

Aquifer vulnerability assessment using the DRASTIC model at Russeifa landfill, northeast Jordan

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Abstract Groundwater is inherently susceptible to contamination from anthropogenic activities and remediation is very difficult and expensive. Prevention of contamination is hence critical in effective groundwater management. In this paper an attempt has been made to assess aquifer vulnerability at the Russeifa solid waste landfill. This disposal site is placed at the most important aquifer in Jordan, which is known as Amman-Wadi Sir (B2/A7). The daily-generated leachate within the landfill is about 160 m³/day and there is no system for collecting and treating this leachate. Therefore, the leachate infiltrates to groundwater and degrades the quality of the groundwater. The area is strongly vulnerable to pollution due to the presence of intensive agricultural activity, the solid waste disposal site and industries. Increasing groundwater demand makes the protection of the aquifer from pollution crucial. Physical and hydrogeological characteristics make the aquifer susceptible to pollution. The vulnerability of groundwater to contamination in the study area was quantified using the DRASTIC model. The DRASTIC model uses the following seven parameters: depth to water, recharge, aquifer media, soil media, topography, impact on vadose zone and hydraulic conductivity. The water level data were measured in the observation wells within the disposal site. The recharge is derived based on precipitation, land use and soil characteristics. The aquifer media was obtained from a geological map of the area. The

topography is obtained from the Natural Resources Authority of Jordan, 1:50,000 scale topographic map. The impact on the vadose zone is defined by the soil permeability and depth to water. The hydraulic conductivity was obtained from the field pumping tests. The calculated DRASTIC index number indicates a moderate pollution potential for the study area.

Keywords Landfill · Groundwater · Leachate · DRASTIC · Pollution potential · Fractured aquifer · Jordan

Introduction

Groundwater is considered to be the major source of water in Jordan, and the only source of water in some areas of the country. Twelve groundwater basins have been identified in Jordan. Most basins are comprised of several groundwater aquifer systems. Approximately 80% of Jordan's known groundwater reserves are contained in three main aquifer systems; Amman – Wadi Es Sir; Basalt and Kurnub sandstone aquifer.

Landfills have served for many decades as the ultimate disposal sites for all types of wastes: residential, commercial and industrial (Farquhar 1989). Physical, chemical, and biological processes interact simultaneously to bring about the overall decomposition of the wastes. One of the by-products of all these mechanisms is chemical leachate (O'Leary and Walsh 1995). The major environmental problem experienced at landfills is the loss of leachate from the site and the subsequent contamination of groundwater (Farquhar 1989).

Groundwater quality issues are receiving widespread attention, and hydrogeologic information is essential for the effective protection and management of groundwater quality (Thirumalaivasan and Karmegam 2001).

Groundwater vulnerability maps are used as a guide for the location of future developments in an area and to minimize the impact projected development will have on the surrounding water resources (Merchant 1994). Numerous studies were concerned with groundwater contamination caused by landfills with insufficient

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leachate collection systems (Lee and Jones 1991; Christenson and others 1993). One of the issues of greatest concern is the impact of an existing landfill on the pollution of groundwaters by landfill leachate (Lee and Jones 1993). Small amounts of landfill leachate can pollute large amounts of groundwater, rendering them unusable for domestic and many other purposes. Gravity causes leachate to move through the landfill, to the bottom and sides, and through the underlying soil until it reaches the aquifer. As leachate moves down the subsurface, they mix with groundwater held in the soil spaces and this mixture moves along the groundwater's flow path as a plume of contaminated groundwater. The leachate contaminants first enter the unsaturated zone and eventually are transported to the groundwater table in the saturated zone (Schnoor 1996).

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. The ultimate goal of vulnerability maps is a subdivision of the area into several hydrogeological units that have different levels of vulnerability. Aquifer pollution vulnerability can be assessed using several approaches.

The aim of the study is to conduct a groundwater aquifer assessment in the vicinity of the solid waste disposal site in the Russeifa area and to predict potential contamination of groundwater resources by leachate. The first and main reason for the choice of this site being that the leachate generated at this landfill is high, about 160 m³/day. Therefore, the risk of having a high volume of leachate and its subsequent seepage into the ground is high. The second reason is that contamination by leachate poses great threats to groundwater resources as leachate contains multiple pollutants, which might not be easy to remove or treat. To perform this evaluation, the DRASTIC model, a standardized system for evaluating groundwater pollution potential was used (Aller and others 1985). 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 (U.S. EPA 1987).

Russeifa landfill site description

The area of the Russeifa landfill is about 1,200 donums (i.e. 1,200,000 m²) and is located near Russeifa City that lies 15 km to the northeast of Amman (Fig. 1). This landfill serves about 2.5 million inhabitants living in Amman, Zarqa and Russeifa areas. The landfill receives more than half of the solid waste in Jordan, which accounts for 2,200 tons/day (Chopra and others 2001). The solid waste generated from the Amman area was about 1,525 tons/day

in 1998. The site of Russeifa landfill was chosen 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 wastewater and cesspools wastewater.

The disposal method practiced at the Russeifa site is known as the sandwich method in which the solid waste is dumped and followed directly by at least 30 cm of compacted earth material (Chopra and others 2001). The site is to be closed this year (2004) and all solid waste is to be transported to a new better-managed landfill called Ghabawi, to the east of the present landfill.

Geological framework

The geological formations outcropping at Russeifa landfill are of Upper Cretaceous age (Masri 1963) with the Ajlun and Balqa Groups, except for the wadi fill deposits, which are Quaternary in age (Fig. 2). The only formation of the Ajlun Group that outcrops in the landfill area is the 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 to 150 m (Howard and Humphreys 1983). The distinguishing feature of this formation is its undulations in addition to the fracturing and jointing of the chert beds. This formation is subdivided into two units: the lower unit is the silicified limestone unit and the upper unit is the phosphorite unit. The silicified limestone unit is characterized by chert beds. The phosphorite unit forms part of the phosphorite belt in which the phosphate horizons were mined in the 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 in the landfill area are the faults that are related to the Amman-Hallabat structure, which extends from the southwest of Amman towards the northeast (Mikbel and Zacher 1986).

