Role of the Geologic Structures on the Aquifers Vulnerability in Arid Areas: Case Study from Swaqa - Ghabawi / Jordan

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ABSTRACT

In this study, the geological structures in the area extending between Ghabawi solid waste and Swaqa hazardous waste deposits were investigated in detail to study the impacts of human activities on the aquifer vulnerability. Two indices were used to evaluate that vulnerability, namely; DRASTIC and SINTACS. The hazardous waste disposal site of Swaqa in the southern part of the study area, the landfill deposit in its northern part and the intended oil shale and uranium mining are the main sources of potential groundwater pollution. The study aims at building a new approach to combine structures with known vulnerability indices to better evaluate the prevailing conditions. Chemical analyses of the groundwater quality in the area were performed to validate the findings. All relevant variables of the study area were put in a GIS environment as digits to ease layering of the different types of spatial data.

The aquifers in the study area refer to the Lower Tertiary and Upper Cretaceous and are composed mainly of carbonate types of rocks. Three major structures are found in the area consisting of faults differently trending in directions. These faults were found to intersect the aquifers in the area. Without the consideration of the effects of the faults, the area would locate in middle vulnerability zones, but their presence caused an elevation in the vulnerability class. This was clear from the spatial distribution of the values of nitrates, which was found to correlate with the structural map of the area.

DRASTIC and SINTACS vulnerability indices are unable alone to evaluate the spatial vulnerability of the aquifers when geologic structures are dominant. Accordingly, some modifications and merging were made to the DRASTIC and SINTACS indices to account for the structures in order to make thse indices suitable to evaluate similar areas with prevailing geologic structures, especially faults and fissures.

KEYWORDS: Swaqa, Ghabawi, Geologic structures, Vulnerability of groundwater, DRASTIC, SINTACS.

INTRODUCTION

Jordan climate is divided into different climatic regions and Jordan is considered the 4^{th} poorest country in the world in terms of water resources (MOWI, 2007). The naturally imposed semi-aridity of Jordan results from limited amounts of rainfall and therefore limited surface and groundwater resources (Salameh, 2001). In addition, population growth, whether due to a high birth rate or to the influx of refugees, is increasing pressure on the scarce water resources (Salameh and Bannayan, 1993). Currently, Jordan is not using all its water resources. This is because some of these resources suffer from quality constraints such as salinity, pollution by domestic, industrial or irrigation return flows, or they are unreachable and positioned far away from centers of demand (Salameh, 2001).

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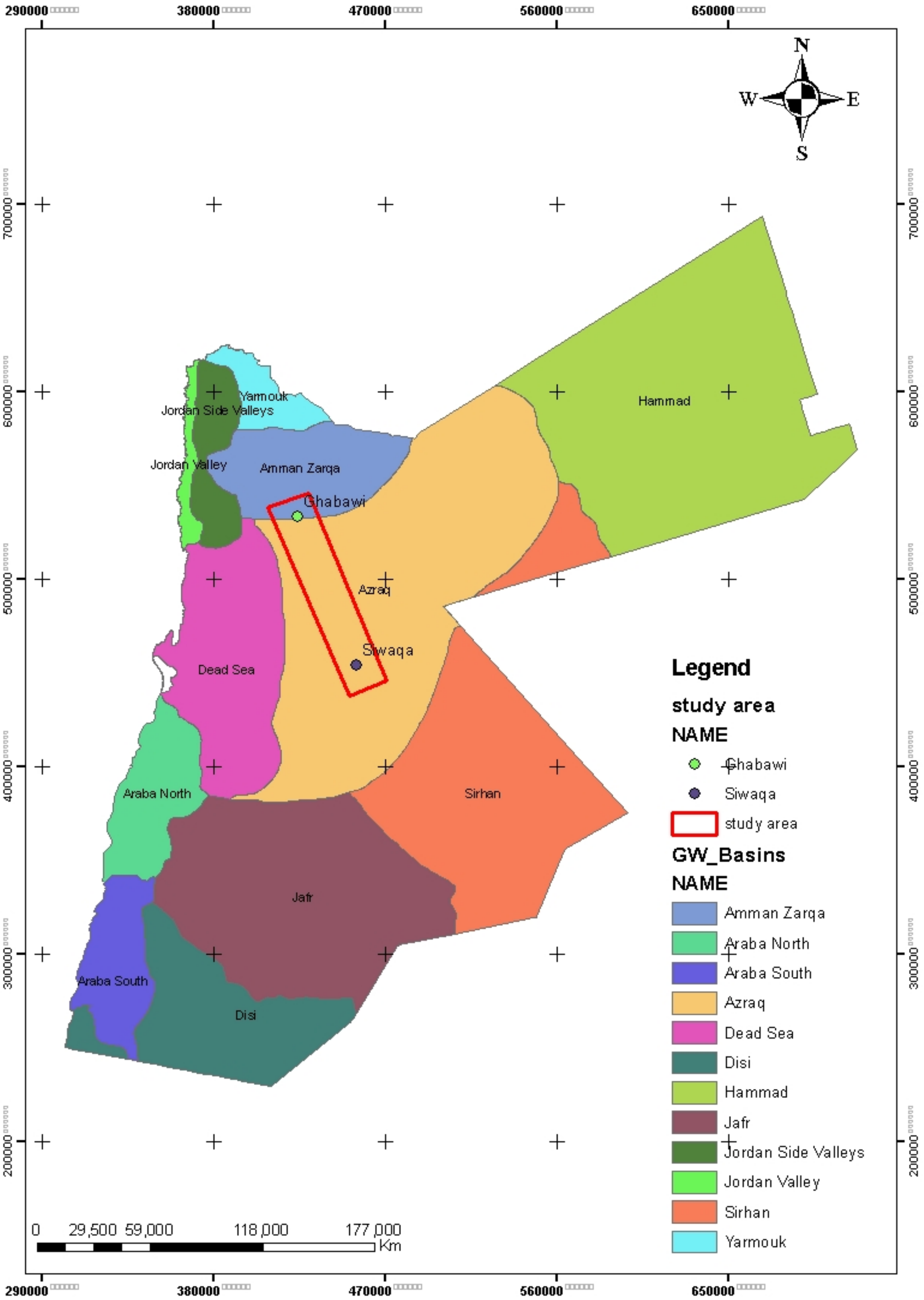

Figure (1): Groundwater basins in Jordan (MWI, 2007) and location of the study area

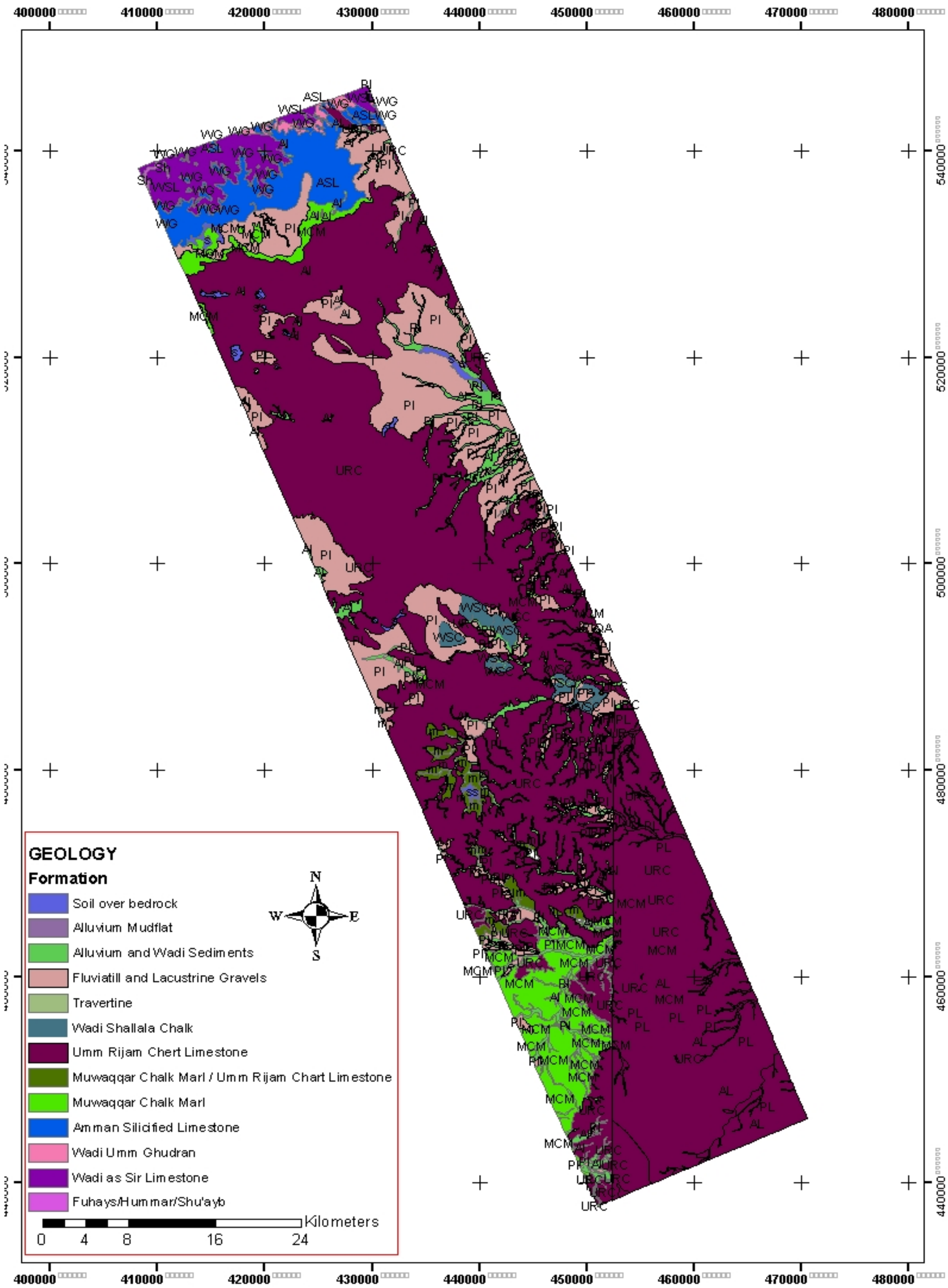

Figure (2): Geologic map of the study area (NRA MAP, 2008)

