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Vulnerability mapping of groundwater aquifer using SINTACS in Wadi Al-Waleh Catchment, Jordan

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Abstract This paper aims at evaluating the level of groundwater vulnerability to pollution in Wadi Al-Waleh wells and South Amman area based on SINTACS model. The Wadi Al-Waleh Catchment (WWC) is considered to be one of the most important sub-basins in the middle part of Jordan. This study creates a map of groundwater vulnerability that shows areas with potential pollution. Areas are then classified into units with different levels of vulnerability based on anthropogenic and hydrogeological factors. The parameters of the SINTACS model are rated and evaluated by weight numerical indices. The vulnerability parameter is set upon fixed percentage interval of the sub-basin's area. SINTACS index values have been categorized into four groups of pollution: very low (green), low (yellow), medium (orange), and medium to high (red). The results reveal that the units with very low levels of vulnerability to pollution cover an area of 0.17 km^2. In addition,

units with low, medium, and medium to high levels of vulnerability to pollution cover areas of 44.13, 1102.37, and 654.97 km^2, respectively. The vulnerability maps show that most of the sub-surface area of WWC is characterized by medium to high levels of vulnerability to pollution, while units with very low and low vulnerability to pollution cover small areas of the western part of WWC. As well, the vulnerability maps show that there is moderate–high risk of pollution in the middle to eastern parts of WWC sub-basin. The risk of pollution in WWC mainly stems from intensive agricultural activities in the area.

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Introduction

Water shortage is a severe problem in Jordan and is a serious challenge for the incoming generations. Jordan is a country that suffers from severe droughts, contains few available water resources, and experiences increasing demands on water every year with the growth in population. Jordan therefore relies mainly on groundwater resources to meet these demands. These resources are under the threat of pollution due to human activities, non-sound management of aquifers, the excessive use of pesticides and fertilizers, and the discharge of chemical substances and waste into water (Al-Rawabdeh et al. 2013; Al-Shatnawi et al. 2014).

Wadi Al-Waleh and Wadi Heedan are considered important valleys in the center of Jordan as these two valleys are located in the course of the valley which is crossed by the Waleh Dam. Both valleys are important sources of water for Madaba and its villages for domestic purposes. However, the basin is sensitive to pollution, and a number of residential, service, industrial, and commercial activities are practiced therein, which

necessitate management of environmental risks to prevent pollutant infiltration to groundwater resources in that area (Water Authority of Jordan 2015). The notion of groundwater vulnerability is fundamentally built upon the presumption that the physical environment can help in protecting against contamination and pollution of sub-surface areas. For the purpose of monitoring and protecting the groundwater resource, the vulnerability maps approach has been chosen in this study. Vulnerability maps help in evaluating land use activities and their potential contribution to pollution of surface and groundwater resources and in assessing vulnerable areas.

Pollution vulnerability assessment entails deep knowledge of the hydrodynamic, hydrochemical, and hydrogeological features of aquifers (Murthy et al. 2015). Since the 1970s, numerous simulation models and methods have been developed for this purpose. Over the past 15 years, the advent of the Geographic Information System (GIS), which allowed for the inventory, archiving, retrieving, and display of spatial data, as well as linking with numerical rating systems (e.g., DRASTIC (Aller et al. 1987) and SINTACS (Civita 1994; Civita and De Maio 1997). has contributed to the wide use of hydrogeological data depending on parametric methods (Ducci 2010; Murthy et al. 2015).

Land areas vary in terms of vulnerability of pollution to groundwater. Some are more vulnerable and others are less.

The vulnerability concept is basically built upon the presumption that the physical environment can help in protecting against contamination that may affect the sub-surface areas. The vulnerability maps identify, and help in classification of, areas that are under the threat of groundwater contamination and pollution based on anthropogenic and hydrogeologic factors. Areas can then be categorized into groups with different levels of vulnerability (Al Kuisi et al. 2006; Hasiniaina et al. 2010; Jha and Sabastian 2005).

