GIS-based DRASTIC method for groundwater vulnerability assessment: a review

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GIS-based DRASTIC method for groundwater vulnerability assessment: a review

S.M. Shirazi*, H.M. Imran and Shatirah Akib

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Groundwater vulnerability is a burning issue all over the world due to the deterioration of groundwater level and increasing contamination which poses serious detrimental risk to the environment. To identify this risk, extensive research has been carried out to assess the groundwater vulnerability by using different methods. Generally, the process-based method, statistical method, and overlay & index methods are used in this regard. DRASTIC method is one type of overlay & index method for vulnerability assessment. This paper represents a comprehensive review of available literature on the applications of Geographic Information System (GIS)-based DRASTIC method for groundwater vulnerability assessment. Also, some other types of overlay & index methods are compared with the DRASTIC method. This study discusses the rescaling of rating ranges and modification of DRASTIC parameters, and shows the comparison of DRASTIC method with other vulnerability assessment methods. In addition, this study identifies some research gaps on the present state of groundwater vulnerability assessment and proposes some research needs for further studies. The findings of this study indicate that the combination of GIS and DRASTIC are more viable for groundwater vulnerability assessment. Furthermore, modified DRASTIC method can be used for agricultural, arid, semi-arid, and basaltic regions.

Keywords: DRASTIC; groundwater; vulnerability; GIS

Introduction

Groundwater vulnerability refers to intrinsic characteristics that determine the sensitivity of the water to be adversely affected by an imposed contaminant load. The anthropogenic and agricultural activities are responsible for deterioration of groundwater level and increasing vulnerability. Due to the deterioration of groundwater level, sustainable development plans are needed to protect these resources (Nageswara and Narendra 2006). Groundwater has a major contribution to agricultural, industrial, drinking, and other municipal uses, particularly in the region where other sources of water are lacking. To get continuous supply of water and mitigate adverse effects, it is urgent to define definite strategies and guidelines for quality control, monitoring and management of groundwater. An assessment of groundwater vulnerability is the most feasible step regarding these purposes. The main con-
cept of groundwater vulnerability assessment is the areas which are more vulnerable to pollution than others (Piscopo 2001). Process-based method, statistical method, and overlay & index methods are generally used to assess groundwater vulnerability in many parts of the world. The limitations of process-based method are availability of adequate data and quality for the capture of physical, chemical and biological reactions which occur from the surface through the groundwater regimes. The statistical method includes uncertainty and tries to minimize the error and used parameters coefficient instead of weight. The lack of this method is proper monitoring data. This method is only applicable to those regions where the groundwater contamination is governed by similar factors. Overlay & index methods are the most suitable method for groundwater vulnerability assessment overcoming all the limitations mentioned above. Some common overlay & index methods are DRASTIC, SEEPAGE, SINTACS, GOD, and EPIK, in which the DRASTIC method is the most recognized worldwide for groundwater vulnerability assessment. This method is based on the assumption that some known major factors control the groundwater vulnerability and that those can be weighted. It is very costly and time consuming to assess groundwater vulnerability for a specific site, whereas DRASTIC method is more economic and less time consuming to assess a wide range of regional groundwater vulnerability, overcoming sloppy, uncontrolled development of land, and undesirable activities. This method was first developed (Aller et al. 1985) for the US Environmental Protection Agency. Then the method has been modified by many researchers and scientists based on geological or hydrogeological settings, climate conditions, and other special situations. Geographic Information System (GIS) is a very efficient tool for analyzing, interpreting, manipulating and incorporating the geological, hydrogeological and geomorphological data (Anbazhagan and Nair 2004; Jha and Peiffer 2006; Jha et al. 2007).

The present paper reviews the concepts, significance, and applicability of GIS-based DRASTIC method for groundwater vulnerability assessment. It enforces the modification of rating ranges of DRASTIC parameters based on geological, hydrogeological, and climatic conditions in the different parts of the world. However, this paper emphasizes the calibration systems of DRASTIC method. Above all, the existing gaps in the current state of knowledge on groundwater vulnerability assessment were required to identify for future research.

