Groundwater vulnerability assessment and evaluation of human activity impact (HAI) within the Dead Sea groundwater basin, Jordan

Ahmad Al-Hanbali · Akihiko Kondoh

Abstract Groundwater vulnerability to contamination was determined within the Dead Sea groundwater basin, Jordan, using the DRASTIC model and evaluation of human activity impact (HAI). DRASTIC is an index model composed of several hydrogeological parameters and, in this study, the recharge parameter component was calculated as a function of rainfall, soil permeability, slope percentage, fault system, and the intersection locations between the fault system and the drainage system, based on the hydrogeologic characteristics of hard-rock terrain in an arid region. To evaluate the HAI index, a land use/cover map was produced using an ASTER VNIR image, acquired for September 2004, and combined with the resultant DRASTIC model. By comparing the DRASTIC and HAI indices, it is found that human activity is affecting the groundwater quality and increasing its pollution risk. The land use/cover map was verified using the average nitrate concentrations in groundwater associated with land in each class. A sensitivity analysis was carried out in order to study the model sensitivity. The analyses showed that the depth to water table and hydraulic conductivity parameters have no significant impact on the model, whereas the impact of vadose zone, aquifer media, and recharge parameters have a significant impact on the DRASTIC model.

Résumé La vulnérabilité des eaux souterraines envers les contaminations a été étudiée sur le bassin hydrogéologique de la Mer Morte en Jordanie, en utilisant le modèle DRASTIC et l'évaluation de l'impact des activités humaines (HAI). DRASTIC est un modèle indexé composé de plusieurs paramètres hydrogéologiques ; dans la présente étude, le paramètre "alimentation" a été calculé comme une fonction des précipitations, de la perméabilité du sol, de la pente, de la fracturation et des positions des intersections entre système de drainage et fracturation, sur la base des caractéristiques hydrogéologiques des roches dures en région aride. Afin d'évaluer l'indice HAI, une carte d'occupation des sols a été construite à partir d'une image ASTER VNIR datant de septembre 2004, puis combinée avec le modèle DRASTIC résultant. La comparaison des indices DRASTIC et HAI fait apparaître que l'activité humaine affecte la qualité des eaux souterraines et augmente les risques de pollution. La carte d'occupation des sols a été validée par les concentrations en nitrates dans les eaux souterraines associées au terrain dans chaque classe. Une analyse de sensibilité a été effectuée dans le but d'étudier la sensibilité du modèle. Les analyses ont montré que la profondeur de la surface piézométrique et la perméabilité n'ont pas d'impact notable sur le modèle, tandis que l'impact de la zone non-saturée, la matrice de l'aquifère et les paramètres d'alimentation ont une influence significative sur le modèle DRASTIC.

Resumen La vulnerabilidad a contaminación de agua subterránea en la cuenca del Mar Muerto, Jordania, fue determinada usando el modelo DRASTIC y la evaluación de impacto de actividad humana (HAI). DRASTIC es un método index compuesto de varios parámetros hidrogeológicos y, en este estudio, el parámetro de descarga fue calculado como una función de la precipitación, permeabilidad del suelo, porcentaje de pendiente, sistema de fallas, y las áreas de intersección entre sistema de fallas y sistema de drenaje, considerando las características de terreno de roca dura en una región árida. Para evaluar el index HAI, un mapa de uso de suelo/cubierta fue producido usando una imagen ASTER VNIR, obtenida en Septiembre 2004, y que fue combinada con el modelo DRASTIC resultante. Por medio de una comparación entre los resultados de DRASTIC y HAI, se encontró que la actividad humana está afectando la calidad del agua subterránea e incrementando el riesgo de contaminación. El mapa de uso de suelo/cubierta fue verificado usando las concentraciones promedio de nitrato en agua subterránea asociadas con cada tipo de suelo. Un análisis de sensibilidad fue realizado para estudiar la sensibilidad del modelo. El análisis mostró que los parámetros profundidad al nivel del agua y conductividad hidráulica no tienen impacto significativo en el modelo, mientras que el impacto de los parámetros zona vadosa, tipo de

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acuífero, y recarga tienen un impacto significativo en el modelo DRASTIC.

Keywords DRASTIC · Groundwater management · Dead Sea · Geographic information systems · Jordan

Introduction

The Dead Sea groundwater basin (DSGWB) is considered as one of the most important basins in Jordan. The surface and groundwater in the basin are used mainly in Amman, Madaba, and Karak counties for domestic, industrial, and partially for irrigation purposes (JICA 2001). Urbanization and agricultural activities on the surface of aquifers could be considered as 'hazards' and potential sources of groundwater pollution, which may alter the water quality and reduce its value to the end user (Babiker et al. 2005). Therefore, assessment of groundwater vulnerability to contamination is very important in order to understand the possible extent of groundwater pollution and to know how to apply an effective groundwater management strategy. The assessment of groundwater quality through field investigations on a regional scale is often not effective, since it is time-consuming and costly. Therefore, several methods have been developed to evaluate groundwater vulnerability. The methods can be divided into three main categories: process based-methods, statistical methods, and overlay and index methods (Vrba and Zaporozec 1994; Tesoriero et al. 1998; Gogu and Dassargues 2000). Choosing an appropriate method will depend on many factors such as the scale of the study area, data availability, and desired results.

The process-based methods are used to predict the contaminant transport in both space and time, and require numerical equations and simulation models. However, they are characterized by insufficient data and computational complexities, and can be useful for local scales but not for regional ones. Statistical methods are based on statistical correlations between spatial variables and actual occurrence of pollutants in the groundwater. These methods are limited by shortage of water quality observations, data accuracy and choices in spatial variables (Babiker et al. 2005).

Overlay and index methods combine maps of the factors that control the movement of contaminants from the ground surface to the saturated zone. The results are in the form of vulnerability indices at different locations. The major advantage is that most of the input data could be available at regional scale, although the main disadvantage of this method is the problem of suitably assigning appropriate numerical values to descriptive components.

The DRASTIC model was developed by the US Environmental Protection Agency (US EPA), and has appeared to be a standardized system for evaluating groundwater vulnerability to contamination (Aller et al. 1987). The DRASTIC index model can be used to recognize areas that are more vulnerable to contamination than others, or to give priorities to areas that need more groundwater monitoring. The DRASTIC model is applicable in humid climates (Babiker et al. 2005; Piscopo 2001; Kim and Hamm 1999; and Osborn et al. 1998) as well as in semi-arid to arid climates (Werz and Hötzl 2007; Al-Adamat et al. 2003; Secunda et al. 1998).