Groundwater protection is a source of serious environmental concern worldwide. In this regard, the assessment of its vulnerability to pollution serves numerous purposes such as the general public, managers of groundwater, regulators of land use, and resource conservationists. Also, maps of groundwater vulnerability are used for allocating resources, help to make decision in land use, increasing awareness of pollution, and management of pollution by evaluating alternative policies for groundwater (Ducci 2010). This study adopts the SINTACS method which was first developed by Civita (1990) and few years later slightly developed by Civita and De Maio (1997). The SINTACS model is a system for assessing the levels of relative vulnerability of groundwater to pollution. This model is an adjustment of the US DRASTIC model that was particularly designed for the Mediterranean environment and conditions (Civita and
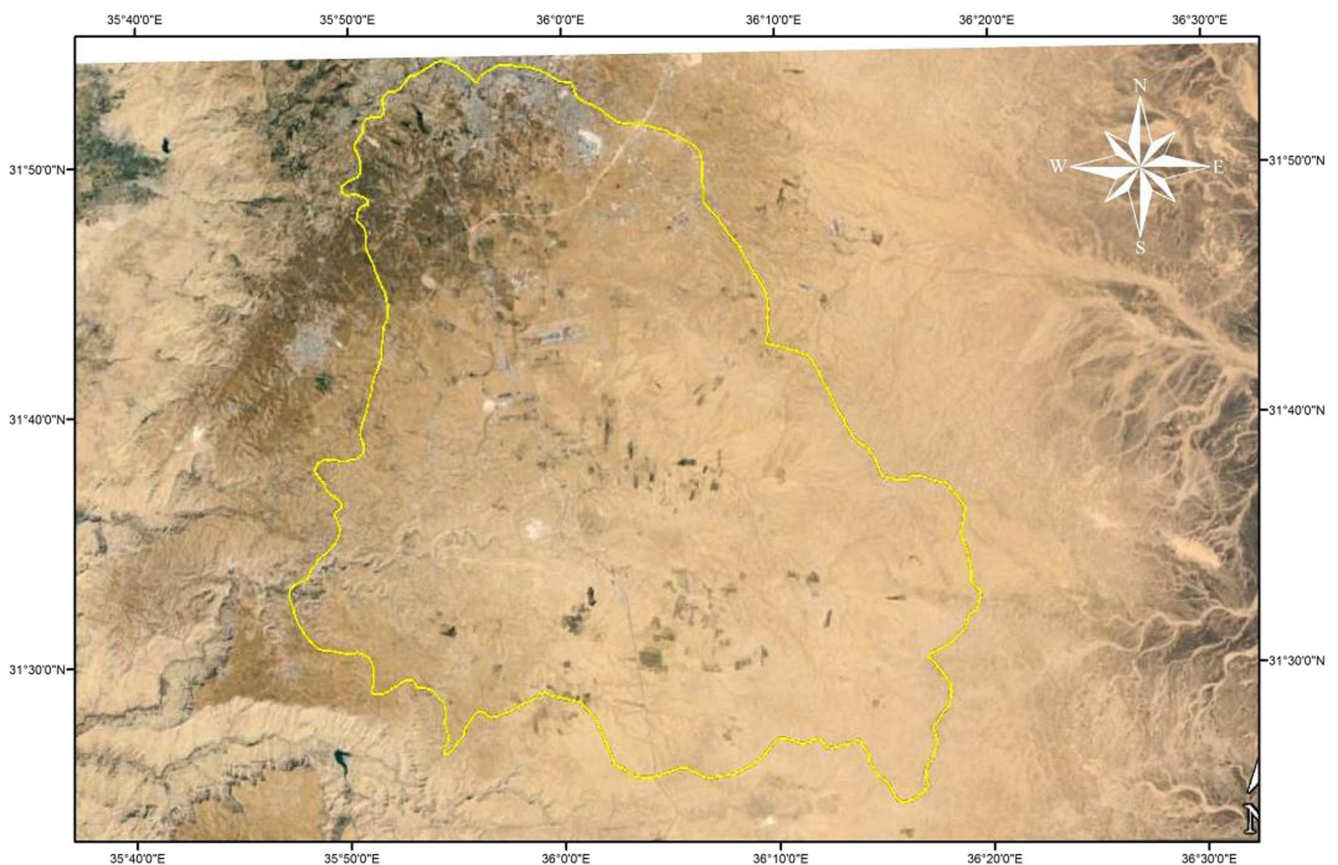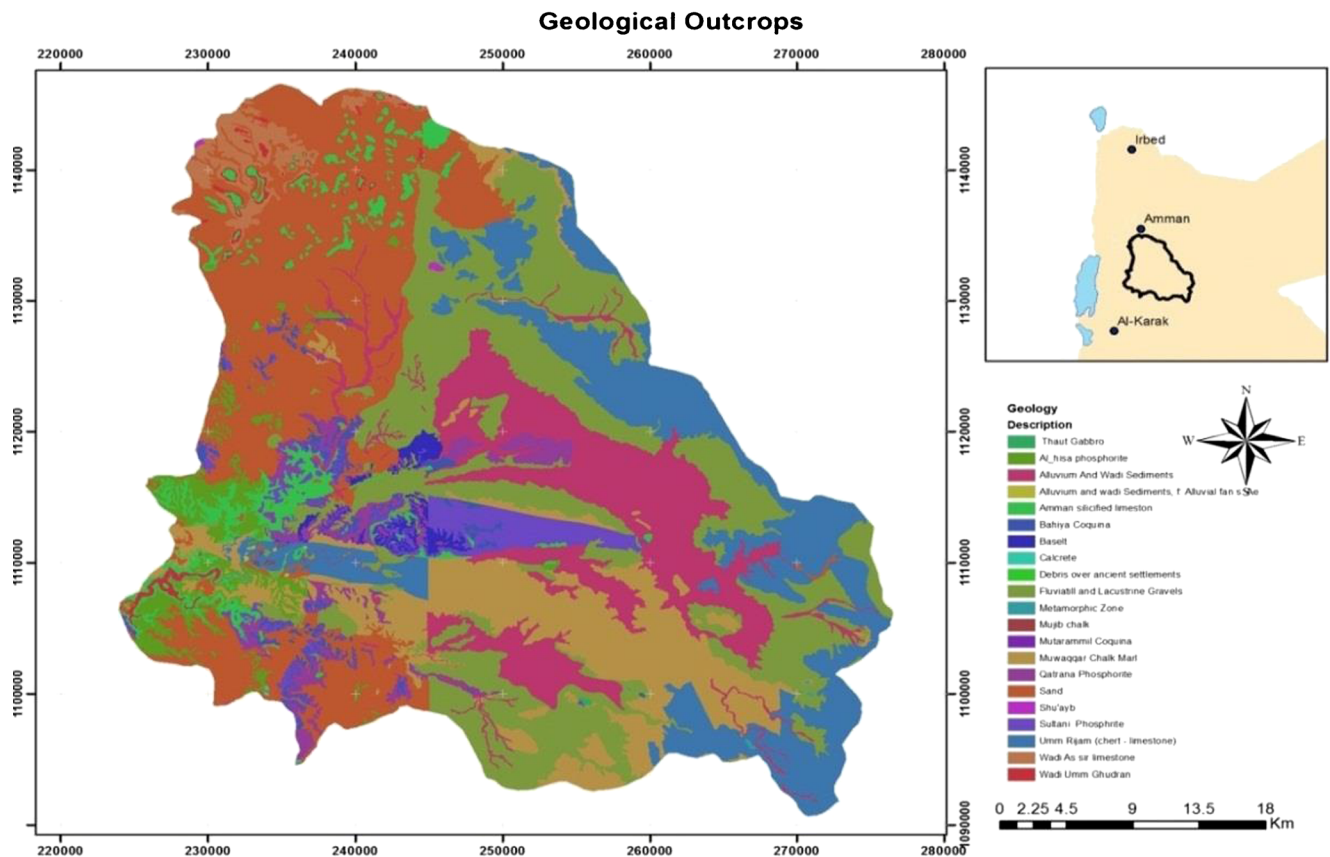

Fig. 1 Location of WWC

Geological Outcrops

Fig. 2 Map of geological outcrop of WWC

De Maio 1998). The DRASTIC model utilizes seven "hydrogeologic parameters: depth to groundwater, effective infiltration action, unsaturated zone attenuation capacity, soil/overburden attenuation capacity, hydrogeologic properties of the aquifer, hydraulic conductivity range of the aquifer, and hydrologic role of the topographic slope" (Al Kuisi et al. 2006).

Al Kuisi et al. (2006) employed the SINTACS modeling approach to evaluate the level of pollution in the Jordan Valley area, which is characterized by intense agricultural activities that depend greatly on shallow groundwater aquifer. It is an area of high vulnerability to pollution due to the absence of sub-surface impermeable layers to protect it. A vulnerability map was prepared to determine areas that are highly vulnerable to pollution in Al Kofren and southern Shona areas using the SINTACS model, which is a perfect model for the Mediterranean environment that takes into consideration natural factors such as topography; hydrologic, geologic, and hydrogeologic factors; and the features of the study area. This allows for reasonable, coherent understanding of these factors and their interplay and, hence, of their integrated effects on vulnerability to pollution of shallow groundwater aquifers. Ultimately, a SINTACS map that delineates vulnerable and highly vulnerable areas was created (Al Kuisi et al. 2006).

Al-Fawwaz (2010) investigated the effects of the human activities on vulnerability to pollution of aquifers in the Swaqa-Ghabawi area, including Swaqa dangerous waste landfill. Two modeling tools were utilized to evaluate vulnerability to pollution: DRASTIC and SINTACS. The study aimed at developing a method that combines geological structures with factors that increase or decrease pollution. For this purpose, water samples were analyzed in order to test for contamination and pollution of the groundwater, obtain information on each geological structure, and introduce the managed data and information to the GIS for further analysis and creation of a pollution vulnerability map.

