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Modified DRASTIC assessment for intrinsic vulnerability mapping of karst aquifers: a case study

Ziad A. Mimi · Nidal Mahmoud · Maher Abu Madi

Abstract Groundwater in karstic aquifers can be dangerously sensitive to contamination. In this paper, DRASTIC assessment was modified and applied, for the first time, to address the intrinsic vulnerability for karst aquifers. The theoretical weights of two of DRASTIC’s parameters (aquifer media and hydraulic conductivity) were modified through sensitivity analysis. Two tests of sensitivity analyses were carried out: the map removal and the single parameter sensitivity analyses. The modified assessment was applied for the karst aquifers underlying Ramallah District (Palestine) as a case study. The aquifer vulnerability map indicated that the case study area is under low, moderate and high vulnerability of groundwater to contamination. The vulnerability index can assist in the implementation of groundwater management strategies to prevent degradation of groundwater quality. The modified DRASTIC assessment has proven to be effective because it is relatively straightforward, use data that are commonly available or estimated and produces an end product that is easily interpreted.

Keywords Aquifer vulnerability · Groundwater · DRASTIC index · Karst · Palestine

Introduction

Most of the Middle-Eastern countries including Palestine, Israel, and Jordan are characterized by aridity and have very limited water resources. Groundwater is the sole source of drinking water in these countries. Future population projections in these countries place severe demands on already fragile reserves. Palestine will experience serious deficit and the water shortage will be 271 million m³ for the year 2020 (Mimi et al. 2003).

Despite the importance of groundwater function to the society, these resources have generally not been provided with adequate protection. The groundwater quality in Palestine is showing trends of increasing nitrate contamination, even if actual concentrations are below the health standards. Combined with biological parameters and much anecdotal information, there are signs that health officials should be concerned about groundwater quality in public supplies, though hard evidence based on empirical data is largely absent (UNEP 2003).

The majority of outcropping formations of the study area, Ramallah District, Palestine (Fig. 1) are the Lower Cenomanian and the Upper Cenomanian–Turonian complexes which are mainly composed of carbonate rocks such as limestone, dolomite and chalk. Carbonate rock outcrops, of which a large part is karstified, cover the land surface (SUSMAQ 2003b, 2004b).

Groundwater in karstic aquifers can be extremely sensitive to contamination from the land surface. Major karstic carbonate aquifers are among our most valuable groundwater sources. Karst aquifers are in need of particular attention constantly (Goldscheider 2005). The DRASTIC assessment developed by Aller et al. (1987) is one of the most widely used methods to assess intrinsic groundwater vulnerability to contamination.

The aim of this paper is to present intrinsic vulnerability mapping for karst aquifers underlying Ramallah District as a case study. The research will modify and apply, for the first time, DRASTIC assessment to address the intrinsic vulnerability for karst aquifers. Although DRASTIC has
been modified in many studies, it has not been adapted to assess the groundwater pollution potential of karst aquifers.

**Study approach**

The concept of groundwater vulnerability is important for a rational management of groundwater resources and subsequent land use planning (Rupert 2001; Connell and Daele 2003). There are two major vulnerability assessment types, intrinsic and specific. Intrinsic vulnerability deals with pollution possibilities without considering a particular pollutant. Specific vulnerability means that vulnerability refers to a specific contaminant of interest.

There is no universal methodology for groundwater vulnerability assessment although a number of different approaches exist. The methods of vulnerability assessment are grouped into three categories: (1) process-based simulation assessments (Voss 1984; Carsel et al. 1985; Wagenet and Histon 1987), (2) statistical assessment (Nolan et al. 2002; Twarakavi and Kaluarachchi 2005) and (3) overlay and index methods (Aller et al. 1987; Banton and Villeneuve 1989; Evans and Mayers 1990; Rupert 2001; Baker et al. 2005; Almasri 2008, Mimi and Assi 2009). The European COST action 620 proposed a comprehensive approach to karst groundwater protection, comprising methods of intrinsic and specific vulnerability mapping, hazard and risk mapping. Unfortunately, it uses data that are commonly unavailable in developing countries (Mimi and Assi 2009).

