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Assessment of Groundwater Vulnerability to Contamination in Irbid Governorate, North Jordan

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Abstract: The main aquifers in northern Jordan showed little signs of contamination when modeled by the DRASTIC method, mainly due to topography and an invariably deep water table. Most of A7/B2 and B4/B5 the aquifers are classified with low vulnerability and small regions classified as moderately vulnerable (0.20% and 0.80% respectively). The dominance of low vulnerability in the study area is mainly attributed to the fact that DRASTIC assumes a very low vulnerability (rating value =1) when water depths are greater than 30 m. Additionally, DRASTIC does not demonstrate the capacity of satisfactorily outlining karst morphology. Both map removal and single-parameter sensitivity analyses showed that depth to water table and topography are the most decisive parameters in determining aquifer vulnerability. Net recharge, hydraulic conductivity, topography and depth to water table contribute significantly to the variation of the vulnerability index across the study area; with the variation index being 75%, 71.5%, 66% and 63.4%, respectively. Aquifer media, depth to water and topography have effective weights of 34%, 26% and 24%, respectively. These are higher than the theoretical weights assigned by the model (13%, 21.7% and 4.3%, respectively). Well AD1296 and spring AD0654 are the most contaminated water resources. The former is located within the vicinity of the Ramtha wastewater treatment plant and the latter is located within areas of agricultural activities and intensive cesspool usage.

DRASTIC did not accurately predict the high concentrations of some chemicals, which highlights the need for new research into procedures for parameter quantification and weighting. Further investigations are also required in order to understand the mechanisms of groundwater recharge and contaminant transport in such aquifers.

Key words: Vulnerability • Groundwater • Hydrochemistry • DRASTIC • GIS • Irbid Jordan

INTRODUCTION

The semi-arid climatic conditions of Jordan result in limited surface and groundwater resources. Moreover, population growth, industrialization, irrigation projects and improving living standards during the last few decades have led to increasing water use and over exploitation. The quantity and quality of groundwater are continuously threatened by inappropriate land use practices and associated pollution and unwise management.

Jordan is divided into 12 groundwater basins, out of which the Yarmouk groundwater basin is among those are being over-extracted. Groundwater in Jordan provides about 506 MCM/yr of the total water demand (1250 MCM/yr), with safe yield of 275 MCM/yr [1].

The Amman-Wadi Es Sir and Umm Rijam and Wadi Shallala aquifer systems in the extreme northern part of Jordan are the main sources of water for domestic, industrial and agricultural use. To ensure that these aquifers remain safe and adequate sources of water for the Irbid governorate (Figure 1),

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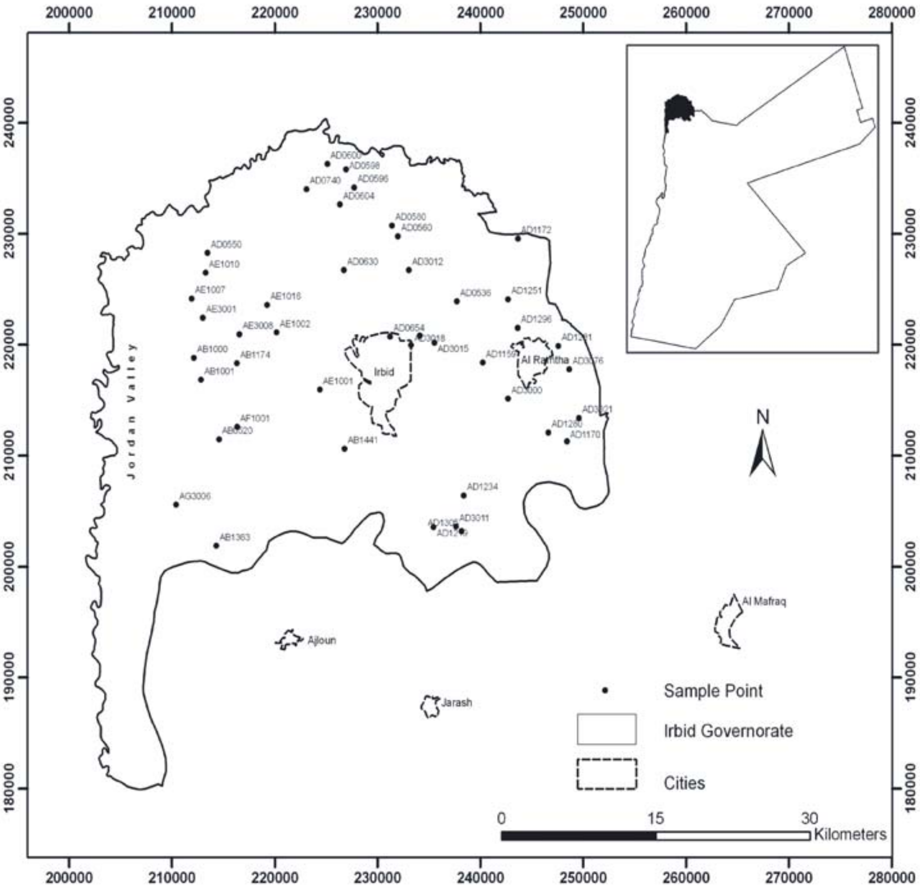