Table 1 SINTACS weights, strings, and the hydrogeological scenarios (Civita and De Maio 1997)

Parameter	Normal I	Severe I	Seepage	Karst	Fissured
S	5	5	4	2	3
I	4	5	4	5	3
N	5	4	4	1	3
T	3	5	2	3	4
A	3	3	5	5	4
C	3	2	5	5	5
S	3	2	2	5	4

Fig. 3 **a** Range and rating of depth of water (the S-parameter), **b** Map of depth of water rating
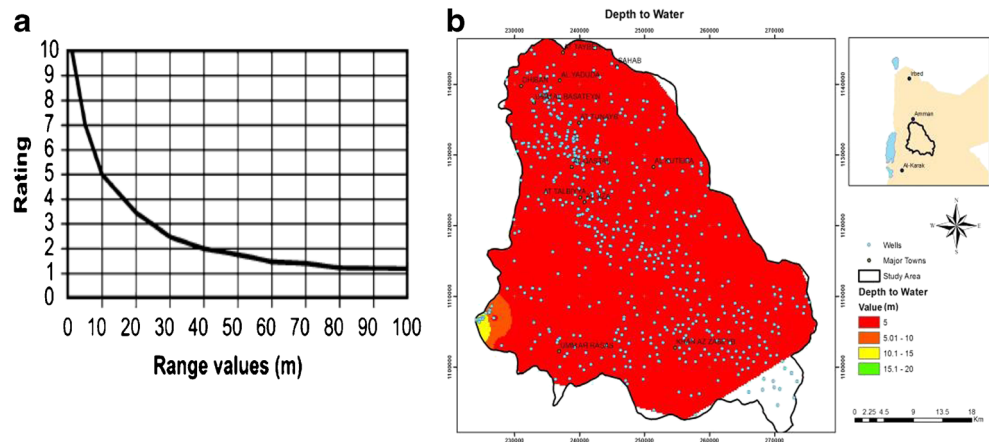
This paper aims at evaluating the vulnerability of the Wadi Al-Waleh Catchment (WWC) to pollution using the SINTACS modeling approach. It is also intended to provide an effective tool for the management of the groundwater quality by combining the strengths of SINTACS and GIS. This approach and the results obtained will help develop strategies for managing land uses in the WWC area and identify highly vulnerable areas for future studies. This paper is organized as follows: The next section describes the study area. "Materials and methods" section briefs the SINTACS model and the vulnerability map calculations procedures. "Results and discussion" section introduces the study results and discusses them. Then, the last section highlights the main conclusions of this study.

Study area

This study covers WWC which is located in the central part of Jordan and includes parts of Southern Amman Governorate as well as the Governorate of Madaba (Fig. 1). The WWC covers 1802 km² of the central area of the Jordan Valley to the eastern escarpment (Kalbouneh et al. 2011). The WWC runs from the south of Amman in Plateau and Jordan Highland at 700 m

above the sea level to Wadi Al-Mujib at about 300 m below sea level and about 3 km away from the Dead Sea. The annual rainfall average depth is 300–400 mm in the northern and central parts in the area of the study, and the average annual evaporation rate is 2200 mm.

Wadi Al-Waleh flow statistics are measured at Karak Road, at a drainage area of 1800 km². Wadi Al-Waleh is characterized by a stable flow that provides from 0.1 MCM every month in the summer to more than 1 MCM every month in winter. The base flow of Wadi Al-Waleh is somehow greater than the base flow of Wadi Al-Mujib at Karak Road even though the drainage area in Wadi Al-Waleh is less than half that of Wadi Al-Mujib. Wadi ath-Thamad lies at the upper stretch of the main stream at an elevation of 700–750 m. Wadi Al-Waleh descends from 700 m at Wadi Al-Mujib to the Dead Sea at the elevation of 100 m below the base level (Cordova 2008).

The plateau has rocks dissected by Wadi Al-Waleh that form it and consist of horizontal and sub-horizontal strata of Cretaceous limestone, phosphorites, and marls. In Wadi Al-Waleh, dipping and bedding control the sedimentation of Cretaceous sedimentary strata. Beds especially in Wadi As-Sir Limestone (WSL) are hard which marks the lowest level of incision among all streams. The structure of the Jordan Rift in

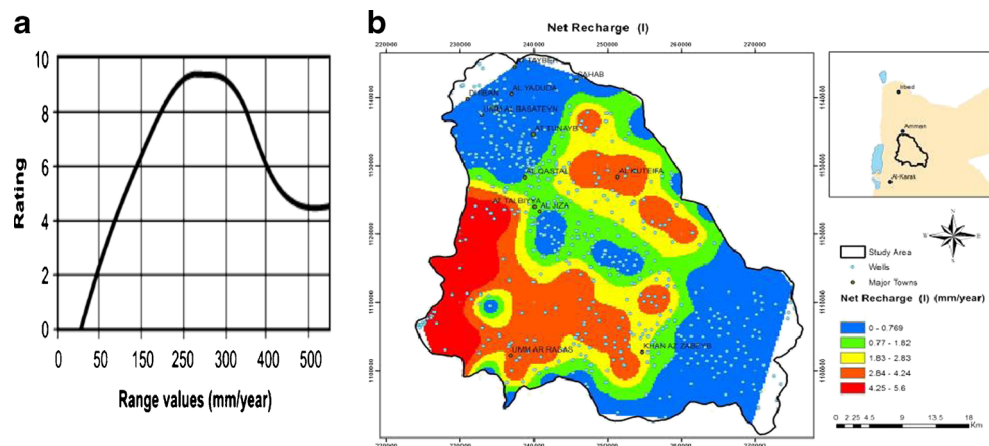**Fig. 4** **a** Infiltration range and rating (the I-parameter). **b** The net recharge map
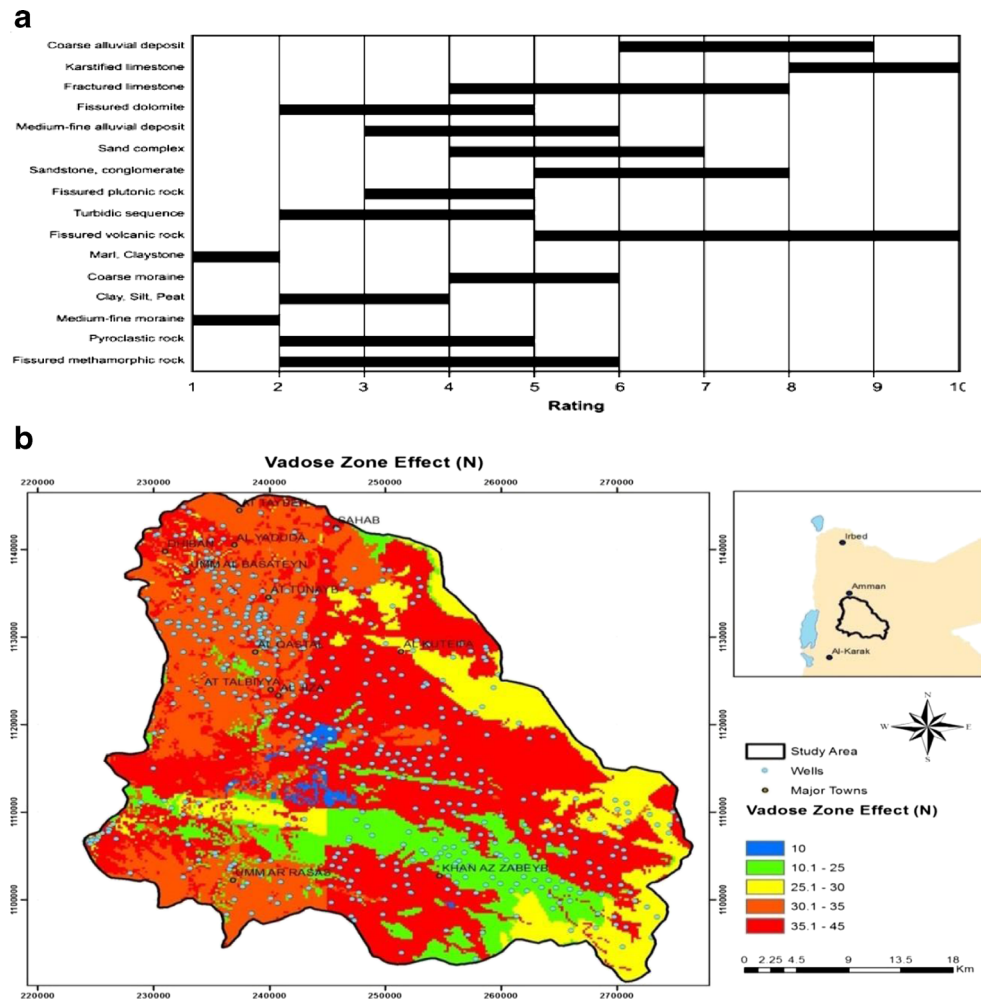
Fig. 5 **a** Unsaturated zone
attenuation capacity. **b** Map of the
impact of the zone vadose
(the N-parameter)

