GIS-based evaluation of groundwater vulnerability in the Russeifa area, Jordan

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ABSTRACT

In recent years, groundwater quality has been deteriorating in many parts of Jordan as result of agriculture expansion, solid waste disposal, and industrialization. A preliminary assessment of vulnerability to groundwater contamination in Russeifa watershed area was undertaken because of the presence of the largest solid waste disposal site in Jordan, which is known as Russeifa landfill. The major geological and hydrogeological factors that affect and control groundwater contamination were incorporated into the DRASTIC model, to produce groundwater vulnerability and risk maps. Moreover, a Geographical Information System (GIS) was used to create a groundwater vulnerability map by overlaying the available hydrogeological data. The final DRASTIC index indicated that the area surrounding the Russeifa landfill is highly vulnerable to groundwater contamination.

Key words: groundwater, vulnerability, contamination, geographic information system, DRASTIC, Russeifa, Jordan.

RESUMEN

La calidad del agua subterránea se ha estado deteriorando en los últimos años en muchas partes de Jordania debido a la expansión de la agricultura, a la disposición inadecuada de desechos sólidos y a la industrialización. En este trabajo se presentan los resultados de una valoración preliminar de la vulnerabilidad del agua subterránea a la contaminación en la divisoria de drenaje de Russeifa. El estudio se emprendió debido a la presencia del vertedero de basura sólida más grande en Jordania, conocido como vertedero de Russeifa. Los factores geológicos e hidrogeológicos principales que afectan y controlan la contaminación de agua subterránea fuen incorporado en el modelo DRASTIC con la finalidad de producir mapas de vulnerabilidad del agua subterránea y mapas de riesgo. Por otra parte, se empleó un sistema de información geográfica (GIS) para crear un mapa de la vulnerabilidad de agua subterránea sobreponiendo los datos hidrogeológicos disponibles. El índice DRASTIC final indicó que el área que rodea al vertedero de Russeifa es muy vulnerable a la contaminación del agua subterránea.

Palabras claves: agua subterránea, vulnerabilidad, contaminación, sistema de información geográfica, DRASTIC, Russeifa, Jordania.

INTRODUCTION

Groundwater is a major source of water for domestic, industrial and agricultural uses in Jordan. Excessive groundwater withdrawal has caused a severe lowering of the water table in some well fields of central and northern Jordan (Margane, 1995). Deterioration of groundwater quality became an increasing serious problem in recent years. The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against natural impacts, especially with regard to contaminants entering the subsurface environment (Napolitano, 1995). Consequently, some land areas are more vulnerable to groundwater contamination than others. Over the past 20 years, groundwater vulnerability maps have been developed in many countries as a basis for developing land use strategies that take into consideration aspects of protection of groundwater from pollution. The ultimate goal of vulnerability maps is the subdivision of the area into several hydrogeological units with different levels of vulnerability. These maps show the distribution of highly vulnerable areas, in which pollution is very common because contaminants can reach the groundwater within a very short time. However, such maps do not replace more detailed studies of the geological and hydrogeological conditions of particular sites for the envisaged use.

The objective of this study is to assess the vulnerability of groundwater to contamination in the vicinity of the solid waste disposal site at Russeifa area using a DRASTIC model (Aller *et al.*, 1987) combined with a Geographic Information System (GIS). This model has been widely used in many countries because the inputs required for its application are generally available or easy to obtain. It is based on seven parameters to be determined as input for computing the DRASTIC index number, which reflects the pollution potential for the aquifer (Aller *et al.*, 1987).

The Russeifa landfill causes severe environmental problems, specially the pollution of groundwater due to leachate seepages through the landfill. The generated leachate at the landfill is high (about 160 m^3/day). Henceforth, the risk of having a high volume of leachate and its subsequent seepage into the ground is high.

DESCRIPTION OF STUDY AREA

The major source of pollution at the Russeifa area is the solid waste disposal site, which is located 15 km to the northeast of Amman (Figure 1). The landfill has an area of about 1.2 km^2 and serves about 2.5 million inhabitants living in the Amman, Zarqa and Russeifa areas. The landfill receives more than half of the solid waste of Jordan, which accounts for 2,200 ton/day (Chopra *et al.*, 2001). The solid waste generated from Amman area was about 1,525 ton/ day in 1998. The site of Russeifa landfill was located over an abandoned phosphate mine. There is no subsurface drainage system to collect the leachate. Therefore, the leachate goes directly to the groundwater; hence, the water depth at the landfill does not exceed 30 m. There is also a liquid waste disposal site, which is near the Russeifa landfill, where the liquid waste comprises untreated industrial and domestic wastewater.

GEOLOGY OF RUSSEIFA AREA

The geological formations outcropping at the Russeifa area belong to the Ajlun and Balqa Groups of Upper Cretaceous age (Masri, 1963), except for the Wadi fill deposits, which are of Quaternary age (Figure 2). The only formation of the Ajlun group that outcrops on the study area is Wadi Sir Formation (A7), which consists mainly of hard crystalline dolomitic limestone, chalky limestone with occasional chert bands and nodules. The thickness of this formation reaches up to 80–100 m and forms a part of the upper aquifer in the Amman-Zarqa Basin (Bender, 1974). The Balqa Group is represented by the Amman Formation (B2). The Amman Formation consists of limestones with chert interbedded with phosphatic layers and marls; it outcrops at the landfill and its surrounding areas and varies in thickness from 80 m to 150 m (Howard and Humphreys, 1983). The distinguishing feature of this formation is the presence of undulations, in addition to fracturing and jointing in the chert beds. This formation is subdivided into two units: the lower unit is the Silicified Limestone Unit (B2a) and the upper unit is the Phosphorite Unit (B2b). The Silicified Limestone Unit is characterized by chert beds. The Phosphorite Unit forms part of the phosphorite belt