The most widely used indexing method is the DRASTIC assessment. The DRASTIC assessment developed by Aller et al. (1987) is an acronym for seven hydrological factors: Depth to water, Net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and Hydraulic Conductivity of the aquifer. Each of the seven hydrogeologic factors mentioned above is assigned a rating from one to ten based on a range of values and on interpretation of available data, field observations, and professional judgment. The ratings are then multiplied by a relative weight ranging from one to five (Table 1). The most significant factors have a weight of five; the least significant have a weight of one. Equation 1 determines the DRASTIC (vulnerability) index (Aller et al. 1987):

\[
\text{DRASTIC Index} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w
\]

(1)

where \(D, R, A, S, T, I, C\) represent the seven hydrogeologic factors, \(r\) designates the rating, and \(w\) the weight.

The resulting DRASTIC index represents a relative measure of groundwater vulnerability. The higher the DRASTIC index, the greater is the contamination vulnerability of the aquifer. A site with a low DRASTIC index is not free from groundwater contamination, but it is less susceptible to contamination compared with the sites with high DRASTIC indices. The DRASTIC index can be converted into qualitative risk categories of low, moderate, high, and very high corresponding to the intervals 1–100, 101–140, 141–200, and greater than 200, respectively.

Table 1 Assigned weights for DRASTIC hydrogeologic factors

<table>
<thead>
<tr>
<th>Hydrogeologic factor</th>
<th>Symbol</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to water</td>
<td>Dw</td>
<td>5</td>
</tr>
<tr>
<td>Net recharge</td>
<td>Rw</td>
<td>4</td>
</tr>
<tr>
<td>Aquifer media</td>
<td>Aw</td>
<td>3</td>
</tr>
<tr>
<td>Soil media</td>
<td>Sw</td>
<td>2</td>
</tr>
<tr>
<td>Topography</td>
<td>Tw</td>
<td>1</td>
</tr>
<tr>
<td>Impact of the vadose zone media</td>
<td>Iw</td>
<td>5</td>
</tr>
<tr>
<td>Aquifer hydraulic conductivity</td>
<td>Cw</td>
<td>3</td>
</tr>
</tbody>
</table>
The method has been widely used throughout the world and has proven to be effective because it is relatively straightforward, use data that are commonly available or estimated and produces an end product that is easily interpreted. However, the DRASTIC method does not make special provisions for extremely susceptible karstic aquifers. Further, it appears that the DRASTIC assessment without modification does not yield pollution-potential values which are an adequate numerical reflection of the relatively greater sensitivity in karst aquifers.

To address carbonate aquifers in karst terrains, this research will modify DRASTIC assessment by evaluating the relative importance of the DRASTIC assessment parameters through sensitivity analysis. Two tests of sensitivity analyses will be carried out; the map removal and the single parameter sensitivity analyses. The modified assessment will be applied on the case study area of this research.

The flexibility of DRASTIC assessment is an appealing aspect of the assessment. Several studies have shown that unimportant DRASTIC parameters may be ignored, and new ones may be added (Al-Adamat et al. 2003; Naqa 2004; Gomezdelcampo and Dickerson 2008). DRASTIC has been successfully modified when certain parameters and ratings in the DRASTIC equation did not change appreciably over a study area. In one study (Evans and Mayers 1990) aquifer media, net recharge, and impact of vadose zone did not vary appreciably and were replaced by factors that varied such as land use/land cover, and septic system density. In situations where hydrologic data are insufficient for one parameter, DRASTIC can still be used with some degree of success. For example, Al-Adamat et al. (2003) analyzed groundwater vulnerability and risk mapping of the basaltic aquifer in Jordan without using hydraulic conductivity in the DRASTIC equation due to insufficient data.