Fig. 1: Location map of Irbid Governorate and water samples

it is necessary to determine whether certain locations in this groundwater basin are more susceptible to receive and transmit pollution. Therefore, the first objective of this study is to evaluate the vulnerability of the aquifers using the DRASTIC method, the empirical model of the U.S. Environmental Protection Agency, which utilizes the parameters: *D*epth to water, net *R*echarge, *A*quifer media, *S*oil media, *T*opography, *I*mpact of vadose zone and hydraulic *C*onductivity [2].

Study Area

Introduction: The Irbid Governorate (Figure 1) is one of the best developed regions in Jordan. In addition, an Economic Development Zone is being implemented by the national government. It comprises Irbid Governorate with all its districts except Al-Aghwar Shamaliyah district in the west. The area has a Mediterranean climate with an average annual precipitation ranging between 200 mm/year in the eastern arid region to 500 mm/year in the southern subhumid Ajlun area.

The urbanized areas are mainly located in the middle and northeastern parts of the study area and are characterized by high population densities, while in the remaining parts of the study area low population communities are sparsely distributed. The topographic features are variable with elevations ranging from less than 150 m below sea level in the lower Yarmouk Valley in the north up to about 1000 m near Ajlun area in the southern part.

The soils of Irbid Governorate are classified as red Mediterranean soils which are mainly derived from limestone and are considered excellent for agricultural use [3]. In the east and northeast, brown alluvial soils derived from basalt contain gravel and boulders are also appropriate for agricultural.

Hydrogeology: The study area comprises two main aquifer systems; the Umm Rijam and Wadi Shallala B4/B5 Aquifer system and the Upper Cretaceous Amman-Wadi Es Sir A7/B2 Aquifer system (Figure 2) [4].

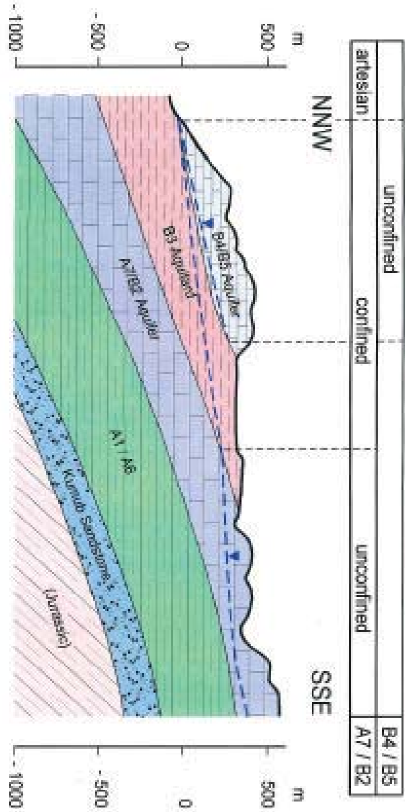

Fig. 2: Schematic hydrogeological cross section through the study area [6]

The Tertiary Umm Rijam (B4) and Wadi Shallala (B5) formations crop out in the area north of Irbid towards the Yarmouk River. The B4 formation is composed mainly of marly limestone, chalky limestone and chert and reaches a maximum thickness of more than 200 m, whereas the B5 formation consists of chalky and marly limestone with glauconite.

Hydraulic conductivity ranges between ($1x10^{-4}$) and ($1x10^{-6}$) m/s, with an average of ($5x10^{-5}$) m/s. Groundwater recharge to the B4/B5 aquifer is estimated at 8 to 10% of the mean annual rainfall [5]. The Umm Rijam formation is the uppermost unconfined shallow aquifer underlain by a thick marly limestone aquitard known as the Muwaqqar Chalk Marl formation (B3). It crops out in a strip reaching from the area south of Ramtha city via the city of Irbid to the slopes of the Jordan Rift Valley in the west.