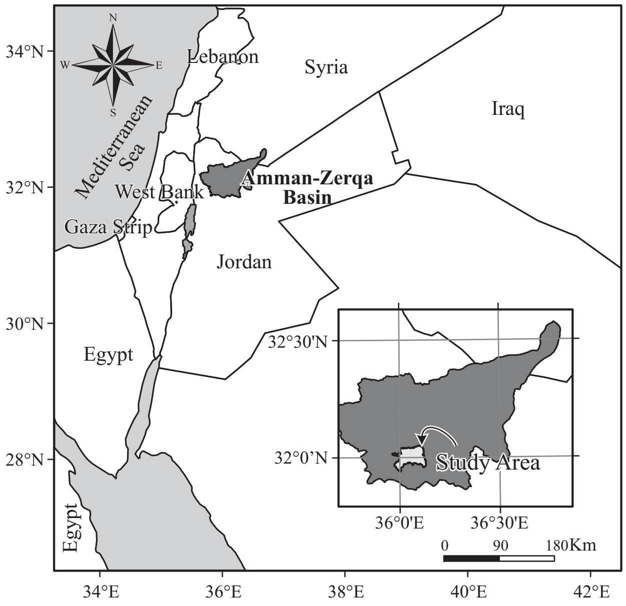

Figure 1. Location map of the study area.

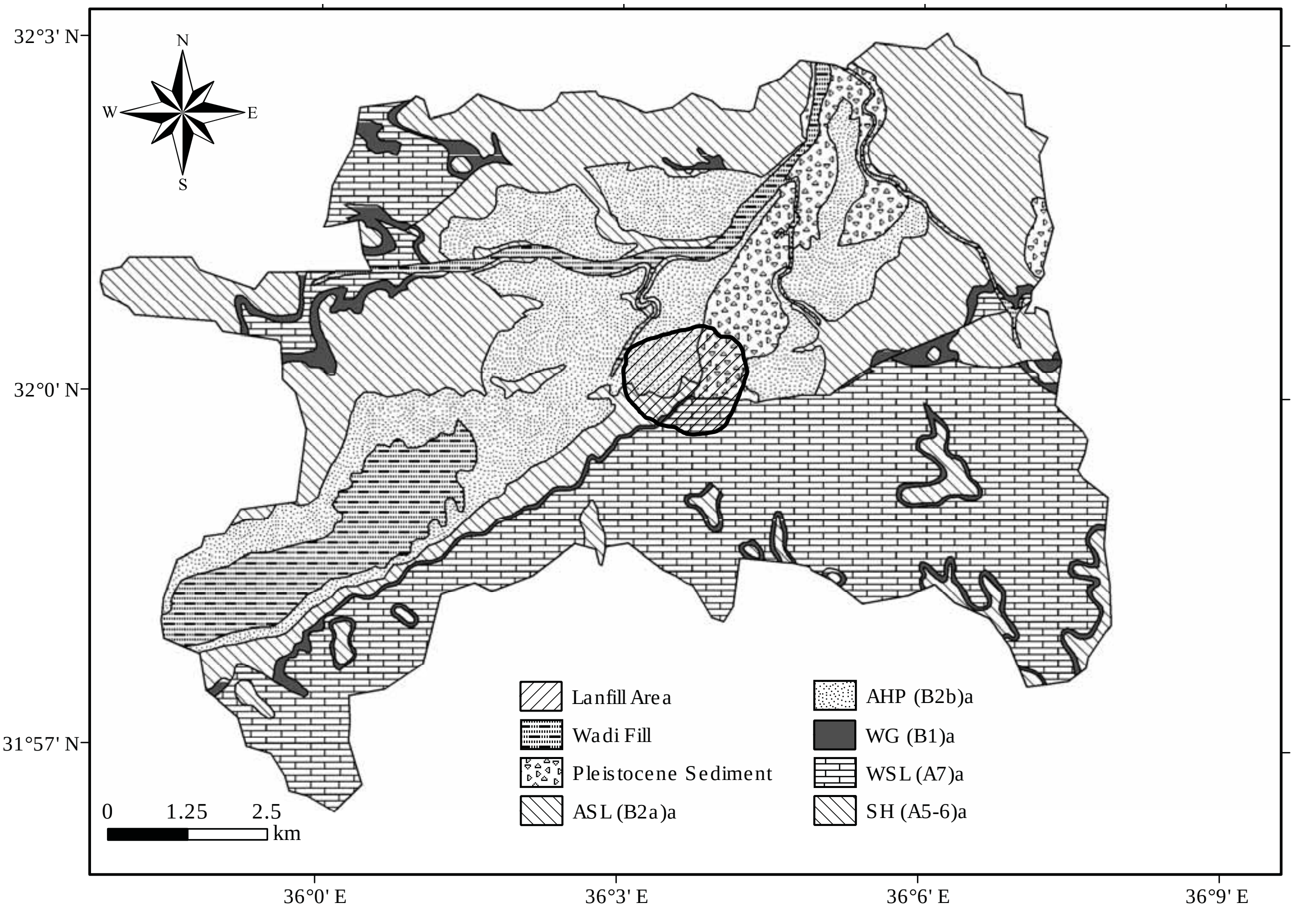

Figure 2. Geological map of the study area. AHP (B2b)a: Phosporite Unit; ASL (B2a)a: Silicified Limestone Unit; SH (A5-6)a: Shuieb Marly Limestone; WG (B1)a: Wadi Ghudran Chalk; WSL (A7)a: Wadi Sir Limestone.

in which the phosphate horizons were mined at Russeifa area. The Wadi fill deposits overlie the Amman and Wadi Sir formations and consist of sands and gravels with variable thickness from 15 to 20 m (Bender, 1974). The main structures encountered at the landfill area are NE-SW faults related to the Amman-Hallabat fault zone, which extends from southwest of Amman towards the northeast (Mikbel and Zacher, 1986).