**Vulnerability assessment for Ramallah District**

The groundwater resources of Palestine are abstracted from aquifers extending from the West Bank to Israel. The main Aquifer Basins in the West Bank are the Eastern, North-eastern and Western Basins. Ramallah District, the case study area of this research, lies over the Eastern and Western Basins (Fig. 1). However, the majority of outcropping formations in Ramallah District are the Lower Cenomanian and the Upper Cenomanian–Turonian complexes which are mainly composed of carbonate rocks such as limestone, dolomite and chalk.

The Western Mountain Basin underlies about 45% of the Ramallah District and its water flows towards the west. It extends from the Judean Desert northward to the Carmel Mountain foothills, and from near the center of the Mountain Belt westward to the Coastal Plain. The basin is underlain by a thick sequence of layered limestone, dolomite, chalk, and marls which form the two aquifers, Upper and Lower Aquifer. It is overlain by Senonian chalks of the Eocene age. The upper and lower aquifers are of Upper Albian and Upper Cenomanian–Turonian age, respectively. Lower Cenomanian sequences with higher amounts of marl divide the two aquifers. Over a small percentage of the area in the west, these units are overlain by younger Neogene and Pleistocene formations consisting of sand, gravel, and conglomerate. The Quaternary series are referred to as Kukar Group (Rofe and Raffety 1963; SUSMAQ 2003a).

The Eastern Mountain Basin underlies the eastern part of Ramallah District and the western part of Jericho district. It includes the eastern part of the Mountain Belt and the steep Western Escarpment of the Jordan Rift Valley. The Jordan Rift Valley forms the eastern boundary of the basin. Annually renewable groundwater from natural rain infiltration forms the principal source of freshwater in the basin and is supplied to wells and springs by three principal aquifers: the Turonian aquifer, the Upper Cenomanian aquifer and the Lower Cenomanian aquifer. (Rofe and Raffety 1963; SUSMAQ 2003a).

The study area, often referred to as the assessment domain, is divided into smaller areas, called cells, such that each area carries one representative value that is assumed constant. Once the discretization of Ramallah District is carried out, all the input parameters are processed in concordant with this discretization. If the input parameters are referred to as layers (a common nomenclature used in GIS), then the internal discretization should be identical compared to the other layers. This is essential to permit the sequential processing of the different parameters as described by Eq. 1. A finite difference grid was used to discretize Ramallah District with uniform squared cell sizes of 50 × 50 m.

For each cell of the finite-difference grid, Eq. 1 is implemented and a unique DRASTIC index is obtained. Therefore, the ultimate output will be a grid comprised of cells where each cell carries a DRASTIC index and the transpired grid is a grid of DRASTIC indices or more specifically the vulnerability map. Preparation of the DRASTIC input parameters entails processing the available data to produce the grids that can be later assigned the ratings.

The seven DRASTIC hydrogeologic factors for Ramallah District were assigned a rating from 1–10 based on interpretation of available data using ArcView software, field observations and literature review. The ratings were then multiplied by a relative weight ranging from 1–5 based on Table 1. The following explains the process of rating.

\[ \text{Vulnerability} = \sum \text{factor} \times \text{weight} \]
Depth to water (D)

The grid layers for Ramallah District were generated by computer subtraction of water level elevation data sets from land surface elevation. Land surface elevations were derived from a digital elevation assessment. The depths to the water levels for Ramallah District are classified into two classes: 20–30 and 39+, therefore the rates for depth to water (Dr) were 3 and 1, respectively; based on Table 2 as shown in Fig. 2.

Net recharge (R)

Recharge values were determined based on rainfall-recharge equations adopted from SUSMAQ (2004a). These equations were applied depending on the outcropping formations in the study area. When the geological formations that form the main aquifers are outcropping, the following rainfall-recharge equations are applied. The recharge map was converted into grid map where each cell has its own recharge factor rate (Rr) based on Table 3 as shown in Fig. 3.

\[
R = 0.6 \left( P - 285 \right) \quad P > 700 \text{ mm} \\
R = 0.46 \left( P - 159 \right) \quad 700 \text{ mm} > P > 456 \text{ mm} \\
R = 0.3 \left( P \right) \quad 456 \text{ mm} > P
\]

where, \( R \) is the recharge from rainfall in mm/y and \( P \) is annual rainfall in mm/y