In the southern part of the study area, the A7/B2 forms the dominant aquifer. The A7/B2 unit comprises massive limestone, dolomitic limestone and chert with intercalating beds of chalk, marl, gypsum and phosphorite. The A7/B2 is a more important aquifer than the B4/B5 because of its wider extent and its favorable hydrological properties and is used for the water supply of most of the communities. Jointing and fracturing is moderate to high and moderate karstification has been documented, especially in the mountain areas. Many of the wells drilled in the A7/B2 and B4/B5 systems are abandoned and no longer used for drinking water supply due to decreasing yield and/or deterioration of water quality.

Previous Studies: The hydrogeology and geology of the study area were investigated by many authors [7-11]. Sharadqah *et al.* [12] evaluated the groundwater vulnerability to contamination using a DRASTIC model in the Ramtha region, which forms the eastern part of the current study area. Margane *et al.* [4] used the method of the German Geological Surveys [13]. The degree of vulnerability is expressed as the protective effectiveness (the ability of the cover above an aquifer to protect the groundwater) of the soil cover down to a depth of 1m (the average rooting depth) and the rock cover (unsaturated zone). Awawdeh and Nawafleh [14] used the EPIK method in the Irbid governorate to investigate the aquifers susceptibility to contamination. Obeidat *et al.* [15] assessed the nitrate contamination of groundwater resources in Bani Kanana, which is the northern edge of the current study area. It was found that nitrate concentrations in spring water ranged from 8 to 192 mg/L.

Methods

Aquifers Vulnerability Assessment: The study of groundwater vulnerability to contamination is a useful tool for environmental planning and decision-making. A vulnerability map identifies areas susceptible to contamination and enables the design of monitoring networks. Groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against the natural and human impacts, especially with regard to contaminants entering the subsurface environment. Water infiltrating at the surface may be contaminated, but is naturally purified to some degree as it percolates through the soil and other fine grained materials in the unsaturated zone [16] that act as natural filters.

Vrba and Zaporozec [16] distinguished between two types of vulnerability: intrinsic (or natural) which was defined purely as a function of hydrogeological factors and "specific" that is related to specific pollutants, for example agricultural nitrate, pesticides, or atmospheric deposition. Many methods have been proposed for vulnerability mapping of aquifers as given in Vrba and Zaporozec [16] and Gogu and Dassargues [17] such as DRASTIC [18] GOD [19] AVI [20]; SINTACS [21] GLA-method [13] EPIK [22] and PI method [23].

The DRASTIC method is one of the most widely used methods in many countries for evaluating groundwater pollution potential, because the required data for its application are generally available or easy to obtain from public agencies [24-29] The DRASTIC model uses a large number of parameters in vulnerability assessment that allows a proper reduction of complex hydrogeological settings. It incorporates major geological and hydro-geological factors which affect the potential for groundwater pollution and control groundwater movement.

DRASTIC is a numerical rating model, which was developed by the United State Environmental Protection Agency as a method for assessing groundwater pollution potential [18] It is an acronym for the major hydrogeological parameters which control the potential for groundwater contamination at a specific site. These parameters are: depth to water table (D), recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone media (I) and hydraulic conductivity of aquifer (C).

A typical ratings range from 1-10 is assigned for each site parameter depending on the degree to which it affects pollution sensitivity in a particular area, the rating of 1 corresponds the least contamination potential and a rating of 10 presents the highest contamination potential. Rating values are based on literature and local experts. Also each DRASTIC parameter have weights from 1-5 according to its relative significance, the higher weights representing greater pollution potential [18].

The final DRASTIC Index number is a measure of the pollution potential (vulnerability) for a given area and is computed by the sum of each parameter ratings multiplied by the assigned weight as shown in the following equation:

DI = Dr* Dw þ+Rr*Rw þ+Ar*Aw +Sr*Sw + Tr* Twþ +Ir* Iwþ +Cr*Cw ….Equation (1)

Where:

DI = DRASTIC Index
r = Rating value for each parameter
w = Weighting associated to each parameter

The distance from the ground surface to the surface of the saturated zone (D) determines the thickness of the unsaturated zone through which a contaminant travels before reaching the aquifer. This is important because the deeper the water table the longer time for the contaminants to reach the aquifer. The "Net Recharge" (R) is the annual total quantity of water which infiltrates from the ground surface to the aquifer. The amount of recharge varies widely from place to another and is dependent on the rate, duration and frequency of precipitation and other factors such as topography, soil type, vegetation and evaporation rate [30]. The greater the recharge the greater the contamination potential because it may lead to leaching and transporting contaminants from the ground surface to the water table. Aquifer media (A) is the type and composition of rock which composes the aquifer matrix and the groundwater fills the pore spaces, fractures and caverns in this matrix [30].

