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A Modified DRASTIC Model for Intrinsic Vulnerability Mapping for Karst Aquifers: A Case Study

تطوير نموذج دراستيك لرسم خرائط الحساسية ليتلائم مع طبقات المياه الجوفية كارست: دراسة حالة

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Abstract: Groundwater in karstic aquifers can be dangerously sensitive to contamination. In this paper, the DRASTIC model was modified and applied to address the intrinsic vulnerability of karst aquifers. The theoretical weights of two 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 model was applied to 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 surface contamination. The vulnerability index can assist in the implementation of groundwater management strategies to prevent degradation of groundwater quality. The modified DRASTIC model has proven to be effective because it is relatively straightforward, using data that is commonly available or estimated and produces an end product that is easily interpreted.

Keywords: *aquifer vulnerability, groundwater, DRASTIC index, Karst, Palestine*.

المستخلص: المياه في طبقات المياه الجوفية الكارستية حساسة جدا للتلوث. في هذا البحث، تم تعديل نموذج دراستيك، لأول مرة، لتطبيقه على طبقات المياه الجوفية الكارستية. الأوزان النظرية لاثنين من عوامل نموذج دراستيك (نوعية الصخر المكون للخزان المائي والتوصيل الهيدروليكى) تم تعديلها من خلال إختبارات تحليل الحساسية. تم إجراء اختبارين لتحليل الحساسية: إلغاء خريطة واحدة في أول إختبار ومن ثم الغاء عامل من عوامل نموذج دراستيك في الاختبار الثاني. تم تطبيق نموذج دراستيك المعدل لطبقات المياه الجوفية الكارستية تحت محافظة رام الله (فلسطين) كدراسة حالة. خريطة الحساسيةالتي نتجت عن النموذج العدل حددت المناطق ذات الحساسية العالية والمتوسطة والقليلة للتلوث لمنطقة الدراسة. إن خريطة الحساسية يمكن أن تساعد في تنفيذ استراتيجيات لإدارة المياه الجوفية لمنع تدهور نوعية المياه الجوفية. نموذج دراستيك لمعدل أثبت أنه فعال لأنه واضح نسبيا، والبيانات المطلوب لتطبيقه يمكن توفرها ويعطي منتج نهائي يتم تفسيره بسهولة.

كلمات مدخلية: *حساسية الخزانات الجوفية، مياه جوفية، نموذج دراستك، المياه الجوفية الكارستية، فلسطين.*

INTRODUCTION

Most of the Middle-Eastern countries including, Palestine 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 the already fragile reserves. It is expected that Palestine would experience serious deficit and the water shortage will reach about 270 million m^3 for the year 2020 (Mimi, *et al*. 2003).

Despite the importance of groundwater to 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 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 (Figure 1), are the Lower Cenomanian and the Upper Cenomanian-Turonian complexes which are mainly composed of carbonate rocks such as limestone, dolomite, chalk and chert. Carbonate rock outcrops, of which a large part is karstified, cover the land surface (SUSMAQ, 2003a; SUSMAQ, 2004a).

Groundwater in karstic aquifers can be extremely sensitive to contamination originating from land surface. Major karstic carbonate aquifers are among the most valuable groundwater sources. Karst aquifers are in need of constant attention (Goldscheider, 2005). The DRASTIC model 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 a case study on the intrinsic vulnerability mapping for karst aquifers underlying Ramallah District. The research will modify and apply, for the first time, the DRASTIC model 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 models (Voss, 1984; Carsel, *et al*. 1985; Wagenet and Histon, 1987), (2) statistical models (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; Babiker, *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, and hazard and risk mapping. Unfortunately, it uses data that are commonly unavailable in developing counties (Mimi and Assi, 2009).

The most widely used indexing method is the DRASTIC model. The DRASTIC model 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 10 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. The equation for determining the DRASTIC (vulnerability) index is (Aller, *et al*. 1987):

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

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 200, respectively.

This method has been widely used throughout the world and has proven to be effective because it is relatively straightforward, uses 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 model 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 model by evaluating the relative importance of the DRASTIC model parameters through sensitivity analysis. Two tests of sensitivity analyses will be carried out; the map removal and the single parameter sensitivity analyses. The modified model will be applied on Ramallah District as a case study for this research.