Aquifer media (A)

The majority of outcropping formations of the study area, Ramallah District, are the Lower Cenomanian and the Upper Cenomanian–Turonian complexes which are mainly composed of carbonate rocks such as limestone, dolomite and chalk. Carbonate rock outcrops, of which a large part is karstified, cover of the land surface (SUSMAQ 2003b, 2004b). Karst aquifers are particularly vulnerable to contamination: due to thin soils, flow concentration in the epikarst (the uppermost, often intensively fractured and karstified layer of a carbonate aquifer) and point recharge via swallow holes. Contaminants can easily reach the

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**Table 2** Rates for depth to water

<table>
<thead>
<tr>
<th>Range of depth to water (m)</th>
<th>Dr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–2</td>
<td>10</td>
</tr>
<tr>
<td>2–6</td>
<td>9</td>
</tr>
<tr>
<td>6–12</td>
<td>7</td>
</tr>
<tr>
<td>12–20</td>
<td>5</td>
</tr>
<tr>
<td>20–30</td>
<td>3</td>
</tr>
<tr>
<td>30–39</td>
<td>2</td>
</tr>
<tr>
<td>39+</td>
<td>1</td>
</tr>
</tbody>
</table>

Source: Aller et al. (1987)

**Table 3** Rates for net recharge

<table>
<thead>
<tr>
<th>Range (m/year)</th>
<th>Rr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–0.05</td>
<td>1</td>
</tr>
<tr>
<td>0.05–0.1</td>
<td>3</td>
</tr>
<tr>
<td>0.1–0.18</td>
<td>6</td>
</tr>
<tr>
<td>0.18–0.25</td>
<td>8</td>
</tr>
<tr>
<td>≥0.25</td>
<td>9</td>
</tr>
</tbody>
</table>

Source: Aller et al. (1987)

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**Fig. 2** Depth to groundwater rating map (Dr)
groundwater, where they may be transported rapidly in karst conduits over large distances. Therefore, the *Aquifer factor rate* \( (Ar) \) was ten for the aquifer media of the study area.

**Soil media (S)**

There are different types of Top soils and Sub soils in the study area. The soil map was converted into grid map where each cell has its own Soil factor rate \( (Sr) \) based on Table 4 as shown in Fig. 4 and Table 5 (SUSMAQ 2003a, 2004a).

**Topography (T)**

Because of unavailability of a slope map, a 3-D topographic map was used to estimate the slopes. The slope rates \( (Tr) \) were assigned 10 for low slopes, 7 for low/moderate slopes, 5 for moderate slopes, 3 for moderate/high slopes and 1 for high slopes as shown in Fig. 5.

**Impact of the vadose zone media (I)**

Impact of vadose zone was predicted for Ramallah District by determining the presence of a protective aquitard above the water table. The information about characteristics of these aquitards was obtained from the aquifer studies, the hydrologic map of the study area, and typical lithology for each formation using stratigraphical section of the West Bank. Table 6 and Fig. 6 present the Impact of vadose zone media factor rates \( (Ir) \) for Ramallah District.

**Hydraulic conductivity of the aquifer (C)**

The hydrogeology of the case study area is characterized by karst hydrogeology which has big implications on recharge, groundwater flow rates, and transport of any contaminants in the subsurface and groundwater. Most source groups are located in, and pump from, karst aquifers. Hence, the hydraulic conductivity of the aquifer factor rate \( (Cr) \) is 10 for the Aquifer.