Soils (S) have significant impacts on the amount of recharge which infiltrate through the surface into the aquifer. The pollution potential of the soil is affected by factors such as soil texture, type and amount of clay present and shrink-swell potential [30]. The less clay with shrink-swell potential and the presence of fine texture decrease the potential of pollution. Topographical (T) differences determine whether or not a contaminant will infiltrate into the ground or will be dispersed as surface runoff. In contrast to steep slope areas, areas with low slope tend to retain water longer, this allows greater infiltration of recharge water and a greater potential for contaminant migration. The vadose zone (I) is the zone between the land surface and the ground water table. The influence of the vadose zone on the vulnerability is influenced by its thickness, lithology and permeability. The hydraulic conductivity (C) is the property of soil or rock that describes the capability at which water can move through pore spaces or fractures under a unit hydraulic gradient. The intrinsic permeability of rocks is due to primary openings formed within the rock and secondary openings created after the rock was formed. It is controlled by the size of openings, the degree of interconnection and the amount of open space (Fetter, 1994). The higher the hydraulic conductivity, the faster contaminants travel times, hence assigned greater pollution potential ratings.

The DRASTIC index number ranges from (23) to (230) with an increasing relative potential for groundwater contamination. The higher the DRASTIC index number, the greater the relative groundwater contamination potential. ArcView GIS 9.2 was used to calculate and produce the vulnerability maps at the local scale by overlaying the layers of available hydro-geological data. The collected water samples were subjected to hydrochemical analysis in the laboratories of the Geology Department at the University of Jordan.

Water Quality Assessment: For the purpose of water quality assessment, water samples from 32 wells and 12 springs were collected during the dry season and the wet season; 44 samples in April 2006 and 40 in November 2006. The collected water samples were analyzed using the standard methods for the examination of water and wastewater [31] to measure the physical and chemical parameters: total dissolved solids (TDS), total hardness (TH), major cations (Ca^{+2}, Mg^{+2}, Na^+, K^+) and major anions (HCO_3^-, Cl^-, $SO_4{}^{\bullet 2}$, NO_3^-).

RESULTS AND DISCUSSION

Drastic Parameters and Aquifers Vulnerability: Water depth of 127 observation and production wells located in the study area was obtained from the database of the Water Authority of Jordan. The depth to water table is less than (50) m in most areas of the B4/B5 aquifer, while the A7/B2 water table ranges from zero in the western parts to about (300) m in the eastern parts of the study area. The ratings for the water depth parameter ranged from the (1) to (10).

According to BGR and WAJ (2001), 9 % of the average annual rainfall is considered as recharge rate for the B4/B5 aquifer and 25 % of rainfall for the A7/B2 aquifer in the study area. Accordingly, the mean groundwater recharge in the study area ranged from about (20-80) mm/year and the ratings ranged from 1 to 3 (Table 1).

The B4/B5 aquifer is mainly composed of limestone, chalk and chert, while the A7/B2 consists of limestone, dolomitic limestone and chert. The aquifer media for A7/B2 is given a rating value of (9) because the degree of its karstification is regarded as moderate and a rating value of (8) for the B4/B5 because the degree of its karstification is less than that of A7/B2 aquifer.

Eleven soil units have been identified within the study area according to the National Soil Survey (Ministry of Agriculture, 1993). The study area is mainly covered by the following soil types: clay, clay loam and clay and clay loam. The soils in the investigated area were assigned rating values in the range (3.5) to (7.5) (Figure 3).