There are two main objectives of this study; namely to evaluate the groundwater vulnerability to contamination within the DSGWB using the hydrogeological parameters of the DRASTIC model, and to evaluate the impact of human activity on the groundwater. To evaluate human activity, Advance Space-borne Thermal Emission and Reflection Radiometer (ASTER) visible and near infrared radiometer (VNIR) data were employed to map urban and agricultural areas within the study area (ERSDAC 2005). Moreover, a sensitivity analysis was applied to evaluate the relative importance of the DRASTIC model parameters based on the characteristics of the DSGWB. A geographic information system (GIS) was used in this research, due to its capability in implementing and representing the DRASTIC index spatially.

Study area

The study area, as shown in Fig. 1, is part of the DSGWB. The major cities such as Amman, Madaba, and Karak, and agricultural activities present 'hazards' and the study area was defined based on the location of these hazards.

The study area covers about 4,483 km^2. It is located in the western part of Jordan, east of the Dead Sea, which is famous for being the lowest point on the Earth at an elevation of 416.3 m below sea level (Closson et al. 2005), and the saltiest lake in the world with a salinity concentration of 332 kg/m^3 (Asmar and Ergenzinger 1999).

Climate

The climate in the study area varies from arid to semi-arid. Specifically, large parts of the study area belong to the eastern highlands of Jordan. Overall, the climate is moderate in summer and cold in winter with an average rainfall of 335 mm/year and the air temperature ranges from 10 to 22°C. The western part of the study area is lowland and arid. It is hot in summer and warm in winter; the average rainfall is less than 75 mm/year, and the air temperature ranges from 20 to 31°C.

Topography

Topographic information was obtained from a digital elevation model (DEM) acquired by the Shuttle Radar Topography Mission (SRTM) of the National Geospatial–Intelligence Agency (NGA) 2006. The DEM has a resolution of 79×79 m, and is available at the Global Land Cover Facility (GLCF) of Maryland University, USA. The elevation of the study area ranges from 416.3 m below sea level to 1,270 m above sea level, as shown in Fig. 2a. The slope angle ranges from 0 to 29.9° with an average of 3.1° towards the Dead Sea.

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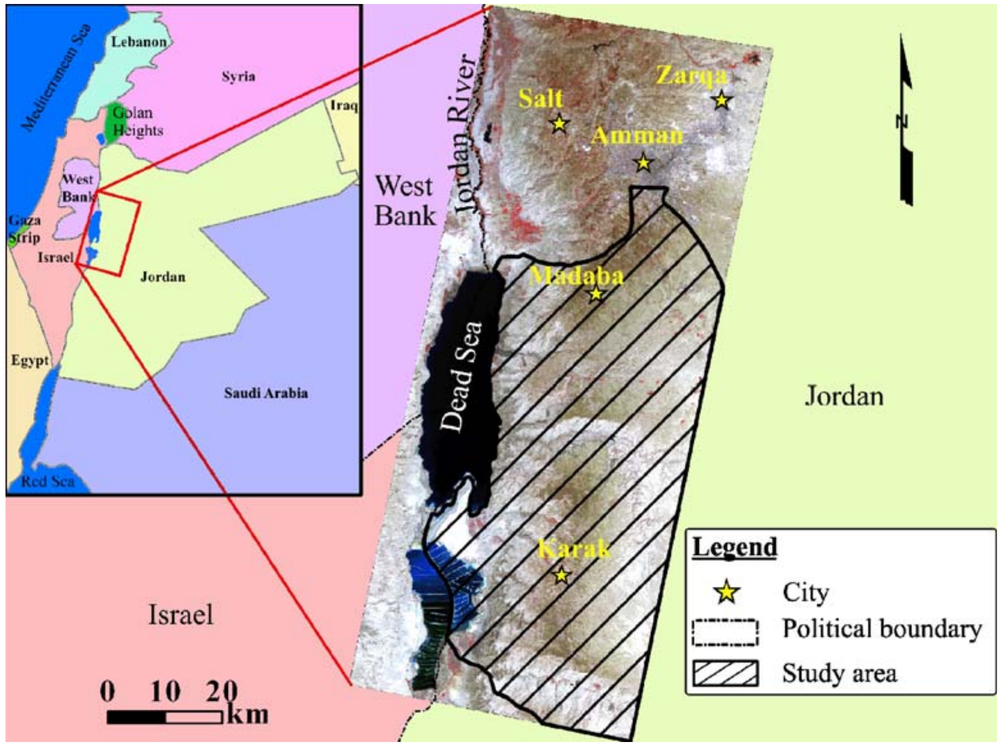

Fig. 1 Location map of the study area in Jordan

Geology

The study area is underlain by Paleozoic, Mesozoic, and Cenozoic sedimentary rocks in addition to some volcanic rocks of Quaternary age (Parker 1970). The Ram Group outcrops in the southwestern part of the study area and incorporates the following formations from base to top; Salib Arkosic Sandstone, Burj Dolomite-Shale, Umm Ishrin Sandstone, and Disi Sandstone (Powell 1988). The group ranges in age from Lower Cambrian to Ordovician and consists of medium to course–grained pebbly and non-pebbly quartz-arenite, sub-arkosic and arkosic sandstone.

The Kurnub Group is exposed in the extreme western part of the study area and consists mainly of massive white and varicolored sandstones intercalated with shales, clays and marls. The Ajlun Group outcrops along the western and central parts of the study area and consists mostly of alternating limestone, marly limestone, marls, and shales. The undifferentiated formations (A1–A6) outcrop in the western part of the study area and overlay the Kurnub Group. Wadi Sir Formation (A7) is exposed along the course of the study area, and it is relatively fractured and karstified (El-Naqa 1994).

The Belqa Group conformably overlies the Ajlun Group and consists mainly of alternating chalks and chalky limestone, cherts, and chalky marl. This group starts with the undifferentiated formation, Ghudran–Amman (B1–B2), which covers the majority of the study area. The Amman Formation (B2) consists mainly of highly fractured chert and limestone, and it is considered an excellent aquifer. The Muwaqqar Formation (B3) overlies the Amman Formation (B2) and consists mostly of soft, thick-bedded chalky marl and chalky limestone.

Pleistocene basalt flows cover the Belqa Group and outcrop in the southern part of the study area as well as near Wadi Zarqa-Ma'in area Fig. 2b. Quaternary fluvial deposits, marls (Lisan Marl), clays and gypsum cover the northern and southern parts of the Dead Sea (Bender 1974; Rimawi and Salameh 1988).

The geological structures in the area are affected by the Jordan Dead Sea Rift Valley (Bender 1974). Therefore, many faults exist within the study area. These faults are supposed to be potential locations for recharging the groundwater, since in these faults the rainfall can percolate directly into the groundwater through the fractured zone.