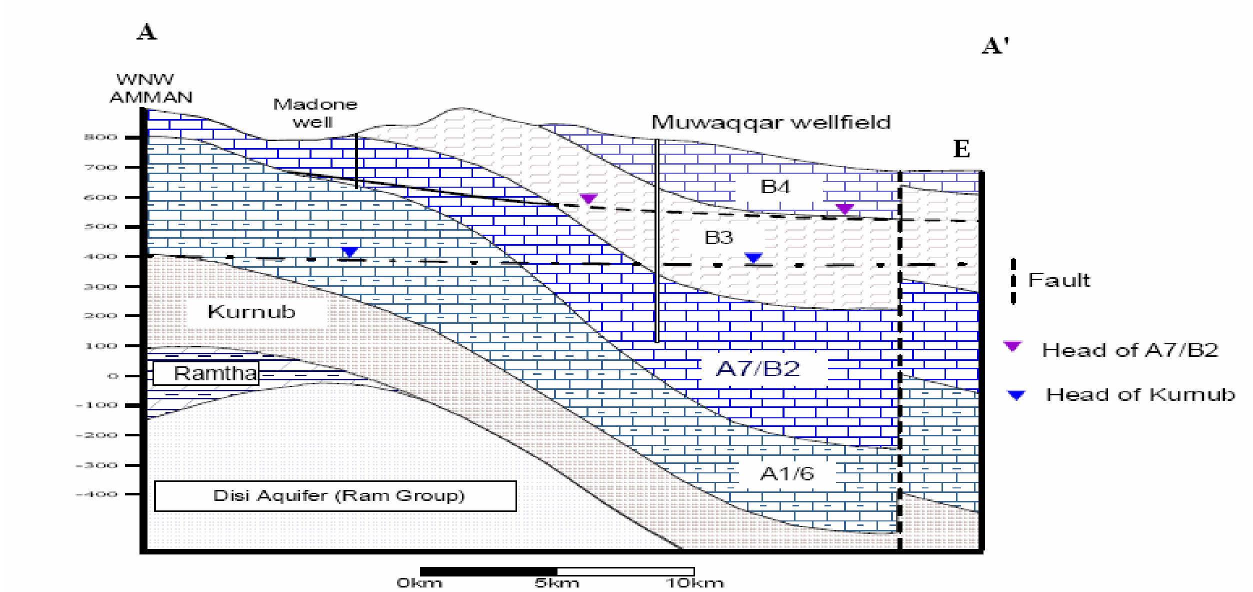

Figure (3): Hydrgeological cross-section A-A' (after WAJ, 1996)

Table (1): Lithostratigraphy in the study area (NRA, 2008)

ERA	PERIOD	AGE	GROUP	HYDRAULIC PROPRTY	FORMATION
CENOZOIC	QUATERNARY	HOLOCINE		AQUIFER	SOIL, ALLUVIUM AND WADI SEDIMENTS
		PLEISTOCENE		AQUIFER	FLUVIATILE AND LACUSTRINE GRAVELS
		PLIOCENE			
	TERTIARY	OLIGOCENE			
		EOCENE	BELQA	SEIMI AQUIFER	WADI SHALLALA
				SEIMI AQUIFER	UMM RIJAM
		PALEOCENE		AQUICLUDE	MUWAQQAR
MESOZOIC	UPPER CRETACEOUS	MAASTRICHTIAN			
		CAMPANIAN		AQUIFER	AMMAN SILICIFIED
		SANTONIAN		AQUICLUDE	WADI UMM GHUDRAN
		CONIACIAN			
		TURONIAN	AJLUN	AQUIFER	WADI SIR
		CENOMANIAN		BAD AQUIFER	FUHEIS/ HUMMAR/ SHUEIB
	LOWER CRETACEOUS		KURNUB GROUP	AQUIFER	KURNUB SANDSTONE

Table (2): Simplified hydrogeological classification of rock units in the study area (MARGANE, 2002)

System	Epoch	Group	Formation	Lithology	Hydrogeological Classification
TERTIARY	Eocene	BELQA (B)	Wadi Shallala (B5)	Chalky and marly limestone	Aquifer
	Paleocene		Rijam (B4)	Limestone, chert, chalk	Aquifer
UPPER CRETACEOUS	Masstrichtian		Muwaqqar (B3)	Chalky marl limestone, bituminous marl, chalk	Aquiclude
	Campanian		Amman-Al Hisa (B2)	Limestone, chert, chalk	Aquifer
	Santonin		W.Umm Ghudran (B1)	Dolomitic, marly limestone, marl, chert, chalk	Semi aquifer
	Coniacian	AJLUN (A)	Wadi Sir (A7)	Limestone, dolomitic limestone, marl, chert	Aquifer
	Turonian		Shueib (A5/6)	Marl, limestone	Aquiclude
	Cenomanian		Hummar (A4)	Limestone, dolomite	Semi aquifer
			Fuheis (A3)	Marl, limestone	Semi aquifer
			Naur (A1/2)	Marl, limestone, dolomite	Semi aquifer
LOWER CRETACEOUS		KURNUB	Kurnub	Sandstone	Aquifer

Table (3): Characteristics of the main hydrogeological units in the area (WAJ, 1996)

Unit	**K horizontal**	**K vertical**	**Specific Storage**	**Specific Yield**
B4/B5	$2.25 * 10^{-5}$ m/s	$2.25 * 10^{-6}$ m/s	10^{-5} /m	0.05
B3	10^{-8} m/s	10^{-10} m/s	10^{-5} /m	0.01
A7/B2	$1.3 * 10^{-5}$ m/s	$2.0 * 10^{-6}$ m/s	$2 * 10^{-5}$ /m	0.03
A1/A6	10^{-6} m/s	10^{-10} m/s	10^{-5} /m	0.01
Kurnub	10^{-5} m/s	10^{-6} m/s	10^{-5} /m	0.03

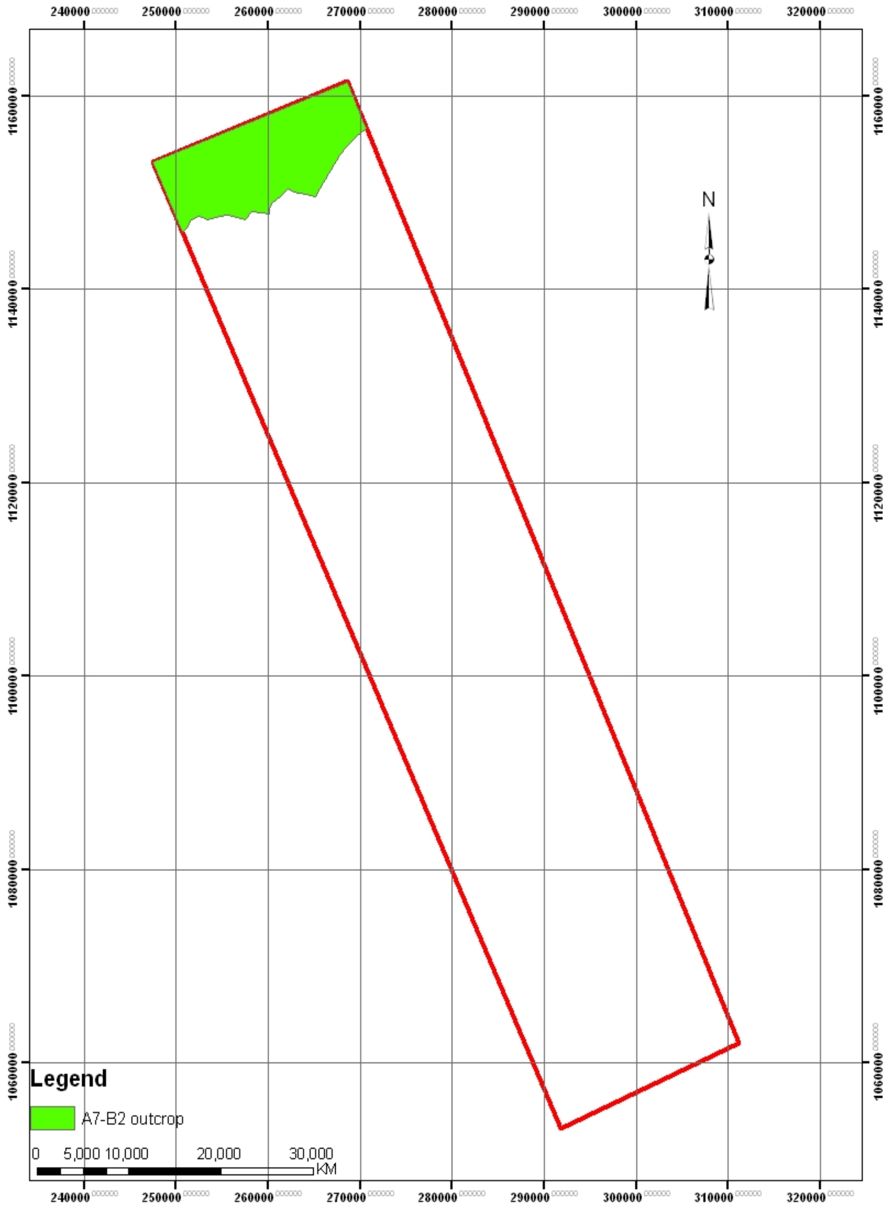

Figure (4): A7/B2 aquifer outcroup in the study area (BGR – WAJ, 2001)

Jordan has an annual precipitation of around 8500 MCM of which between 85% and 92% is lost to evaporation. Between 5% and 11% infiltrates for the groundwater and 2% - 4% generates runoff (Allison, 1998; Allison *et al*., 2000).

Groundwater is considered to be the major water resource in many areas in Jordan and the only source of water in some areas. Groundwater can be divided into two types (Salameh and Bannayan, 1993):

1) Renewable groundwater resources;

2) Non-renewable groundwater resources.