Table 1: Assigned weights and ranges of rating values for various hydrogeological parameter settings in DRASTIC model [18]

Depth to Water (m) Range Rating		Recharge (mm) Range Rating		Aquifer Media Range Rating		Soil Media Range Rating		Topography (%) Range Rating`		Impact of vadose Zone Range Rating		Conductivity (m/s) Range Rating	
0 - 1.5	10	0.0 – 50.8	1	Massive shale	2	Thin or absent	10	0-2	10	Confining layer	1	4.716*10-7-4.716*10-5	1
1.5 - 4.57	9			Metamorphic/									
				igneous	3	Gravel	10			Silt/clay	3		
4.57 - 9.14	7	50.8 – 101.6	3	Weathered									
				metamorphic		Sand	9	2-6	9	Shale	3	4.716*10-5 – 1.41*10-4	
9.14 - 15.24	5			/igneous	4	Peat	8			Limestone	3		
15.24 - 22.86	3	101.6 – 177.8	6	Glacial till	5	Shrinking clay	7	6-12	5	Sandstone	6	1.41*10-4 – 3.3*10-4	4
22.86 - 30.48	2			Bedded sandstone,		Sandy loam	6			Bedded limestone,			
> 30.48	1	177.8 – 254	8	limestone	6	Loam	5	12-18	3	Sandstone	6	3.3*10-4 – 4.716*10-4	6
				Massive									
				sandstone	6	Silty loam	4			Sand and gravel			
		> 254	9	Massive									
				limestone	8	Clay loam	3	> 18	1	with silt	6	4.716*10-4 – 9.43*10-4	8
				Sand and gravel	8	Muck	2			Sand and gravel	8		
				Basalt	9	No shrinking							
						clay	1			Basalt	9	> 9.43*10-4	10
				Karsts						Karsts limestone	10		
				limestone	10								
DRASTIC Weight;5		DRASTIC Weight; 4		DRASTIC Weight; 3		DRASTIC Weight; 2		DRASTIC Weight; 1		DRASTIC Weight; 5		DRASTIC Weight; 3	

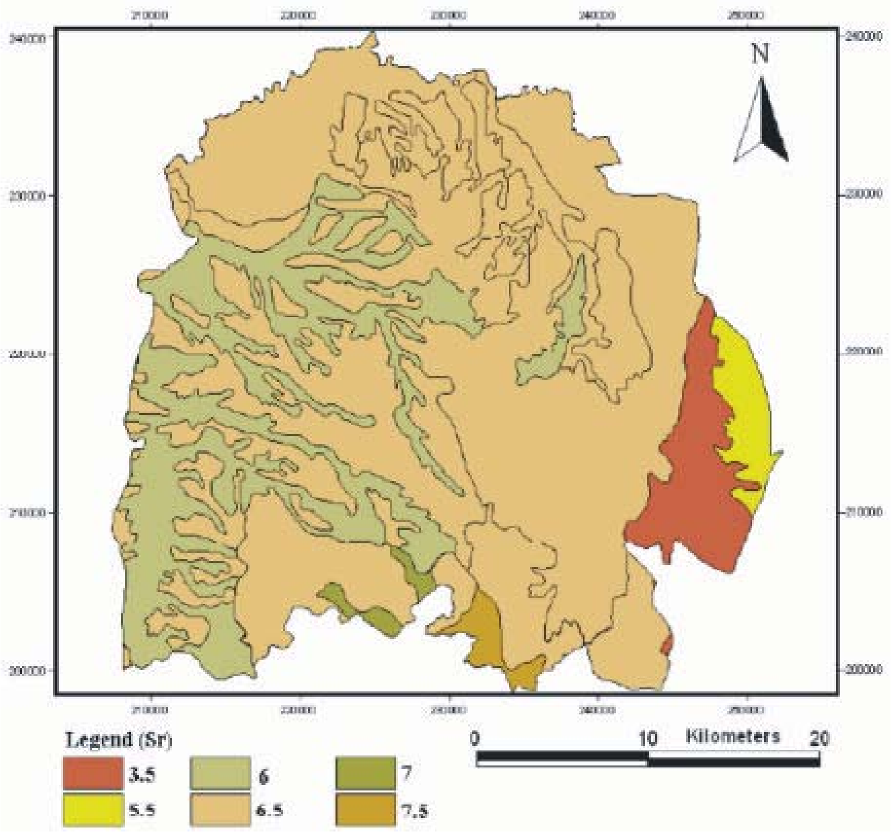

Fig. 3: The spatial distribution for the ratings of the soil media parameter in the study area

A digital elevation model ((DEM) with a (90) m cell size was used to extract the slopes of the study area. The slope degree in the study area ranges between 0-55 %. Areas with slopes greater than 15% occurred in the highland areas in the western part of the study area and given the lowest rating value, whereas the highest rating was given for the areas in the east which showed a gentle slope (less than 10 %).