Wadis

Due to the high difference in elevation in the study area, many wadis are identifiable, as shown in Fig. 2b. Two of them are major wadis and the rest are small wadis: the major wadis are Wadi Mujib in the central part of the study area and Wadi Hasa in the southern part of the study area. The small wadis from, north to south, are Wadi Zarqa-Ma'in, Wadi Heidan, Wadi Shaqeeq, Wadi Iben Hammad, Wadi Karak, Wadi Esal, and Wadi Numeira. The wadis represent the drainage system within the DSGWB.

Soil

There are five soil textures in the study area; sand, loam, silt loam, silty clay loam, and silt clay (Batjes et al. 2003), and the latter covers most of the study area as shown in Fig. 2c.

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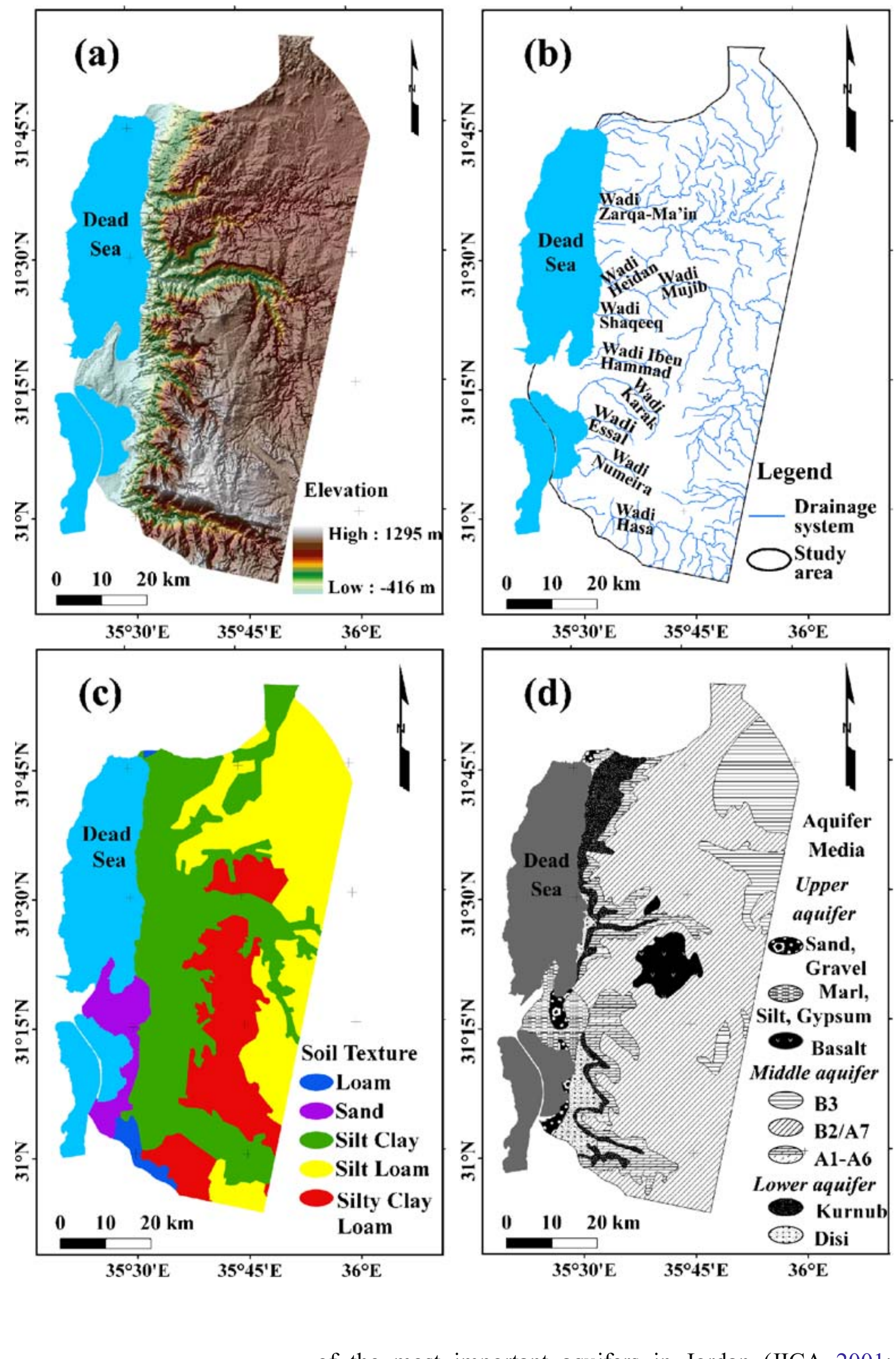

Fig. 2 Description of the study area: **a** topography relative to sea level (derived from a digital elevation model), **b** drainage system and wadis, **c** soil texture, and **d** aquifer media. *B3* Muwaqqar Formation, *B2/A7* Amman-Wadi Sir aquifer system, *A1–A6* Ajlun Group

Hydrogeology

Three major aquifer systems exist within the study area: the lower aquifer system, the middle aquifer system, and the upper aquifer system (JICA 2001) as shown in Fig. 2d. The lower aquifer system consists of two geological groups: the Ram Group and Kurnub Group. These two groups are hydraulically interconnected, forming the lower aquifer system. The average thickness of the lower aquifer system is about 1,000 m, and it is considered one of the most important aquifers in Jordan (JICA 2001; Bender et al. 1989). The lower aquifer system is overlain by undifferentiated formations of the Ajlun Group (A1–A6) of low permeability, consequently acting as an aquitard separating the lower aquifer system from the middle aquifer system (JICA 2001; El-Naqa 1994; Bender et al. 1989).

The middle aquifer system covers most of the study area. The main aquifer in this system is called the

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Amman-Wadi Sir aquifer system (B2/A7). This aquifer is affected by tectonic deformations that are characterized by the presence of fracturing and karstification within the matrix (El-Naqa 1994). The B2/A7 aquifer behaves as a phreatic aquifer, where precipitation enters directly through the fractured outcrops of the Amman - Wadi Sir Formations. In the eastern side of the study area, the aquifer is overlain by the Muwaqqar Formation (B3), which acts as a confining layer. The upper aquifer system, of Quaternary age, consists mainly of sand and gravel layers, and basalt. The upper aquifer system outcrops in the northwestern and southwestern parts of the study area, as well as in the central part of the study area.