The flexibility of DRASTIC model is an appealing aspect of the model. 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 Myers, 1990) Aquifer Media, Net Recharge, and Impact of the 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

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, Northeastern and Western Basins. Ramallah District lies over the Eastern and Western Basins (Figure 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, chalk and chert.

The Western Mountain Basin underlies about 45% of 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, chert, chalk, and marls which form two aquifers, the Upper and Lower Aquifers. It is overlain by Senonian chalks of the Eocenian 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. A small percentage of the area in the west 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, 2003b).

Fig. 1. Location map for Ramallah District.

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, 2003b).

The study area, often referred to as the model domain, is divided into smaller areas, called cells, such that each area carries a 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).

For each cell 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. The preparation of the DRASTIC input parameters entails processing of 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.

Table 1. Assigned weights for DRASTIC hydrogeologic factors.

Hydrogeologic Factor	Symbol	Weight
Depth to Water	Dw	5
Net Recharge	Rw	4
Aquifer Media	Aw	3
Soil Media	Sw	2
Topography	Tw	1
Impact of the Vadose Zone Media	Iw	5
Aquifer Hydraulic Conductivity	Cw	3

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 model. 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 (Figure 2).

Table 2. Rates for depth to water (Aller, *et al*. 1987).

Range of depth to water (m)	Dr
0-2	10
2-6	9
6-12	7
12-20	5
20-30	3
30-39	2
39+	1

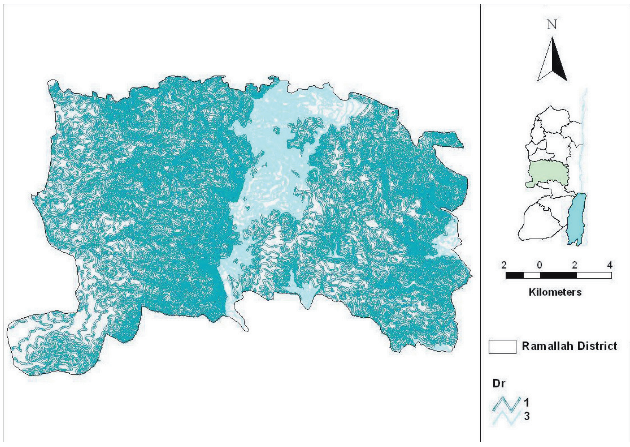

Fig. 2. Rates for depth to water (Dr).

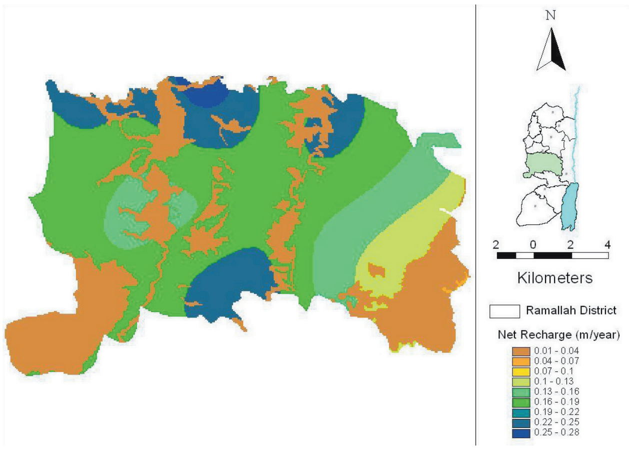

Fig. 3. Recharge for Rammallah District (m/yr).

Table 3. Rates for net recharge (Aller, *et al*. 1987).

Net Recharge(m/year)	
Range	**Rr**
0 – 0.05	1
0.05 -0.1	3
0.1 – 0.18	6
0.18 – 0.25	8
>= 0.25	9

Net Recharge (R)

Recharge values were determined based on rainfall-recharge equations adopted from SUSMAQ, (2004a). These equations were applied depending on outcropping formations in the study area. When the geological formations that form the main aquifers are outcropping, a set of equations (1) for Rainfall-Recharge are applied. Figure (3) presents the recharge (mm/y). The recharge map was converted into grid map where each cell has its own Recharge factor rate (Rr) based on (Table 3) and as shown in (Figure 4).