The vadose zone stratigraphy was obtained from lithological columns of 97 wells drilled by the Ministry of Water and Irrigation in order to determine the layer types and the low permeability zones (limiting factor layer) above water table. The rates were given for each layer in each well and then a grid was built. Where parts of A7/B2 aquifer are confined, the vadose zone material was considered as the same as the confining layer material. Because a confining layer is usually a low permeability unit, it is automatically assigned the lowest rating (1). These areas form about 22% of the study area. About 69% of the study area was assigned a rating value of (3).

The hydraulic conductivity (K) in meters per day was calculated according to the equation by Todd (1980) T= K*b, where T is the transmissivity (m^2/day) and b represents the saturated thickness (m). Most of the study area (86%) is dominated by the rating (1) of the hydraulic conductivity and the remainder by rating value (2), as seen in tables.

The final vulnerability maps of both aquifers were obtained by overlying layers of the hydrogeologic information using the ArcView GIS to calculate a pollution potential index.

The vulnerability maps (Figures 4 and 5) of both aquifers (B4/B5 and B2/A7) showed only two classes of vulnerability: low (<100) and moderate (>100). Although the low vulnerability class dominates the study area, the moderate vulnerability class of the B4/B5 aquifer (0.80%) is relatively larger than that of the A7/B2 aquifer (0.2%). This is may be due the karstified nature of the B4/B5 aquifer. The predominant DRASTIC low degree of vulnerability is controlled by the high thickness of the vadose zone, low recharge rate (clayey) soils and the deep water table.