Methodology

Development of DRASTIC model

The DRASTIC model is composed of seven hydrogeologic parameters: *D*epth to water table, net *R*echarge, *A*quifer media, *S*oil media, *T*opography (slope), *I*mpact of the vadose zone, and hydraulic *C*onductivity. Each of these hydrogeologic factors is assigned a rating (1–10) and a weighting (1–5). The DRASTIC index is calculated applying a linear combination of all the factors according to the following equation:

$$\text{DRASTIC index} = 5D + 4R + 3A + 2S + T + 5I + 3C \quad (1)$$

Data are obtained from several sources to construct thematic layers of the seven model parameters. A description of each DRASTIC parameter and its source for this case study is available in Table 1. The rating and weighting system of Aller et al. (1987) is used for each of the traditional seven parameters of DRASTIC methodology. In the methodology section, focus will be put on calculating the recharge parameter by taking into consideration the fault and drainage systems.

Net recharge

The recharge is calculated based on the method of Piscopo (2001), whose research replaced the recharge parameter (net recharge) as defined by the US EPA with the potential of an area to have recharge. In other words, the net recharge parameter changed to the ability of an area to act as a recharge zone relative to another area. Therefore, Piscope used Eq. (2) to calculate the potential recharge;

$$\text{RV} = \text{RF} + \text{S\%} + \text{SP} \quad (2)$$

Where RV = recharge value, RF = rainfall factor (or rainfall amount), S% = slope percentage, and SP = soil permeability.

Each of these parameters (RF, S%, SP) is assigned a rating based on its ability to increase the potential recharge value. Then, this recharge value is grouped into a range of values that are given a rating for use in the final DRASTIC calculation. However, since the study area is located in an arid region, the recharge locations are very limited. Therefore, the parameters mentioned in Eq (2) are not the only effective parameters for groundwater recharge, but there are also other parameters which can increase the groundwater recharge. Specifically, the presence of faults and the intersection locations between the fault and drainage systems are very effective and very important factors for feeding the groundwater.

Particularly, the distance from the fault system (F) should be taken into consideration during the calculation. The closer the fault system, the higher the rating, as shown in Fig. 3. The locations in which the drainage

Table 1 The DRASTIC model parameters used in this study

Factor	Description	Source
Depth to water	Represents the depth from the ground surface to the water table. Deeper water table implies lesser chance for pollution to occur	Well data obtained from Ministry of Water and Irrigation, Jordan
Net recharge	Represents the amount of water that penetrates the vadose zone and reaches the water table. Recharge water represents the vehicle for transporting pollutants	Calculated in this research
Aquifer media	Refers to the saturated zone material properties, which control the pollutant attenuation processes	Interpretation of geological map scale 1:250,000 obtained from Natural Resources Authority, Jordan
Soil media	Represents the uppermost weathered portion of the vadose zone and controls the amount of recharge that can infiltrate downward	Soil map scale 1:800,000 (Batjes et al. 2003)
Topography	Refers to the slope of the land surface. It indicates whether the runoff will remain on the surface to allow pollutant percolation to the saturated zone	Digital elevation model (DEM) of SRTM data available at Global Land Cover Facility (GLCF) of Maryland University
Impact of vadose zone	This is defined by the vadose zone material, which controls the passage and attenuation of the contaminated material to the saturated zone. In this research, vadose zone and aquifer media are the same material	Interpretation of geological map scale 1:250,000 obtained from Natural Resources Authority, Jordan
Hydraulic conductivity	Indicates the ability of the aquifer to transmit water, thus determines the rate of flow of the contaminant within the groundwater system	Derived from previous literature such as Bender et al. (1989)

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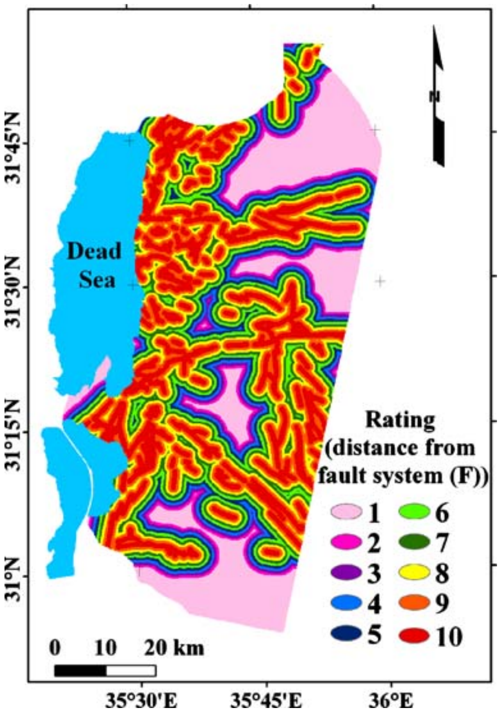

Fig. 3 The ratings assigned to the distance from the fault system (*F*). A rating of 10 was given to distance 0–500 m, whereas, a rating of 1 was given to distance >4,500 m

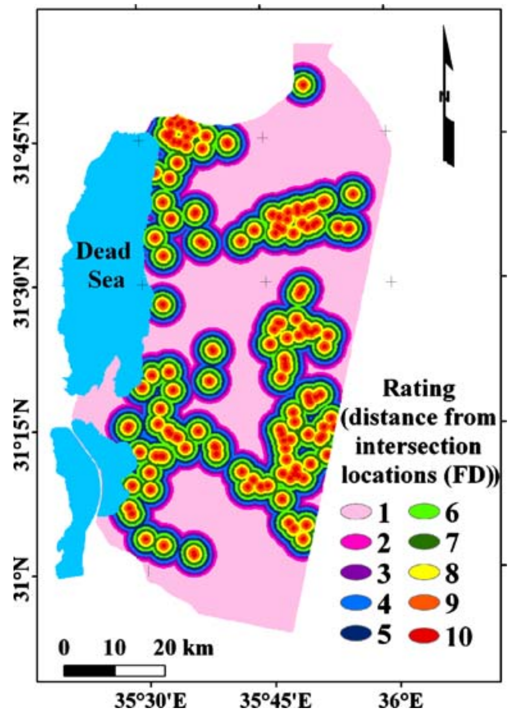

Fig. 5 The ratings assigned to the distance from the intersection locations (FD). A rating of 10 was given to distance 0–500 m, whereas, a rating of 1 was given to distance >4,500 m

system intersects the fault system are considered the most rechargeable locations as shown in Fig. 4, and should also be taken into consideration. In these locations the water is assumed to infiltrate directly through the vadose zone and reach the water table. Thus, the shorter the distance to these locations (FD), the higher the rating as shown in Fig. 5.