Jordan's groundwater resources are found in 12 basins (Figure 1). Some of the renewable groundwater resources are presently exploited at maximum capacity and in some cases are exploited beyond the safe yield (Salameh, 2008). The study area (Figure 1) lies within Azraq surface catchment and Azraq groundwater basin (Figure 1).

Location

The study area (Figure 1) is located between Swaqa and Ghabawi and contains two landfill sites, one for normal solid waste disposal; Ghabawi, and the other for disposing special hazardous wastes of chemical and radioactive residues. The study area also contains small types of industries, animal husbandries and agricultural activities.

The area is a part of the Azraq groundwater basin (Fig 1). Groundwater in the Azraq basin is present in three aquifer complexes; Upper, Middle and Lower, or shallow, intermediate and deep aquifers, separated from each other by low permeability aquitards.

Geologically, the area is built up of Upper Cretaceous and Tertiary rocks of limestone, marl, oil shale, chalk, chert and phosphatic rocks among others, see (Fig. 2) and (Table 1). Some of these rocks (e.g. the marl and oil shale) may form good barriers for any infiltration of water and pollutants into the aquifers. But, the secondary permeability produced by geological structures, for example: faults, weakness zones and widened joints, may serve as good pathways enhancing water infiltration and down percolation into the aquifers. In addition, Swaqa fault passes that basin from east to west.

The groundwater flow in the study area is directed towards the Azraq basin. In between the study area and the Azraq basin, numerous wells extract groundwater for domestic use. Therefore, it is very important to protect these groundwater resources from deterioration by the infiltration of leachates from the disposal sites of Swaqa and Ghabawi and other human activities.

This study will try to clarify the potentials of environmental impacts on the groundwater quality.

Hydrogeology

Generally, groundwater is considered the main source for potable water in Jordan. Its importance is revealed by its limited quantities and the need for large amounts and good qualities of it to satisfy the increasing needs of the growing population.

In Jordan, the subdivision of the geological succession into lithostratigraphical units of aquifers and aquitards has been established since the 1960s (e.g. Mc Donald ,1965; FAO/NRA, 1969/1970; FAO/NRA, 1971; GTZ/NRA, 1977; Abu-Ajamieh et al., 1988; BGR/WAJ, 1994). The hydrogeological units of the area are summarized in Table (2) and Figure (3) and qualitatively grouped as aquifers and aquitards.

The sequence of aquifers and aquitards in the study area has been divided into the following hydraulic complexes (Fig. 3):

The ***shallow aquifer,*** this aquifer consists of the chalky marly Rijam Formation (B4), which is in places separated from the underlying middle aquifer by the marls and chalk of the Muwaqqar Formation (B3).

The ***middle aquifer*** system, this aquifer consists of the limestone and chert of the A7/B2 Amman and Wadi Sir Formations. In the study area, this aquifer is confined and forms a major aquifer. Recharge into the aquifer takes place along the northwestern part of the study area.

The ***deep aquifer***. This aquifer consists of the Kurnub Sandstone Group. In the study area, this aquifer is under confined condition and does not crop out.

In this study, less emphasis will be given to the middle and deep aquifers, especially because they are separated from the ground surface activities by the aquiculudes of the B3 and A1/6, respectively.

Hydraulic characteristics of the Aquifers

The study area consists mainly of four units with different characteristics as presented in Table (3).

The A7/B2 aquifer system is one of the most important aquifer systems in Jordan because of the high potentiality of this aquifer.

This aquiferous unit is confined in the central and western parts of the area and unconfined in the rest of the area (Fig. 4), where the confining formation is the B3. The thickness of this unit varies from 44 m in the outcrops near Sahab City, NW part of the study area reaching 670 m in the eastern and southern parts, the underlying Formation is the A1/6 Formation which has a very low hydraulic conductivity.

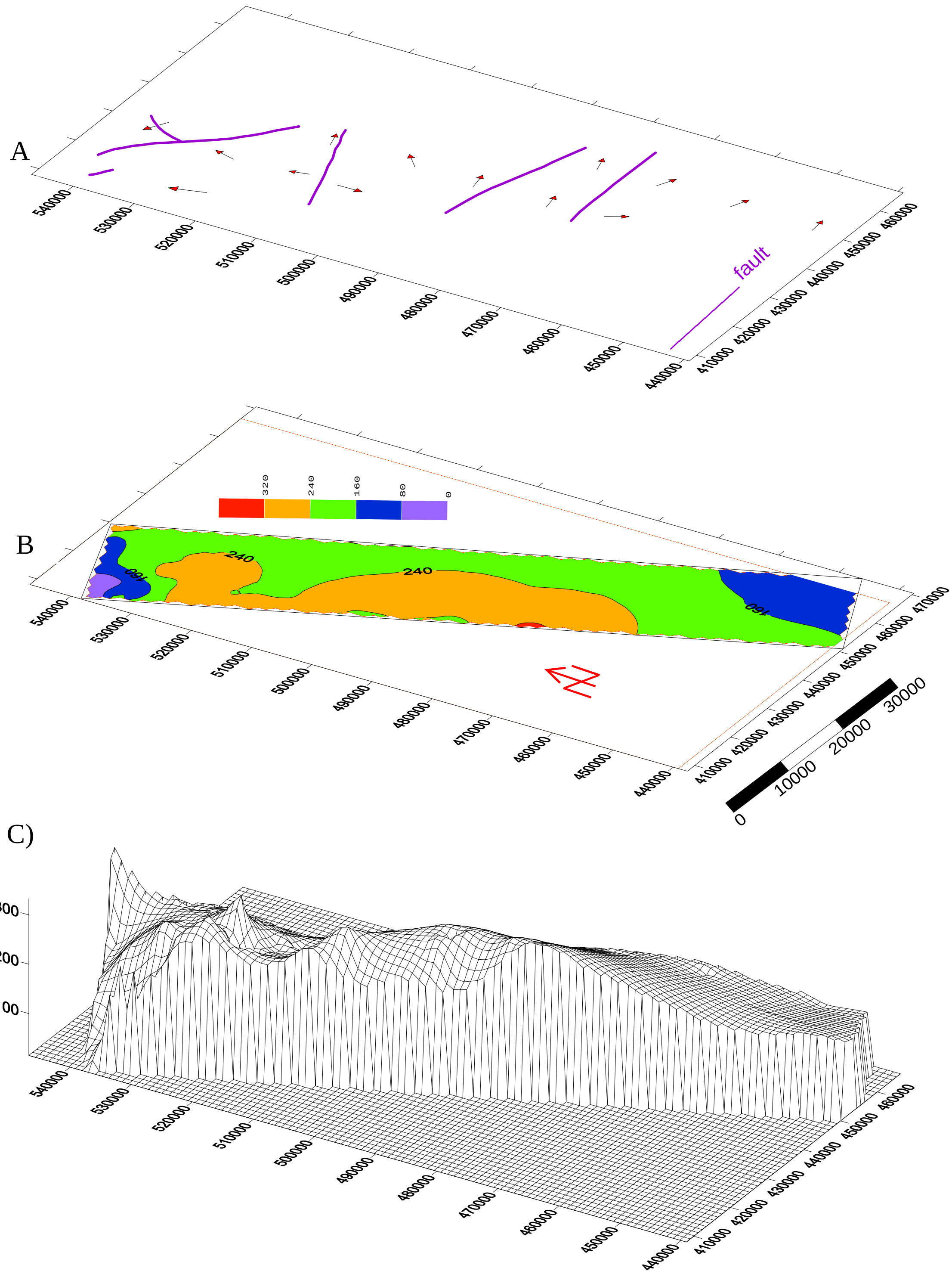

Figure (5): Groundwater level and flow for the A7/B2 aquifer in the study area and its surroundings A) Vector map of groundwater flow directions, B) Groundwater level contours and C) 3D representation of the ground surface topographies

Table (4): Descriptive statistics of the chemical analysis of the water samples

Parameter	Valid N	Mean	Minimum	Maximum	Std.Dev.
EC µS/cm	15	1047.7	667	1986	361.1
pH-Value	15	7.25	6.7	7.64	0.24
Temp. (ºC)	15	11.99	7.3	31	6.43
Ca (meq/L)	15	5.6	3.82	9.5	1.54
Mg (meq/L)	15	1.62	0.8	4.31	1.16
Na (meq/L)	15	4.54	1.58	19.9	4.55
K (meq/L)	15	0.23	0.05	1.2	0.29
HCO_3 (meq/L)	15	3.57	2.94	4.9	0.54
Cl (meq/L)	15	5.1	1.75	18.35	4.26
SO_4 (meq/L)	15	2.97	1.1	8.9	2.44
NO_3 (meq/L)	15	0.12	0.02	0.4	0.14

Table (5): DRASTIC weights and ratings relevant for the study area
(1: after Knox *et al.*, 1993, 2: after Piscopo, 2001)

<table>
<tr><th colspan="2">D: Depth to Groundwater[1]</th><th colspan="2">R: Recharge[2]</th><th colspan="2">A: Aquifer media[1]</th></tr>
<tr><th>Range (m)</th><th>Dr</th><th>Range</th><th>Rr</th><th>Material</th><th>Ar</th></tr>
<tr><td>More than 30</td><td>1</td><td>9 – 11</td><td>8</td><td>aquitard</td><td>3</td></tr>
<tr><td rowspan="2">Weight (Dw)</td><td rowspan="2">5</td><td>7 – 9</td><td>5</td><td>Bedded limestone</td><td>6</td></tr>
<tr><td>5 – 7</td><td>3</td><td>Massive limestone</td><td>7</td></tr>
<tr><td colspan="2" rowspan="2">S: Soil media[1]</td><td rowspan="2">Weight (Rw)</td><td rowspan="2">2</td><td>sand and gravel</td><td>8</td></tr>
<tr><td>Weight (Aw)</td><td>3</td></tr>
<tr><td>Soil type</td><td>Sr</td><td colspan="2">T: Topography[1]</td><td colspan="2">I: Impact of the vadose zone[1]</td></tr>
<tr><td>Sandy loam</td><td>6</td><td>Slope (%)</td><td>Tr</td><td>Material</td><td>Ir</td></tr>
<tr><td>Silty loam, Silty clay loam</td><td>4</td><td>0-2</td><td>10</td><td>Confining layer</td><td>1</td></tr>
<tr><td>Clay loam</td><td>3</td><td>2-6</td><td>9</td><td>Fractured limestone</td><td>10</td></tr>
<tr><td>Weight (Sw)</td><td>5</td><td>6-12</td><td>5</td><td>Weight (Iw)</td><td>4</td></tr>
<tr><td colspan="2" rowspan="4"></td><td>12-18</td><td>3</td><td colspan="2">C: Conductivity (Hydraulic)[1]</td></tr>
<tr><td>More than 18</td><td>1</td><td>Value</td><td>Cr</td></tr>
<tr><td rowspan="2">Weight (Tw)</td><td rowspan="2">3</td><td>less than $0.5*10^{-4}$ m/s.</td><td>1</td></tr>
<tr><td>Weight (Cw)</td><td>3</td></tr>
</table>

Groundwater Level and Flow Direction for the A7/B2 Aquifer

The groundwater contour map for the A7/B2 aquifer in the study area was constructed depending on the static water levels taken from the Water Authority of Jordan (WAJ open files). Figure (5B) represents the groundwater contour map for the A7/B2 aquifer in the study area in 2008.