$$
\begin{aligned}
&R=0.6\,(P-285) && P>700\text{ mm} \\
&R=0.46\,(P-159) && 700\text{ mm}>P>456\text{ mm} \qquad (1) \\
&R=0.3\,(P) && 456\text{ mm}>P
\end{aligned}
$$

where:

R = Recharge from rainfall in mm/y
P = Annual rainfall in mm/y

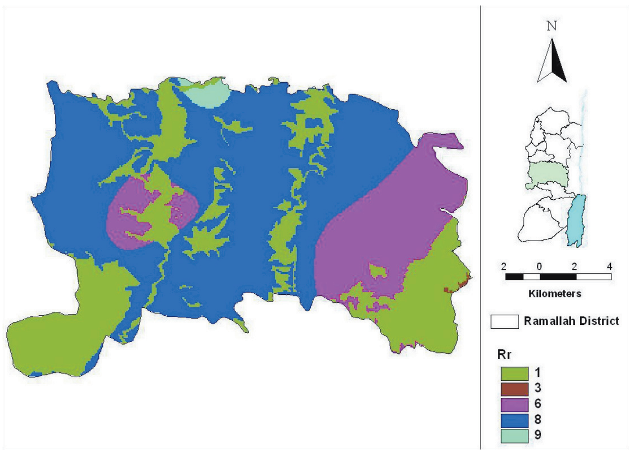

Fig. 4. Rates for net recharge (Rr).

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 composed mainly of carbonate rocks such as limestone, dolomite, chalk and chert. Carbonate rock outcrops, of which a large part is karstified, cover the land surface (SUSMAQ, 2003b; SUSMAQ, 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 groundwater, where they may be transported rapidly in karst conduits over large distances. Therefore, the *Aquifer factor rate* (Ar) was 10 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 as shown in (Figure 5). The soil map was converted into a grid map where each cell has its own Soil factor rate (Sr) based on (Table 4) as shown in (Figure 6) and (Table 5). (SUSMAQ, 2003a; SUSMAQ, 2004a).

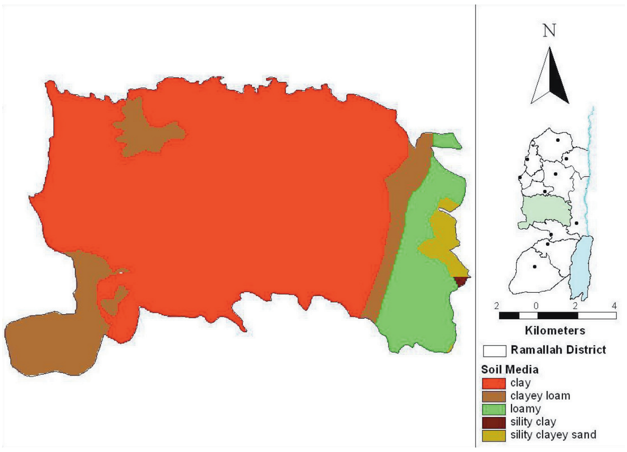

Fig. 5. Soil types distribution for Ramallah District.

Table 4. Rates for net soil media (Aller, *et al*. 1987).

Soil Media	
Range	**S-factor rates (Sr)**
Thin or Absent	10
Gravel	10
Sand	9
Peat	8
Shrinking and/or Aggregated Clay	7
Sandy Loam	6
Loam	5
Silty Loam	4
Clay Loam	3

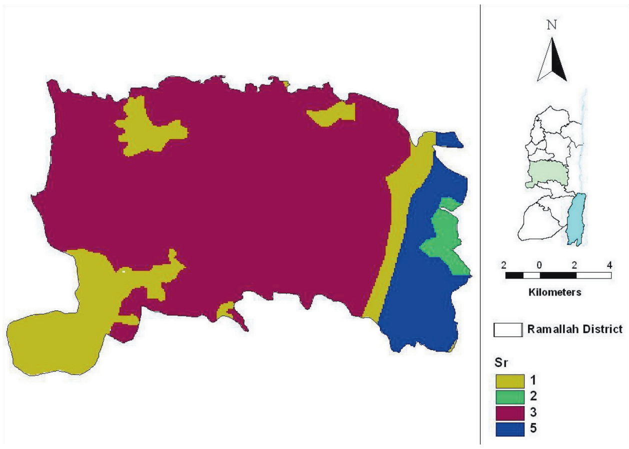

Fig. 6. Rates for soil media (Sr).