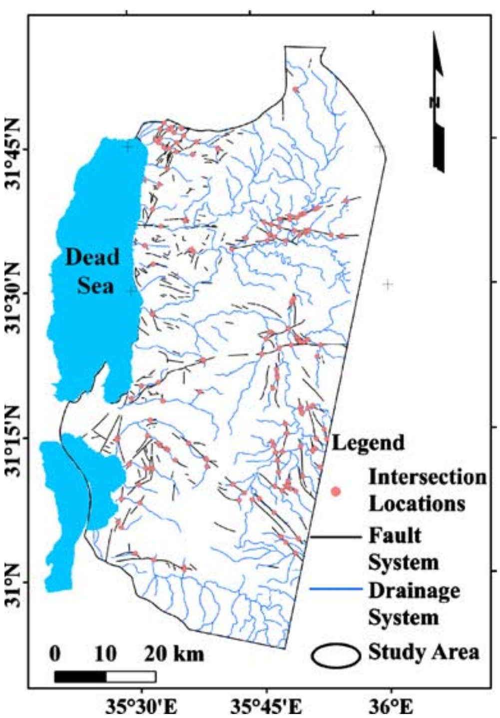

Fig. 4 The intersection locations between the drainage system and the fault system

The distance from the fault system (F) and from the intersection location (FD) are measured using a GIS technique at intervals of 500 m. The distance range 0 m–500 m is assigned a rating of 10, whereas the distance of more than 4,500 m is assigned a rating of 1 as illustrated in Table 2. However, in some places, the surface water drainage system does not exist and only the fault system exists. Therefore, these areas should have lower ratings than the areas that contain both drainage and fault systems. For this reason, the average of the distance from the fault system and the distance from the intersection locations $\left(\overline{\mathrm{F}-\mathrm{FD}}\right)$ is calculated as shown in Fig. 6 and then added to Eq. (2).

Equation (3) shows the final formula for calculating the recharge value:

$$\mathrm{RV}=\mathrm{RF}+\mathrm{S}\%+\mathrm{SP}+\overline{\mathrm{F}-\mathrm{FD}} \tag{3}$$

Where $\left(\overline{\mathrm{F}-\mathrm{FD}}\right)$ = rating of the average of the distance from the fault system (F) and the distance from the intersection locations between the fault and the drainage systems (FD).

To estimate rainfall amount, the average yearly rainfall value is used in Eq. (3). Rainfall data are derived from seven meteorological stations distributed in the whole study area. Since the average yearly rainfall in the study area is less than 500 mm/year, the rainfall factor (RF) is assigned a rating of 1 for the whole area. The slope (S%) map is created from the DEM, and it is classified based on the rating system of Aller et al. (1987). The soil

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Table 2 Parameters used to calculate recharge value (RV) and their ratings

RF (mm)	Rating	S%	Rating	SP (Range)	Rating	F (m)	Rating	FD (m)	Rating	$\overline{(F-FD)}$ (m)	Rating	RV (Range)	RV Rating
<500	1	0–2	10	High	5	0–500	10	0–500	10	0–500	10	24–26	10
		2–6	9	Moderate	3	500–1,000	9	500–1,000	9	500–1,000	9	21–23	9
		6–12	5	Low	2	1,000–1,500	8	1,000–1,500	8	1,000–1,500	8	19–20	8
		12–18	3			1,500–2,000	7	1,500–2,000	7	1,500–2,000	7	17–18	7
		> 18	1			2,000–2,500	6	2,000–2,500	6	2,000–2,500	6	15–16	6
						2,500–3,000	5	2,500–3,000	5	2,500–3,000	5	13–14	5
						3,000–3500	4	3,000–3500	4	3,000–3500	4	11–12	4
						3,500–4,000	3	3,500–4,000	3	3,500–4,000	3	9–10	3
						4,000–4,500	2	4,000–4,500	2	4,000–4,500	2	7–8	2
						>4,500	1	>4,500	1	>4,500	1	5–6	1

RF rainfall factor, *S%* slope percentage, *SP* soil permeability, *F* distance from fault system, *FD* distance from intersection locations, and $\overline{(F-FD)}$ refers to the average of the distance from the fault system (*F*) and the distance from the intersection locations between the fault system and drainage system (*FD*)

permeability (SP) map is classified as low, moderate, and high permeability. Finally, the resultant average distance map is rated according to criteria mentioned in Table 2.

The resultant recharge map from Eq. (3) is then grouped into a range of recharge values that are given a rating (RV Rating) from 1–10 as shown in Table 2 and Fig. 7.

Development of human activity impact (HAI)

Industrial activities, traffic, septic tanks and sewer systems within urban areas and fertilizers, used in agriculture, are considered as 'hazards' (Zwahlen 2004) and categorized under the HAI parameter. These hazards can affect the groundwater quality and increase its pollution risk.

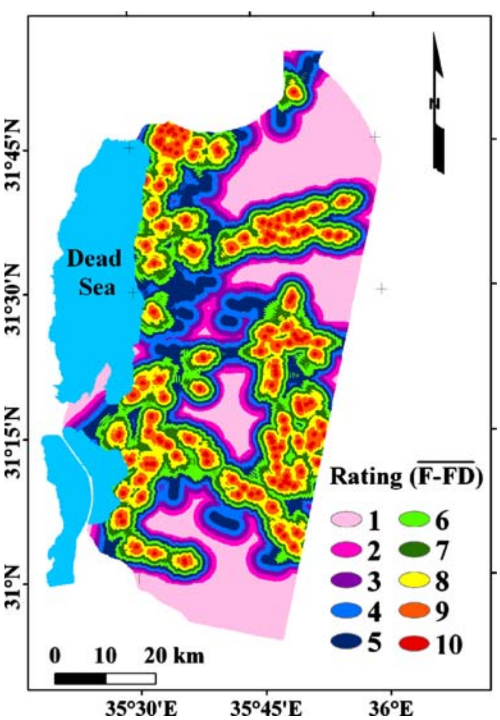

Fig. 6 The ratings assigned to $\overline{(F-FD)}$ distance—$\overline{(F-FD)}$ refers to the average of the distance from the fault system (*F*) and the distance from the intersection locations between the fault system and drainage system (*FD*)

To study HAI on the groundwater, a land use/cover map was produced using ASTER VNIR data, 15-m spatial resolution acquired for September 2004, as shown in Fig. 8a. The ASTER image is georeferenced to Universal Transverse Mercator (UTM) projection and the WGS84 ellipsoid. A supervised classification system using a maximum likelihood classifier was applied. Maximum likelihood classification assumes that the statistics for each class in each band are normally distributed and calculates the probability that a given pixel belongs to a specific class. The ASTER image is classified into six land use/cover classes: urban, agriculture, natural vegetation, water, evaporation pond, and bare land, as illustrated in Fig. 8b. However, the water and evaporation pond classes are excluded from the calculation since the objective of this research is to evaluate the groundwater risk from the land surface and not from water bodies.