**Conventional DRASTIC method**

DRASTIC method generally used seven hydrogeological parameters to assess groundwater vulnerability. The parameters were considered as depth to groundwater table ($D$), net recharge ($R$), aquifer media ($A$), soil media ($S$), topography ($T$), impact of vadose zone ($I$) and hydraulic conductivity ($C$). The input information such as borehole data, meteorological data, hydrological data, geology data, soil data, lithology data, contour map, and topography map were used to develop GIS database. The method was used to consider various circumstances such as arid or semi-arid regions, agricultural, industrial, municipal, coastal, septic tank, and landfill areas. The parameters were rated and weighted due to their relative importance to contamination. Weighting and rating ranges were considered from 1 to 5 and 1 to 10, respectively. A multiplier defined as weight was multiplied with each parameter rating for each interval and then the products were summed up to calculate the final DRASTIC index. This index indicated the relative degree of groundwater
vulnerability of an area. Higher index value indicated the greater possibility of contamination. Final vulnerability map was generated by integrating all the thematic maps of DRASTIC parameters through the GIS environment. ArcGIS software was a powerful tool to generate different thematic maps, GIS database, format conversion, overlaying maps, integrating maps, and so on. Some extension tools (spatial analyst, 3D analyst, and geostatistical analyst) of GIS software were extensively used in DRASTIC method. Many researchers and scientists assessed groundwater vulnerability based on the above concept and used the Equation (1) (Kim and Hamm 1999; Ibe, Nwankwor, and Onyekuru 2001; Withowski et al. 2003; Tovar and Rodriguez 2004; De Silva and Hohne 2005; Jarsotia and Singh 2005; Shahid and Hazarika 2007; Chitsazan and Akhtari 2009; Moghaddam, Fijani, and Nadiri 2010).

\[
\text{DRASTIC Index (DI)} = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \quad (1)
\]

Groundwater vulnerability assessment in the coastal region was an important issue. The colluvial–alluvial sediment region was more vulnerable to contamination (Junior Silva and Pizani 2003). The input data sources were used as groundwater depth, aquifer recharge, lithology, soil types, topography, and permeability. Anthropogenic activities and seawater intrusion were prevailing factors for groundwater vulnerability. Conventional DRASTIC method was used in the arid region of Barka region of Oman (Jamrah et al. 2008). The study showed the long-term changes of vulnerability index for 1995 and 2004. Groundwater samples were analyzed for major ions, nutrients, COD (Chemical Oxygen Demand), BOD (Biochemical Oxygen Demand), and bacteria to cross check the DRASTIC vulnerability index. Major anions such as \(\text{NO}_3^-, \text{NO}_2^-, \text{Cl}^-, \text{SO}_4^{2-}, \text{PO}_4^{3-}, \text{F}^-\), and \(\text{Br}^-\) were analyzed and developed correlations between vulnerability index values and specific groundwater quality parameters to valid the DRASTIC method.

**Sensitivity analysis of DRASTIC parameters**

Sensitivity analysis was carried out to show the relationship between the effective and theoretical weight of the DRASTIC parameters. The analysis helped to avoid the subjectivity to nature for vulnerability assessment which provided very important information to assign the weighting and rating ranges of the parameters. Two types of sensitivity analysis – namely map removal sensitivity and single parameter removal sensitivity analysis – were carried out on this regard. First one represented the sensitivity of final vulnerability map to remove one or more map layers and worked-out Equation (2). The single parameter removal sensitivity analysis test indicated the influence of each parameter on final vulnerability measurement. Effective weight of each subarea was estimated by the Equation (3). From the sensitivity analyzed results, researchers understood that their assign weight was perfect or in need of modification. Both the conventional DRASTIC method and sensitivity analysis were used to groundwater vulnerability assessment by many researchers and scientists (Kwansiririkull et al. 2004; Babiker et al. 2005; El-Naqa, Hammouri, and Kuisi 2006; Ckakraborty, Paul, and Sikdar 2007; Bazimenyera and Zhonghua 2008; Rahman 2008; Hasiniaina, Zhou, and Guoyi 2010; Al Hallaq and Elaish 2011; Samake et al. 2011).
Sensitivity, \( S_v = \left[ \frac{V/N - V'/N'}{V} \right] \times 100 \) \( (2) \)

The differences of theoretical weight and effective weight also calculated by the Equation (3):

\[
W_c = \left( \frac{P_p P_w}{V_p} \right) \times 100
\]

A GIS-based groundwater vulnerability assessment carried out in the Russeifa area of Jordan (El-Naqa, Hammouri, and Kuisi 2006). The relevant data such as topography, geology, land use, hydrology, rainfall, existing aerial photographs, and satellite imagery were used. ArcGIS software was used to compile all the geospatial data and generate groundwater vulnerability map. The impact of vadose zone was calculated due to soil permeability and depth to water table parameters. There was a significant concern that the study area was situated at the landfill site. DRASTIC index was calculated due to pesticide effect and included the map removal sensitivity by statistical analysis. The study indicated that the groundwater was highly vulnerable due to the landfill of the surrounding study area.