Table 5. Top soils and sub-soils and corresponding Sr.

Top Soil Type	Sub-soil type	Sr
Terra Rossa, Brown Rendzinas and Pale Rendzinas	Clay	1
Brown Rendzinas and Pale Rendzinas	Clayey loam	3
Grumusols	Clay	1
Brown Lithosols and Loessial Serozems	Silty clayey sand	5
Brown Lithosols and Loessial Arid Brown Soil	Loamy	5
Loessial Serozems	Silty clay	1

Topography (T)

Due to the 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 high slopes as shown in (Figure 7).

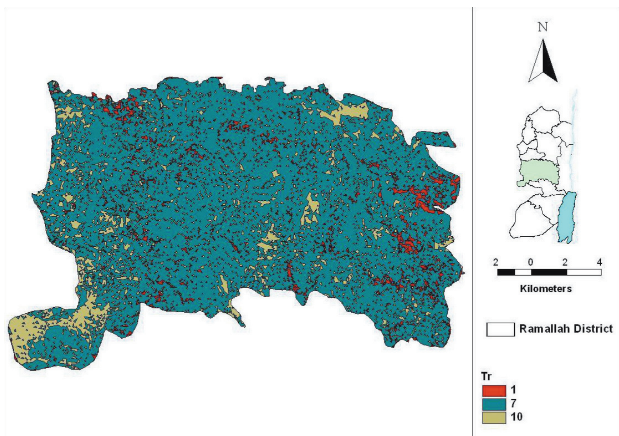

Fig. 7. Rates for topography (Tr).

Impact of the Vadose Zone Media (I)

The impact of the 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 as shown in (Figure 8) by using the Stratigraphical Section of the West Bank (SUSMAQ, 2003b). Table 6) and Figure (9) present the Impact of the vadose zone media factor rates (Ir) for Ramallah District.

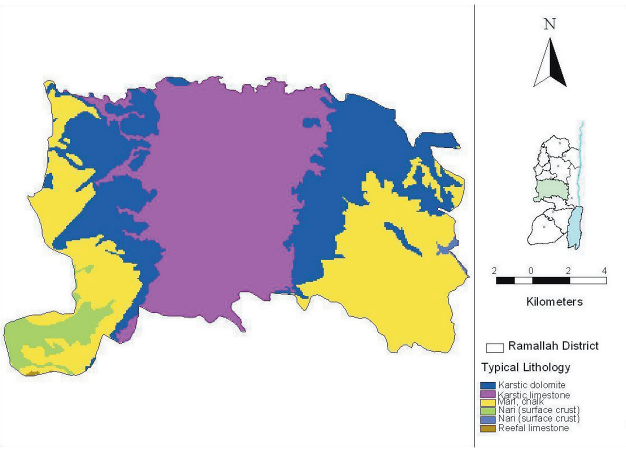

Fig. 8. Typical lithology for geological formation in Ramallah District.

Table 6. Impact of vadose zone media factor rates (Ir).

Protective Aquitards in Subsurface	Ir
Karstic limestone	10
Confining layer	1
Karstic limestone	10
Confining layer	1
marl, marly limestone, dolometic limestone, shale	6
Karstic limestone	10
Confining layer	1
Karstic limestone	10

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 in the 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.

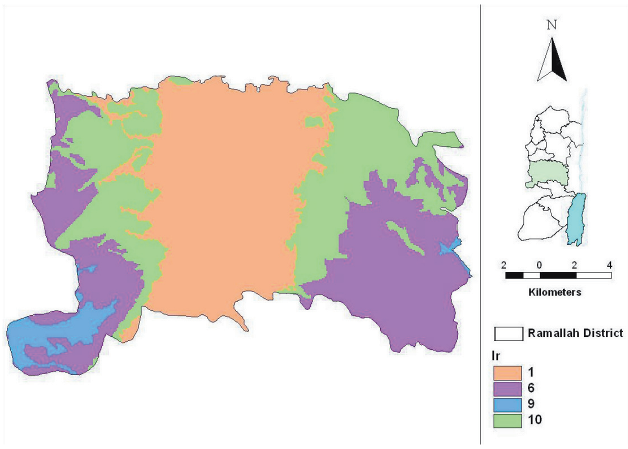

Fig. 9. Rates for impact of the vadose zone media (Ir).