The three dimensional elevation map (Fig. 5) for the study area was constructed by using topographic maps with a scale of 1:10000. The groundwater flow direction is presented on the map, scaled to relative changes in groundwater head. Also, a vector map has been prepared as a third layer to illustrate the effect of topography on the groundwater flow directions.

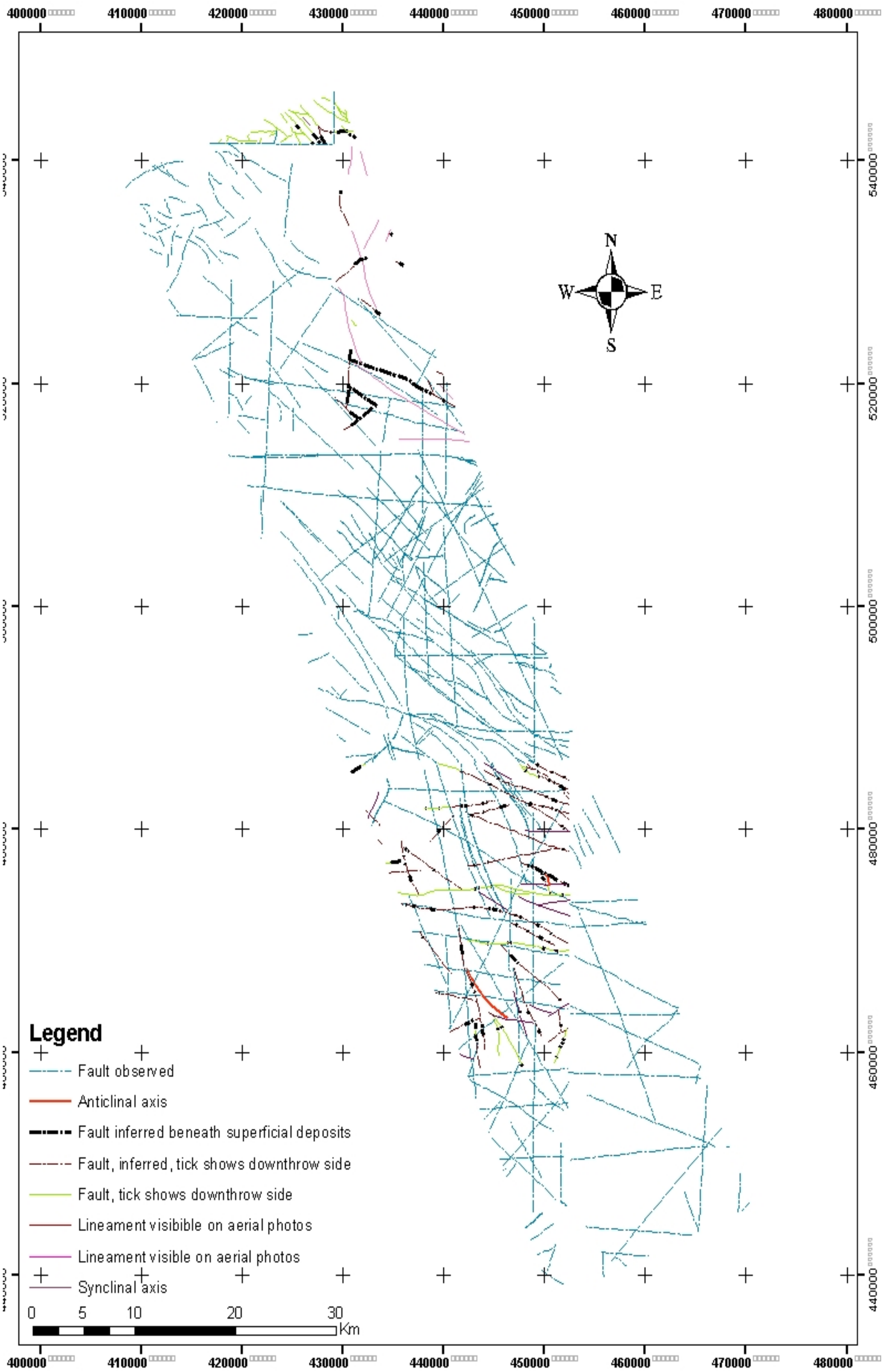

Figure (6): Major faults, lineaments, linear features and folds in the study area (NRA, 2008)

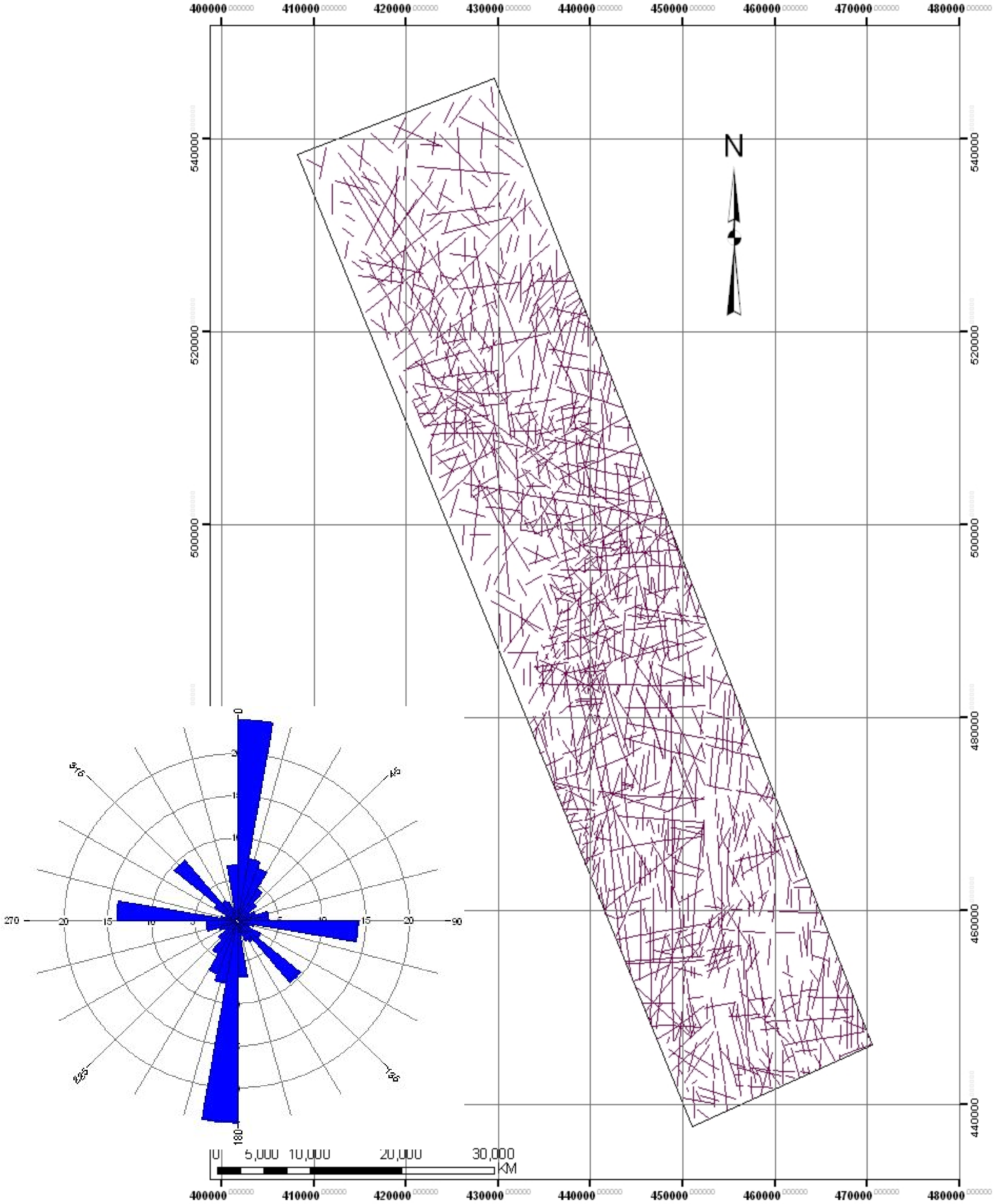

Figure (7): Fractures in the study area (NRA, 2008) and rose diagram representing prevailing fracture directions