AQUIFER CHARACTERIZATION

The study area falls within the Amman-Zarqa Basin, which is considered the most important groundwater basin in Jordan. The renewable groundwater amounts on average to 88 million cubic meters per year in this basin (Salameh and Bannayan, 1993). Table 1 summarizes the geological and hydrogeological classification of the rock units in the Amman-Zarqa basin (Rimawi, 1985). The two main aquifers in the Amman-Zarqa basin [the Amman/Wadi Sir formation (B2/A7) and the Hummar (A4) formation] are both exposed in the high rainfall region. Rainfall reaches 400 mm/year to the west of Amman, whereas it does not exceed 150 mm/year in the study area. The regional groundwater flow in the B2/A7 is influenced by the recharge/discharge areas, the topography and the structural characteristics in the region. The main recharge occurs from the south-western side of the area. A part of water flows to the west and increases the level of the springs in the Wadi Sir. The rest of the groundwater flows north-eastward down the Amman-Zarqa syncline to recharge the upper aquifer, or flows into the desert (Kuisi, 1992) (Figure 3).

The hydrogeology of the study area is controlled by the prevalent geological conditions in the area. The major aquifer system in the area is the Amman/Wadi Sir (B2/A7), which is known as the Upper Aquifer. These aquifers are well jointed and fissured, and on a local scale exhibit solution channels and karstic features. It is considered that the two aquifers are hydraulically connected and that in some locations they are separated by an aquiclude (*i.e.*, Ghudran Formation, B1), which consists of chalk, marl and marly limestone. The Amman formation (B2), which acts as an aquifer, consists mainly of chert and limestone with phosphate beds. The Wadi Sir Aquifer lies below the Amman Formation and consists mainly of highly-fractured limestone, dolomitic limestone and some chert concretions.

Table 1. Geological and hydrogeological classification of the rock units in the Amman – Zarqa Area (Rimawi, 1985).

Epoch	Age	Group	Formation	Members	Symbol	Rock type	Thickness (m)	Aquifer Potentiality	Permeability (m/s)
Tertiary	Holocene	Balqa	Wadi Fill			Soil, sand and gravel	10 – 40	Good	2.4×10^{-7}
	Pleistocene		Basalt		V	Basalt; clay	0 – 50	Good	–
Upper Cretaceous	Maestrichtain		Muwaqqar		B3	Chalk, marl and chalky limestone	60 – 70	Poor	–
	Campanian		Amman	Silicified Limestone Unit (ASL)	B2a	Chert, limestone with phosphate	80 – 120	Excellent	$10^{-5} – 3\times10^{-4}$
				Phosphorite Unit (AHP)	B2b				
	Santonian		Wadi Ghudran	Wadi Ghudran Chalk (WG)	B1	Chalk, marl and marly limestone	15 – 20	Poor	–
	Turonian	Ajlun	Wadi Sir	Wadi Sir Limestone (WSL)	A7	Hard crystalline limestone; dolomitic and some Chert	90 – 110	Excellent	$1\times10^{-7} – 1\times10^{-4}$
	Cenomanian		Shueib	Shuieb Marly Limestone (SH)	A5-6	Light grey limestone interbeded with marls and marly limestone	75 – 100	Fair to poor	$6.3\times10^{-5} – 7.2\times10^{-4}$
			Hummar		A4	Hard dense limestone and dolomitic limestone	40 – 60	Good	$8.1\times10^{-7} – 7.6\times10^{-4}$
			Fuheis		A3	Gary and olive green soft marl; marly limestone and limestone	60 – 80	Poor	$5.3\times10^{-7} – 1.7\times10^{-5}$
			Na'ur		A1-2	Limestone interbeded with a thick sequence of marl and marly limestone	150 – 220	Poor	$2\times10^{-8} – 3.1\times10^{-5}$
Lower Cretaceous	Albian–Aptian		Kurnub		K	Massive white and varicolored sandstone with layers of reddish silt and shale	300	Good	$6.9\times10^{-3} – 5.2\times10^{-2}$

Most of the groundwater wells surrounding the Russeifa landfill extract water from these aquifers.

The hydraulic parameters of the aquifer were obtained by analyzing the pumping test data of some groundwater wells in the area. The pumping test data were obtained from the databank of the Ministry of Water and Irrigation. Table 2 shows aquifer hydraulic parameters of groundwater wells penetrating the (B2/A7) aquifer.

VULNERABILITY MAPPING MODEL

Vulnerability refers to the sensitivity of groundwater to contamination, and is determined by intrinsic characteristics of the aquifer. It is distinct from pollution risk, which depends not only on vulnerability but also on the existence of significant pollutant loading. The seriousness of the impact on water use will depend on the magnitude of the pollution episode and the value of the groundwater resource.

In this study, the DRASTIC model and a geographic information system (ArcGIS) were used to produce the vulnerability map for groundwater contamination around the Russeifa landfill. This involves: (1) collecting hydrogeological and geological data, (2) standardizing and digitizing source data, (3) constructing an environmental database, (4) analyzing the DRASTIC factors, (5) calculating the DRASTIC index for the hydrogeological settings, and (6) rating these areas as to their vulnerability to contamination.