**Different equations for net recharge calculation of DRASTIC method**

Different types of equations were used to calculate the net recharge of DRASTIC method in many parts of the world based on the variation of geology, hydrogeology, lithology, land use categories, topography, and climatic and other conditions. The following Equation (4) was used for net recharge calculation by Bazimenyera and Zhonghua (2008).

\[
N_n = (P_p - E_p) \times R_t
\]

Net recharge was calculated using other Equations (5) and (6) considering gravel, sand, sandy loam, and loamy sand geology, respectively by (Al Hallaq and Elaish 2011).

\[
PI = \frac{(P_p - 10.28)^2}{P_p + 15.43}
\]

\[
PI = \frac{(P_p - 15.05)^2}{P_p + 22.57}
\]

Recharge was estimated considering the summation of rainfall and irrigation return flow, and subtracting the evapotranspiration (Jayasekera, Kaluarachchi, and Villholth 2011). Soil moisture content was accounted to calculate the irrigation return flow. The volume of storage water available for plants was calculated using Equation (7):
\[ S_w = \frac{\pi D_b^2}{4} \times \frac{\text{AWHC}}{100} \times \text{MAD} \times Z \]  

The assumptions were \( Z = 0.5 \) m; \( \text{AWHC} = 8\% \) and \( \text{MAD} = 1.0 \) for desert plants and 0.5 for others plants. It was used for the approximate infiltration fraction as 0.4 based on rainfall (Kuruppuarachchi 1995). The calculated fraction of irrigation water recharge to groundwater table was 0.63 over the area. Fault system, fault density, the distance between fault system intersection and drainage system intersection, rainfall amount, slope of the area, and soil permeability were greatly considered (Al-Hanbali and Kondoh 2008) to estimate the net recharge using Equation (8).

\[ \text{RV} = \text{RF} + S_p + SP + F - FD \]  

A study was carried out by greatly considered the net recharge calculation method and its rating system by Kim and Hamm (1999). In this case, Soil Conservation Service (SCS) method was used (Morel-Seytoux and Verdin 1981) to define the net recharge rate. Cumulative direct runoff \( (T_q) \) was calculated by the Equations (9)–(11):

\[ T_q = \frac{(P_p - I_a)^2}{P_p - I_a + S_{sw}} \]  

Again, \( I_a = 0.2S_{sw} \)  

\[ S_{sw} = \frac{25,400}{\text{CN}} - 254 \]  

CN value depended on watershed soil types and land use categories. The soil was classified according to SCS classification and land use was classified according to US geological survey. Under SCS method, runoff potential was determined based on antecedent moisture conditions (AMC). CN and \( S_p \) values were taken with respect to AMC classification which taken from SCS chart. Finally, cumulative direct runoff \( (T_q) \) was calculated for each landuse category using the Equation (12):

\[ T_q = \frac{(P_p - 0.2S_{sw})^2}{P_p + 0.8S_{sw}} \]

<table>
<thead>
<tr>
<th>RPR (%)</th>
<th>Runoff</th>
<th>Land use</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–15</td>
<td>Low</td>
<td>Forest and agricultural land</td>
<td>5</td>
</tr>
<tr>
<td>15–25</td>
<td>Moderate</td>
<td>Barren land and alluvium</td>
<td>4</td>
</tr>
<tr>
<td>25–30</td>
<td>High</td>
<td>Residential area and channel deposit</td>
<td>2</td>
</tr>
<tr>
<td>130</td>
<td>Very high</td>
<td>Water</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1. Recharge rating systems.
The net recharge rating ranges (Table 1) were developed based on Runoff Potential Ratio (RPR) which calculated on each land use category and by the following Equation (13):

\[
\text{RPR} = \frac{T_q}{P_p}
\]  

(13)

To evaluate the relative weight of RPR value, the actual runoff \( Q \) was calculated using Equation (14):

\[
Q = \frac{P_a}{100} \times T_q
\]  

(14)

The new rating ranges of net recharge were selected based on (RPR) whereas RPR mainly depended on land use categories. The study showed that shallow aquifers were more vulnerable due to higher recharge and hydraulic conductivity, and coarse soil. The domestic and industrial waste water were the main sources of pollution.

A recession curve displacement method was used to estimate the net recharge. Stream flow data within the study area were used for recession curve displacement method (Fritch et al. 2000) and suggested the three concepts for vadose zone rating ranges. (a) If overlaying material’s thickness of the aquifer was less or equal to the thickness of weathered zone, then vadose zone media was considered as materials of the aquifer media. (b) If overlaying material’s thickness of aquifer was greater than the weathered zone, but less or equal to vadose zone, then the vadose zone could be adequately described as a weighted average: \([\text{the aquifer material media rating} \times \text{its thickness}] + [\text{the overlying material media rating} \times \text{its thickness}]\)/total thickness of the vadose zone. (c) If overlaying material’s thickness of the aquifer was greater than the weathered zone and vadose zone, then vadose zone should be rated according to the overlaying material’s characteristics.