Quaternary and Tertiary is organized by strike-slips and nor-
mal faults of Both Wadi Ath-Thamad and Wadi Al-Waleh
systems (Cordova 2008).

The sloping of the west-flowing stream in Wadi Al-Waleh
is controlled by the east dipping beds of WSL. The WSL
faulting beds, which lie about 800 m downstream from
Khirbet Iskander, create a knick point that produces another

water drop that Ottoman grist mills use. The downstream then
allows little deposition and the upstream creates alluvial units
among the Late Quaternary (Cordova 2008). Wadi Al-Waleh
had always carried a continuous flow of water. However, after
the intense water pumping that started in late twentieth centu-
ry, recently, water flows in it only after the storms and this
Wadi is dry most of the year. There are barren landscapes

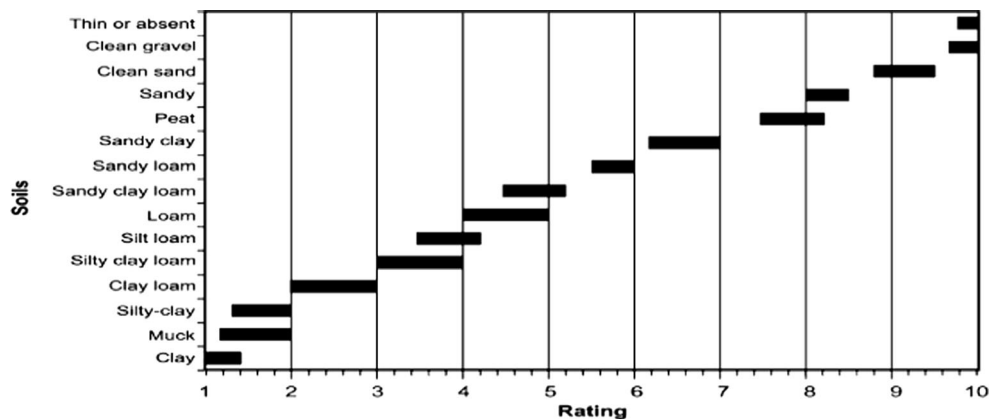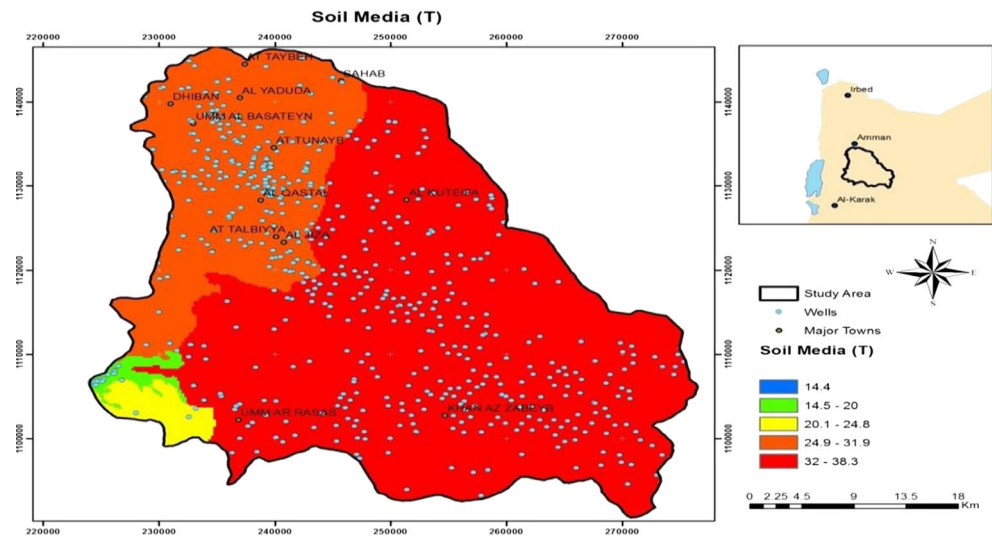Fig. 6 Soils overburden
attenuation capacity

Fig. 7 Soil media map
(the T-parameter)

around Wadi Al-Waleh except for some vegetable orchards and olive groves irrigated with pump water (Cordova et al. 2005; Cordova 2008).

Groundwater resources

Wadi Al-Waleh Catchment lies within the Dead Sea groundwater basin where a sedimentary sequence forms the main aquifers of the watershed. These aquifers that lie within the escarpment are drained by incised valleys in the west direction heading to the Dead Sea. The groundwater level in Al-Mujib basin ranges from 5 to 25 m due to overexploitation of the groundwater, especially in the last decade, which resulted in drop in the water level and declines both in base and spring flows in Al-Mujib basin (Kalbouneh et al. 2011).

The major aquifer system

Due to the tectonic and erosion activities that formulated the Jordan rift millions of years ago, the hydrogeology of Jordan is dominated by three main aquifer systems that can be identified within Zara Maieen Mujib) ZMM(watershed. At a smaller scale, the hydrogeology of the WWC is defined by two major systems: the upper aquifer and the lower aquifer. The upper is denoted by (B2/A7), and the lower is (sandstone of the Kurnub and older ages), along with another aquitard (A1-6) that separates these two aquifers. There are other less important aquifers like Neogene and the Tertiary (Kalbouneh et al. 2011). The Geological Outcrop Map of the WWC is shown in Fig. 2.

Materials and methods

In this paper, the SINTACS model function in Arc Map GIS 10.1 was used to assess vulnerability of the sub-surface basin

of WWC to pollution. SINTACS is a very trustworthy model for the assessment of groundwater vulnerability to pollution by a wide range of possible contaminants (Ducci 2010). Using SINTACS model has many advantages; for example, the input that the application requires is easy to obtain from any public agency (Al Kuisi et al. 2006).
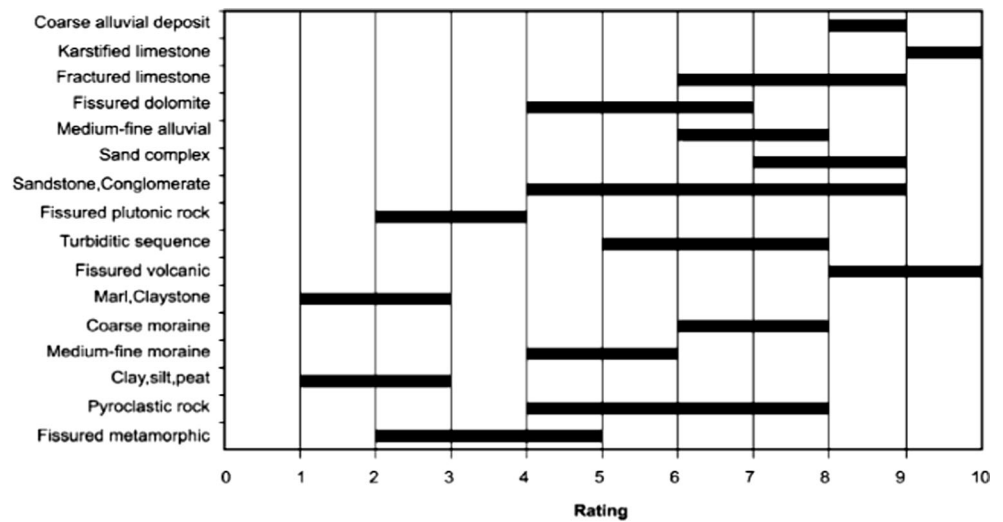
The SINTACS model