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 equation 1 as shown in (Figure 10). For better assessment, the DRASTIC values were converted into qualitative indices (see Figure 11) based on the classifications furnished earlier. It can be concluded that the study area is under low and moderate vulnerability to groundwater contamination.

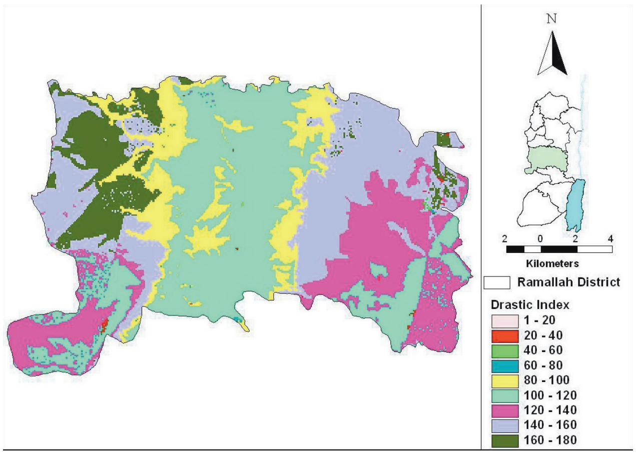

Fig. 10. The vulnerability DRASTIC indices for Ramallah District.

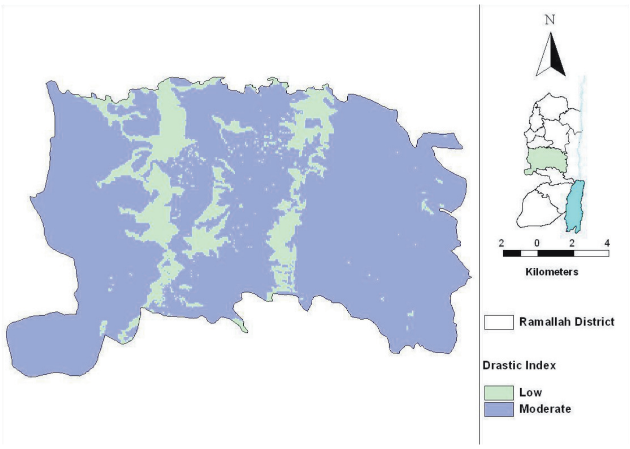

Fig. 11. Aquifer vulnerability map for Ramallah District.

Sensitivity analysis of the model

The DRASTIC model 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 parameter from the vulnerability analysis and is computed using the following equation (Babiker, *et al*. 2005):

$$S = \frac{\left|(V/N)-(V'/n)\right|}{V} \times 100 \qquad (2)$$

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 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, by increasing the number of the removed parameters, the variation index does increase.

Table 7. Statistics of the map removal sensitivity analysis.

Parameter Removed	Variation Index (%)			
	Mean	Minimum	Maximum	Standard Deviation
D	0.98	0.00	3.17	0.61
R	1.31	0.04	4.39	0.63
A	2.17	0.51	11.90	0.98
S	1.53	0.42	2.38	0.38
T	1.63	0.06	2.38	0.58
I	1.95	0.88	7.65	0.76
C	2.15	0.51	4.56	0.91

Table 8. Statistics of map removal sensitivity analysis.

Parameter used	Variation Index (%)			
	Mean	Minimum	Maximum	Standard Deviation
D,R,S,T,I and C	2.17	0.51	11.90	0.98
D,R,S,T and I	5.14	0.05	11.43	2.24
R,S,T and I	5.28	0.02	14.28	3.63
R,S and T	7.54	0.07	14.28	2.83
R and S	7.68	0.00	14.28	3.64
R	7.91	0.25	26.39	3.82

Single parameter sensitivity analysis

The single parameter sensitivity analysis compares the effective weights with the theoretical weights of the parameters used in the DRASTIC index computation (see Table 1). The effective weight is computed for each cell in the model domain using the following formula (Babiker, *et al*. 2005):

$$W = \frac{PrPw}{V} X100 \tag{3}$$

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 model. 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 with a mean effective weight is 27.36% while the hydraulic conductivity comes in second place with a mean effective weight of 26.95%.