Different models found in the literature can be applied to mapping of groundwater vulnerability. Their application obviously depend on the nature and type of aquifer: sedimentary, karstic, fractured, etc. A commonly used model in assessing groundwater vulnerability is the DRASTIC model (Aller *et al.* 1985, Deichert and Hamlet, 1992, Aller *et al.*, 1987). DRASTIC methodology was originally developed by the U.S. Environmental Protection Agency and is one of the worldwide used, standardized systems for evaluation of groundwater vulnerability that can be used for site intercomparison. The DRASTIC acronym stands for the seven hydrogeological parameters: Depth to water, net Recharge, Aquifer media, Soil media, Topography (slope), Impact on the vadose zone media, and hydraulic Conductivity of the aquifer. The DRASTIC model has four assumptions: 1) the contaminant is introduced at the ground surface; 2) the contaminant is flushed into the groundwater by precipitation; 3) the contaminant has the mobility of water; 4) the

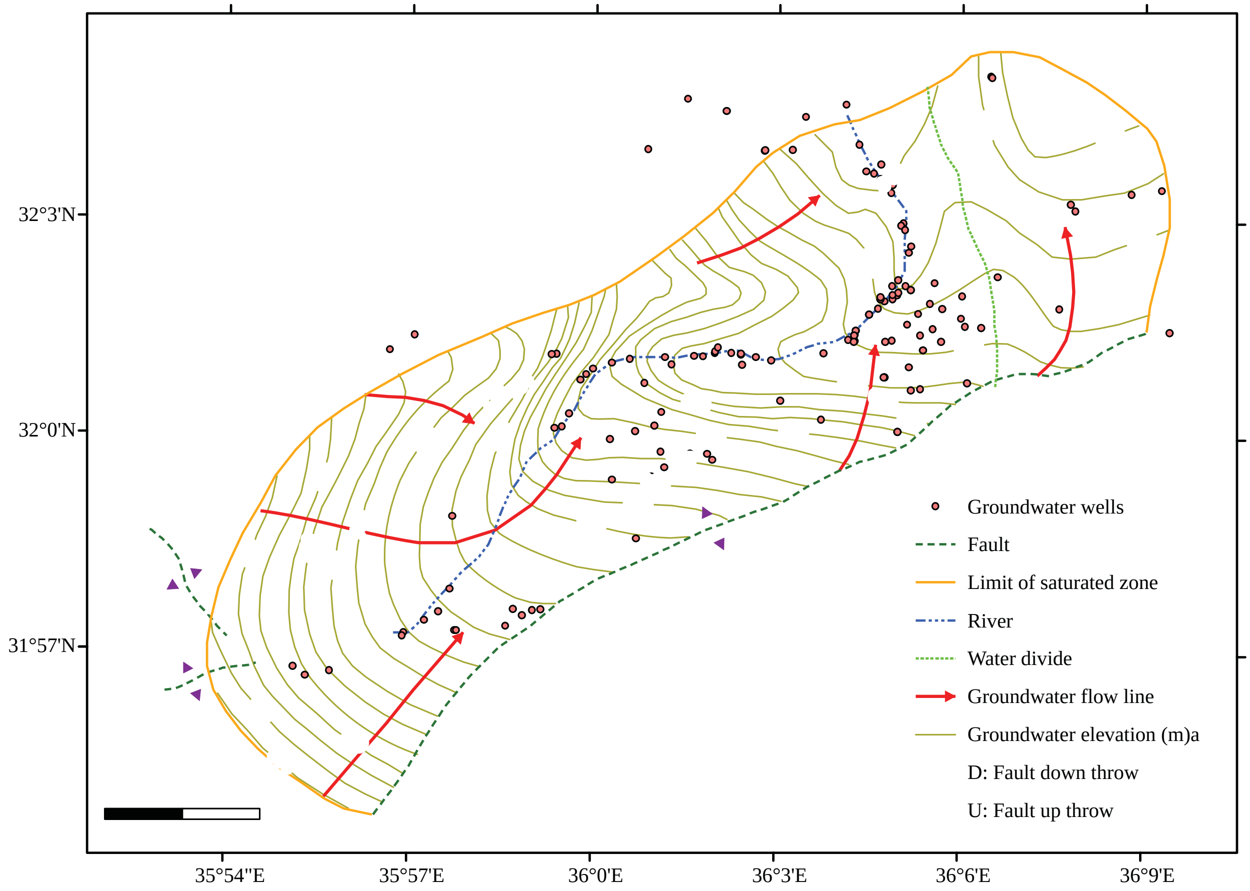

Figure 3 Regional groundwater contour map of the Amman-Wadi Sir (B2/A7) aquifer (Kuisi, 1992).

area being evaluated by DRASTIC is 100 acres (0.4 km^2) or larger.

DRASTIC is a methodology for identifying vulnerability to groundwater pollution. The seven previously mentioned parameters, which are a combination of geologic, hydrologic, geomorphologic, and meteorological factors, are used to relate an aquifer to its water sources and to the constituents within that water (Nagar and Mirza, 2002). The parameters of DRASTIC are weighted according to their relative importance in determining the ability of a pollutant to reach an aquifer (Table 3).

DRASTIC includes various hydrogeologic settings, which influence the pollution potential of a region. A hydrogeologic setting is defined as a mappable unit with common hydrogeologic characteristics. This model employs a numerical ranking system that assigns relative weights to various parameters that help in the evaluation of relative groundwater vulnerability to contamination.