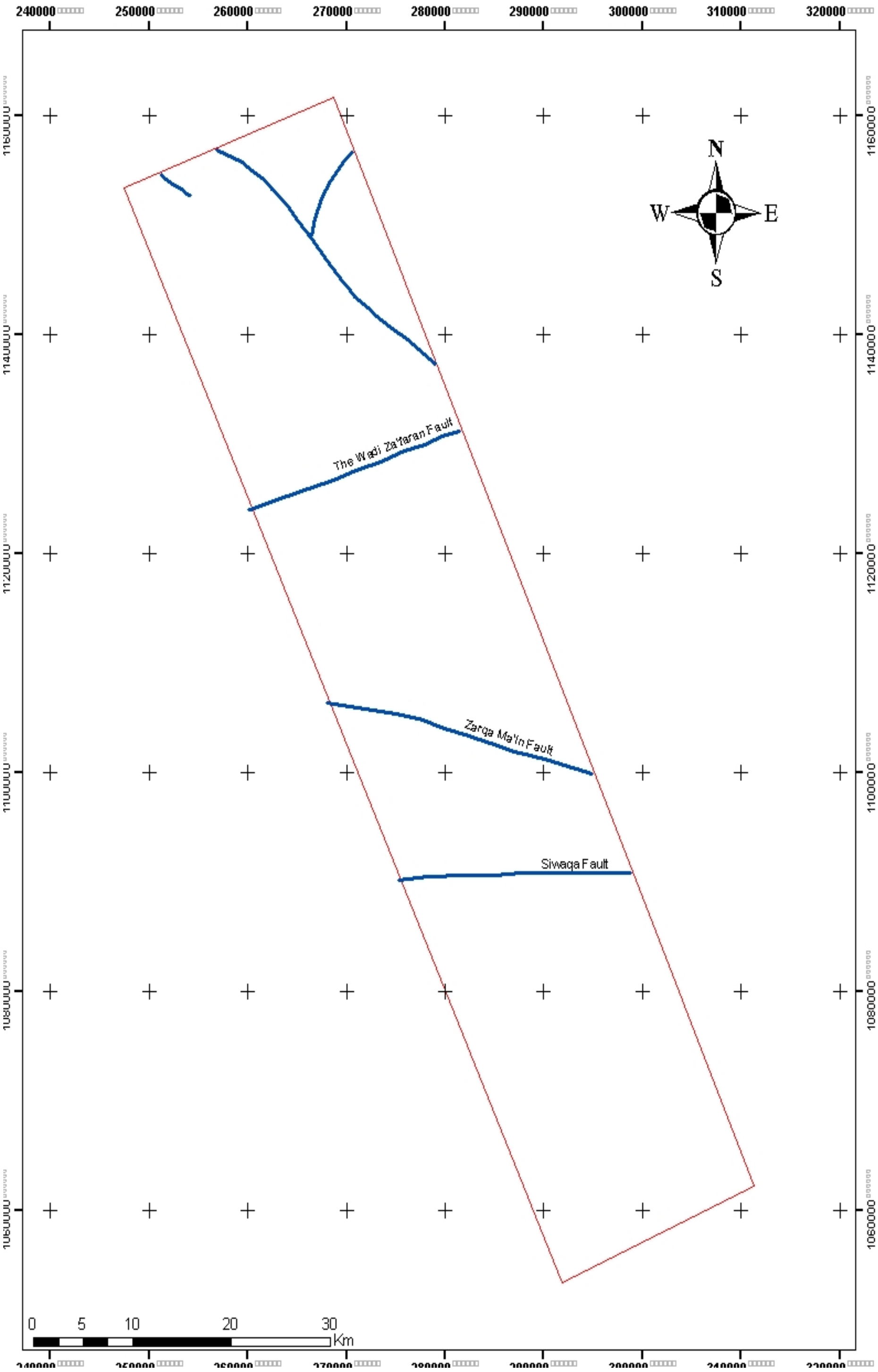

Figure (8): Major faults in the study area (NRA, 2008)

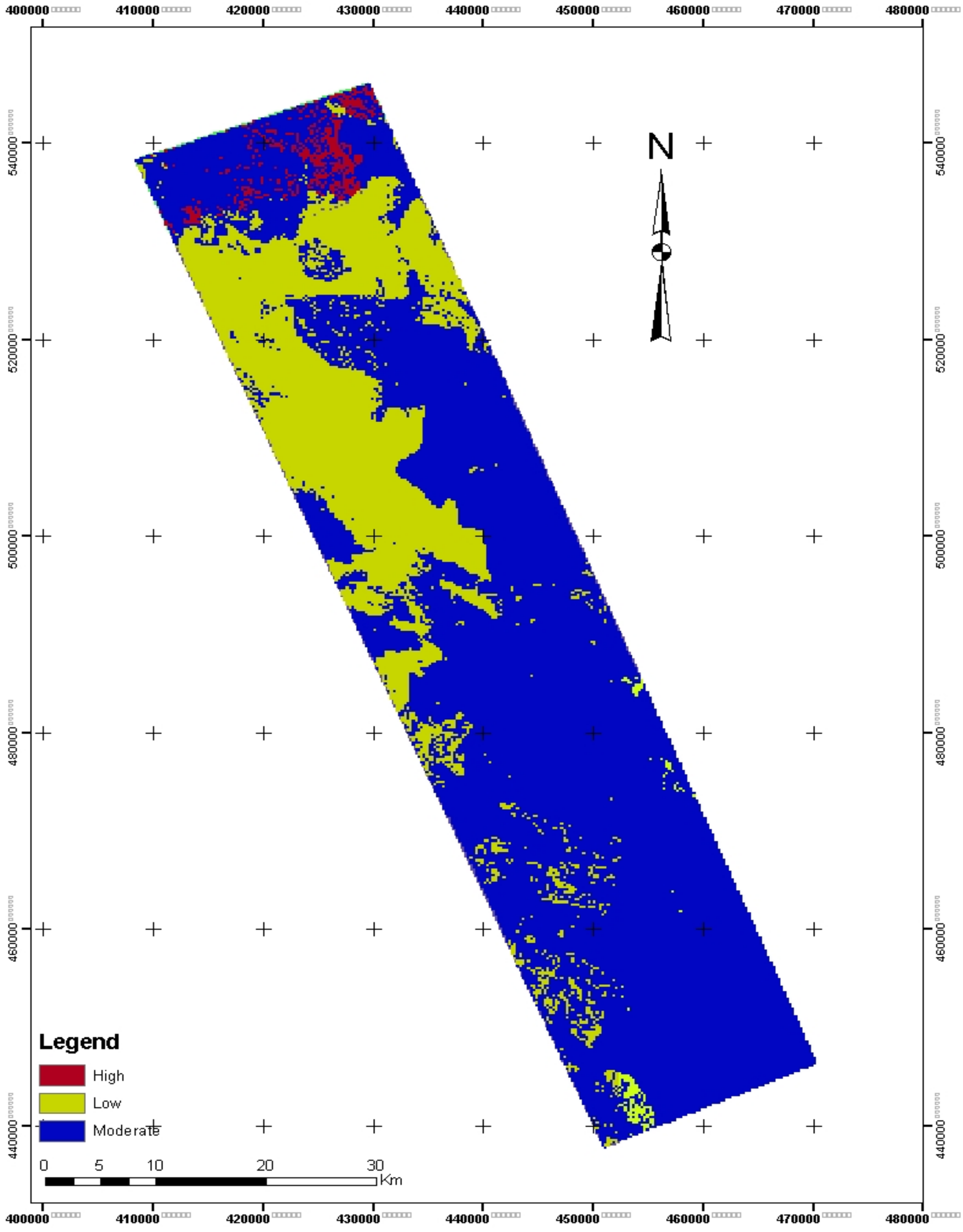

Figure (9): DRASTIC index map of the study area

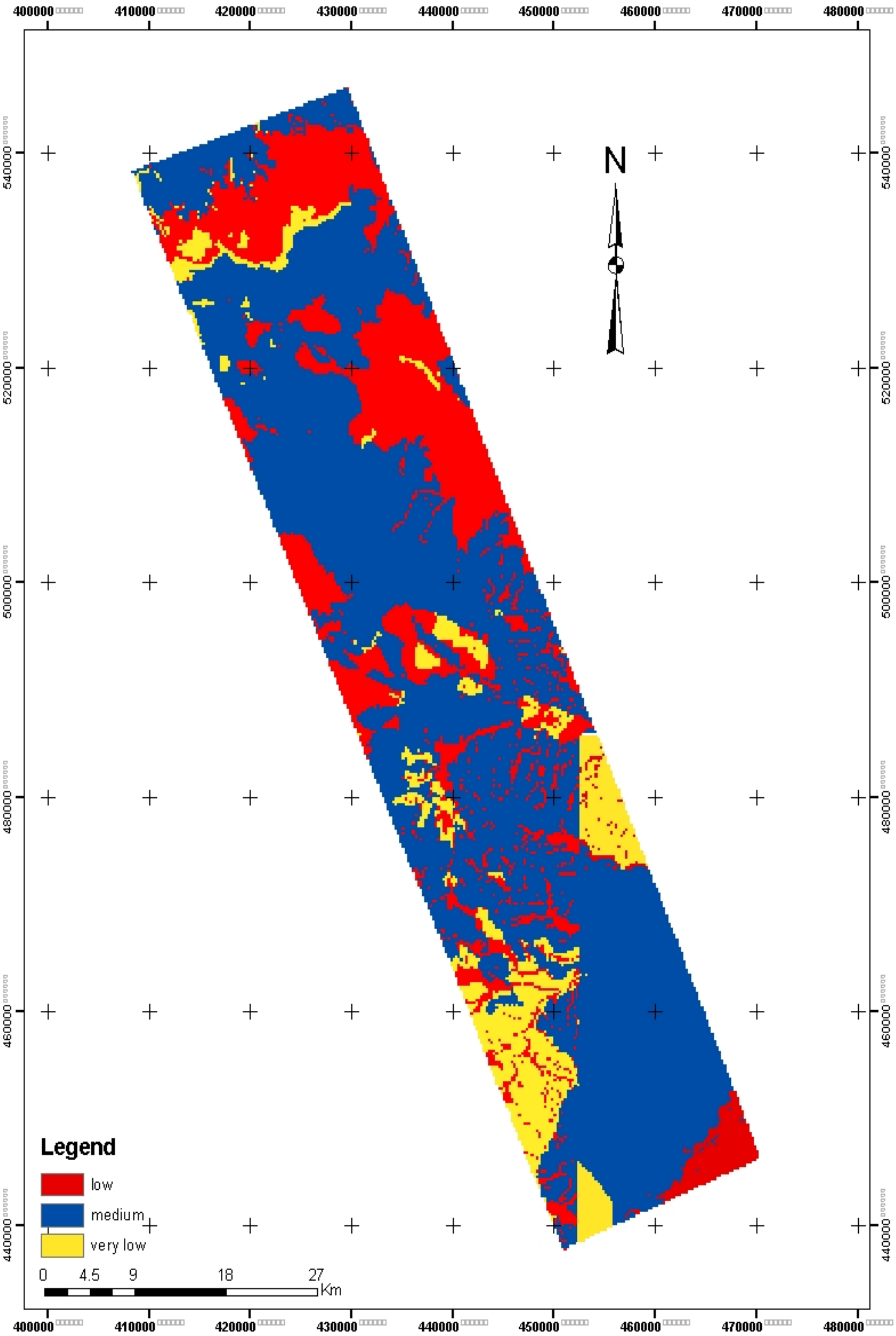

Figure (10): Vulnerability evaluation according to SINTACS rating in the study area