Hydrogeological features of the landfill area

The Russeifa landfill is within the Amman-Zarqa Basin, which is considered the most important groundwater

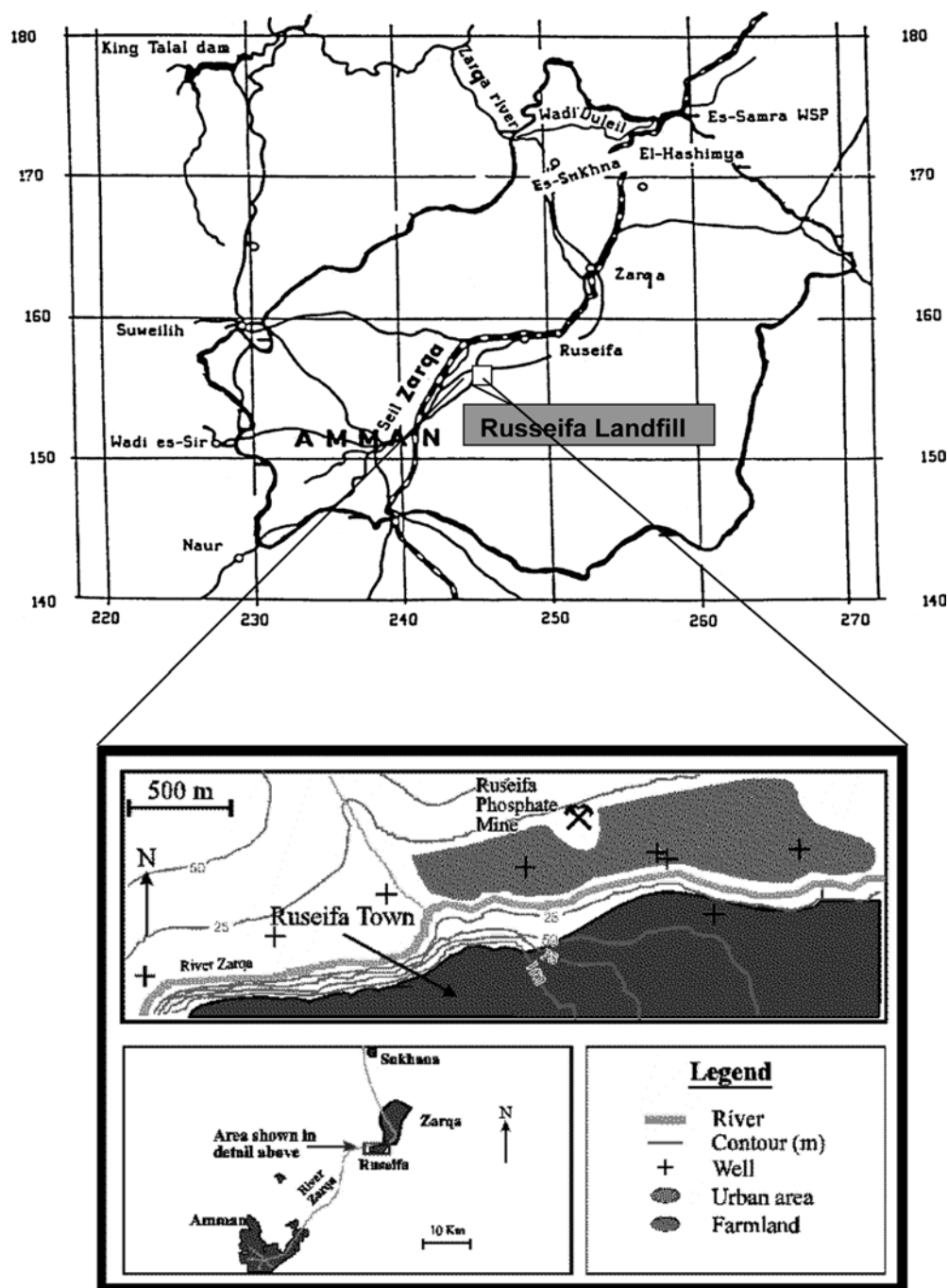


Fig. 1
Location map of the Russeifa landfill site, northeast Jordan

basin in Jordan. The renewable groundwater amounts on average to 88 million m^3 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 which reaches 400 mm/year to the west of Amman, while in the study area, the rainfall does not exceed 150 mm/year. The regional groundwater flow in the B2/A7 is influenced by the recharge/discharge areas, topography and the

structural characteristics in the region. The main recharge occurs from the south-western side of the area. A part of the 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 and the rest flows into the desert (Kuisi 1992; Fig. 3).

