefore, the highest rate is in the southern and northern parts of the Sefid-Dasht aquifer.

**Net recharge**

The net recharge rating map was created according to the instructions mentioned above. In accordance with Table 2 the rates of this parameter were 1, 3 and 5. Particularly in the southern part of the aquifer, net recharge is higher than in other parts. Accordingly, the southern part of this aquifer will be more vulnerable (Rahman 2008).

**Aquifer media**

The types of soil in aquifer media are clay, sandy clay and gravel-sand with clay. Based on Table 4, the reclassified map represented the ratings of 5, 6, 7 and 9. Gravel-sand with clay soils are in the southern and northern parts of this aquifer. Coarse media was allocated a high rating value. This means that the vulnerability of an area with coarse media will be high.

**Soil media**

Permeability of soil can vary because of its substance (Rahman 2008). Silt and clay soils are of small size and have low permeability, so less contaminant can be transported. The types of soil in this aquifer are sand, sandy loam and clay loam with low permeability. The descriptive map of soil media was reclassified to 3, 6 and 9.

**Topography**

Topography refers to the slope variability of the ground. The slope of this aquifer is about 0% to 26%. The rate of this parameter in the reclassified map was 1–10, but in most of the areas the rate was around 9 and 10.

**The impact of the vadose zone**

High permeability leads to the free movement of contaminants and this makes the region vulnerable and increases the potential for groundwater pollution (Buyukdemirci 2012). The types of soil in the vadose zone are clay with low percentage of sand in the southern and eastern parts of the aquifer and clay with high sand percentage in the northern part of the aquifer. The descriptive map of this parameter was reclassified to 4, 5, 6 and 7.

**Hydraulic conductivity**

The amount of hydraulic conductivity varied from 4 to 105. In accordance with Table 3, it was reclassified using ArcGIS10.1 and the rating map was prepared. It varied from 1 to 10 and an increase in this parameter in the south and southwest of the aquifer was observed.

**DRASTIC index**

Figure 3 illustrates the rating index map of the study area. The DRASTIC index value is from 65 to 132 and it is classified into two categories: low and moderate vulnerability. Based on the DRASTIC vulnerability index map, 69.5% and 30.5% of the aquifer have low and moderate pollution vulnerability, respectively.

**Quality assessment and GQI**

In accordance with the qualitative values and Equations (3) and (4), the quality ratings maps for TDS, Ca, Na, Mg, Cl and SO4 were created.

The maximum concentration of TDS in the southwest of the Sefid-Dasht aquifer was observed and the quality zoning of Ca in this aquifer was similar to the quality zoning of TDS. Qualitative changes from the north to the south and southwest were observed, with the highest concentrations in the southwest of the Sefid-Dasht aquifer. The maximum concentration of Na was observed in the southwest and center of the aquifer and the maximum concentration of Mg was observed in the southwest of the aquifer. The maximum concentration of Cl was in the southwest of the Sefid-Dasht aquifer, and the maximum concentration of SO4 was in the southeast and center of the Sefid-Dasht aquifer.

**GQI index**: The resulting GQI index varied between 92% and 95%, which indicates a suitable water quality. Qualitative changes in the aquifer from the north to the
south and southwest were observed, with the highest concentration of main ions in the southwest of the aquifer. Figure 4 presents the groundwater quality index (GQI).

**CONCLUSIONS**

The following conclusions can be summarized considering the results.

The vulnerability map represents the study area as classified in two categories: low (65–92) and moderate vulnerability (93–132). The results of the DRASTIC method describe the south of the Sefid-Dasht aquifer and a small part of the central and northern parts of this plain as being more vulnerable. Based on the DRASTIC vulnerability index map, 69.5% and 30.5% of the aquifer have low and moderate pollution vulnerability, respectively. In the south of the study area, the depth to water was low and the hydraulic conductivity was high, which resulted in an increase in the vulnerability of the aquifer. Because the types of soil in the aquifer media, vadose zone and soil media consist of massive limestone, sandy clay, sandy loam and sand-gravel with silt, the vulnerability may be decreased. The resulting GQI indicated the ion concentration is high in the southwest of the study area and these parts are more prone to damage. However, groundwater quality in the study area is suitable because the results varied between 92% and 95% for this index. The GQI map showed a lower quality of water in the
southwest of the aquifer. The reason may be due to the flow direction of the groundwater that affected the transport of pollutants (from the north and northeast to the centre and southwest, and from the south and southeast to the centre and southwest of the region). Comparison of the vulnerability maps with the GQI maps indicated a poor relation between them. The DRASTIC method does not study the movement of groundwater. However, the movement of groundwater can displace contaminants.

The study shows that GIS can be applied to prepare various maps of different data layers and that comparing these maps is useful for groundwater management, to see how a particular area is vulnerable to groundwater pollution.

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