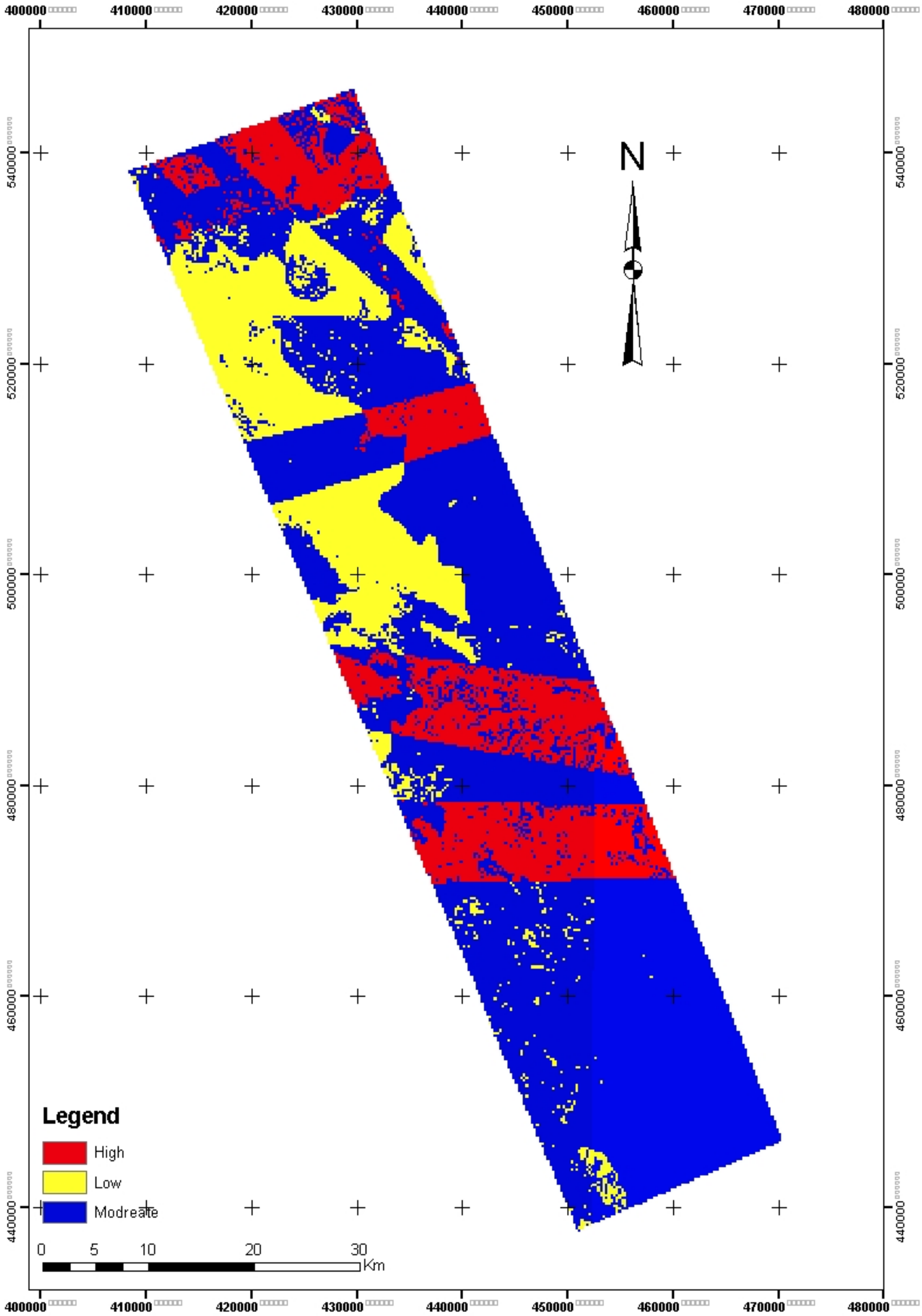

Figure (11): Final vulnerability map in DRASTIC index including the effects of structures on the vulnerability

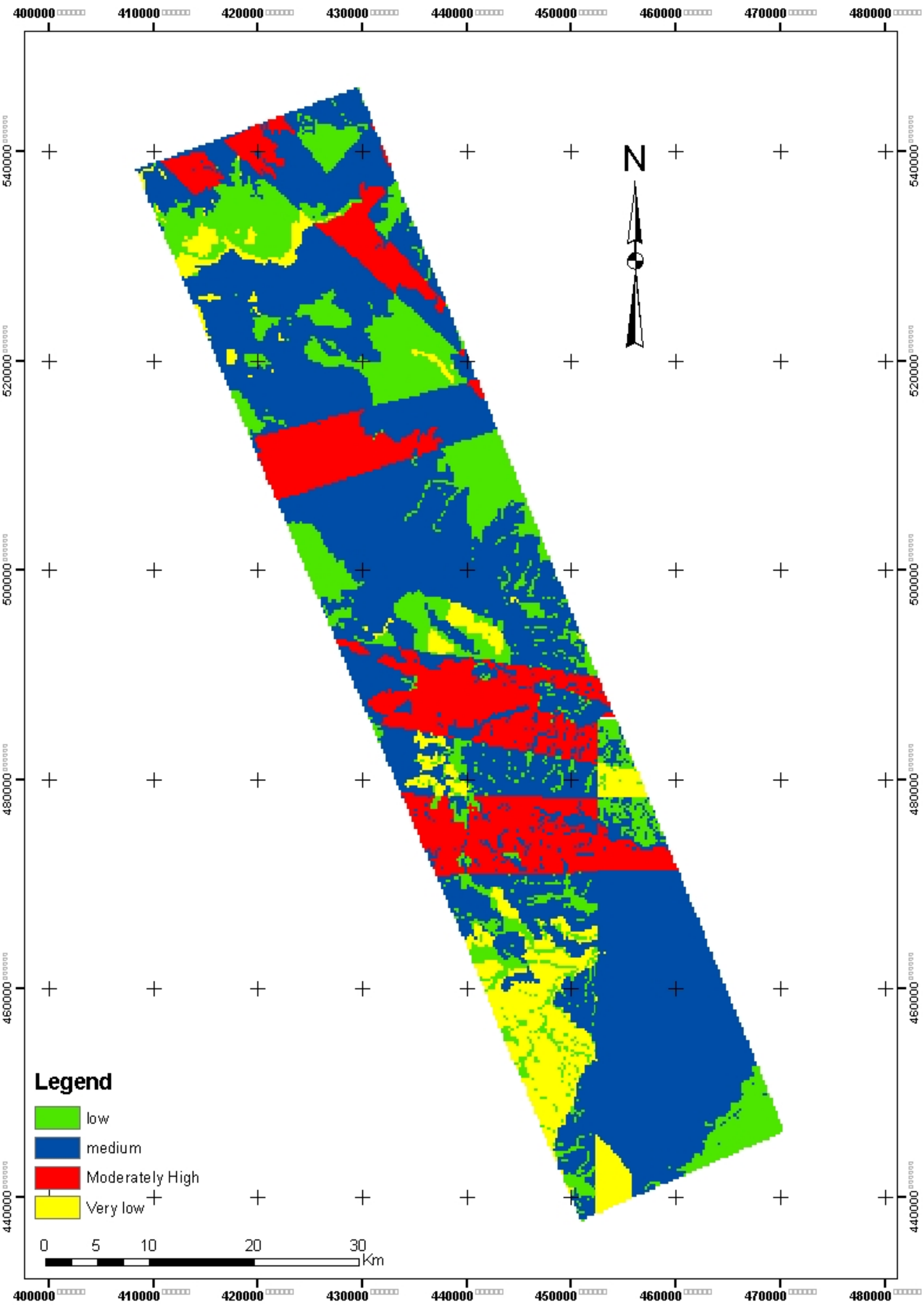

Figure (12): Final vulnerability map in SINTACS index including the effects of structures on the vulnerability

As a result, it can be stated that generally, groundwater levels in the area follow the topographic changes which create outlets for the groundwater to flow to the ground surface. Steep groundwater gradients are found in areas with strong changes in topography (Fig. 5B).

Figure (5A) represents the main groundwater flow directions and indicates that the flow is directed towards the Azraq depression. In the northwestern part of the study area, the flow is directed to the Amman- Zarqa basin. In the southern part, the water flow is directed to the southeast, because of the effects of the Swaqa fault in this part of the study area functioning as a drainage conduit.

Hydrogeochemistry and Statistical Analysis

The chemical composition of water is derived from many different sources of solutes, gases and aerosols, from the atmosphere, weathering and erosion of rocks and soil, solution and precipitation reactions occurring below the land surface and effects resulting from human activities. Groundwater chemically evolves by interacting with aquifer minerals or internal mixing among different groundwaters along flow paths in the subsurface (Domenico, 1972; Wallick and Toth, 1976; Toth, 1984). Therefore, the spatial distribution of chemical species gives an idea about the groundwater movement, water rock interactions and mixing processes.