**Modified DRASTIC approach**

Land use had a potential impact on groundwater vulnerability and risk mapping which were produced as a consequence of groundwater contamination. Modified DRASTIC method was used to assess the groundwater vulnerability and risk mapping including land use (Secunda, Collin, and Melloul 1998). Al-Adamat, Foster, and Baban (2003) considered \( D, R, A, S, T, \) and \( I \) parameters because of lacking the hydraulic conductivity data and also, a fixed value of 68 assumed instead of \( (D_rD_w + A_rA_w + I_rI_w) \) index value. Since the possible minimum and maximum DRASTIC index were 24 and 220, respectively. The vulnerability classes were divided into four categories namely: (a) 24–71 (No risk), (b) 72–121 (Low), (c) 122–170 (moderate) and, (d) 171–220 (High). Final modified DRASTIC index \( (MD_i) \) was calculated using the following Equation (15):

\[
MD_i = DI + L_rL_w
\]  

(15)

Khan, Umar, and Lateh (2010) focused on the land use and impact of vadose zone effect on groundwater vulnerability and risk with DRASTIC method. Land use weight was considered as 5 and hydraulic mean approach (Hussain et al. 2005)
was used to calculate the impact of vadose zone parameter. The following Equation (16) was used to achieve the approach and final vulnerability index calculated using the Equation (1):

\[ I_r = \frac{T_v}{\sum_{i=1}^{n} \left( \frac{T_i}{T_v} \right)} \]  

(16)

Al-Hanbali and Kondoh (2008) also used the Equation (1) to assess groundwater vulnerability. Modified DRASTIC parameters and rating ranges were used in most cases of arid and semi-arid regions. Weight and rating ranges were changed due to hydrogeologic settings, land use categories, rainfall, and climatic and other conditions. In some cases, some parameters of DRASTIC were removed or added to develop the modified DRASTIC method by many researchers. Modified equations, weight and rating ranges were given satisfactory result for groundwater vulnerability assessment in different regions. The new weight values were considered as 5, 4, 3, 5, 3, 3, and 2 for D, R, A, S, T, I, and C factor respectively, based on pesticide contamination (Al-Zabet 2002). A fixed index value of 10 was assumed instead of the parameters depth to water table and impact of vadose zone to calculate DRASTIC index (Hasiniaina, Zhou, and Guoyi 2010). The study area belonged to oil field and minerals region. The conductivity map generated by two components (aquifer thickness and conductivity) and greatly considered the relation \( T=Kb \), where \( T= \) transmissivity, \( K= \) hydraulic conductivity, and \( b= \) the thickness of the aquifer. Modified DRASTIC method was applied considering the land use parameter and except hydraulic conductivity in Azraq basin (Jasem and Alraggad 2010). The new weighting and rating ranges were used for each DRASTIC parameter (Table 2).

A case study was carried out on aquifer vulnerability assessment to Arsenic pollution using DRASTIC and GIS of North Bengal plain in West Bengal of India (Ckakraborty, Paul, and Sikdar 2007). The assumption was that the contaminants moved vertically downwards with water and reached groundwater table. The new rating ranges were proposed for \( D, R, T, \) and \( I \) parameters of DRASTIC method (Table 2).

DRASTIC-Fm method was applied to assess the groundwater vulnerability for the structural characteristics of fractured-bedrock aquifers (Denny, Allen, and Journeay 2007). The fractured media was strictly considered identifying its effect on groundwater vulnerability. The fractured media was classified as three categories (Fracture orientation, Fracture length, and Fracture density) and also the rating ranges were assigned for those categories. The final Fm factor was rated according to the average value of each category rate (Table 3). The weight of Fm factor was considered as 3.

Calibration of DRASTIC method

Groundwater vulnerability was assessed in many parts of the world considering nitrate contamination. Nitrogen is the basic need for agricultural plants to insure the high production (Lake et al. 2003; Schröder et al. 2004; Shirazi, Sholichin et al. 2011). Groundwater greatly affected by nitrate contamination all over the world (Birkinshaw and Ewen 2000; Saâdi and Maslouhi 2003; Kyllmar, Mårtensson, and Johnsson 2005; Liu, Ming, and Ankumah 2005). Nitrate contamination mainly occurred in the agricultural areas due to application of fertilizers. The soil compo-
Table 2. Modified weighting and rating values of DRASTIC parameters.