The hydrogeology of the landfill area is controlled by the prevalent geological conditions in the area. The schematic hydrogeological cross section at Russeifa landfill is shown in Fig. 4. This figure shows the depth to water table of the Amman-Wadi Sir aquifer (B2/A7), which does not

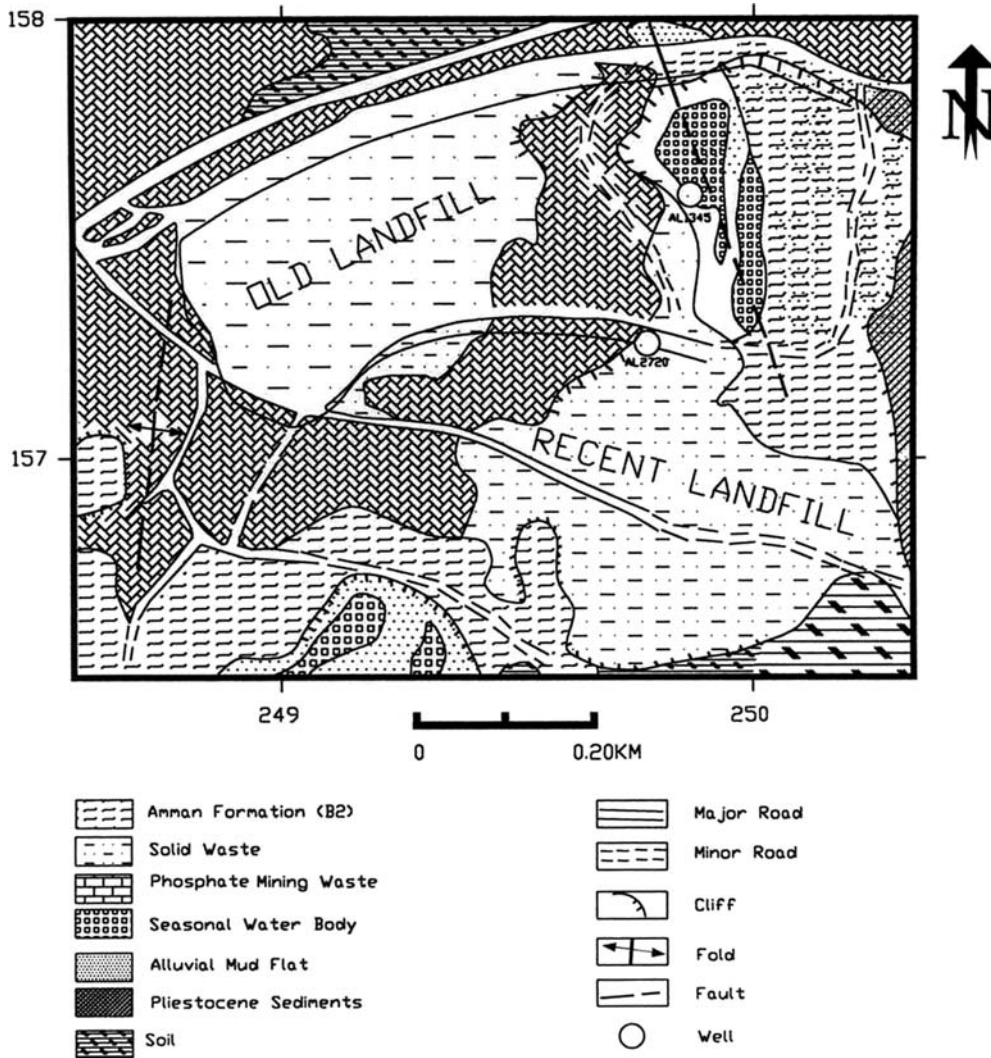


Fig. 2
Generalized geological map of the
Russeifa landfill

exceed 30 m, in addition to the location of solid wastes. The major aquifer system in the area is (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 believed that the two aquifers are hydraulically connected and 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. Most of the groundwater wells surrounding the landfill are used to extract water from these Aquifers. The aquifer hydraulic parameters were obtained by analyzing the pumping test data of some groundwater wells in the vicinity of the landfill site such as the waste disposal monitoring well (AL2720); Phosphate Mine No.7 (AL1345); and Phosphate Mine No.10 (AL1350). The pumping test data was analyzed using GWW software, (Braticevic and Karanjac 1997) which used different

techniques to derive the hydraulic parameters of the aquifer including the Theis, Jacob and Hantush methods. Table 2 shows the aquifer hydraulic parameters of the (B2/A7) Aquifer.

The pumping test for the waste disposal monitoring well (AL 2720) was carried out in the period from 4/8 to 7/8/ 1992, and indicated that the discharge of the well was 52.2 m³/h with a drawdown of 1.63 m.

From the pumping analyses, the aquifer parameters were derived. The transmissivity (T) values of the (B2/A7) aquifer system range from 33.9 to 409 m²/day. With knowledge of the saturated thickness of the aquifer it was possible to estimate the hydraulic conductivity of the aquifer. The values of hydraulic conductivity (K) range from 0.38 to 5.18 m/day.

The groundwater velocity can be calculated on the basis of the hydraulic conductivity and the hydraulic gradient values. The hydraulic gradient is 2.0×10^{-3} in the landfill area. Therefore, the groundwater velocity can be calculated using the following equation: $V = KI$; where K is the hydraulic conductivity (m/d) and I is the hydraulic gradient. The groundwater velocity is 1×10^{-7} m/s.

Table 1
Geological and Hydrogeological Classification of the Rock units Unit in Amman – Zarqa Area (Rimawi 1985)

Epoch	Age	Group	Formation	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}	
Upper Cretaceous	Pleistocene Maastrichtian		Basalt	V	Basalt, clay	0–50	Good	–	
			Muwaqqar	B3	Chalk, marl and Chalky limestone	60–70	Poor	–	
		Campanian	Amman	B2	Chert, limestone with phosphate	80–120	Excellent	10^{-5} – 3×10^{-4}	
		Santonian	Ghudran	B1	Chalk, marl and marly limestone	15–20	Poor	–	
		Turonian	Ajlun	Wadi Sir	A7	Hard crystalline limestone, dolomitic and some chert	90–110	Excellent	1×10^{-7} – 1×10^{-4}
		Cenomanian		Shueib	A5–6	Light Grey limestone interbedded with marls and marly limestone	75–100	Fair to poor	6.3×10^{-5} – 7.2×10^{-4}
			Hummar	A4	Hard dense limestone and dolomitic limestone	40–60	Good	8.1×10^{-7} – 7.6×10^{-4}	
			Fuheis	A3	Gary and olive green soft marl, marly limestone and limestone	60–80	Poor	5.3×10^{-7} – 1.7×10^{-5}	
			Na'ur	A1–2	Limestone interbedded with a thick sequence of marl and marly limestone	150–220	Poor	2×10^{-8} – 3.1×10^{-5}	
Lower Cretaceous	Albian – Aptian		Kurnub	K	Massive white and varicolored sandstone with layers of reddish silt and shale	300	Good	6.9×10^{-3} – 5.2×10^{-2}	