This part of the work aims primarily at providing information on the characteristics, water types and genesis of the groundwater in the A7/B2 aquifer in the area. To achieve this purpose, all accessible water sites such as wells were sampled. All samples were analyzed for the major and minor constituents. pH, EC and temperature were measured *in situ*.

Table 4 summarizes the descriptive statistics of the chemical analyses of the water samples.

The average value of 7.25 for the pH controls the carbonate species in the system, only at pH values close to 6.4 both species of HCO_3^- and CO_3 are present, below pH 6 all the dissolved carbonates species are in the form of H_2CO_3 and over pH 7 the carbonate species will be HCO_3^- (Drever, 1997).

The mean pH value of the samples indicates that the dissolved carbonates are predominantly in the form of HCO_3. Correlation matrices were developed to understand the relations between different variables using STATISTICA software (Swan and Sadilands, 1995).

The relationships among the different constituents and parameters can be summarized as follows (depending on r = correlation coefficient):

a. r > 0.90 : very high significant linear relationship.
b. 0.90 > r > 0.85: high significant linear relationship.
c. 0.85 > r > 0.80: significant linear relationship.
d. 0.80 > r > 0.70: good relationship.
e. 0.70 > r > 0.60: medium acceptable relationship.
f. r < 60: weak to very weak relationship.

STRUCTURAL GEOLOGY OF STUDY AREA

In the study area, structures of faults, joints and folds are common. They are of high importance for the vulnerability study. In the following part of the study, the main geologic structures are described, classified in terms of their directions and magnitudes.

Tectonic Setting of the Study Area

Paleostress analysis indicates that two main stress fields affected the area. The first is characterized by ESE-WNW compression, corresponding to NNE-SSW extension.

The second stress field is characterized by NNW-SSE compression with corresponding ENE-WSW extension. Both stress fields were associated with strike-slip movements. The first one is the Syrian Arc Stress (SAS) which started in the Turonian, and the second one is the Dead Sea Stress (DSS) which is still active since Middle Miocene (Quennell, 1958).

Faults

Faults and fractures in the study area (Fig. 6) were obtained from the different mapping carried out in the area and from aerial photos and landsat images (NRA open files).

The most prominent directions of faults and lineaments are N-S, E-W and NW-SE (Figs. 7 and 8).

The most significant faults in the study area are the E-W trending Swaqa and Zarqa Ma'in strike-slip faults. The NW-SE trending Wadi Za'faran normal faults (Beicip, 1981) generally have throws of a few meters (Fig. 8).

The less important fault trends in the study area are: NNW-SSE, NNE-SSW and ESE-WNW.

Vulnerability Assessment

The worldwide concern about groundwater contamination problems has resulted in the development of the concept of groundwater vulnerability. This concept depends on the assessment and representation of various attributes such as vadose zone characteristics, aquifer depth and the amount of recharge (Murray and Rogers, 1999).

Groundwater vulnerability maps are important tools to draw the attention of land use planners to existing problems. It is also used to anticipate the movement of pollutants in the soil, allowing planners to modify the potential occurrence of harmful conditions, such as groundwater contamination, before serious impacts occur (Murray and Rogers, 1999).

DRASTIC Index for the A7/B2 Aquifer

DRASTIC is an overlay and indexing method which is widely used to assess intrinsic groundwater vulnerability. Merchant (1994) argued that DRASTIC has been used throughout the world with exceptional frequency. In this model, spatial datasets on Depth to groundwater, 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) are combined to prepare vulnerability index of an area (Engel *et al.*, 1996). Determination of the "Agricultural DRASTIC" index involves multiplying each factor weight by its point rating and summing the total (Knox *et al.*, 1993). The governing equation of the DRASTIC index was defined by Aller et al. (1987):

$$\mathbf{DI = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \quad \ldots\ldots (1.1)}$$

where (1) D: depth to groundwater, (2) R: recharge rate (net), (3) A: aquifer media, (4) S: soil media, (5) T: topography (slope), (6) I: impact of the vadose zone, (7) C:

conductivity (hydraulic) of the aquifer (8) r: rating for the area being evaluated and (9) w: importance weight for the parameter.

The ratings and weights for the DRASTIC parameters for the study area were estimated based on Aller et al., 1987) (Table 5).

The recharge ratings were based on Equation 1.2 (Piscopo, 2001) instead of using the total recharge.

$$\mathbf{Recharge\ value = Slope\ \% + Rainfall + Soil\ permeability \quad \ldots\ldots (1.2)}$$

ArcView GIS (9.2) was used to produce the DRASTIC index using Equation 1.1.

Figure 9 shows the resulting DRASTIC index map of the study area.

The rating value for the hydraulic conductivity element was built based on the results of hydraulic conductivities of the different aquifer systems (Table 3). The analyses of the hydraulic conductivity values obtained from WAJ open files for all aquifer systems within the study area indicate low values, with most of them having a hydraulic conductivity of less than $0.5*10^{-4}$ m/s. The rating values for these hydraulic conductivities are based on (Aller et al., 1987) classification. This results in a value of one of the categories for the hydraulic conductivity element (Cr*Cw). The result of multiplying Cr by Cw is equal to 3.

Table (6): Values assigned to vulnerability classes (Aller et al., 1987)

DRASTIC	Vulnerability Class
1-100	Low
101-140	Moderate
141-200	High
More than 200	Very High

Table (7): SINTACS weights and ratings relevant for the study area (Civita and De Maio, 1998)

S: Depth to groundwater		N:Unsaturated conditions		A: Aquifer	
Range (m)	**Sr**	**Material**	**Nr**	**Material**	**Ar**
More than 100	1	Marl	1	Marl	2
Weight (Sw)	**5**	Limestone	8	Medium marine	5.5
		Weight (Nw)	**5**	coarse marine	7.5
I: Infiltration		**T: Typology and overburden**		sand and gravel	8.5
				Weight (Aw)	**3**
Value	**Ir**			**C: Aquifer permeability**	
less than 50 mm/ yr	2	**Material**	**Tr**	**Value**	**Cr**
Weight (Iw)	**4**	Clay loam	2.5	-7	2
S: Topographic slope		Silty clay loam	3.5	-5	5
Slope	**Sr**	Silty loam	3.7	**Weight (Cw)**	**3**
4-2	**1**	Sandy clay loam	4.8		
6-5	**2**	**Weight (Tw)**	**4**		
9-7	**3**				
12-10	**4**				
15-13	**5**				
18-16	**6**				
21-19	**7**				
25-22	**8**				
30-26	**9**				
Weight (Sw)	**3**				

Table (8): Vulnerability rating by merging DRASTIC and SINTACS indices

		DRASTIC Classes		
		Low (1)	**Moderate (2)**	**High (3)**
SINTACS Classes	**Very Low (0)**	**1**	**2**	**3**
	Low (1)	**2**	**3**	**4**
	Medium (2)	**3**	**4**	**5**
	Moderately High (3)	**4**	**5**	**6**

Table (9): Vulnerability classes after merging DRASTIC and SINTACS indices

1-2	**Low**
3-4	**Medium**
5-6	**Moderately High**

SINTACS Index

The SINTACS vulnerability assessment method is similar to DRASTIC. The method utilizes the same parameters, but it has four different weighting systems depending on the hydrogeological setting. The weighting system has been designed to illustrate the relative importance of the parameters in different settings, which are known as Normal, Severe, Seepage, Karst and Fissured. Normal and Severe reflect the density of human settlement and the intensity of land use (Uricchio et al., 2004; Manos et al., 2004).

The ratings and weights for the SINTACS parameters for the study area were estimated from (Civita and De Maio, 1998) (Table 7).

Figure 10 shows the resulting SINTACS index map of the study area.

Modifying of Vulnerability Classes

Geologic structures are very important factors in the vulnerability assessment although such factors are not well reflected in a normal vulnerability assessment. Higher vulnerability classes are expected along rock weak zones, allowing pollutants to move easier, hence increasing the vulnerability of the groundwater.

Geological structures affect aquifers. Most geological structures in the study area are composed of faults and faulting systems.

Faults in "Aller Classification" are given a rating of 10 equal to Karstified Limestone, and a weight of 3 as aquifer media weighting.

When modified, the vulnerability map after introducing the effects of the fault system will present the final vulnerability map in DRASTIC index (Fig.11) and the final vulnerability map in SINTACS index (Fig. 12).

Merging of DRASTIC and SINTACS

A new vulnerability index is obtained by merging both DRASTIC and SINTACS indices to produce another vulnerability map for the study area. The rating ranges between 1 and 5 and the classes between low vulnerable and moderately high vulnerable. Tables 8 and 9 give the values and classes of the new index.

A comparison between the vulnerability map and the land use map is carried out. as shown in Figure 14.

CONCLUSIONS

1- The study area can be classified into three categories in what concerns the vulnerability of the groundwater resources to human activities.
2- The faults were found to intersect the aquifers in the area and along their extension and with the fact that they locate in middle vulnerability zones. In addition, they were found to elevate the vulnerability in accordance with the structural map of the area.
3- The new approach to combine structures with known vulnerability indices of DRASTIC and SINTACS seems to better evaluate the prevailing conditions.
4- The study shows that the previous indices are unable alone to evaluate the spatial vulnerability of the aquifers when structures are dominant. Accordingly, some modifications and merging had to be made on the DRASTIC and SINTACS indices introducing into them the geologic structures to make them prone and to evaluate similar areas with prevailing geologic structures.
5- Care should be taken when allocating landuses in the study area. This is because any allocation, not based on the vulnerability evaluation which takes geologic structures as an integral and essential part of aquifer vulnerability, will not satisfy the criteria of groundwater protection.