Many studies on DRASTIC system application using GIS have been carried out: Smith *et al.* (1994), Merchant (1994), Melloul and Collin (1998), Secunda *et al.* (1998), Kim and Hamm (1999), Fritch *et al.* (2000a, 2000b), Mclay *et al.* (2001), Al-Zabet (2002), Lee and Kim (1996), Lee and Choi (1997), Jo *et al.* (1999), Lee *et al.* (1998).

Determination of the DRASTIC index number (pollution potential) for a given area involves multiplying each factor rating by its weight and adding together the resulting values. Higher sum values represent a greater potential for pollution or a greater vulnerability of the aquifer to contamination. For a particular area being evaluated, each factor is rated on a scale from 1 to 10 indicating the relative pollution potential of that factor for that area. Once each factor has been assigned a rating, it is weighted. Weight values, from 1 to 5, express the relative importance of the factors with respect to each other. Finally, the total impact factor score, the DRASTIC index number, can be calculated:

$$\text{DRASTIC Index} = \begin{array}{l} DrDw + RrRw + ArAw + SrSw + \\ TrTw + IrIw + CrCw \end{array} \quad (1)$$

Where r = rating for area being evaluated (1–10), and w = importance weight for the factor (1–5). Factor ratings are derived from data on each factor while importance weights are found in a generic DRASTIC table that lists weights for factors having greater applicability (Aller *et al.*, 1987). The higher the DRASTIC index, the greater the relative pollution potential. The DRASTIC index can be further divided into four categories: low, moderate, high, and very

Table 2. Hydarulic parameters of selected groundwater wells in the study area. SWL: Static water level; GWL: Groundwater level; T: Transitivity; K: Permeability.

Name	Code	East	North	SWL (m)	Drawdown (m)	Specific capacity (m^3/h/m)	GWL (m)	Yield (m^3/h)	T m^2/d	K m/d
Ain El-Ruseifa	AL1295	248.705	158.66	NA	NA	NA	NA	NA	NA	NA
Phosphate No. 7	ALl 1345	249.856	157.582	42.6	4.6	16.96	595.4	78	247	2.47
Phosphate No. 8	AL1346	251.865	158.492	46	4.1	14.63	573.0	66		
Phosphate No. 10	AL1350	250.56	157.135	14.8	40	NA	644.2	NA	33.9	0.38
Ruseifa Municipality	AL1352	248.228	158.808	24	4.0	31.5	598	NA	NA	NA
Waste Disposal	AL2720	249.75	157.25	29.6	1.63	40.5	590.4	NA	409	5.18
Ruseifa Deep	AL3287	248.5	158.5	96.3	101.2	0.86	503.7	NA	NA	NA
Ruseifa Municipality	AL1551	248.85	158.7	20.9	0.84	142.86	-	120	247	NA
–	A 105	251.409	159.365	NA	NA	NA	574	NA	1673.2	53.12
–	A 73	247.815	158.842	NA	NA	NA	598	NA	2.88	0.21
–	A 83	250.040	158.750	NA	NA	NA	585	NA	NA	NA
Ruseifa Landfill monitoring well No.2	AL3385	250.601	158.041	62.9	NA	NA	592.1	NA	NA	NA
Ruseifa Monitoring well No.3	AL3386	249.998	157.873	31.1	NA	NA	623.9	NA	NA	NA

NA: Not available.

high. The sites with high and very high categories are more vulnerable to contamination and hence can be reviewed by a specialist. These weights are relative and a site with low pollution potential does not necessarily mean that it is free from groundwater contamination, but that it is relatively less susceptible to contamination compared to the sites with high or very high DRASTIC ratings.

METHODOLOGY

All data relevant to the vulnerability of groundwater were collated, including for instance, but not exclusively, topography, geology, land use, hydrology, hydrogeology and rainfall, as well as existing aerial photographs and satellite imagery.

The ArcGIS was used to compile the geospatial data, to compute the DRASTIC index, and to generate the final vulnerability maps. The grid layer for depth to water was generated by computer subtraction of water-level elevation data sets from land surface elevation. Land surface elevations were derived from a digital elevation model (DEM) for Amman-Zarqa Basin from 1:100,000-scale maps. The water-level elevation data sets were obtained from the groundwater well records published by the Water Authority of Jordan (WAJ). The depth to water table is in the range from 30 m to 60 m from the ground surface. Figure 4a shows the factor score map for depth to water, where it ranges from 5 to 25.

Table 3. Assigned weights for DRASTIC parameters.

Feature	"Generic" DRASTIC weights	"Pesticide" DRASTIC weights
Depth to water	5	5
Net recharge	4	4
Aquifer media	3	3
Soil media	2	5
Topography	1	3
Impact on the vadose zone media	5	4
Hydraulic conductivity	3	2

The grid layer for net recharge was computed using the long-term water balance for the Amman-Zarqa Basin. Recharge rates for the aquifers were usually derived from groundwater flow models and represent averages over large areas. The recharge rate was estimated to be 12.9 mm/year. Figure 4b shows the factor score map for net recharge, where it ranges from 4 to 12.

The grid layer for aquifer media was extracted from the geological map, scale of 1:10,000, where the aquifer media is composed of highly-fractured limestone of B2 and A7 formations. Factor score for the aquifer media in the study area is 30 as shown in Figure 4c.

The grid layer of soil media was obtained from grain size analysis of twenty soil samples that indicated a sandy loam soil type and fractured limestone (Tadros, 2000). Figure 4d shows the factor score map of soil media, where the ratings range from 14 to 20.