To determine how fast the leachate can reach the groundwater, the soil samples have been collected from the top and the base of the landfill. The grain size analysis of the soil samples shows 35% of gravels, 40% of sand, 11.5% of silt and 14% clay. The soil permeability was estimated based on the grain size analysis and using the Hazen empirical formula. The average value of soil permeability is 3.3×10^{-7} m/s. Based on the permeability value of the soil, the leachate will reach the water table, which is approximately at a depth of 30 m, after approximately 10 years.

Hydrochemistry of Amman-Wadi Sir aquifer

At each sampling location in the study area a 60-ml filtered (0.45 mm) sample of the water was taken which was then acidified to 1% using HCl. The sample containers were made out of polyurethane and were cleaned prior to sampling by washing with 10% HNO₃. This sample would be used for the analysis of major and minor elements. Also at each sampling site a 60-ml filtered (0.45 mm) sample

was taken which was not acidified. This sample was used for anion analysis.

The leachate composition affects the chemistry of groundwater, as leachate percolates through the soil horizon reaching the subsurface groundwater aquifers. The most important indicators that reflect the leachate moving through the subsurface groundwater aquifer beneath the landfill are the increase in the concentration of inorganic constituents, which represent a threat to groundwater quality. Therefore, 13 groundwater wells have been selected to monitor the groundwater quality and they were analyzed for their inorganic, organic and microbiological constituents. The following parameters were measured: temperature, pH, electrical conductivity (EC), TDS, Ca, Mg, Na, K, Cl, SO₄, HCO₃, NO₃, in addition to microbiological parameters such as biological oxygen demand (BOD), chemical oxygen demand (COD), total coliform, and fecal coliform bacteria. The methods of analysis were carried out according to the Standard Method of Water and Wastewater Examination (Arnold and others 1992).

The historical data for these wells were taken from the data bank in the Ministry of Water and Irrigation. Table 3

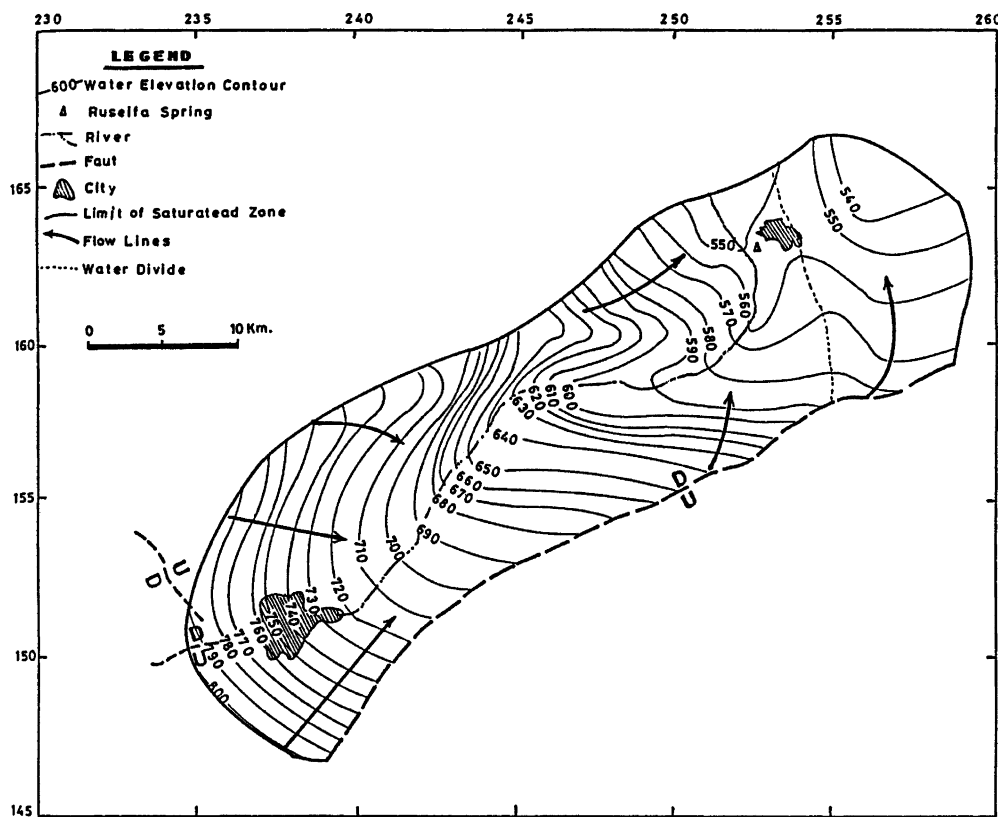


Fig. 3
Groundwater contour map of Amman-Wadi Sir aquifer (B2/A7)