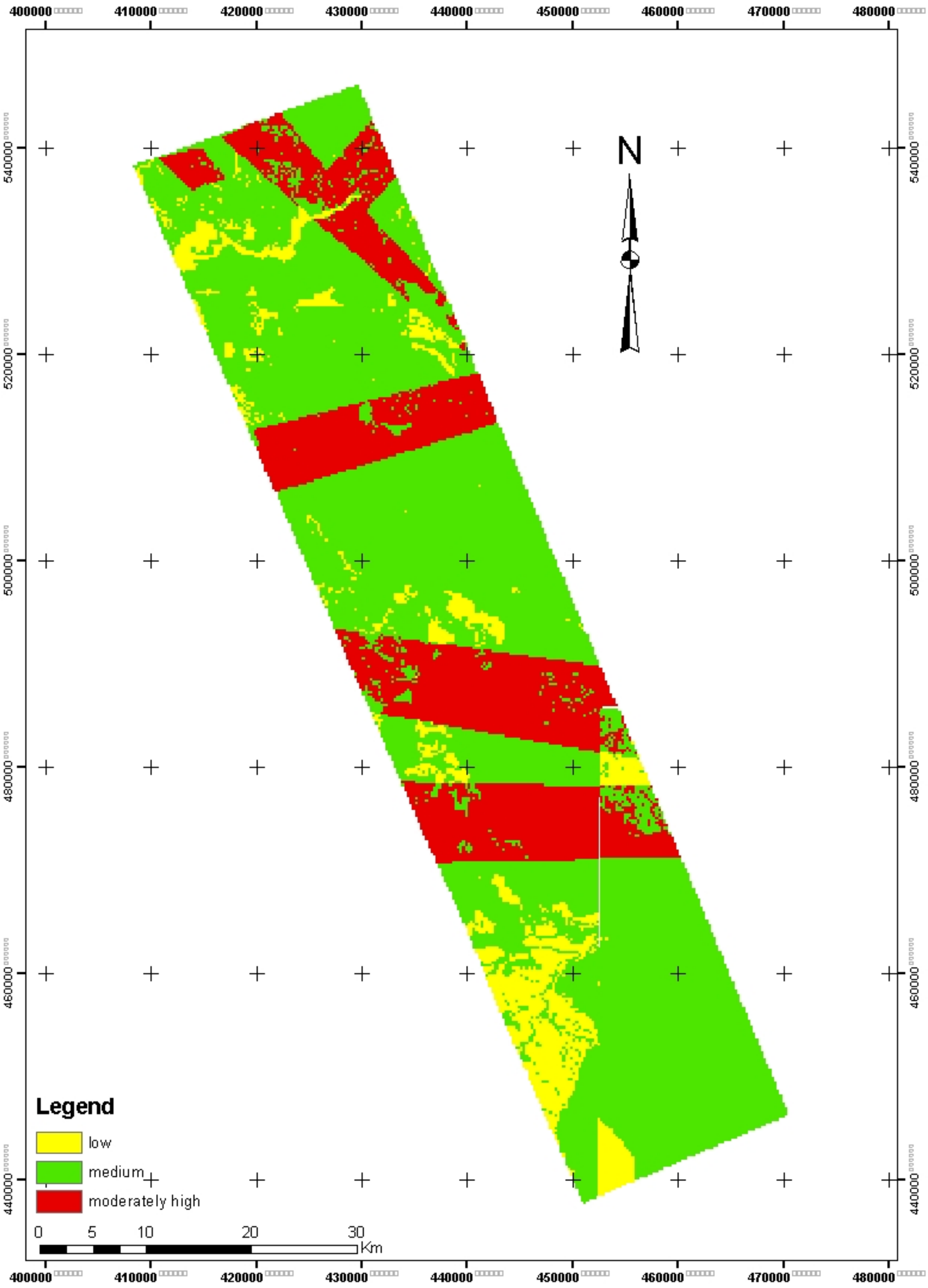

Figure (13): Vulnerability map of the study area obtained by merging DRASTIC and SINTACS vulnerability indices

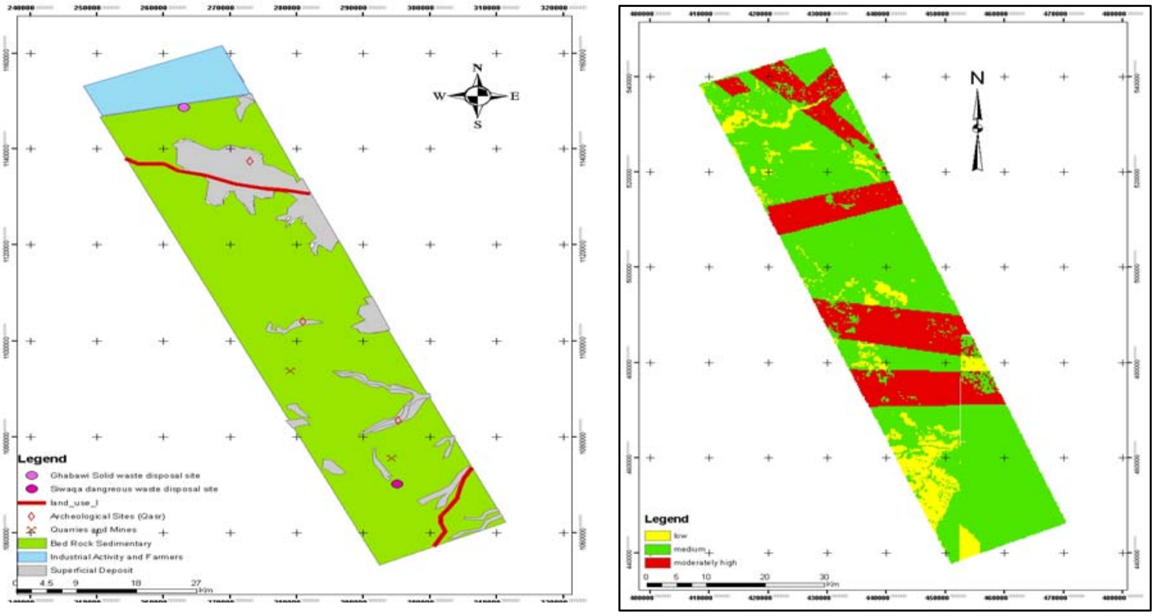

Figure 14: Vulnerability and landuse maps of the study area

REFERENCES

Abu Ajamieh, M. 1998. Water quality improvement and conservation project assessment of brackish groundwater in Jordan. –USAID in coop. with the Ministry of Water and Irrigation MWI., Amman.

Beicip. 1981. Structural study of Jordan. Natural Resources Authority (NRA). Amman, Jordan.

BGR and WAJ. 1994. Groundwater resources of northern Jordan. Vol. 3, Structural features of the main hydrogeological units in northern Jordan. Water Authority of Jordan (WAJ) and Federal Institute for Geosciences and Natural Resources (BGR). (Project No. 112708), Amman.

Civita, M. and De Maio, M. 1998. Mapping groundwater vulnerability by the point count system. Chapter 11, in Managing Hydro-Geological Disasters in a Vulnerable Environment, ed. K. Andah, Publ. Grifo Publishers.

Domenico, P. A. 1972. Concepts and models in groundwater hydrology. McGraw- Hill, New York.

Drever, J. I. 1997. The geochemistry of natural waters. 2nd edition. Prentice Hall Inc., New York.

Engel, B. *et al.* 1996. Estimating groundwater vulnerability to non-point source pollution from nitrates and pesticides on regional scale. *Application of Geographic Information System in Hydrology and Water Resources Management*, IAHS Publication No. 235. Oxfordshire, England.

Fortin, M., Thomson, K. P. B. and Edwards, G. 1997. The role of error propagation for integrating multisource data within spatial models: the case of the DRASTIC groundwater vulnerability model, *Earth Surface Remote Sensing Procedure SPIE Conference*, London, 358-361.

Fritch, T. G. *et al*. 2000. An aquifer vulnerability assessment of the paluxy aquifer, central Texas, USA, using GIS and a modified DRASTIC approach. *Environmental Management*, 25 (3): 337-345.

GTZ and NRA. 1977. National water master plan of Jordan. Agrar – und Hydrotechnik, GmBH ESSE. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany.

Knox, R. C., Sabatini, D. A. and Canter, L. W. 1993. Subsurface transport and fate processes. Lewis Publishers, USA.

Margane, A. 2002. Contributions to the hydrogeology of northern and central Jordan. Hannover, Germany.

McDonald, Sir M. and Partners in Cooperation with Hunting

Geological Survey, Limited. 1965. East Bank water resources. Ministry of Water and Irrigation, Vol.5, Amman, Jordan.

Merchant, J. M. 1994. GIS-based groundwater pollution hazard assessment: a critical review of the DRASTIC model. *Photograommetric Engineering and Remote Sensing*, 60 (9): 1117-1127.

Ministry of Water and Irregation of Jordan. 2007. Water master plan of Jordan. Amman, Jordan.

Murray, K. S. and Rogers, D. T. 1999. Groundwater vulnerability, Brownfield redevelopment and land use planning. *Journal of Environmental Planning and Management,* 42 (6): 801-810.

Natural Resources Aothurity geologic maps and landsat images for the area. 2008.

Piscopo, G. 2001. Groundwater vulnerability map, explanatory notes, Castlereagh Catchment, NSW Department of Land and Water Conservation, Australia, Found at: http://www.dlwc.nsw.gov.au/care/water/groundwater/reports/pdfs/castlereagh_map_note.pdf.

Quennell, A. M. 1958. The structural and geomorphic evolution of the dead sea rift. *Quart. J. Geol. Soc.,* London.

Salameh, E. 2001. Searching the origin of groundwater salinity in Aqaba due to aerosols from the sea. (Unpublished), Personal contact.

Salameh, E. and Bannayan, H. 1990. Water resources of Jordan: present status and future potentials. First edition, Friedrich Ebert Stiftung, Amman, Jordan.

Toth, J. 1984. The role of regional gravity flow in the chemical and thermal evolution of groundwater. In: Proceedings of the First Canadian/American Conference on Hydrogeology.

Wallick, E. T. and Toth, J. 1976. Methods of regional groundwater flow analysis with suggestions for the use of environmental isotope and hydrochemical data in groundwater hydrology. IAEA, Vienna, 37-64.