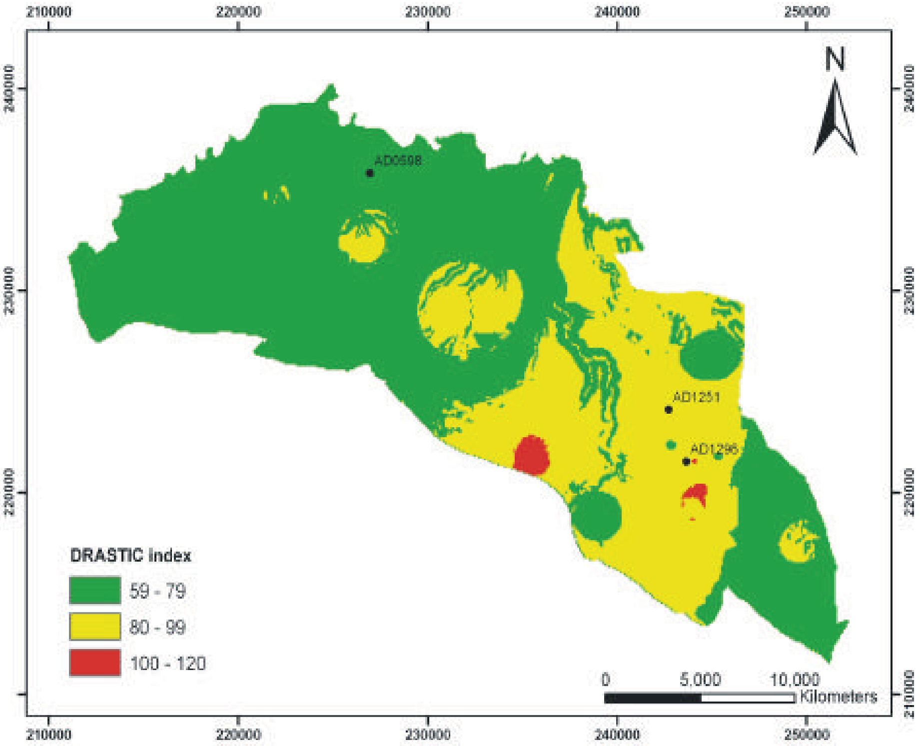

Fig. 4: Groundwater vulnerability map of the aquifers B4/B5 using DRASTIC method

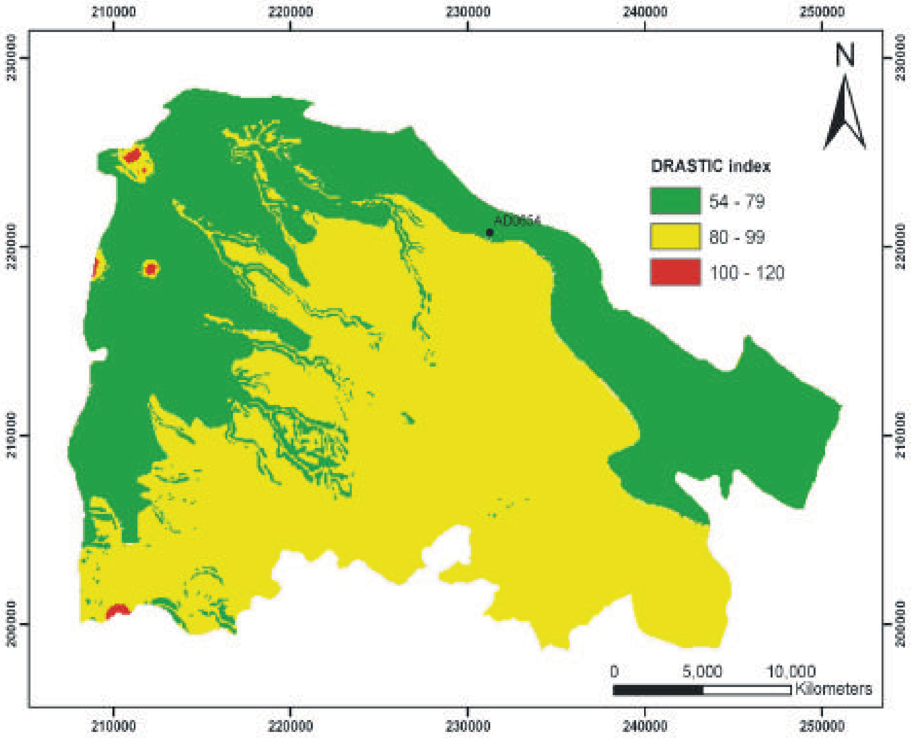

Fig. 5: Groundwater vulnerability map of the aquifers A7/B2

Table 2: Contaminated groundwater wells and springs

Chemical parameter	AD1296	AD1251	AD0654	AD0598	WHO (Jordanian) standards-mg/L
Total dissolved solids	•	•	•		1000 (500-1500)
Total hardness	•		•		300-500 (100-500)
Ca^{+2}			•		75-200 (100-500)
Na^{+}	•	•			200 (200-400)
K^{+}			•	•	10-50 (20-80)
Cl^{-}	•				250 (200-500)
$SO_4\bullet^{2}$			•		250 (200-500)
NO_3^{-}	•		•		50

Water Chemistry: Of all water samples (Figure 1) only two groundwater wells and two springs showed chemical concentrations above the permissible levels for drinking water according to the Jordanian standards [35] and World Health Organization (WHO) guidelines [35]. Well AD1296 is contaminated by nitrate, chlorine, sodium, total hardness and TDS. Spring AD0654 is contaminated by nitrate, sulphate, potassium, calcium, total hardness and TDS. Well AD1251 is contaminated by TDS and sodium and spring AD0598 by potassium only (Table 2). Both AD1251 and AD1296 are located within the upper low vulnerability class (80-99), but the latter is very close to the moderate vulnerability class. The most probable source of contamination is the Ramtha wastewater treatment plant since the depth of water level is shallow (less than 50m). Although spring AD0654 is located within the low vulnerability class, it is very close to areas with intensive agricultural activities and cesspool usage. The samples AD1296, AD1251 and AD0598 are emerging from B4/B5 aquifer that is karstified and accelerate the process of contamination.

Data Errors and Sensitivity Analysis: Groundwater vulnerability maps are accurate to the scale at which they are produced and it is recommended not to expand this scale. The only way to accurately depict aquifer vulnerability is to combine all the relevant data at an appropriate scale, typically 1:25,000. The main sources of uncertainty considered in this study include: 1) data related errors and 2) subjectivity in selection of parameters, weights and ratings. Considering the data related errors; the original geological, hydrogeological and soil data scale1:50,000 seem to be quite satisfactory for this study. However, the number of soil profiles and groundwater wells could be increased to obtain more information for better characterization of the study area. For the preparation of the data layers, the continuous surfaces are formed from the interpolation of the raw point data (depth to water, soil media and hydraulic conductivity). During this interpolation process, some errors may have occurred due to lack of more observation points. It was tried to minimize these errors by applying several surface fitting methods (inverse distance weighting, local polynomial and kriging) and choosing the method with least Root-Mean-Square Error (RMSE) value. The applied methods yielded an RMSE of 0.50, 0.55 and 0.82 ,respectively which is considered acceptable. The interpolated data were represented by a 90 m cell size which is the resolution of the digital elevation model. DRASTIC has been criticized for its subjectivity in selecting its parameters and their ratings and weights [36]. Sensitivity analysis studies the contribution of individual variables and of input parameters, on the resultant output of an analytical model. Two sensitivity tests are usually carried out: the map removal sensitivity analysis and the single parameter sensitivity analysis. The first test identifies the sensitivity of DRASTIC index by removing one parameter each time of running the model. A variation index (*VI*) for each parameter is worked out using the following equation [17]:

$$VI = (P-P\ddot{I}/P)*100 \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq.}$$

Where:

VI : The variation index

P : The potential value in each cell computed using Equation 4.1

PÏ : The potential value of each cell excluding the one parameter

The variation index can be positive or negative, depending on the influence of the single parameter in decreasing or increasing, respectively, the DRASTIC index. The value of this index gives an

Table 3: Statistics of the variation index (*VI*%) and single parameter sensitivity analysis

Parameter	*VI*(%)	Theoretical weight (%)	Effective weight (%)
D	65.40	21.7	26 (+4.3%)
R	75.00	17.4	11
A	07.70	13	34 (+21%)
S	25.00	8.7	8
T	66.00	4.3	24 (+19.7%)
I	34.50	21.7	16
C	71.50	13	7

idea of the magnitude of such a variation. Variation index (*VI*) calculations (Table 3) showed that net recharge, hydraulic conductivity, topography and depth to water table are highly variable (*VI* are 75%, 71.5%, 66% and 63.4%, respectively), which implies high contribution to the variation of the vulnerability index across the study area. The impact of the vadose zone and soil media are moderately variable (*VI* are 34.5% and 25%, respectively). Aquifer media is the least variable parameter (*VI* is 7.7%). The low variability of a parameter implies a smaller contribution to the variation of the vulnerability index across the study area.

Uncertainty may be also due to the arbitrary assignment of weights and rates for each parameter of DRASTIC. The single-parameter sensitivity compares the "effective" (real) weight of each input parameter with the "theoretical" weight assigned by DRASTIC model. The "effective" weight of each cell is obtained using the formula:

$$W = (X_r X_w / Vi) \text{ x}100$$

Where W refers to the "effective" weight of each parameter, Xr and Xw are the rating value and weight of the parameter X and Vi is the overall vulnerability index.

The 'effective' weight is a function of the value of the single parameter with regard to the other six parameters as well as the weight assigned to it by the DRASTIC model. The 'effective' weights of the DRASTIC parameters exhibited some deviation from their 'theoretical' weights (Table 3). Aquifer media, depth to water and topography have effective weights (mean effective weights are 34%, 26% and 24%, respectively) higher than the theoretical weights assigned by the model (13%, 21.7% and 4.3%, respectively). These parameters tend to be the most effective in the vulnerability assessment. The rest of the parameters exhibit lower 'effective' weights compared to the 'theoretical' weights.

CONCLUSIONS

The goals of this investigation were to perform a susceptibility assessment of the aquifers within the Irbid Governorate using DRASTIC method and compare the results of the assessment with water chemistry data.

The dominance of the low vulnerability in the study area is mainly attributed to the fact that DRASTIC assumes a very low vulnerability (rating value =1) when water depths are greater than (30) m. This fact is ascertained by the results of the sensitivity analysis. Both map removal and single-parameter sensitivity analyses showed that depth to water table and topography are the most effective parameters in determining aquifer vulnerability. Additionally, DRASTIC does not demonstrate the capacity of satisfactorily outlining karst morphology.

The significance of depth to water and topography layers highlights the importance of obtaining accurate, detailed and representative information about these factors and other factors as well.

For the above reasons, DRASTIC did not depict accurately the high concentrations of some chemicals. One more reason for the high concentrations of chemicals in wells/springs is the possible surficial contamination sources e.g. cesspools.

The results of this study indicate the need for new research into procedures of parameters quantification and weighting and further investigations are required in order to understand the mechanisms of groundwater recharge and contaminant transport in such aquifers. However, the choice of vulnerability method remains a subjective decision for the hydrogeologist. As stressed by Aller *et al*. (1987), vulnerability methods are screening tools. They must not replace the professional expertise and field studies needed for more quantified answers.

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