<table>
<thead>
<tr>
<th>References/parameters</th>
<th>Range (m)</th>
<th>Rating</th>
<th>D</th>
<th>Aquifer media types</th>
<th>Rating</th>
<th>A</th>
<th>Soil type</th>
<th>Rating</th>
<th>S</th>
<th>Range (Slope)</th>
<th>Rating</th>
<th>T</th>
<th>Vadose zone</th>
<th>Rating</th>
<th>I</th>
<th>Land use types</th>
<th>Rating</th>
<th>LU</th>
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</thead>
<tbody>
<tr>
<td>Jasem and Alraggd (2010)</td>
<td>0–2</td>
<td>10</td>
<td>-</td>
<td>Limestone</td>
<td>1</td>
<td>Clay</td>
<td>1</td>
<td>&gt;2%</td>
<td>7</td>
<td>Uncovered</td>
<td>4</td>
<td>-</td>
<td>Rain fed agriculture</td>
<td>1</td>
<td></td>
<td>Barred rocks</td>
<td>1</td>
<td>WWTP</td>
</tr>
<tr>
<td></td>
<td>2–10</td>
<td>8</td>
<td></td>
<td>Sandstone bed</td>
<td>2</td>
<td>Silty loam</td>
<td>2</td>
<td>2–6%</td>
<td>6</td>
<td>Soil</td>
<td>3</td>
<td></td>
<td>Irrigated agriculture</td>
<td>3</td>
<td></td>
<td>Streams</td>
<td>6</td>
<td></td>
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<tr>
<td></td>
<td>10–20</td>
<td>6</td>
<td></td>
<td>Sands &amp; gravels</td>
<td>3</td>
<td>Loam</td>
<td>3</td>
<td>6–10%</td>
<td>5</td>
<td>Unconfined unit</td>
<td>2</td>
<td></td>
<td>Urban areas</td>
<td>5</td>
<td></td>
<td>Dams</td>
<td>5</td>
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<td></td>
<td>20–40</td>
<td>4</td>
<td></td>
<td>Basalt</td>
<td>5</td>
<td>Sand</td>
<td>4</td>
<td>10–16%</td>
<td>3</td>
<td>Confining unit</td>
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<td>Barred</td>
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<td></td>
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<td></td>
<td>40–60</td>
<td>2</td>
<td></td>
<td>Limestone chalk</td>
<td>4</td>
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<td>16–25%</td>
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<td>Streams &amp; WWTP</td>
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<td></td>
<td>&gt;60</td>
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<td>Modified weight</td>
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<tr>
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<th>Rating</th>
<th>S</th>
<th>Range (Slope)</th>
<th>Rating</th>
<th>T</th>
<th>Vadose zone</th>
<th>Rating</th>
<th>I</th>
<th>Land use types</th>
<th>Rating</th>
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<td>10</td>
<td>&lt;0.2</td>
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<td>-</td>
<td>-</td>
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<td>0–2%</td>
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<td>Clay and silt</td>
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<td>-</td>
<td>-</td>
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<td></td>
<td>3–4</td>
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<td>Sandy clay</td>
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Javadi et al. (2011)

<table>
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<tr>
<td>Sand and gravel</td>
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Journal of Risk Research
Table 3. Modified DRASTIC-Fm rating values.

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<th>30° fault orientation classification and associated DRASTIC-Fm ratings</th>
<th>Length classifications and associated DRASTIC-Fm ratings</th>
<th>Fracture density classifications and associated DRASTIC-Fm ratings</th>
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nent variations (soil leaching potential) had a great effect on decision support system (DSS) to minimize the agrochemical pollution of groundwater (Brown et al. 2003; Holman, Dubus, and Hollis 2004; Shirazi et al. 2010; Shirazi, Ismail et al. 2011). The nitrate concentration in groundwater depends on soil nitrate levels, and the timing and amount of surface loading (Di and Cameron 2002). One of the non-point source pollution of groundwater is caused by nitrate in the agricultural areas (Hubbard and Sheridan 1994; McLay et al. 2001; Shamrukh et al. 2001; Harter et al. 2002; Almasri and Kaluarachchi 2004; Chowdhuary et al. 2005). On-ground nitrogen concentration was considered to assess the groundwater vulnerability. Nitrogen database was very effective to validate the intrinsic vulnerability (Holman et al. 2005). The on-ground nitrogen loading was rated and weighted, and then added with DRASTIC index. Finally, the composite DRASTIC index (CDI) was calculated by the following Equation (17):

$$\text{CDI} = \text{DI} + N_w N_r$$

The intrinsic vulnerability of groundwater was assessed to nitrate contamination and considered five parameters for modification of DRASTIC method (Mishima, Takada, and Kitagawa 2011). Only vertical movement of contamination was considered for this modification. In this case, the aquifers were shallow and aquifer media had narrow ranges. Soil media were governed by the aquifer media parameter. Hydraulic conductivity and aquifer media were less effect for contamination. The more recharge value was considered as less rating value and less recharge value was considered as high rating value which was opposite of conventional DRASTIC and the Equation (18) was used to calculate the nitrate concentration:

$$N_{\text{con}} = \frac{E_{\text{rate}} \times F_{\text{ert}}}{W_{\text{perc}}}$$

Finally, Modified DRASTIC index was calculated by Equation (19):

$$G_v = D_r D_w + R_r R_w + S_r S_w + T_r T_w + I_r I_w$$

The new weighting and rating ranges were proposed for five parameters of DRASTIC based on agricultural areas (Javadi et al. 2011). The new rating ranges are shown in Table 2.

