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Groundwater recharge zones mapping using GIS: a case study in Southern part of Jordan Valley, Jordan

**Nezar Hammouri · Hani Al-Amoush ·
Marwan Al-Raggad · Sura Harahsheh**

Abstract This paper aims at mapping the potential groundwater recharge zones in the southern part of Jordan Valley (JV). This area is considered as the most important part for agricultural production in Jordan. The methodology adopted in this study is based on utilizing the open ended SLUGGER-DQL score model, which was developed by Raymond et al (2009). Geographic information systems were used in this study to build up the different layers of this model and to create the potential groundwater recharge zones. Based on the generated SLUGGER-DQL potential map, it was found that about 70.8 % of the investigated area was categorized as high potential for groundwater recharge, 18.7 % as moderate, and 10.5 % as low potential for groundwater recharge. To validate the model results, sensitivity analysis was carried out to assess the influence of each model parameter on the obtained results. Based on this analysis, it was found that the slope parameter (S) is the most sensitive parameter among SLUGGER-DQL model parameters, followed by water level in summer (L), well density (D), water quality (Q), runoff availability (R), land use/land cover, geology (GE), whereas the lowest sensitive parameter is the geology parameter (GE). Moreover, the parameters R, D, and Q show the lowest effective weights. The effective weight for each parameter was found to differ from the assigned theoretical weight by SLUGGER-DQL index model.

N. Hammouri (✉)
Faculty of Natural Resources and Environment,
Hashemite University, Az Zarqa, Jordan
e-mail: nezar@hu.edu.jo

H. Al-Amoush · S. Harahsheh
Institute of Earth and Environmental Sciences,
Al al-Bayt University, Mafraq, Jordan

M. Al-Raggad
Water and Environmental Research Center, University of Jordan,
Amman, Jordan

Introduction

Jordan is an arid to semiarid country, with an area of about 90,000 km^2 and variable topographic features. The mean annual precipitation ranges from <50 mm in the eastern and southern deserts, to more than 600 mm in the northwestern highlands where Mediterranean climate conditions are dominated (Salameh and Bannayan 1993). The temperature is also variable in space and time; for example, in Jordan Valley (JV), the temperature may rise to 45 °C in summer and drops to few degrees around zero in winter (DOM 2010). Rainfall is the main source of surface and groundwater in Jordan. The prevailing climatic conditions and climatic changes have led to severe complications regarding the groundwater resources and their availability. The per capita water share in Jordan is about 234 m^3/year in the year 2000, and it is expected to become 111 m^3/year in 2020 as a consequence of the high population growth rate and limited water resources. This actually figures out the water problem in the country and place Jordan in the bottom 20 % of the water poverty scale (Lawrence et al. 2002).