The SINTACS is a model used to assess the pollution vulnerability and it is designed to be applied in the Mediterranean area. It is a model for assessing the vulnerability of groundwater to pollution. It was developed by Civita (1990) and later slightly modified by Civita and De Maio (1997) to assess the pollution of groundwater relative to vulnerability by means of seven hydrogeologic variables (Al Kuisi et al. 2006; Aller et al. 1987; Al-Rawabdeh et al. 2013; Hammouri and El-Naqa 2008; Kumar et al. 2013).

Many parametric models like SINTACS are based on a system that counts points score for each factor. During analysis, an additional weight is to decrease or increase its relative importance. Environmental characteristics such as widespread pollution sources and high dispersion from surface water bodies control the additional weight. The seven factors of the

Table 2 Percentage of soil rating values

The soil rating value	Percentage
14	1.72
20	2.38
24	25.6
32	0.25
38	70.5

Fig. 8 Hydrogeologic characteristics of the WWC

SINTACS model are "depth to groundwater, effective infiltration action, unsaturated zone attenuation capacity, soil/overburden attenuation capacity, hydrogeologic characteristics of the aquifer, hydraulic conductivity range of the aquifer, and hydrologic role of the topographic slope" (Al Kuisi et al. 2006).

Each of these factors has a range of scores from 0 to 10 according to importance in determining vulnerability. Environmental and anthropogenic conditions of an area determine weights which in turn modify the score. The SINTACS model considers five main conditions: areas with fissuring phenomena, areas with severe water losses due to hydraulic networks aquifers, areas that suffer from karstic phenomena, areas with many pollution sources, and normal areas (Al Kuisi et al. 2006; Kumar et al. 2013). The following equation defines the intrinsic

vulnerability index, and Table 1 gives the potential weights for the parameters of this equation:

$$I\,\mathrm{SINTACS} = \sum_{i-1}^{7} \mathrm{Pi\,X\,Wi} \qquad (1)$$

In this equation, I refers to the index number which indicates intrinsic vulnerability to pollution, P_i is score of the ith parameter, and W_i is parameter's relative weight (Hammouri and El-Naqa 2008; Al Kuisi et al. 2006).

The values of the index of intrinsic vulnerability, I, are classified into six main classes as follows (Civita and De Maio 1997; Al Kuisi et al. 2006). very low vulnerability as I <80, for low vulnerability 80<I<105, medium vulnerability I falls between 105 and 140. If 140<I<186 then, it means

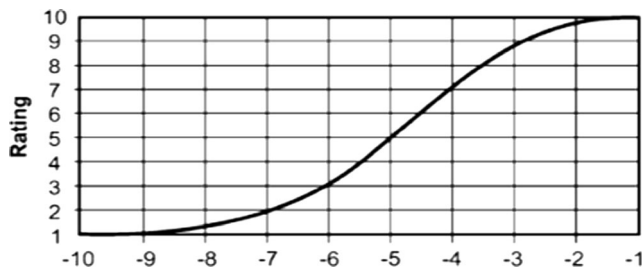**Fig. 9** Aquifer media map (the A-parameter)
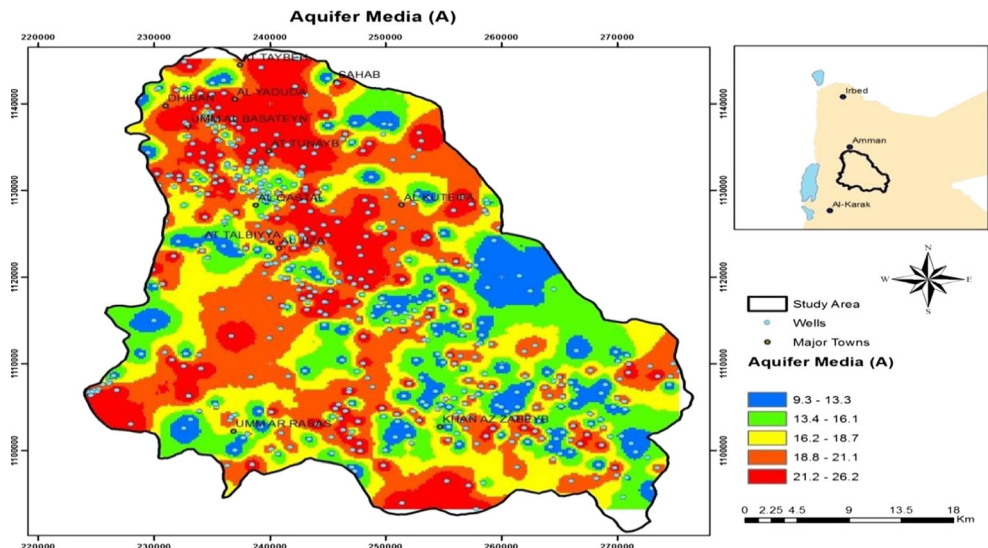
Fig. 10 Hydraulic conductivity rating

moderately high vulnerability. High vulnerability means that I is between 186 and 210, and its very high vulnerability if $I>$ 210.

Results and discussion

The following sub-sections present and discuss WWC vulnerability maps as well as SINTACS models for the seven parameters of priority consideration in vulnerability analysis, which have been calculated by ArcMap GIS.

Depth to the water table (the S-parameter)

The distance between the groundwater table level and the ground surface is called depth of water. The water information system (WIS) was the main source of the water depth information for 646 production wells in WWC. In the Hummer aquifer (A4), the depth of water ranges from 150 to 954 m in the northern parts of WWC while in the B2/A7 aquifer, the depth to water table ranges from 77 to 760 m in outcrop areas of the aquifer. Figure 3a shows that the rating scores range from 1 to 10. The information stored in the database of the study wells was interpolated to prepare the water level map. The Ministry of Water and Irrigation in Jordan and the employed WIS provided the data of water levels (Ministry of Water and Irrigation 2014). The Inverse Distance Weighting (IDW) approach was employed to measure the

depth to water argument and the SINTACS model's parameters. Digital Elevation Model (DEM) was used to obtain the ground surface elevation data. Figure 3b presents the interpolated thematic layer for water depth which was used to obtain the ratings of depth to water values.

The figure shows that values decrease in all parts of study area due to the fact the groundwater is very deep in this area. However, it can be seen that the values increase near Al-Waleh wells and Heedan wing to that the wells there are shallow.