The grid layer for the topography of the landfill was generated from a DEM, to calculate percent slopes. Most of the slopes in this study were in the range of 2 to 12 percent. Figure 5a shows the rating map for topography, where ratings range from 5 to 9.

The grid layer for the impact on the vadose zone in the landfill area depends on soil permeability and depth to water table. The equation used to calculate the impact on the vadose zone incorporates the following factors (Piscopo, 2001):

$$\text{Impact on the vadose zone} = \text{Soil permeability} + \text{Depth to water table} \qquad (2)$$

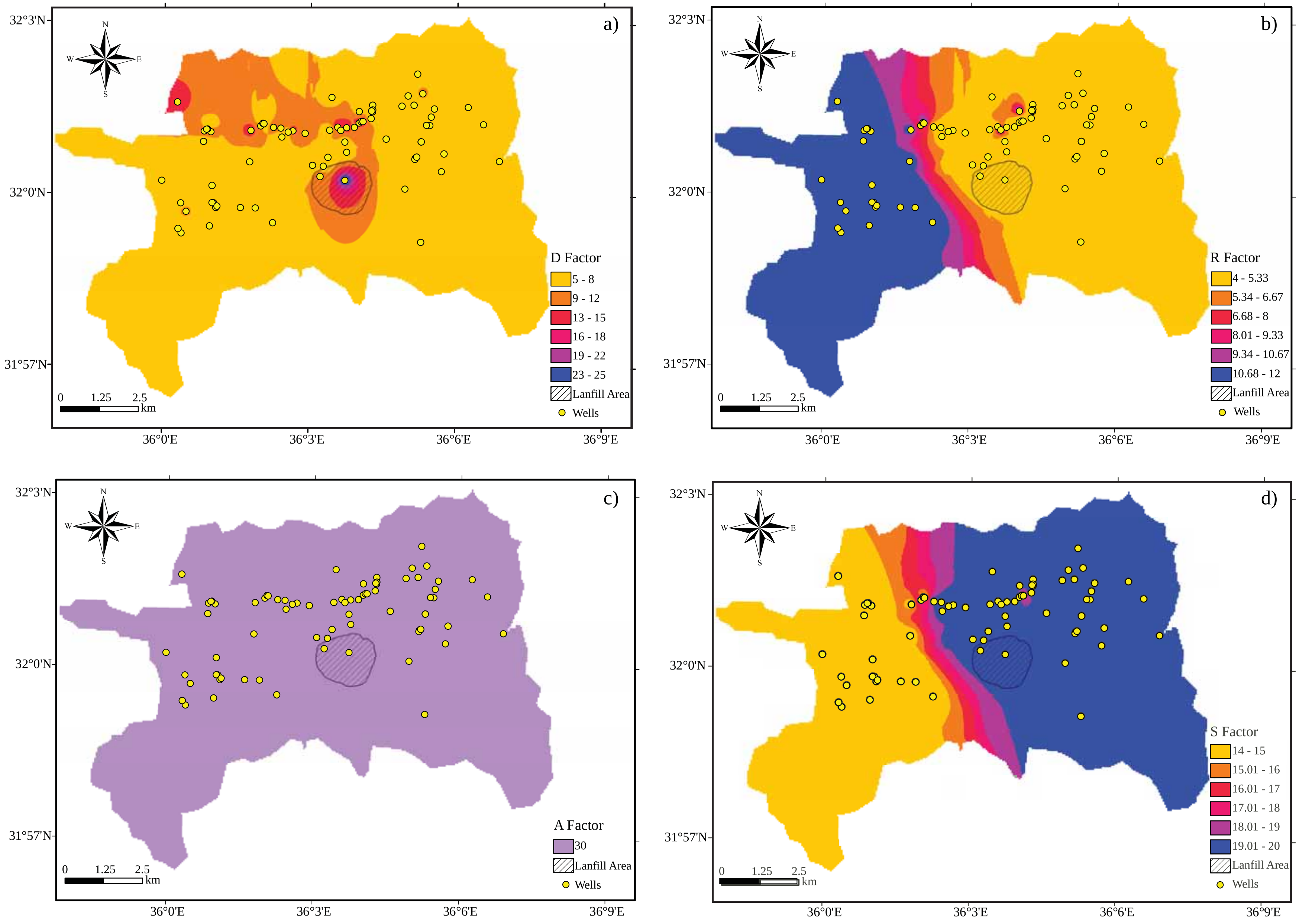

Figure 4. a: Factor score for depth to water (D); b: Factor score for net recharge (R); c: Factor score for aquifer media (A); d: Factor score for soil media (S).

In the study area, the soil permeability is considered to be high so the rating is 5 and depth to water table is about 30 m, which takes a rating of 1. The rating of impact on the vadose zone is 6 as shown in Figure 5b.

The hydraulic conductivity of the aquifer was obtained from pumping test analysis of the groundwater wells near the landfill. Figure 5c shows the score factor map for hydraulic conductivity.

The DRASTIC index map (Figure 5d) was prepared to determine the vulnerability to groundwater contamination (*i.e.*, pollution potential). This map shows moderate to high vulnerability (101–200) of the aquifer to contamination from the landfill, with the most vulnerable areas to groundwater contamination –indicated by the highest DRASTIC indexes– located close to the landfill area.