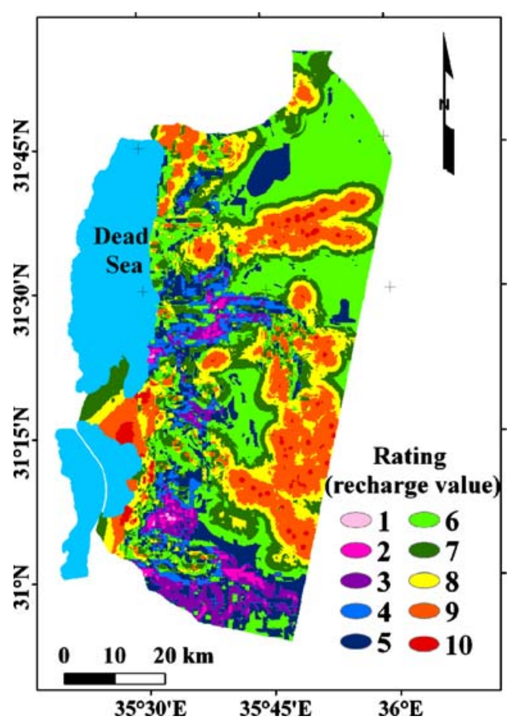

Fig. 7 The ratings assigned to the recharge parameter

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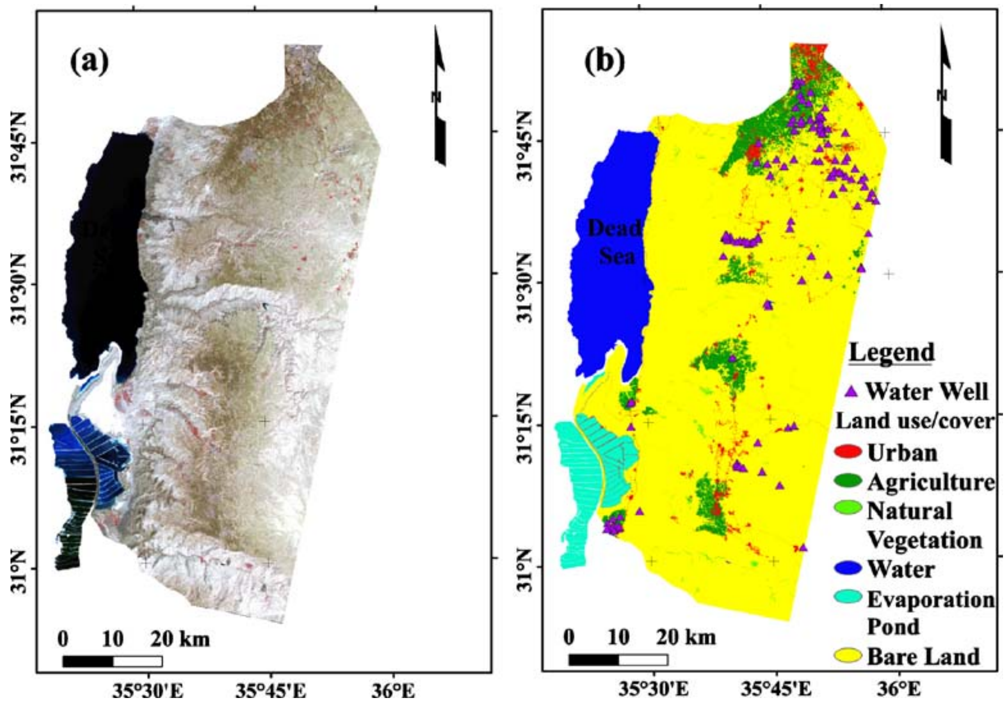

Fig. 8 **a** A subset of ASTER VNIR image acquired for September 2004. **b** Land use/cover classification map of the Dead Sea groundwater basin based on the analysis of ASTER VNIR for 2004

In the study area, most of the hazards exist within the urban and agriculture classes. Therefore, a rating of 8 is assigned to both classes. The detailed ratings for the other classes are given in Table 3. The land use/cover map is given a weighting of 5, due to the potential impact of this parameter on the groundwater (Secunda et al. 1998). Equation (4) is used to evaluate the impact of human activity on groundwater quality:

$$HAI = \text{DRASTIC index} + LUC_w LUC_r \quad (4)$$

Where HAI = human activity impact, LUC_w and LUC_r = weighting and rating of land use/cover parameter, respectively.

Sensitivity analysis

Like in all other parametric techniques, subjectivity is unavoidable in the selection of rating and weighting values related to DRASTIC parameters. This subjectivity can strongly affect the final vulnerability map. Sensitivity analysis provides helpful information on the influence of rating and weighting values assigned to each parameter and assists the analyst in judging the significance of subjective elements (Gogu and Dassargues 2000). The sensitivity analysis depends on the characteristics of the study area, and therefore, it varies from one region to another.

There are two types of sensitivity analysis: map removal sensitivity analysis introduced by Lodwick et al. (1990) and the single-parameter sensitivity analysis introduced by Napolitano and Fabbri (1996). The map removal sensitivity measure identifies the sensitivity of the vulnerability towards removing one or more maps from the vulnerability analysis and is computed as follows:

$$S = (|V/N - V'/n|/V) \times 100 \quad (5)$$

where S = the sensitivity measure expressed as variation index, V and V' = the unperturbed and perturbed

Table 3 Description of and rating for each land use/cover type

Land use/cover type	Description	Rating
Urban	Construction material, e.g. asphalt and concrete, typical commercial and industrial buildings, dams, dikes, residential development (including single/multiple houses) transportation facilities, e.g. highways and local roads	8
Agriculture	Agricultural areas such as olive farms, vegetable fields, and annual crop fields, cultivated areas (irrigated and non-irrigated vegetation)	8
Natural vegetation	Rangeland with grass and bushes used mainly for sheep, other herbaceous plants, and areas of sparse vegetation cover (less than 20%)	2
Water	All areas of open water, including streams and lakes	3
Evaporation pond	Industrial evaporation ponds used for mineral extraction	7
Bare land	Consolidated land, e.g. bare rock areas, gravels, stones, and boulder areas and hardpan areas. Unconsolidated land, e.g. bare soil areas	1