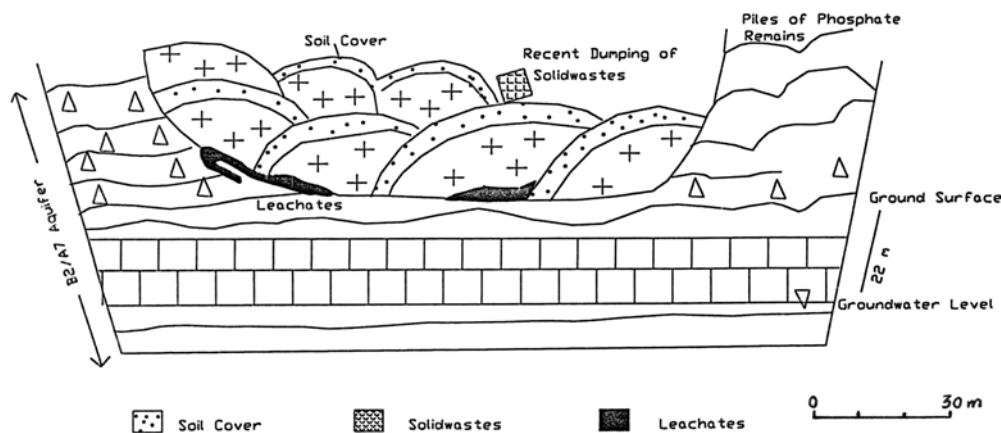


Fig. 4
Schematic hydrogeological cross section at Russeifa landfill

shows the results of the chemical analyses of the selected groundwater wells in the study area. The different water samples have been classified according to their chemical composition using the Piper diagram (Fig. 5; Piper 1944). HCO_3 and Ca are the dominant ions and the chemistry of these waters originated from the dissolution of limestone aquifers.

Effect of landfill leachate on groundwater

To show the effect of the leachate contamination to groundwater, three wells very close to the landfill have

been selected: Phosphate Mine No.7 (AL1345), Phosphate Mine No.10 (AL1350) and Russeifa landfill monitoring well No.2 (AL3385) in the northern part of the landfill. The complete chemical analyses of these wells are summarized in Table 4.

Comparing the results of chemical analysis of the monitoring well (AL3385) which was carried out in 1992 and 1994, it is apparent that there is an increase in salinity from 650 to 788 mg/l and an increase in the other inorganic constituents; the concentration of Cl has increased from 4.8 to 232 mg/l; and SO_4 increased from 0.59 to 56 mg/l. Also the Fe concentration reaches 0.3 mg/l. The Russeifa landfill monitoring well No.3 (AL3386) was found to be full of dirty used vehicle oil, which means that there is another source of pollution coming from the vehicle oils

Table 2

Groundwater well data at the Russeifa landfill and its surroundings

Code	Name	Easting	Northing	SWL (m)	Draw-down (m)	Specific capacity (m ³ /h/m)	GWL (m)	Yield (m ³ /h)	T (m ² /d)	K (m/d)
AL1295	Ain El-Ruseifa	248.705	158.66	NA	NA	NA	NA	NA	NA	NA
AL1345	Phosphate No. 7	249.856	157.582	42.6	4.6	16.96	595.4	78	247	2.47
AL1346	Phosphate No. 8	251.865	158.492	46	4.1	14.63	573.0	66		
AL1350	Phosphate No. 10	250.56	157.135	14.8	40	NA	644.2	NA	33.9	0.38
AL1352	Ruseifa municipality	248.228	158.808	24	4.0	31.5	598	NA	NA	NA
AL2720	Waste disposal	249.75	157.25	29.6	1.63	40.5	590.4	NA	409	5.18
AL3287	Ruseifa deep	248.5	158.5	96.3	101.2	0.86	503.7	NA	NA	NA
AL1551	Ruseifa municipality	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
AL3385	Ruseifa landfill monitoring well No.2	250.601	158.041	62.9	NA	NA	592.1	NA	NA	NA
AL3386	Ruseifa monitoring well No.3	249.998	157.873	31.1	NA	NA	623.9	NA	NA	NA

*NA: Not available

dumped at the landfill. The static water level measured in 1998 was 28.8 m.

At phosphate mine No.10, 800 m to the east of the landfill, the chemistry of the groundwater is affected by the landfill and showed increasing concentration of different constituents including Ca, Mg, Na, Cl, SO₄ and NO₃. The concentration of Cl increased from 40 mg/l to around 70 mg/l; the concentration of SO₄ increased from 17 mg/l to 31 mg/l.

At Phosphate mine No.7, 700 m from the Russeifa landfill monitoring well No. 2 (AL3385) in the northeastern part of the landfill, the static water level was measured to be 42.5 m from the Earth's surface. There is an increase in the concentration of different cations and anions; for example, the Cl concentration increased from 35.5 mg/l in 1991 to 276.9 mg/l in 2002; the SO₄ concentration slightly increased from 30.7 mg/l in 1991 to 38.4 mg/l in 2002; and the Na concentration increases from 20.7 mg/l to 137.1 mg/l. Therefore, the increase of inorganic constituents such as Cl, Na, SO₄, and HCO₃ occurred along the groundwater flow path towards the east and northeast direction.

A few water samples were collected from the groundwater wells and they were analyzed for their sanitary parameters, such as BOD, COD and their bacteria count. The BOD and COD and bacteria count of the collected samples is summarized in Table 5. The phosphate mine well (AL1350), to the northeast of the landfill, showed increasing values in coliform from 5.1 Most Probable Number (MPN) to 300 MPN and the BOD value measured in 2000 was found to be 0.2 mg/l (Tadros 2000) which indicated pollution of the groundwater. In addition, the fecal coliform increased from 162 MPN to 900 MPN at the Russeifa landfill monitoring well (AL3385) where the BOD values were found to be 34 mg/l. Also, the bacteriological analysis of the Waste Disposal monitoring well (AL2720) indicates that the

measured total coliform and fecal coliform were 2,400 MPN/100 ml and 150 MPN/100 ml, respectively. It can be concluded from these analyses that the landfill is polluting directly the upper part of the aquifer; hence, the depth to water table is about 29.6 m.