DRASTIC method was improved by calibrating the point rating scheme to measured nitrate & nitrite concentration in groundwater (Rupert 2001). Statistical correlation was developed between the land use, soils, depth to water level, and nitrate & nitrite concentrations. GIS and statistical techniques were applied to enumerate the correlations. Based on the correlations, the probability map of nitrate & nitrite were generated. Then uncalibrate DRASTIC map and probability map were compared with the independent set of nitrate & nitrite data. The comparison showed that poor correlations were found between the uncalibrated DRASTIC map and nitrate & nitrite concentrations. There was no significance difference of nitrate & nitrite concentration in groundwater between the low, medium, high, and very high vulnerability categories areas. Good correlations were found between the probability map and nitrate & nitrite concentration. The significant difference of nitrate & nitrite concentration in groundwater indicated between the low, medium, high, and
very high vulnerability categories areas. The study suggested that groundwater vulnerability and probability maps can be used to develop the prevention guidelines for high susceptible to contamination areas. Groundwater vulnerability was assessed considering the severe human impact, semi-arid climate, and very little slope variation (Chitsazan and Akhtari 2009). The main geomorphologic features of the area were hills, plains, sand dunes, sabkha, steams, and brines. The most aquifers system of the study area was unconfined. DRASTIC method was evaluated by nitrate concentration of the study area. The correlations were shown between the DRASTIC parameters and nitrate concentration using multivariate statistical method.

Comparison of DRASTIC with other methods
A regional scale of groundwater vulnerability assessment was carried out based on nitrate contamination using conventional DRASTIC and System for Early Evaluation of Pollution Potential of Agricultural Groundwater Environments (SEEPAGE) method (Navulur 1996). The study results of DRASTIC method indicated that 24% area was highly vulnerable and 28% area was very highly vulnerable according to the assessment of SEEPAGE method. The Bayesian probability map also developed for both methods for computing the probabilities of nitrate occurrence. The probability maps using DRASTIC and SEEPAGE factors showed 26% and 21% area with a probability of nitrate recognition > 50%, respectively. The water quality data indicated 76% of the nitrate recognitions were within the areas with probability of recognition > 50%. The study suggested that statistical techniques can be used to generate the regional scale risk maps where data availability were limited and DRASTIC performance was better than SEEPAGE.

DRASTIC and Aquifer Vulnerability Index (AVI) methods were used to assess groundwater vulnerability mapping and checked the validation of DRASTIC method (Leal and Castillo 2003). To validate the weighting and rating ranges of the parameters, the raw data maps and parameters rating maps were compared. Overlaying isoline map pair's technique was used to compare between different maps. If major variations were detected then the rating ranges were modified. Depth to water table parameter was adjusted and proposed for rescaling the rating ranges. The simplification was represented by matrix form as Equation (20):

\[ T_d \cdot A_i = C_p \]  \hspace{1cm} (20)

Again, critical parameter \( C \) affected by the weight function \( W \) and it presented by Equation (21).

\[ W \cdot C_p = V_i \]  \hspace{1cm} (21)

Effective weight was calculated (Napolitano and Fabbri 1996; Gogu and Dasargues 2000) based on the Equation (22).

\[ W_e = \frac{X_{ri} \times X_{wi}}{V_i} \times 100 \]  \hspace{1cm} (22)
The vulnerability variation was calculated (Lodwik, Monson, and Svoboda 1990) based on Equation (23) and proposed new rating for depth to water table parameter.

\[
V_{vX_i} = \left( \frac{V_i - V_{Xi}}{V_i} \right) \times 100
\]  

(23)

The comparison between different vulnerability assessment method such as AVI, GOD (Groundwater occurrence, G; Overall lithology of aquifer, O; and Depth to groundwater level, D), DRASTIC, and EPIK (Epikarst, E; Protective cover, P; Infiltration conditions, I; and Karst network development, K) were conducted for diffuse flow carbonate aquifers (Vias et al. 2004). The aquifer was highly vulnerable according to the AVI method and moderately vulnerable according to the other three methods. The vulnerability maps indicated that AVI method was not suitable whereas GOD method was adequate for vulnerability assessment of diffuse flow carbonate aquifers. Lithological parameters were the most significant for groundwater pollution potential while depth to groundwater level had minor influence. High vulnerability area was derived by EPIK method for the fractured zones were contradicted with very low karst areas. Among the above methods, EPIK is adequate for karstification areas and GOD is adequate for poorly karstification carbonate areas. Moreover, DRASTIC and AVI methods are more suitable for land use management.