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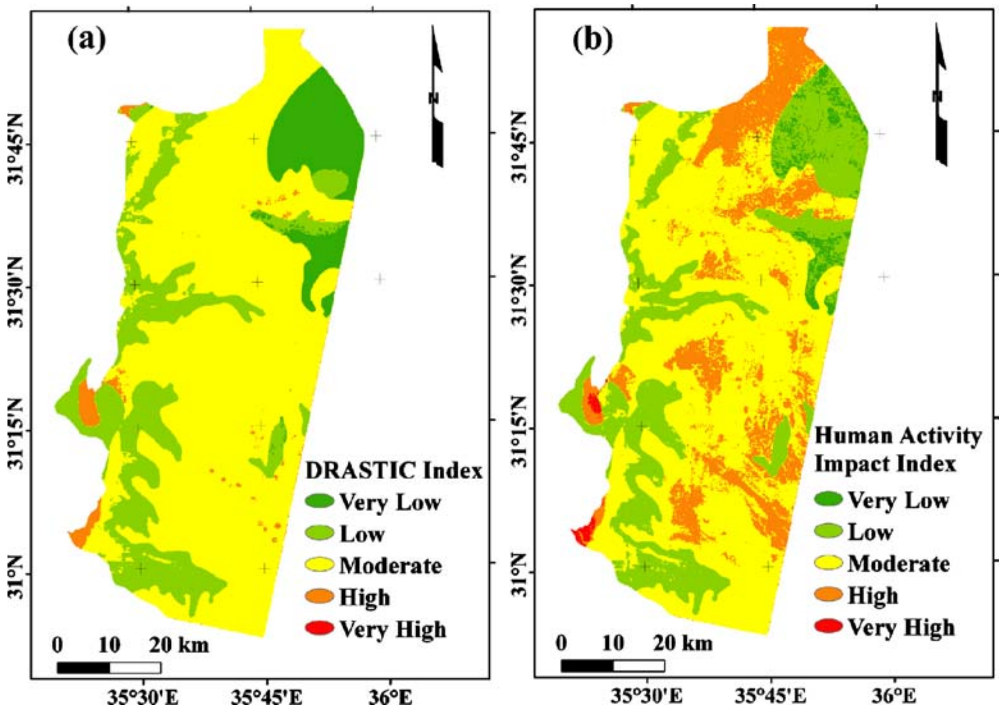

Fig. 9 The groundwater vulnerability to pollution within the Dead Sea groundwater basin, based on **a** DRASTIC index and **b** human activity impact (HAI) index

vulnerability indices respectively, and N and n = the number of parameters used to compute V and V', respectively. In this research the vulnerability index achieved using the seven parameters is considered as unperturbed vulnerability, whereas the vulnerability acquired using a lower number of factors is considered as perturbed.

The single-parameter sensitivity analysis is used to evaluate the impact of each of the DRASTIC factors on the vulnerability index. This analysis compares the effective weighting of each input parameter with empirical weighting assigned by the analytical model. The effective weighting is calculated as follows:

$$W = (P_r P_w / V) \times 100 \qquad (6)$$

Where W = effective weighting of each parameter, P_r and P_w = the rating and weighting values of each parameter, and V is the overall DRASTIC index computed by Eq. (1).

Results and discussion

The DRASTIC vulnerability index

Figure 9a shows the vulnerability map within the DSGWB. The minimum possible DRASTIC index is 23, whereas the maximum possible index is 230. The DRASTIC index map is divided into five equal classes: very low (23–64.4), low (64.5–105.8), moderate (105.9–147.2), high (147.3–188.6), and very high (188.7–230). Table 4 shows that 69.5% of the study area has a moderate class of groundwater vulnerability to contamination, whereas a total of 28.8% of the study area has very low and low classes. Only 1.7% of the study area falls within the high groundwater vulnerability class using DRASTIC, and there are no areas in the very high vulnerability class.A very large area (89.1%) in low and moderate vulnerability classes within the study area is attributed to the depth to the water table being at more than 30 m (a rating score of 1) and the aquifer having a very low hydraulic conductivity (a rating score between 1 and 4).

The impact of human activity on the groundwater

Figure 9b shows the impact of human activity on groundwater calculated using Eq. (4). Figure 9b illustrates that the percentages of areas in “very low” and “moderate” classes is reduced when compared with the DRASTIC method, while the percentages of areas in “low”, “high” and “very high” classes has increased, as shown in Table 4. The location of urban areas and agricultural activities, especially, over the B2/A7 aquifer (see Fig. 2) increases the pollution risk and changes the region of moderate vulnerability (classified using DRASTIC) to high and very high vulnerabilities. Based on previous studies, most heavy metals distributed in the soils and dust, especially

Table 4 Effect of method (DRASTIC index and HAI index) on areas classified according to groundwater vulnerability

Vulnerability class	DRASTIC index		HAI index	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Very low	386.3	9.2	157.3	3.8
Low	821.4	19.6	953.7	22.8
Moderate	2,907.8	69.5	2,409.8	57.6
High	69.8	1.7	647.7	15.5
Very high	0.1	0.0	16.6	0.4

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Table 5 Relationship between land use/cove type and nitrate concentrations

Land use/cover type	Nitrate concentration (NO_3–N mg/L)			No. of wells		
	Min.	Max.	Avg.	Total	No. exceeding the nitrate standard	% exceeding the nitrate standard
Urban	1.0	30.5	13.8	17	10	59
Agriculture	0.3	43.8	16.9	80	51	64
Bare land	0.0	34.5	5.9	29	5	17

The number of samples are one sample per well, and the relevant standard for drinking water is 10 mg/L NO_3–N (EPA 2003)

within Amman, Karak, and Madaba areas, are from anthropogenic sources such as industrial activities, vehicle exhausts, and vehicle tires in urban areas, and from fertilizers in agricultural areas. Particularly, the use of phosphatic and commercial fertilizers could be sources of heavy metals (e.g. Cd, Pb, and Hg) in agricultural areas (Banat et al. 2005; Al-Khashman 2004, 2007). There are other hazards such as septic tanks, sewer systems, wastewater treatment plants and solid wastes disposal sites. Any leachate from these sources may increase the groundwater pollution risk, and consequently, deteriorate the groundwater quality.

Verification using nitrate concentrations

To verify the effect of land use/cover on groundwater quality, the measured nitrate concentrations in milligram per liter (mg/L) are used as a pollution indicator in the study area. The nitrate concentration data associated with groundwater, provided by the Jordanian Ministry of Water and Irrigation, were obtained from 126 water wells distributed in the study area as shown in Fig. 8b. The wells are superimposed on the land use/cover map, in order to determine which vulnerability classes correspond to the highest values of nitrate concentration.