Net recharge or infiltration (The I-parameter)

The net recharge map can be generated by means of an equation for calculating certain area ability to act as a recharge zone in relation to other areas. To produce recharge map for any area, there are several factors to be considered such as soil permeability, slope, and rainfall distribution. A DEM of 90-m resolution was used in this study in order to calculate recharge. Figure 4a presents the criteria which have been utilized to classify the slopes in this study. One of the most important factors that affect aquifer vulnerability assessment is the effective infiltration, which is defined as the difference between the cumulative loss by direct runoff and the sum of total precipitation and effective evapotranspiration. The Soil Conservation Service (SCS) technique and hydrologic data were used to determine net recharge ratings. Figure 4b is the resultant net recharge map.

The middle and western parts of the southern areas have high net recharge since these parts are rainy and dominated by agriculture. The net recharge values decrease in the southern parts of the study area due to human activities and density of buildings in them.

Impact of the vadose zone (the N-parameter)

The data from geological maps, excavation of trenches, and drilling logs where interpreted was determined. Figure 5a shows the levels of the impacts of the vadose zone on

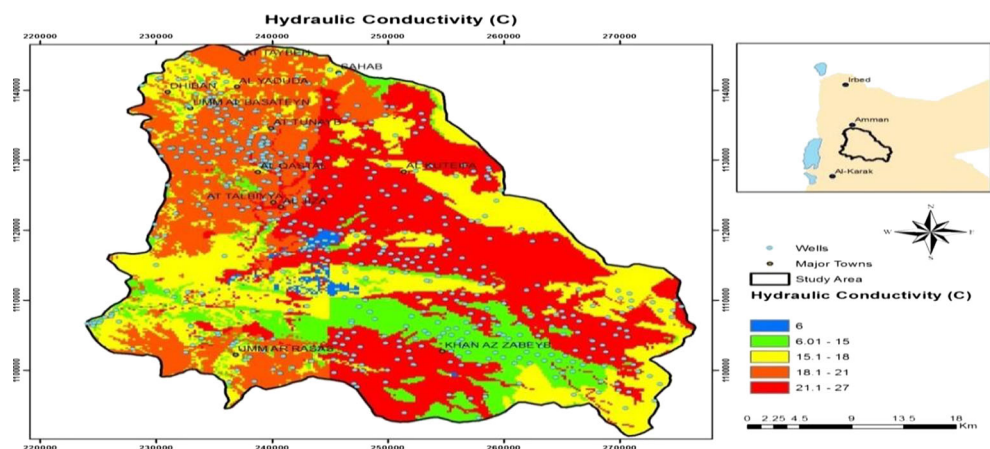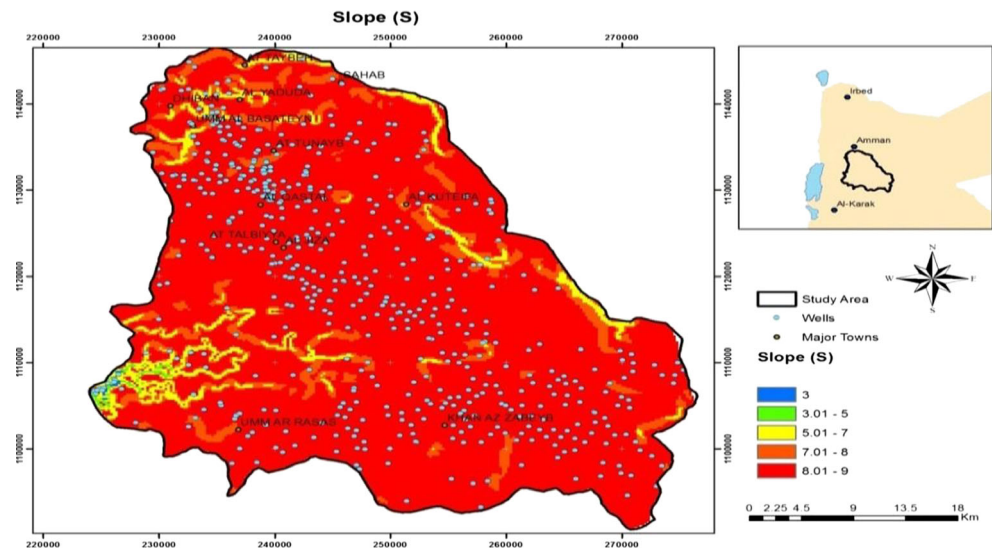**Fig. 11** Hydraulic conductivity of the aquifer (the C-parameter)

Fig. 12 Topography and sloping of land surface of the study area (the S-parameter)

pollutions, which include lithological units rated on the basis of the relevant diagram on the figure. The thematic layer of rating values of impacts of the vadose zone is presented in Figure 5b. The SINTACS model allows for depiction of distribution of the lithologic units in order to assess the vadose zone impact. That is why the aquifer medium is the same as the vadoze medium for unconfined aquifer systems. The Ministry of Water and Irrigation in Jordan selected 63 wells that were drilled to obtain lithological columns for vadose zone stratigraphy. Identifying wells in the study area is important for determining the types of low permeability layers (i.e., limiting factor layers) above the water table.

Water depth in the study area ranges from 10 to 45 m. The high depth values (~35–45 m) characterize the middle and eastern parts of the study area where there are many private and public wells.

Soil media (the T-parameter)

The impact of soil is very important on volume of the recharge that infiltrates into ground and on potential for contaminants to reach to the vadose zone (Amadi et al. 2014). Contaminant migration and soil relative permeability can be reduced by using fine-textured materials like clays and silt (Tilahum and Merkel 2010; Amadi et al. 2014). In Jordan in 1995, a project was implemented by the Ministry of Agriculture for National Soil Mapping which provides all needed information about soil in the country (Hunting Technical Services 1995). Figure 6 displays the data rating, and Fig. 7 presents the spatial distribution of the soil media ratings in the study area.

Each soil class is given a certain rating value, and then the soil layer in the study area is classified according to its
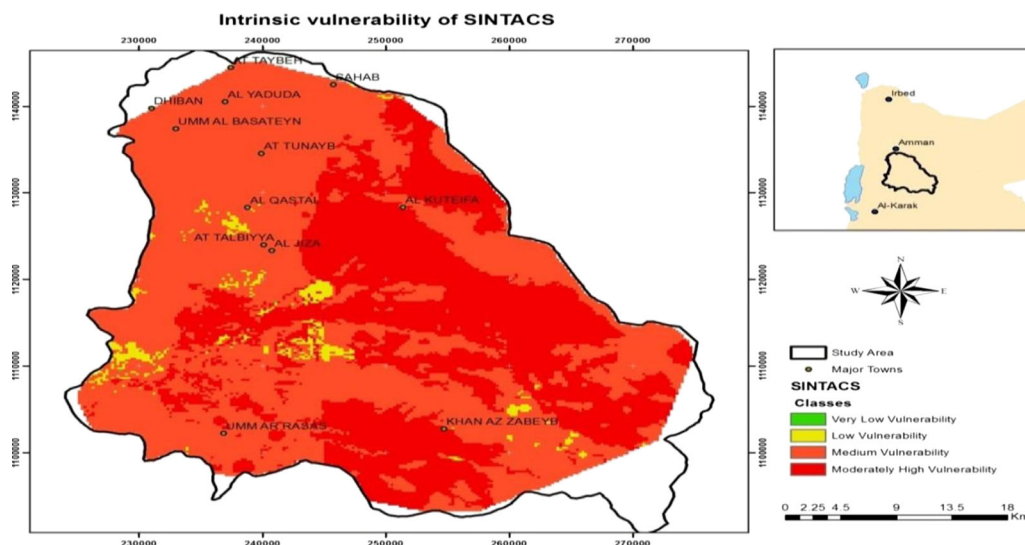