**Vulnerability DRASTIC indices for Ramallah District**

The vulnerability indices for the case study area were calculated based on the assigned factors’ rating, and weights using Eq. 1 as shown in Fig. 7. For better assessment, the DRASTIC values were converted into qualitative indices based on the classifications furnished earlier. It can

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**Table 4 Rates for soil media**

<table>
<thead>
<tr>
<th>Range</th>
<th>S-factor rates (Sr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin or Absent</td>
<td>10</td>
</tr>
<tr>
<td>Gravel</td>
<td>10</td>
</tr>
<tr>
<td>Sand</td>
<td>9</td>
</tr>
<tr>
<td>Peat</td>
<td>8</td>
</tr>
<tr>
<td>Shrinking and/or Aggregated clay</td>
<td>7</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>6</td>
</tr>
<tr>
<td>Loam</td>
<td>5</td>
</tr>
<tr>
<td>Silty loam</td>
<td>4</td>
</tr>
<tr>
<td>Clay loam</td>
<td>3</td>
</tr>
</tbody>
</table>

Source: Aller et al. (1987)
be concluded that the study area is under low and moderate vulnerability of groundwater to contamination.

Sensitivity analysis of the assessment

The DRASTIC assessment relies on seven parameters to evaluate the intrinsic vulnerability of groundwater to contamination. Sensitivity analysis can help in determining the most important and influential parameters on the groundwater vulnerability map. Two tests of sensitivity analyses were carried out; the map removal and the single parameter sensitivity analyses (Babiker et al. 2005).

Map removal sensitivity analysis

The map removal sensitivity analysis determines the sensitivity of the vulnerability map towards removing one or more parameters from the vulnerability analysis and is computed using Eq. 2 (Babiker et al. 2005):

$$S = \frac{|(V/N) - (V'/n)|}{V} \times 100$$

where $S$ is the sensitivity measure expressed in terms of variation index; $V$ and $V'$ are the unperturbed and the perturbed vulnerability indices, respectively; and $N$ and $n$ are the number of data layers used to compute $V$ and $V'$. The actual vulnerability index obtained using all seven parameters was considered as an unperturbed vulnerability index while the vulnerability computed using a lower number of data layers was considered as a perturbed one.

The results of the map removal sensitivity analysis computed by removing one or more data parameters at a time are presented in Tables 7 and 8. Table 7 summarizes the variation of the vulnerability index as a result of removing only one parameter at a time. As can be inferred from Table 7, the vulnerability index seems to be most sensitive to aquifer media and hydraulic conductivity.

In Table 8, the statistical measures of the sensitivity analysis of the DRASTIC index for the removal of multiple parameters at once are summarized. In carrying out this multiple parameter sensitivity analysis, two or more parameter layers were taken off, the vulnerability index was computed, and the corresponding statistical measures of the variation index were calculated. As can be noticed from the table and with increasing the number of the removed parameters, the variation index does increase.

Single parameter sensitivity analysis

The single parameter sensitivity analysis compares the effective weights with the theoretical weights of the

---

Table 5 Top soils and sub-soils and corresponding Sr

<table>
<thead>
<tr>
<th>Top soil type</th>
<th>Sub-soil type</th>
<th>Sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terra Rossa, Brown Rendzinas and Pale Rendzinas</td>
<td>Clay</td>
<td>1</td>
</tr>
<tr>
<td>Brown Rendzinas and Pale Rendzinas</td>
<td>Clayey loam</td>
<td>3</td>
</tr>
<tr>
<td>Gnunusols</td>
<td>Clay</td>
<td>1</td>
</tr>
<tr>
<td>Brown Lithosols and Loessial Serozems</td>
<td>Silty clayey sand</td>
<td>5</td>
</tr>
<tr>
<td>Brown Lithosols and Loessial Arid Brown Soil</td>
<td>Loamy</td>
<td>5</td>
</tr>
<tr>
<td>Loessial Serozems</td>
<td>Silty clay</td>
<td>1</td>
</tr>
</tbody>
</table>
parameters used in the DRASTIC index computation (see Table 1). The effective weight is computed for each cell in the assessment domain using Eq. 3 (Babiker et al. 2005):

\[
W = \frac{PrPw}{V} \times 100
\]  

where \( W \) is the effective weight of each parameter, \( Pr \) and \( Pw \) are the rating value and weight of each parameter, and \( V \) is the overall vulnerability index. The effective weight is a function of the value of the single parameter with regard to the other six parameters as well as the weight assigned to it by the DRASTIC assessment. The effective weights of the DRASTIC parameters exhibited some deviation from their theoretical weights as summarized in Table 9. The aquifer media tends to be the most effective parameter in the vulnerability assessment (mean effective weight is 27.36%) while the hydraulic conductivity comes in the second place in this regard with a mean effective weight of 26.95%.