SENSITIVITY ANALYSIS

Aquifer vulnerability methods require validation to reduce subjectivity in the selection of rating ranges and to increase reliability (Ramos-Leal and Rodríguez-Castillo, 2003). Sensitivity analysis provides valuable information on the influence of rating values and weights assigned to each parameter and helps hydrogeologists to judge the significance of subjective elements (Gogu and Dassargues, 2000). The sensitivity analysis was performed to evaluate the sensitivity of each parameter between thematic map layers. Similar analyses have been applied in the assessment of aquifer vulnerability using EPIK (Gogu and Dassargues, 2000) and SINTACS methods (Napolitano and Fabbri, 1996).

The first step of the analysis was to compute the vulnerability values using six maps instead of seven (*i.e.*, removing one map). For each sub-area, vulnerability index was calculated using combinations of 6 of the 7 parameters (Gogu and Dassargues, 2000). For comparability, the output values were re-scaled by a factor 7/6. Comparing the new index with the initial one provides a direct measure of the influence of the missing parameter. Lodwik *et al.* (1990) define a map-removal sensitivity measure that represents the sensitivity associated with removing one or more maps. This measure can be expressed as:

$$\mathrm{Si} = \left|\frac{\mathrm{Vi}}{\mathrm{N}} - \frac{\mathrm{Vxi}}{\mathrm{n}}\right| \tag{3}$$

where Si is the sensibility, Vi is the vulnerability index for the i^{th} cell, N is the total number of parameters used in obtaining the vulnerability for each of the cells. VXi represents the vulnerability index of the i^{th} cell excluding the Xi parameter, and n is the number of parameters used in the sensitivity analysis. The variation index (Vxi) can be computed from the following expression (Gogu and Dessargues, 2000):

$$\mathrm{Vxi} = \frac{\mathrm{Vi} - \mathrm{Vxi}}{\mathrm{Vi}} \tag{4}$$

where Vi is the vulnerability index computed using Eq. (1) in the i^{th} subarea.

Each parameter contributes with an effective weight (Napolitano and Fabbri, 1996) to the final vulnerability index. This effective weight (WXi) can be calculated for each sub-area as:

$$\mathrm{Wxi} = \frac{\mathrm{Xri} * \mathrm{Xwi}}{\mathrm{Vi}} * 100 \tag{5}$$

where Xri and Xwi are, respectively, the rating values and the weights for the parameter X assigned in the subarea i, and Vi is the vulnerability index as computed in Eq. (1) in the subarea i. For each subarea, the sum of the four parameter effective weights is 100 %.

The variability expression (Eq. 3) proposed by Lodwik *et al.* (1990) apparently is different from that proposed by Napolitano and Fabbri (1996) to analyze the parameter weight (Eq. 5), but they are equivalent (Ramos-Leal and Rodríguez-Castillo, 2003).

Table 4 shows the statistics on sensitivity to removal of one parameter on the vulnerability values. The most sensitive parameter to contamination is the aquifer media, impact on the vadose zone, followed in importance by depth to water table, recharge, topography, hydraulic conductivity, and soil type. The highest values are associated with the aquifer media (2.01), and the impact on the vadose zone (2.01). The soil media shows the lowest sensitivity value (0.46). The variation index (Vxi) for each DRASTIC parameter is computed as shown in Table 5. The (A) and (I) parameters show the highest variation index (23.92), followed by (C) parameter (21.29). This variation index measures the effect of the removal of each parameter. The positive value means that removal of the parameter reduces the vulnerability index, thereby increasing the calculated vulnerability. A negative value means that removal of the parameter increases the vulnerability index, thereby reducing the calculated vulnerability (Gogu and Dassargues, 2000). In our case, the Vxi values are positive which means that the vulnerability index will be reduced if one parameter is removed from the DRASTIC method, which will thereby increase the calculated vulnerability.

Table 6 shows the statistics of the calculated effective weights or variability for each DRASTIC parameters. (T)

Table 4. Statistics on sensitivity to removing one parameter.

Parameter of Sensitivity	Min	Max	Mean	Standard deviation
D	0	2.25	1.9	0.27
R	1	2.86	1.78	0.56
A	1.48	2.1	2.01	0.07
S	0	0.9	0.46	0.19
T	1.4	2.4	1.75	0.35
I	1.48	2.1	2.01	0.07
C	0.8	2	1.47	0.4