Assessment of aquifer vulnerability with the DRASTIC Model

Aquifer vulnerability is determined using hydrogeologic characteristics that affect the transport of contaminants through the vadose zone to the water table. The DRASTIC model was developed by the EPA to be a standardized system for evaluating groundwater pollution potential. The acronym DRASTIC stands for *Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and Hydraulic Conductivity* region (Aller and others 1985; Deichert and Hamlet 1992). DRASTIC is a methodology for identifying vulnerability to groundwater pollution. It uses seven parameters, which are a combination of geologic, hydrologic, geomorphologic, and meteorological factors to relate an aquifer to the sources of its water and the constituents within that water (Nagar 2002). The parameters of DRASTIC are weighted according to their relative importance in determining the ability of a pollutant to reach an aquifer. 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. The

Table 3
Results of chemical analyses of groundwater wells within the study area

Code No.	Well name	Easting	Northing	EC ($\mu\text{S}/\text{cm}$)	TDS (mg/l)	pH-value	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Cl (mg/l)	HCO ₃ (mg/l)	SO ₄ (mg/l)	NO ₃ (mg/l)
AL 1336	Abu Khurma	252.86	157.92	683.00	516.90	7.80	51.90	34.99	33.10	0.39	67.40	273.90	42.70	12.40
AL 1339	Phosphate mine 1	247.88	158.94	1140.00	729.60	7.37	106.00	28.30	101.20	8.20	162.20	349.50	25.90	76.20
AL 1340	Phosphate mine 2	247.81	158.84	1230.00	787.20	7.38	112.80	32.00	84.40	6.60	166.90	325.10	33.10	76.10
AL 1344	Phosphate mine 6	247.64	158.30	610.00	390.40	8.23	48.80	25.70	34.50	2.70	57.50	210.50	40.80	7.30
AL 1345	Phosphate mine 7	249.86	157.58	560.00	358.40	8.00	49.80	28.10	27.80	3.50	44.70	223.90	43.70	5.10
AL 1346	Phosphate mine 8	251.87	158.49	650.00	416.00	8.00	41.80	25.00	50.80	3.50	118.90	173.90	4.80	7.00
AL 1347	Phosphate mine 9	250.03	159.00	635.00	406.40	7.30	28.80	30.00	52.90	3.50	98.00	208.60	9.60	1.90
AL 1350	Phosphate mine 10	250.56	157.14	632.00	403.60	7.62	56.30	20.40	18.40	3.90	30.50	250.10	19.68	4.34
AL 3217	Abu lughud Ayyad	252.98	157.12	1124.00	752.90	7.50	92.18	32.32	84.20	3.90	198.50	265.40	41.30	34.10
AL1307	Jordan dairy	251.37	159.14	1587.00	1052.99	7.30	131.06	37.50	133.20	6.63	281.80	348.90	58.10	55.80
AL 1664	Al-Intag	249.25	158.63	1892.00	1181.90	7.20	128.00	42.80	180.30	6.24	358.00	366.00	54.70	45.90
AL 1551	Ruseifa NO.4	248.94	158.80	1362.00	929.00	7.30	115.43	30.50	116.60	6.24	241.06	333.10	36.50	49.60
AL 1826	Ruseifa NO.18	247.27	158.70	631.00	500.80	7.50	62.32	33.30	21.95	3.12	39.30	315.40	23.00	2.50

hydrogeologic settings, which make up the acronym DRASTIC are:

- [D] Depth to water table: the more the depth to water table the less the chance for the contaminant to reach it as compared to a shallow water table.
- [R] Recharge (net): it is the process through which the contaminant is transported to the aquifer and hence the greater the recharge the more vulnerable the aquifer is.
- [A] Aquifer media: it reflects the attenuation characteristics of the aquifer material reflecting the mobility of the contaminant through the aquifer material.
- [S] Soil media: soil of different types have a differing water-holding capacity and influence on the travel time of the contaminant.
- [T] Topography (slope): high degree of slope increases runoff and erosion, which is composed of the pollutant.
- [I] Impact of vadose zone: it reflects the texture of the soil in the unsaturated zone above the water table.
- [C] Hydraulic conductivity: the amount of water percolating to reach the groundwater through the aquifer is influenced by the hydraulic conductivity of the soil media.

The DRASTIC model defines ranges, ratings for the classes associated with each of the above factors and a weight for each factor. 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:

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

Where:

- r = Rating for area being evaluated (1–10)
- 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 and others 1987). Table 6 shows assigned weights for DRASTIC parameters.

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 high. The sites with high and very high categories are more