DRASTIC Modifications

From the map removal and the single parameter sensitivity analyses discussed above, 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 shorter amounts 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 permeabilities.

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.

The DRASTIC model assigned medium theoretical weight (3) for both aquifer media and hydraulic conductivity parameters are shown in (Table 1). Based on the sensitivity analysis discussed above, the theoretical weight for both parameters was modified and increased to 5 to account for the karst settings.

Figure (12) presents the modified aquifer vulnerability map for Ramallah District after the above modifications on the DRASTIC model. It shows that the case study area is under low, moderate and high vulnerability to groundwater contamination. It can be concluded here that the theoretical weight for the aquifer media and hydraulic conductivity used in the DRASTIC model should be increased in order to be applied for Karst aquifers.

Table 9. Statistics of the single parameter sensitivity analysis.

Parameter	Theoretical Weight	Theoretical weight (%)	Effective weight (%)			
			Mean	Minimum	Maximum	Standard Deviation
D	5	21.7	9.58	0.00	33.33	5.14
R	4	17.4	10.65	0.00	40.67	8.00
A	3	13.0	27.36	17.34	85.71	5.89
S	2	8.7	5.05	0.00	11.76	2.32
T	1	4.3	4.52	0.00	13.88	3.49
I	5	21.7	15.86	0.00	60.24	12.49
C	3	13.0	26.95	0.00	41.66	6.14

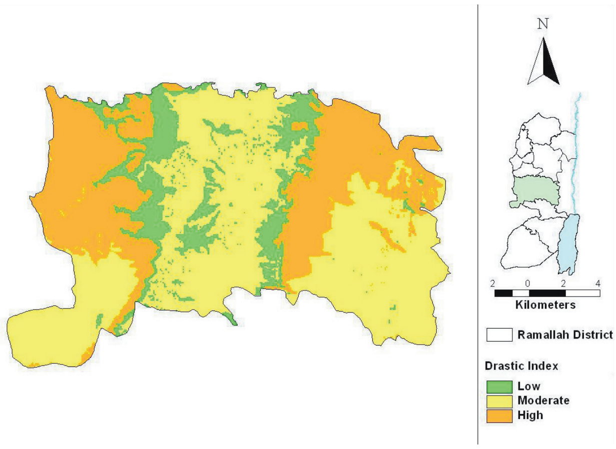

Fig. 12. Modified aquifer vulnerability map for Ramallah District.

CONCLUSION AND RECOMMENDATIONS

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 shows that the model is highly adaptable and modifications can enhance the DRASTIC output for specific locations and practices.

To address carbonate aquifers in karst terrains, the DRASTIC model was modified by evaluating the relative importance of the DRASTIC's model parameters through sensitivity analysis. Map removal and the single parameter sensitivity analyses indicated 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 two factors. It can be concluded here that the theoretical weight for the aquifer media and hydraulic conductivity used in the DRASTIC model 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 to groundwater contamination. The application of DRASTIC model for groundwater vulnerability assessment of the case study area has provided a base of information which helps further define the classification system and its potential role in groundwater management in aquifer basins. Also, it has significantly improved 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 different 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 to the stakeholders to raise awareness of the resource.

REFERENCES

Al-Adamat, R, Foster, I, and **Baban, S** (2003). Groundwater vulnerability and risk mapping for the Basaltic aquifer of the Azraq basin of Jordan using GIS, Remote Sensing and DRASTIC. *Applied Geography* **23:** 303–324.

Almasri, M (2008) Assessment of intrinsic vulnerability to contamination for Gaza coastal aquifer, Palestine. *Journal of Environmental Management* **88 (4)**: 577-1662.

Aller, L, Bennett, T, Lehr, J, Petty, R, and **Hackett, G** (1987) *DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings*. US Environ Prot Agency (EPA) /600/2-87/035.

Babiker, I, Mohamed, M, Hiyama, T, and **Kato, K** (2005) A GIS based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, Central Japan. *Science of the Total Environment* **345 (1-3)**: 127–140.

Banton, O, and **Villeneuve, J** (1989) Evaluation of groundwater vulnerability to pesticides: a comparison between the pesticides DRASTIC index and the PRZM leaching quantities. *Journal of Contaminant Hydrology* **4:** 285–296.