Fig. 13 Intrinsic vulnerability map of SINTACS for WWC

Table 3 Percentage of WWC area which falls within each vulnerability class

Value	Vulnerability class	Count of pixels	Percentage of total area (%)	Area (km^2)
1	Very low	3	0.009	0.17
2	Low	805	2.44	44.13
3	Medium	20,116	61.19	1102.73
4	Moderately high	11,948	36.34	654.97
Sum		32,872		1802 km^2

rating value. In the present case, the values range from 3.6 to 9.6. The soil rating is multiplied by a soil weight of 4 in order to produce a soil index map (Fig. 7). In this study, a rating value of about 14 characterizes 1.72 % of the total study area. The rating value of 20 corresponds to 2.38 % of the study area. A rating value of 24 pertains to about 25.6 % of the study area, while the rating value of 32 is associated with nearly 0.25 % of the study area, and the rating value of 38 characterizes about 70.5 % of the study area. A summary of soil rating values is presented in Table 2.

Most of the study area has high rating values due to the sandy nature of its soil where water and concomitant pollutants leak easily to the vadoze zone and even lower.

Hydrogeologic characteristics of the aquifer (the A-parameter)

The aquifer properties describe the elements of the vulnerability assessment method when contaminants mix with groundwater. Aquifer typology can interact with any process that takes place underneath the water level like dilution, dispersion, and absorption. These and similar processes are significantly affected by lithological kinds and aquifer permeability. So, all the previous characteristics must be considered in conducting vulnerability assessment. Figure 8 shows the ranges of rating values obtained from the SINTACS model. Aquifer media were then rated by means of a rating chart using geolithological information. All aquifer media ratings are represented in Fig. 9.

The aquifer media influence areas of the effective materials that come in contact with the aquifer as well as the route and length of the path. Six types of aquifer systems could be identified in the study area, including the B4 and the B2/A7 systems. The B4 system, which lies in the eastern and mid parts of the basin (Fig. 4), and the B2/A7 aquifer system, which is located in the uppermost section of the aquifer in the north and western parts. The B4 system consisted mainly of limestone and chert, while the B2/A7 system composes of limestone, chert, and dolomitic limestone. The aquifer media are given

Fig. 14 Land use map overlain on the intrinsic vulnerability map of SINTACS for WWC watershed
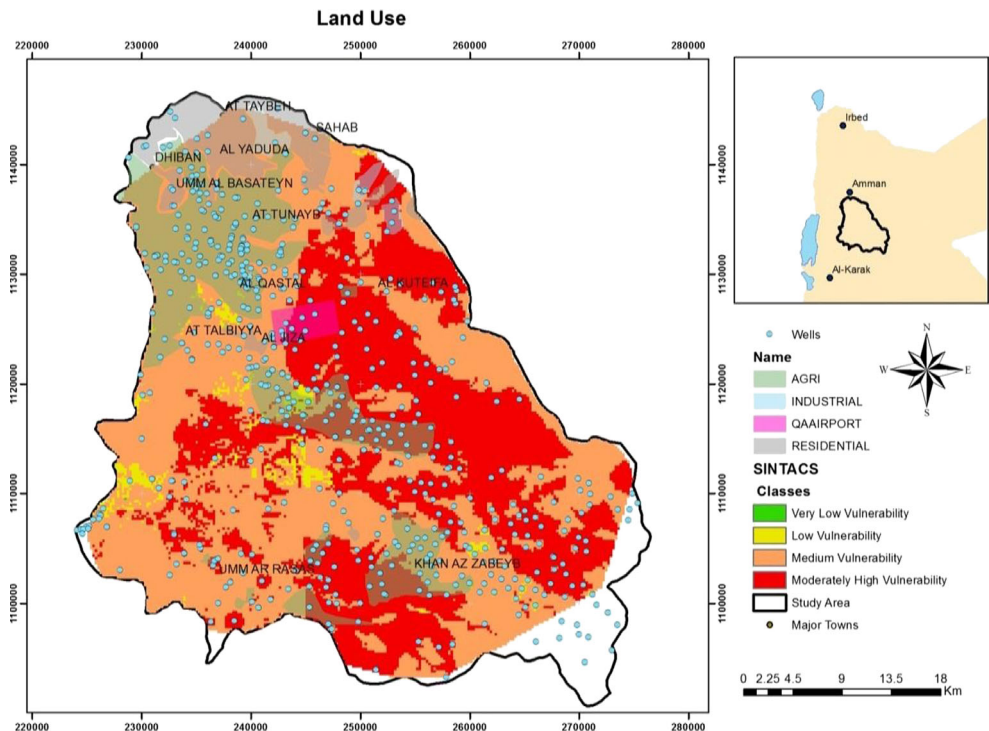
Table 4 Average levels of main pollution indicators for Waleh and Heedan wells during the period 2002–2014 (Water Authority of Jordan 2015)

Name of wells	NH_4^+	NO_3^-	TDS	*E. coli* (GeoMean)
Heedan well no. 2	0.1	20.86	1289	2.38
Heedan well no. 4	0.1	19.74	602	12.12
Heedan well no. 6A	0.1	22.67	599	4.97
Heedan well no. 7	0.1	22.55	600	28.29
Heedan well no. 9	0.1	23.91	600	18.88
Heedan well no. 12	0.1	22.72	693	5.54
Heedan well no. 12A	0.1	37	699	22.19
Heedan well no. 12B	0.1	19.99	737	15.06
Heedan well no. 13	0.1	19.32	704	19.77
Heedan well no. 15	0.1	21.28	705	39.61
Heedan well no. 16A	0.1	21.83	669	25.01
Heedan well no. 16B	0.1	21.39	689	15.77
Waleh well no. 4	0.1	7.32	775	20.06

a value weight of 3. Figure 5a introduces the aquifer media indices calculated by multiplying the aquifer weighting value (AW) by the aquifer rating value (AR) in study area.

The lithological sequence in the drilled wells is very important in this study for description of the sequences of the geological materials and rock layers, besides the high peaks prevailing in large parts of the study area due to the sequential nature of the rock layers in this area.

## Aquifer's hydraulic conductivity (the C-parameter)

Hydraulic conductivity controls groundwater flow below a prescribed hydraulic gradient. This study utilized pumping tests conducted by the Water Authority of Jordan (WAJ) to obtain estimates of hydraulic conductivity. However, owing to that the hydraulic conductivity data are very difficult to obtain, SINTACS offers simple method for deriving distinctive scores for the hydraulic conductivities on the basis of Fig. 10. In this figure, the aquifer's principal lithological units are portrayed together with the appropriate hydraulic conductivity values. The rating distribution map of hydraulic conductivity of the upper aquifer is given by Fig. 11.

The hydraulic conductivity expresses the capability of the geological layers to permeate water and contaminants. The hydraulic conductivity values in the map (Fig. 11) indicate that large areas of the northern, central, and southern parts of the study area have high potential for transfer of contaminants to the aquifers.