Chemical analysis of groundwater in the vicinity of Russeifa

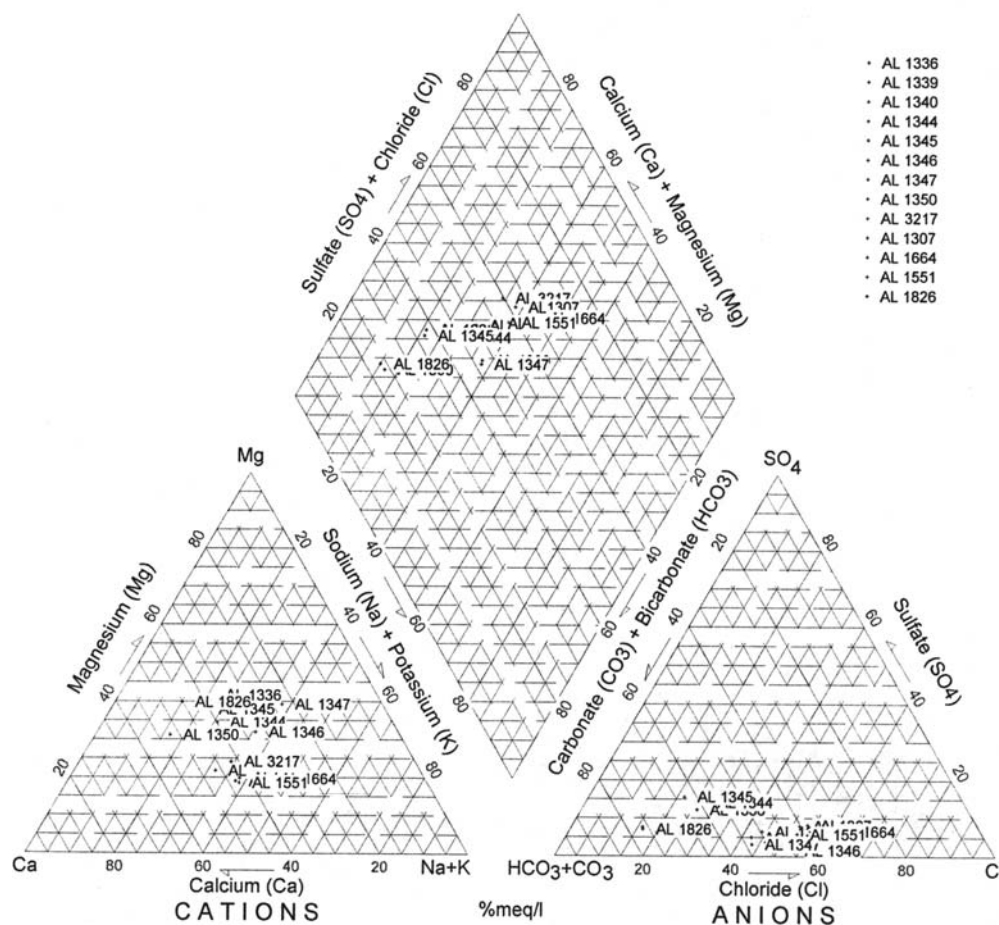


Fig. 5
Piper diagram of the water samples collected from the groundwater wells located in vicinity of the Russeifa landfill

Table 4
Results of chemical analyses of three groundwater wells

Parameter	Phosphate 7 (AL 1345)			Phosphate 10 (AL 1350)					Landfill monitoring well No.2 (AL 3385)	
	1992	1994	2002	1990	1993	1994	1995	2002	1992	1994
PH-value	7.8	7.22	7.0	7.59	7.47	7.65	7.49	7.5	7.21	7.11
EC ($\mu\text{S}/\text{cm}$)	537.6	687.5	1,290	546	586	611.7	521	783.8	1015.6	1,231
TDS (mg/l)	416	440	825.6	419.3	419.9	391.5	374.3	501.6	650	788
Ca (mg/l)	58.0	65.8	85.8	59	65	62	60	71.9	-	-
Mg (mg/l)	32.9	35.2	37.3	22	18	20	22.8	17.9	-	-
Na (mg/l)	20.7	102.9	137.1	17	22	18	22.7	23	-	-
K (mg/l)	3.1	1.6	1.2	2.3	5.9	1.5	0.98	2.73	-	-
HCO ₃ (mg/l)	223	235	264.7	255	240	230	201.3	267.8	-	-
Cl (mg/l)	35.5	52	276.9	29	40	29	46.2	69.8	4.8	232
SO ₄ (mg/l)	30.7	34	38.4	26	17	22	11.52	31.1	0.59	55
NO ₃ (mg/l)	6.7	17	43.9	9	12	9	8.8	17.4	42	56
NH ₃ (mg/l)	0.1	0.38	0.40	0.1	0.1	0.12	-	0.03	0.05	0.06
Fe (mg/l)	0.77	2.42	-	0.029	0.017	0.06	-	-	-	0.3
Total hardness (TH)	91	101	123	81	83	82	83	90	-	417
Fecal coliform	4	37	-	-	-	3	-	-	150	-

vulnerable to contamination and hence can be reviewed by a specialist. These weights are relative and a site with low pollution potential need not necessarily mean that it is

free from groundwater contamination but it is relatively less susceptible to contamination compared to the sites with high or very high DRASTIC ratings.

Table 5

Measurements of sanitary parameters BOD, COD and bacteriological analysis

Well no.	Well name	BOD (mg/l)	COD (mg/l)	Total coliform (MPN/100 ml)	Fecal coliform (MPN/100 ml)
AL1350	Phosphate mine No.10	0.2	0.9	5.1 to 300	300
AL2720	Waste disposal monitoring well	-	-	2,400	150
AL 3385	Russeifa landfill monitoring well No.2	34.0 32	57 52	30 900	<2 900

Methodology of vulnerability assessment

The water table depth data was obtained from the groundwater monitoring wells within the landfill. The depth to water table is in the range from 30 to 40 m from the ground surface. The aquifer recharge was computed using the long-term water balance for the Zarqa River watershed. The recharge rate was estimated to be 12.9 mm/year. Aquifer media was extracted from a geological map with a scale of 1:10,000 where the aquifer media is composed of highly-fractured limestone of B2 and A7 Formations. The soil media within the landfill was determined to be sandy loam based on the grain size analysis of 20 soil samples (Tadros 2000). The topography of the landfill was obtained from a topographic map of 1:50,000 scale, where the slope aspect is less than 5%. The factors considered important in defining the impact of the vadose zone in the landfill area include soil permeability and depth to water table. The equation used to calculate the impact on vadose zone incorporates the following factors (Piscopo 2001):

– Impact of vadose zone = soil permeability + depth to water table

based on Table 7 which summarizes the numerical rating of soil permeability and depth to water table (Piscopo 2001). In the study area, the soil permeability is considered to be high so the rating is 5 and the depth to water table is about 30 m, which takes a rating of 1. The rating of impact on the vadose zone is 6. According to the ratings proposed by Piscopo (2001) the ranges for the vadose zone will be 8. The hydraulic conductivity of the aquifer was obtained from pumping test analysis of three groundwater-monitoring wells within the landfill.