Carsel, R, Mulkey, L, Lorber, M, and **Baskin, L** (1985) The pesticide root zone model (PRZM): a procedure for evaluating pesticide leaching threats to ground water. *Ecological Modeling* **30:**49–69.

Connell, L, and **Daele, G** (2003) A quantitative approach to aquifer vulnerability mapping. *Journal of Hydrology* **276:** 71–88.

Evans, B, and **Mayers, W** (1990) A GIS-based approach to evaluating regional groundwater pollution potential with DRASTIC. *Journal of Soil and Water Conservation* **45:** 242–245.

Goldscheider, N (2005) Karst groundwater vulnerability mapping: application of a new method in the Swabian Alb, Germany. *Hydrogeology Journal* **13:** 555–564.

Gomezdelcampo, E, and **Dickerson, R** (2008) A modified DRASTIC model for Siting Confined Animal Feeding Operations in Williams County, Ohio, USA. *Environmental Geology* **55** (**8**): 1821-1832.

Greene, E, and **Rahn, P** (1995) Localized anisotropic transmissivity in a karst aquifer. *Ground Water* **33(5):**806–816.

Hearne, G, Wireman, M, Campbell, A, Turner, S, and **Ingersoll, G** (1992*) Vulnerability of The Uppermost Ground Water to Contamination in The Greater Denver Area*. US Geol Survey Water Resourorces Report, 92-4143.

Naqa, A (2004) Aquifer vulnerability assessment using the DRASTIC model at Russeifa landfill, northeast Jordan. *Environmental Geology* **43**: 51–62.

Nolan, B, Hitt, and **K, Ruddy, B** (2002) Probability of nitrate contamination of recently recharged ground waters in the conterminous United States. *Environmental Science and Technology* **36 (10):** 2138–2145.

Mimi, Z, Ziara, M, and **Nigim, H** (2003) Water conservation and its perception in Palestine – a case study. *Water and Environmental Management J* **17:** 152-156.

Mimi, Z, and **Assi, A** (2009) Intrinsic vulnerability, hazard and risk mapping for Karst Aquifers: a case study. *Journal of Hydrology* **364(3-4):** 298-310.

Rofe and Raffety, (1963) *West Bank Hydrology*. Rofe and Raffety Consulting Engineers, Westminister, London.

Rupert, M (2001) Calibration of the DRASTIC ground water vulnerability mapping method. *Ground Water***39 (4):** 630–635.

SUSMAQ, (2003a) *Compiled Base Data for The Numeric Flow Model of The Western Aquifer Basin, Sustainable Management of The West Bank & Gaza Aquifers*. Palestinian Water Authority and University of Newcastle Upon Tyne, Ramallah, 314pp.

SUSMAQ, (2003b) *Hydrogeochemistry of Aquifers of The West Bank. Review and Interpretation of The Available Data With Regard to Recharge, Water Quality And Groundwater Flow*. Palestinian Water Authority and University of Newcastle Upon Tyne.

SUSMAQ, (2004a) *Steady State Flow Model of the Western Aquifer Basin, Sustainable Management of The West Bank & Gaza Aquifers*. Palestinian Water Authority and University of Newcastle Upon Tyne.

SUSMAQ, (2004b) *Hydrogeological Map of The West Bank, 1: 250 000 Scale, British Geological Survey*. University of Newcastle Upon Tyne. Palestinian Water Authority.

Twarakavi, N, and **Kaluarachchi, J** (2005) Aquifer vulnerability assessment to heavy metals using ordinal logistic regression. *Ground Water* **43 (2):** 200–214.

UNEP, (2003) *Desk Study on The Environment in the Occupied Palestinian Territories*. United Nations Environment Program.

Voss, C (1984) *A finite Element Simulation Model for Unsaturated Saturated Fluid Density-Dependent Groundwater Flow with Energy Transport or Chemically Reactive Single-Species Solute Transport*. USGS Water Resource Investigations Report 84-4369, US Geological Survey, Reston, VA.

Wagenet, R, and **Histon, J** (1987) Predicting the fate of nonvolatile pesticides in the unsaturated zone. *Journal of Environmental*

Quality **15:** 315–322.

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