Topography, or slope, of land surface (the S-parameter)

The slope controls the settling degree and the extent of infiltration of runoff and associated pollutants. Slope information

Fig. 15 Location of Waleh and Heedan wells related to vulnerability map
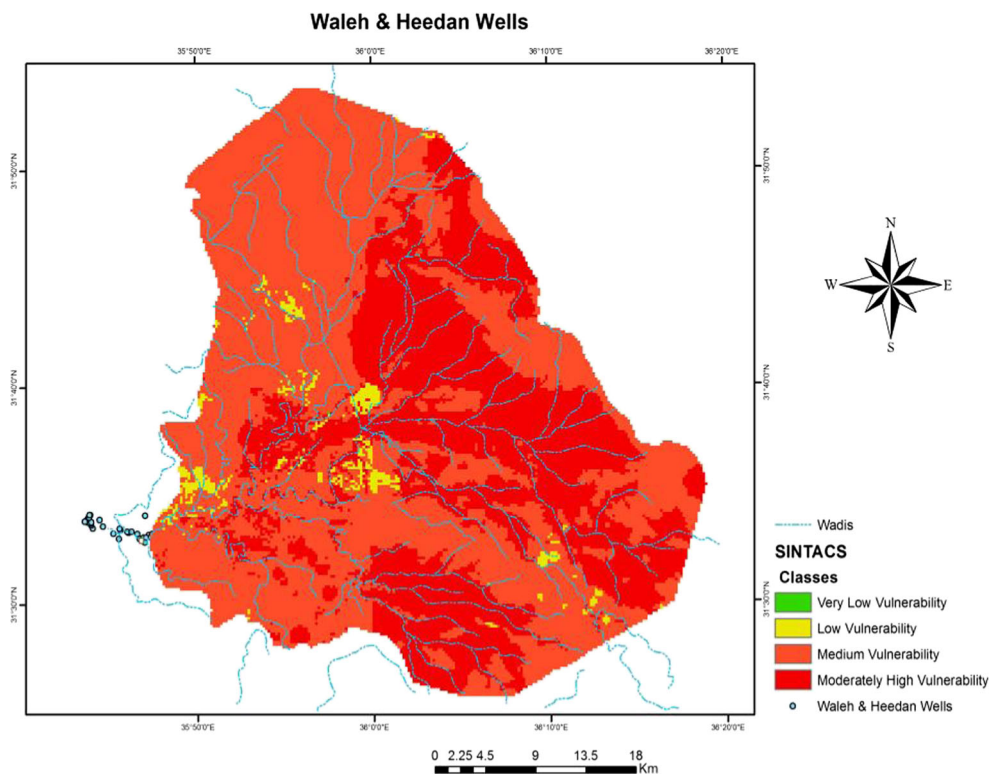
was obtained using a DEM of 90-m resolution. Figure 12 shows the topography and estimates of sloping in the study area.

The study area is a flat-leaning area with limited steep slopes, except the area of Wadi Al-Waleh and Heedan where the low slopes allow water to settle on the surface for long periods of time, thus allowing for recession and gradual leakage of polluted water into aquifers.

The SINTACS map

The final SINTACS vulnerability thematic layer was developed by counting number of pixels in each SINTACS thematic parameter. Every parameter was multiplied by its weight. The final index values vary from 89 to 159.5. However, to make it easier to interpret the results, the obtained ranges were normalized to the range of 0–100. This step allows for expressing vulnerability in four levels: very low, low, moderate, and moderately high as standard measurement. Figure 13 shows the final results expressed in a SINTACS vulnerability map.

The SINTACS index map indicates that the potential for polluting groundwater is moderately high, especially in areas close to agricultural lands in the middle part of the study area. More attention must be given to cultivating these areas which have high potential to absorb and retain pollution than other areas. Finally, this map is used to help in avoiding more contamination and pollution of the groundwater and conducting high-risk activities in a land planning study by considering the vulnerability of that area.

Figure 13 indicates that according to the SINTACS model, sensitivity to contamination ranges from low to relatively high. Table 1 shows the percentage of the WWC area which falls within each vulnerability category as obtained from the attribute table of the vulnerability map.

Table 3 reveals that about 654.97 km^2 of WWC has a moderately high vulnerability to pollution and that the largest proportion of the catchment area (1102.73 km^2; 61.2 % of total area) has medium vulnerability to pollution. Hence, it is concluded that most of WWC has medium to moderately high vulnerability to pollution.

It is noticed that most of the industrial, agricultural, and other human activities intensify in the areas of medium vulnerability to pollution even though the sources of pollution are sometimes industrial, agricultural, and other human activities which concentrate in the area of medium vulnerability to pollution. This is part of the environmental management decision which entails forcing industries to be sited and operated in areas whose geologic nature prohibits or obstructs pollutants from reaching to groundwater layers. However, pollution may spread through surface valleys to areas of high vulnerability to pollution. Strict actions should be taken in order to stop the spread of industrial activities in vulnerable areas in the future. Figure 14 displays the land uses dominant in WWC overlain on the intrinsic vulnerability map of SINTACS for WWC watershed.

Validation

With reference to data on biological and chemical indicators of pollution reported by the Jordan Water Authority for Waleh and Heedan wells during the period 2002 to 2014, see Table 4, it has been found that levels of NH_4^+, NO_3^-, TDS, and *Escherichia coli* bacteria exceeded the respective levels of the national drinking water standards (20 mg/L, 50 mg/L, 1000 mg/L, and 1.1 MPN/100 mL, respectively) (Water Authority of Jordan 2015).

In view of this, the Waleh and Heedan water wells falling down the water intercept are polluted due to being located in areas with average high levels of vulnerability to pollution as can be noticed in Fig. 15 and to sensitivity of the S-parameter, namely, the depth to the water table, which is shallow in that area.

Based on results of the laboratory analysis obtained from the Water Authority of Jordan for the well under consideration shown in Table 4, which has been interpolated on the sensitivity map shown in Fig. 14, it is found that all wells fall within areas of average high levels of vulnerability to pollution, which confirms that surface pollutants migrated to groundwater layers.

Conclusions

This paper aimed at assessing aquifer vulnerability in the WWC area. Using SINTACS index values, which ranged from 65 to 96, and the existing data, an overall assessment of vulnerability to pollution of groundwater wells in WWC was obtained. For areas with low vulnerability to pollution, the SINTACS index values ranged from 33 to 64. Approximately 29.6 % of WWC total area pertains to areas with moderate vulnerability to pollution for which the SINTACS index values ranged from 97 to 128. On the other hand, for areas having moderately high vulnerability to pollution (22 % of the overall study area), the SINTACS index values fell in the range of 129–160. This paper was an attempt for assessment of aquifer vulnerability to pollution in WWC area using the GIS and the SINTACS model in an effort to stop or prevent groundwater pollution that resulted from anthropogenic activities. The results showed that the study area has a high potential for pollution. Generally, the vulnerability map shows that low to very low levels of vulnerability to pollution characterize the southwestern parts of the study area. In addition to that, and on the basis of SINTACS model land use maps, the study concludes that most of the agricultural, industrial, and service activities are prevalent in areas characterized by having low to moderate vulnerability to pollution.

Some agricultural activities are located in the most vulnerable areas, especially near Khan Al Zabib.

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