DRASTIC modifications

From the map removal and the single parameter sensitivity analyses discussed above, it seems that both aquifer media and hydraulic conductivity pose a high influence on the vulnerability index which is true since the aquifers are karst.

Greater permeability has a greater pollution-potential rating because they allow contaminants to move greater distances in less duration of time (Hearne et al., 1992). Limestone, permeable sandstone, and unconsolidated sand and gravel have a relatively higher rating for aquifer media because of their higher permeability.

In karst settings, dissolution of limestone and dolomite by groundwater flow along fractures can result in greatly increased hydraulic conductivity (Greene and Rahn 1995). Faster contaminant travel times, which are a function of hydraulic conductivity and hydraulic gradient, have been assigned greater pollution-potential ratings.

DRASTIC assessment assigned medium theoretical weight which is three for both aquifer media and hydraulic conductivity parameters as shown in Table 1. Based on the sensitivity analysis discussed above, the theoretical weight for both parameters was modified and increased to five to account for the karst settings.

Figure 8 presents the modified aquifer vulnerability map for Ramallah District after the above modifications on DRASTIC assessment. It shows that the case study area is under low, moderate and high vulnerability of groundwater to contamination.

It can be concluded here that the theoretical weight for the aquifer media and hydraulic conductivity used in
Fig. 6 Impact of vadose zone media rating map (Ir)

Fig. 7 Groundwater vulnerability map

<table>
<thead>
<tr>
<th>Parameter removed</th>
<th>Variation index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>D</td>
<td>0.98</td>
</tr>
<tr>
<td>R</td>
<td>1.31</td>
</tr>
<tr>
<td>A</td>
<td>2.17</td>
</tr>
<tr>
<td>S</td>
<td>1.53</td>
</tr>
<tr>
<td>T</td>
<td>1.63</td>
</tr>
<tr>
<td>I</td>
<td>1.95</td>
</tr>
<tr>
<td>C</td>
<td>2.15</td>
</tr>
</tbody>
</table>
DRASTIC assessment should be increased in order to be applied for Karst aquifers.

Conclusions

The hydrogeologic settings given in the original DRASTIC method documented by Aller et al. (1987) do not make special provisions for dangerously sensitive karstic and fractured carbonate rock domains. The different uses of DRASTIC show that the assessment is highly adaptable and modifications can enhance DRASTIC output for specific locations and practices. To address carbonate aquifers in karst terrains, DRASTIC assessment was modified by evaluating the relative importance of the DRASTIC’s assessment parameters through sensitivity analysis.
Map removal and the single parameter sensitivity analyses show that net aquifer media and hydraulic conductivity are the most significant environmental factors which dictate the high vulnerability of the aquifer. This highlights the importance of obtaining accurate, detailed, and representative information about these factors. It can be concluded here that the theoretical weight for the aquifer media and hydraulic conductivity used in DRASTIC assessment should be increased in order to be applied for Karst aquifers.

The DRASTIC aquifer vulnerability map indicated that the case study area is under low, moderate and high vulnerability of groundwater to contamination.

The application of DRASTIC assessment for groundwater vulnerability assessment of the case study area has provided a base of information which helps to further define the classification system and its potential role in groundwater management in aquifer basin. In addition, it has significantly improved the knowledge of the characteristics of aquifers.

The vulnerability index can assist in the implementation of groundwater management strategies to prevent degradation of groundwater quality.

Operational policies for groundwater assessment activities should be developed for the different aquifer classes; including types of investigations, monitoring programs and other initiatives that support management. The role of the classification system and how it is integrated with other environmental and resource management activities should be further defined.

Finally, classification results should be explored. Maps and summary information could be made available to the public and stakeholders to raise awareness of the resource.

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