Susceptibility Index (SI) method and nitrate concentration map were used to evaluate the DRASTIC model for groundwater vulnerability assessment (Stigter, Ribeiro, and Dill 2006). It was considered the weights of the parameters as Table 2. The DRASTIC index and SI calculated as the following Equations (24) and (25):

\[
\text{DRASTIC Index (DI)} = 5D + 4R + 3A + 2S + T + 5I + 3C
\]

(24)

\[
\text{SI} = 0.186D + 0.212R + 0.259A + 0.121T + 0.222LU
\]

(25)

The DRASTIC vulnerability map, SI index map, and nitrate concentration map were compared to each other and large discrepancies were found. To remove these discrepancies, a new map was generated by subtracting the assessed vulnerability class from the nitrate concentration vulnerability class at all location. Where the class differences were minus one or zero or one, the vulnerability was considered as correct. Where the differences were two or three and four or five above the nitrate concentration class, it was considered that vulnerability assessed by overestimated or extremely overestimated. The DRASTIC method was optimized using the statistical method and GIS (Panagopoulos, Antonakos, and Lambrakis 2006). To modify the weight of DRASTIC parameters, the correlations were established between the DRASTIC parameters and nitrate concentration. Based on correlation value, negligible parameter removed from DRASTIC model and developed new Equation (26) for groundwater vulnerability assessment.

\[
V_{(\text{intrinsic})} = 3D + R + 5A + 2T + 2.5I
\]

(26)
The land use weighting and rating ranges were assigned based on nitrate concentration of the study area. The buffer zone radius of nitrogen was calculated based on the Equation (27).

$$R_c = \sqrt{\frac{Q_p \cdot t}{\pi \cdot n \cdot H}}$$  \hspace{1cm} (27)

Finally, specific vulnerability of groundwater was calculated considering land use parameter and by the Equation (28):

Aquifer Pollution Risk,

$$V_{\text{specific}} = 3D + R + 5A + 2T + 2.5I + 5L$$  \hspace{1cm} (28)

EPIK and DRASTIC methods were used to assess the groundwater vulnerability and indicated the protection zone (Hammouri and El-Naqa 2008). The EPIK was a multiattribute method which was mainly used in karst region. The factor $E$ and $K$ were determined with respect to geological and morphological informations, whereas the $P$ and $I$ factor were determined from soil and land use/cover maps. The final protection index $F$ was calculated by the Equation (29):

$$F = \alpha E + \beta P + \gamma I + \delta K$$  \hspace{1cm} (29)

The DRASTIC model is a straightforward method and generally it is applicable where the hydrological data are available. EPIK is used the region which is subjected to karst features (holes, caves, and sinkholes).

Groundwater vulnerability based approach was used to delineate the groundwater protection zones around springs of fracture media (Pochon et al. 2008). Unconsolidated porous media was used as protective materials. Considering the hydrological diversity, individual solution was applied for each hydrological setting. Distance method and isochrone protection method were applied for low vulnerability and slightly vulnerability springs which consist of three protection zones such as S1, S2, and S3. Zone S1 suggested that the distance must extended at least 10 m around or upstream of the springs which integrated drains, draining trenches, and galleries. Zone S2 suggested the outer distance of S1 and S2 zones must at least 100 m and zone S3 suggested that the distance between the external limits of S2 and S3 zones equal to the same distance between the outer limits of S1 and S2 zones.

DISCO (Discontinuities and protective Cover parameter) method was applied for highly vulnerable springs. DISCO method was applied at four stages. Firstly, the discontinuities and protective cover parameters maps were prepared for whole catchment area and rated the value of ‘D’ (range 0–3) and ‘P’ (range 0–4) based on hand drilling, on-site soil analysis, geomorphological map, geophysics, and infiltration test. Secondly, intermediate protection factor was calculated by the Equation (30):

$$F_{\text{int}} = 2D_c + P_i$$  \hspace{1cm} (30)

Then intermediate protection map was prepared. Thirdly, final protection map was modified by updating the intermediate protection map based on runoff parameter, slope gradient, and soil permeability. Fourthly, protection map was converted
into protection zones using some conversion factor. The discontinuity and protective cover factors were considered to generate the discontinuity map and protection zone map for the study area. In conclusion, the effectiveness of the study needs to verify from data of long-term groundwater quality monitoring and further case studies.

**Research needs**

The concept of groundwater vulnerability mapping is developed mainly based on hydrogeological settings. The vulnerability mapping assumes that the physical environment (soil–rock–groundwater system) may provide self-purification or natural attenuation. The following research needs are mentioned for further studies:

1. Further research can be carried out on the relationship between the soil and protective cover such as cation-exchange capacity and anion exchange capacity and its characteristics.
2. Contaminant mobility indices and screening models can be developed for groundwater vulnerability assessment based on field observation and comparison with physics-based simulations of coupled solute transport and fluid flow in saturated or unsaturated systems.
3. More studies should be done on groundwater protection methods and techniques; moreover, some study has been carried out on this regard which is not adequate and well established.
4. Developing DSS approach to combine with groundwater vulnerability map based on stochastic screening model for groundwater resources management and monitoring.