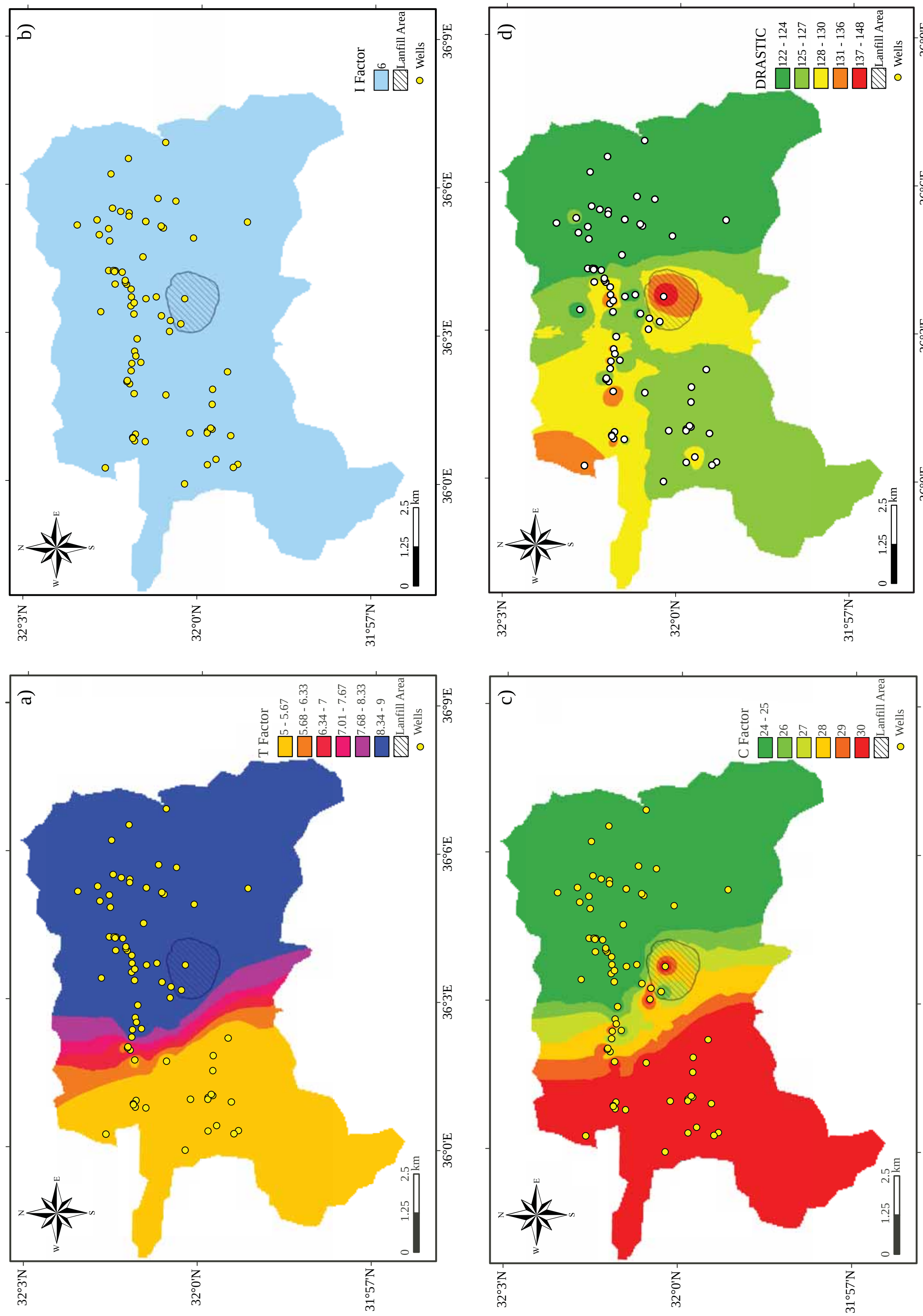

Figure 5. a:Factor score for topography (T); b: Factor score for impact on the vadose zone (I); c: Factor score for hydraulic conductivity (C); d: Vulnerability map based on DRASTIC Index.

Table 5. Variation index of the excluded parameter in the DRASTIC.

Variation Index	Min	Max	Mean	Standard deviation
D	3.88	16.87	5.16	1.4
R	2.7	9.52	5.75	2.79
A	20.28	24.59	23.92	0.56
S	10.3	16.39	14.05	2.36
T	3.68	7.38	5.92	1.53
I	20.28	24.59	23.92	0.56
C	17.84	23.81	21.29	1.82

and (S) show the lowest effective weights. As shown in this table, the effective weight for each parameter differs from the theoretical weight assigned by the DRASTIC method. This difference is highly noticed in the soil media parameter (S), which means that the theoretical weight of this parameter should be revised for computing the vulnerability index.

CONCLUSIONS

In this research an attempt has been made to assess aquifer vulnerability in the Russeifa area. The major cause of groundwater contamination is the presence of Russeifa solid waste disposal site, which was placed on the most important aquifer in Jordan, which is known as Amman-Wadi Sir (B2/A7). The vulnerability of groundwater to contamination in the study area was quantified by using the DRASTIC model combined with GIS. The vulnerability index of Russeifa area indicates that groundwater resources in the surrounding area are susceptible to pollution to a moderate degree by the Russeifa landfill. The vulnerability map has a range from the most vulnerable for contamination to the least vulnerable.

Sensitivity analysis was performed in the present study to validate and evaluate the consistency of the parametric methods in the vulnerability assessment. This analysis provides an efficient interpretation of the vulnerability index. In fact, the effective weights are strongly related to the value of the single parameter in the context of values chosen for the other parameters The effective-weights analysis is very useful when the user of the vulnerability-assessment method wishes to revise the weights in the chosen equation for computing the vulnerability index. In this case study, the effective weights for each parameter are sometimes different from the theoretical weights assigned by the DRASTIC method.

Statistical analysis of the sensitivity of the effective weight parameters indicates that the depth to water (D) and the impact on the vadose zone (I) parameters dominates the vulnerability index with an average weight of 22.91 % against the theoretical weight of 21.74 %, and the effective weight of soil media parameter is smaller than the assigned weight and will vary as a function of the rating values of the other parameters. Therefore, for each case study it is desirable to know the effective weights and compare it with the theoretical ones. In this way vulnerability assessment can be evaluated more efficiently using sensitivity analysis.

Table 6. Statistical analyis of the effective weight.

Effective weight factor	Assigned weight (*Xwi*)	Assigned weight %	Mean calculated weight (*Wxi*)	Calculated weight, *Xwi*	Average effective weight (%)
D	5	21.74	5.16	4.92	22.91
R	4	17.39	5.75	3.93	18.3
A	3	13.04	23.92	2.95	13.73
S	2	8.7	14.05	0.83	3.86
T	1	4.35	5.92	0.98	4.56
I	5	21.74	23.92	4.92	22.91
C	3	13.04	21.29	2.95	13.73

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