It is found that in the agriculture, urban, bare land and natural vegetation class areas, there are 80, 17, 29, and 0 wells, respectively. The minimum, maximum, and average values of nitrate concentration in each class are shown in Table 5. It is clear from this table that the minimum and maximum values of nitrate do not show any differences among the land use/cover classes except for the agriculture class, in which the maximum nitrate concentration is about 44 mg/L as NO_3–N. However, the average values have shown that agriculture has the highest average nitrate concentration, followed by urban, and then bare land. This high occurrence of nitrate in groundwater within the agriculture area is attributed to the extensive use of fertilizers. Moreover, the leachate of wastewater from septic tanks, wastewater treatment plants, and solid waste disposal sites within urban areas has also increased the nitrate concentration in the groundwater, and consequently, deteriorated the groundwater quality.

The average nitrate concentrations are also compared with the standard for NO_3–N in drinking water, which is 10 mg/L according to the US EPA standards (EPA 2003). The agriculture class has 64% of its wells exceeding the standard for NO_3–N, urban has 59%, and bare land has 17%.

Sensitivity of the DRASTIC model

Map removal sensitivity analysis

Table 6 shows the statistical results of the map removal sensitivity analysis computed by removing one parameter at a time. Based on the characteristics of the study area, a low variation of the vulnerability index is expected upon the removal of the depth to water-table parameter (mean variation index = 5.8%). This could mainly be ascribed to the low ratings assigned to this factor (rating score 1), due to the water-table depths exceeding 30 m within the Dead Sea groundwater basin. A low variation index is also expected upon the removal of the hydraulic conductivity parameter, due to the low ratings assigned to the parameter (rating scores between 1 and 4), since the aquifer in most of the study area has very low hydraulic conductivity values of less than 6.6×10^{-3} m/s.

The DRASTIC vulnerability index seems to be sensitive to the removal of aquifer media and impact of vadose zone, due to the high ratings assigned to the parameters (rating scores between 8 and 10), as a result of karstification within the carbonate aquifer of B2/A7, besides the presence of basaltic and sandstone aquifers within the study area.

The model also is sensitive to the recharge parameter, which has been given high ratings due to the high occurrence of fractures, faults, and drainage systems within the study area. High ratings, especially, have been given to areas located close to the fault and drainage systems.

Furthermore, the model seems to be sensitive to the removal of the topography layer (slope) although this parameter is considered theoretically less significant (weighting 1), because most of the study area has gentle slopes (S% ranges from 0 to 6), which have been assigned high ratings (rating scores range from 9 to 10). Therefore, the pollutant has enough time to percolate to the saturated zone, which may increase the contamination risk of the

Table 6 Statistics of map removal sensitivity analysis

Parameter removed	Variation index (%)	
	Average	Standard deviation
D	5.8	4.9
R	19.9	8.1
A	20.5	7.4
S	11.0	3.9
T	15.7	9.5
I	20.5	7.4
C	6.6	3.7

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Table 7 Statistics of single-parameter sensitivity analysis

Parameter	Empirical weighting	Empirical weighting (%)	Effective weighting (%)	
			Average	Standard deviation
D	5	21.7	8.8	7.4
R	4	17.4	24.5	10.8
A	3	13.0	18.3	6.1
S	2	8.7	6.8	2.8
T	1	4.3	5.1	3.5
I	5	21.7	30.6	10.2
C	3	13.0	6.0	3.4

groundwater. In conclusion, the characteristics of the study area play a major role with some parameters being more sensitive than others. Therefore, the sensitivity of DRASTIC parameters may differ when the DRASTIC model is applied in different locations.

Single-parameter sensitivity analysis

The single parameter-sensitivity analysis compares the effective weightings with the empirical weightings of the DRASTIC model parameters. The effective weighting is a function of the value of the single parameter with respect to the other six parameters as well as the weighting assigned to it by the DRASTIC model.

In this research, there are some deviations of the effective weightings of the DRASTIC parameters compared with the empirical weightings as shown in Table 7. The depth to water table and hydraulic conductivity parameters tend to be less effective parameters in the vulnerability assessment (mean effective weightings = 8.8% and 6.0%, respectively) compared with their empirical weightings of 25 and 13%, respectively. The impact of vadose zone, aquifer media, and recharge parameters exhibit higher effective weightings (mean effective weightings = 30.6, 18.3, and 24.5%, respectively) compared with their empirical weights values.

The results of single-parameter sensitivity analysis agree with the results of map removal sensitivity analysis. In other words, both sensitivity analyses have shown that in highly arid region such as the Dead Sea groundwater basin, the depth to water-table parameter has no significant impact on the groundwater vulnerability, due to the presence of the water table being >30 m. However, the depth to water-table parameter may have significant impact in an area located in humid regions, in which the water table may exist at shallow depths. Therefore, the sensitivity analyses reflect the importance of parameters to the groundwater vulnerability based on the characteristics of the study area.

Collecting detailed information on fault types, orientations, lengths and densities, and considering the heterogeneity of their hydraulic functions, can improve the output of DRASTIC model in order to provide more sensible results. This kind of improvement, to include different types of faults and fractured zones, was introduced by Denny et al. (2007).

Moreover, the methodology applied in this research takes the average of the distance from the fault system (F) and the distance from the intersection locations between the fault system and drainage system (FD) as criteria, without considering that water flows downhill or downgradient, respectively. This is because it is still not possible to define the flow directions with a vulnerability mapping technique; this is better achieved through numerical three-dimensional groundwater finite difference and finite element models.

Summary and conclusions

In this study, a modification was applied to the recharge parameter by adding the average of the distance from the fault system and the distance from the intersection locations between the fault system and drainage system, to the recharge calculation equation under the DRASTIC model.

The DRASTIC model showed that most of the study area, especially within the central part, was within “low” and “moderate” classes of groundwater vulnerability, with small percentages of “very low” and “high” classes. The locations of hazards such as agriculture and urban areas were obtained from satellite remote sensing data. The HAI index map revealed that there was a greater groundwater pollution risk within the study area compared with the DRASTIC method, which was verified using nitrate data obtained from wells and from previous research in the study area.

Based on the characteristics of the study area, the results from both map removal and single-parameter sensitivity analyses showed that the depth to water table and hydraulic-conductivity parameters have no significant impact on the DRASTIC model, whereas the impact of vadose zone, aquifer media, and recharge parameters have a significant impact on the DRASTIC model. This highlights the importance of obtaining accurate, detailed, and representative information about these factors.

Collecting more detailed information on the properties of faults and fractured zones, especially, within the Dead Sea groundwater basin can enhance the output from groundwater vulnerability models and provide more realistic results. However, defining flow directions with a vulnerability mapping technique is still not possible; this is better achieved through numerical three-dimensional groundwater finite difference and finite element models. On the other hand, the vulnerability mapping approach can provide decision makers with regional groundwater vulnerability and risk maps, due to the accessibility of most of the input data at regional scales, which cannot be achieved using real groundwater flow models.

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