Table 6

Assigned weight for DRASTIC parameters

Feature	“Generic” DRASTIC weights	“Agricultural” DRASTIC weights
Depth to water	5	5
Net recharge	4	4
Aquifer media	3	3
Soil media	2	5
Topography	1	3
Impact of the vadose zone media	5	4
Hydraulic conductivity	3	2

The values of the factors for the Russeifa landfill area were calculated from the collected data and summarized in Table 8. These rating values are multiplied by their importance weight then added together to arrive at the DRASTIC index number:

$$\begin{aligned} \text{DRASTIC index number} &= \text{DrDw} + \text{RrRw} + \text{ArAw} \\ &\quad + \text{SrSw} + \text{TrTw} + \text{IrIw} + \text{CrCw} \\ &= 2 \times 5 + 1 \times 4 + 10 \times 3 \\ &\quad + 10 \times 2 + 9 \times 1 + 8 \times 5 \\ &\quad + 5 \times 3 \end{aligned}$$

$$\text{DRASTIC index number} = 128$$

The DRASTIC index number (pollution potential) shows moderate vulnerability (101–140) of the aquifer to contamination from the landfill. Accordingly, moderate vulnerability indicates that, a detailed groundwater site investigation is required. Also, the work should include an ongoing monitoring program, details on the protection design factors, (natural attenuation, physical barriers, etc) in addition to the previous levels of investigation.

Conclusions

The aquifer vulnerability index can be used as a guide to identify the impact of waste disposal sites on groundwater resources. DRASTIC is a methodology for identifying vulnerability to groundwater pollution. It uses seven parameters, which are a combination of geologic, hydrologic, geomorphologic and meteorological factors, to relate an aquifer to the sources of its water and the constituents within that water. The vulnerability index in the Russeifa area indicates that groundwater resources in the surrounding area are susceptible to pollution to a moderate degree (DRASTIC index = 128) by the Russeifa landfill. Furthermore, Bajalli (1997) has taken the concentration of NO_3^- , ^3H and TDS as an indication of groundwater contamination either by organic or inorganic sources. He also used the fuzzy logic model using SPAN-GIS to determine the most vulnerable areas for contamination as shown in Fig. 6. This vulnerability output map has a range from the most vulnerable for

Table 7

Numerical rating of soil permeability and depth to water table (Piscopo 2001)

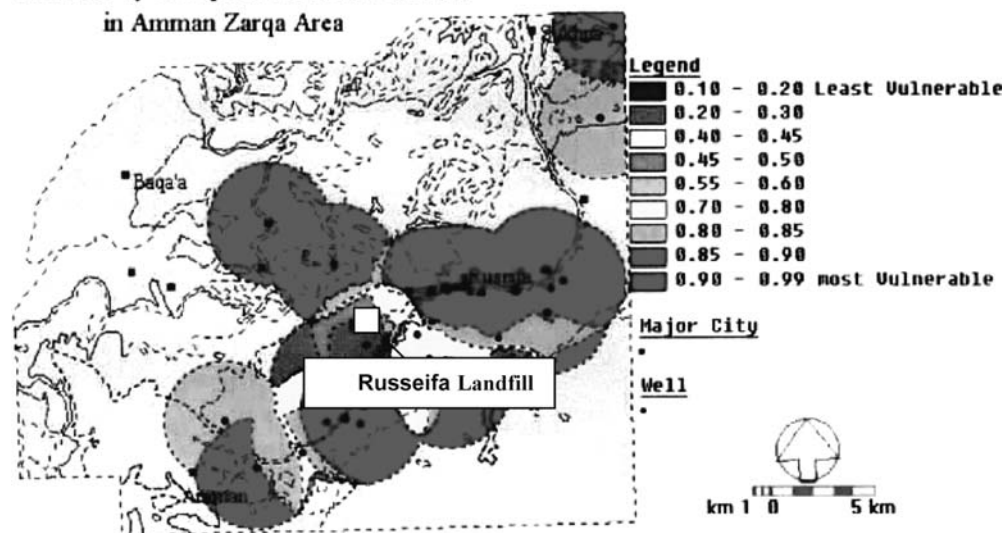
Soil permeability		Depth to water table (m)		Ranges and rating for vadose zone impact	
Range	Factor	Range	Factor	Range	Rating
High	5	<5	5	8–10	10
Mod-high	4	5–10	4	6–8	8
Moderate	3	10–15	3	4–6	5
Slow	2	15–20	2	3–4	3
Very slow	1	>20	1	2–3	1

Table 8

Calculation of DRASTIC index number at Russeifa landfill

No.	FACTOR	Description	Rating	Weight	Score
1	Depth to water	29.6 m	2	5	10
2	Net recharge	12.9 mm/yr	1	4	4
3	Aquifer media	Fractured limestone	10	3	30
4	Soil media	Sandy loam	10	2	20
5	Topography	5%	9	1	9
6	Impact of the vadose zone media	Sand and gravel	8	5	40
7	Hydraulic conductivity	4.4×10^{-4} to 6×10^{-3} m/s	5	3	15
DRASTIC index number					128

Vulnerability of Aquifer for Contamination in Amman Zarqa Area

**Fig. 6**

Groundwater vulnerability map to contamination in the vicinity of Russeifa landfill

contamination to the least vulnerable. The most vulnerable areas were found in the Ain Ghazal, Russeifa and Shukneh areas.

In addition, more industries discharge their wastes in the landfill. The pollution risk to drinking water will increase as a result of the landfill. Thus, it is prudent to protect the drinking water by determining the aquifer pollution risk through the mapping of aquifer vulnerability in the area as a whole, in addition detailed groundwater site investigation and monitoring programs are required to protect the groundwater resources in the vicinity of the landfill.

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