**Summary and conclusions**

Groundwater vulnerability is a widespread problem in worldwide. Two main components are considered for DRASTIC method; firstly, the map able units which termed as hydrogeologic settings and secondly, the application of numerical values of relative ranking of hydrogeologic factors. The paper attempts to present the application of DRASTIC method for groundwater vulnerability assessment, moreover some comparison between DRASTIC and other related methods are presented. The GIS techniques are provided the great facilities to accomplish and handle the complex and extensive databases for groundwater vulnerability assessment. The salient conclusions are summarized below:

1. The modified DRASTIC method is better than conventional DRASTIC method in the arid, semi-arid, basaltic, and agricultural and land fill regions.
2. Sensitivity analysis is very helpful for DRASTIC method. It indicates which parameter has the most significant contribution to groundwater vulnerability. The differences between theoretical and effective weights of DRASTIC parameters are demonstrated by sensitivity analysis.
3. Extensive approaches are established to net recharge calculation based on different geological and hydrogeological conditions.
4. The DRASTIC method is calibrated by nitrate concentration in groundwater or others-related method. The evaluation system is the comparison between
Notations

\( A_r \) assigned ranges for critical parameter
\( \text{AWHC} \) available water holding capacity
\( \text{CN} \) curve number
\( C_p \) critical parameter
\( D_c \) discontinuity ranges
\( D_b \) diameter of basin
\( E_p \) evaporation
\( E_{\text{rate}} \) elution rate
\( F \) protection index
\( F_{\text{int}} \) intermediate protection factor
\( F - FD \) rate of the average of the distance from the faults system (F) and the distance from the intersection locations between the faults and the drainage systems (FD)
\( F_{\text{cert}} \) fertilizer input
\( G_v \) groundwater vulnerability
\( H \) length of the well screen, namely the saturated thickness of the aquifer for full penetrating wells
\( I_a \) initial abstraction
\( I_r \) weighted harmonic mean of vadose zone
\( I_{ri} \) rating of layer 1 of vadose zone
\( L \) contaminant loading per land use category
\( L_r \) land use rating and weighting
\( \text{LU} \) land use
\( \text{MAD} \) management allowable depletion (dimensionless)
\( n \) porosity
\( N \) and \( N' \) the number of data layers used to compute the \( V \) and \( V' \)
\( N_n \) net recharge
\( N_{\text{con}} \) nitrate concentration in percolation water
\( N_w \) and \( N_r \) weight and rating that given the total on-ground nitrogen loading
\( P_a \) percentage of the total area covered by each land use category
\( P_c \) cumulative amount of rainfall
\( \text{PIL} \) percolation index
\( P_a \) annual average rainfall/Precipitation
\( P_{ri} \) and weight and rating of individual DRASTIC parameters that used for effective\( P_w \) weight calculation
\( P_t \) protective cover ranges
\( Q \) actual runoff
\( Q_p \) pumping rate of the well
\( r \) rating of the parameters
\( R_c \) radius of the circle
\( R_r \) recharge rate
\( \text{RF} \) rainfall factor
\( \text{RPR} \) runoff potential ratio
\( \text{RV} \) recharge value
\( S_{sw} \) maximum watershed storage
\( \text{SI} \) susceptibility index
\( \text{SP} \) soil permeability
\( S_p \) slope percentage
\( S_c \) sensitivity analysis
\( S_w \) volumes of storage water
\( T_d \) applied transformations to a data series
\( T_{qi} \) cumulative direct runoff
\( T_v \) total thickness of the vadose zone
\( t \) travel time for which volume was being calculated
vulnerability index maps of various methods or correlation between the vulnerability index values and nitrate concentration values over the study area.

(5) The presence of nitrate in groundwater easily indicates the pollution potentiality by the contaminants since nitrate is not generally present in groundwater under natural conditions.

(6) Land use map is very effective to generate groundwater risk map and helps to explanation the on-ground nitrogen loadings and permits realistic allocations in various nitrogen sources.

(7) In some cases, the DRASTIC parameter’s weighting and rating ranges can be modified and one or more parameters also can be added or subtracted from conventional DRASTIC method based on the geology, hydrogeology, land use categories, and climatic and other conditions.

(8) In agricultural areas, it is better to rescale the weighting and rating ranges of conventional DRASTIC parameters due to land use and nitrate concentration resulting from pesticides and fertilizers.

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References