JV is one of the most important agricultural production areas in the country, due to the availability of water and special climate conditions allowing fruit and vegetable production in the winter season. During the last few decades, the increasing need for water has led to extensive exploitation of the groundwater resources. During winter seasons, high quantities of surface water flow through the eastern side wadis towards Jordan River, and then to the Dead Sea where the water becomes saline and useless. Therefore, the capturing the winter-flood water is one of the most critical aspects of water resources management in the JV area (Al-Amoush 2006).
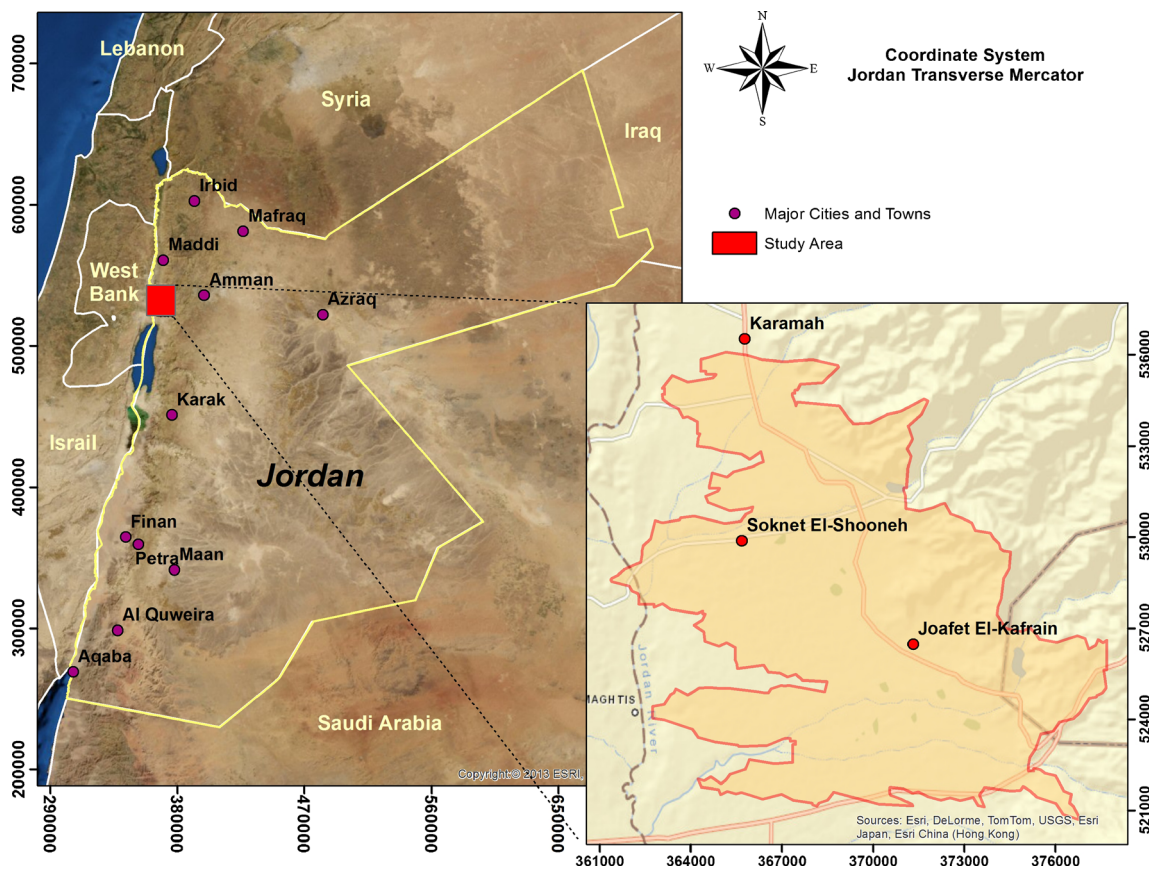
Fig. 1 Location map of the study area

Groundwater artificial recharge is one practical option to utilize the unused water resources in replenishment of aquifers. This includes the use of conventional and nonconventional water resources such as treated sewage effluents and excess storm water (runoff) to recharge aquifers. Therefore, delineation and identification of potential zones for groundwater recharge is a primary objective to augmentation the groundwater in aquifers. Conventional hydrogeological studies would not be sufficient in studying the parameters for large areas on their suitability for artificial recharge because of the many controlling parameters that must be independently derived and integrated (Shanker and Mohan 2005). In recent years, several studies have been implemented using different new methods such as remotely sensed data, geographic information system (GIS) approach as well as geophysical methods, in order to identify suitable sites for artificial groundwater recharge, which takes into account different geological and hydrogeological criteria (Saraf and Coudhary 1998). Goyal et al. (1999) used the approach of remote sensing and GIS for groundwater exploration and identification of artificial recharge sites (Shahid and Nath 1999). Jaiswal et al. (2003) used GIS techniques for generation of groundwater prospect zones for rural development. Al-Amoush (2006) investigated the potential of the northern part of the Jordan Valley for groundwater artificial recharge using hydrogeophysical

methods and drilling. Raymond et al. (2009) used GIS techniques for mapping the potential recharge zones in parts of Pune city. In the present study, the objective is to identify the potential groundwater recharge zones in the southern part of Jordan valley using integrated geographical information system approach.

Description of study area

JV is situated in the northwestern corner of Jordan and extends from Lake Tiberias at an elevation of 212 m below mean sea level (bmsl) southward to Dead Sea at an elevation of 423 m (bmsl). The area of study extends from the southern to the middle part of the JV, with the coordinates (521000N–536000N) and (360000E–378000E) in Jordan Transverse Mercator coordinate system (Fig. 1). It covers an area of 173 km^2. The topographic elevation ranges from 380 m (bmsl) to 215 m above mean sea level (Fig. 2). The drainage in the study area is almost towards the west, which finally joins the Jordan River flowing south to the Dead Sea. Two major wadis are dominated in the study area; these are Wadi Kafrien and Wadi Shuieb. The climate in the study area is considered of semiarid type, and the mean annual rainfall ranges between 100 mm in the south and 250 mm in the north.
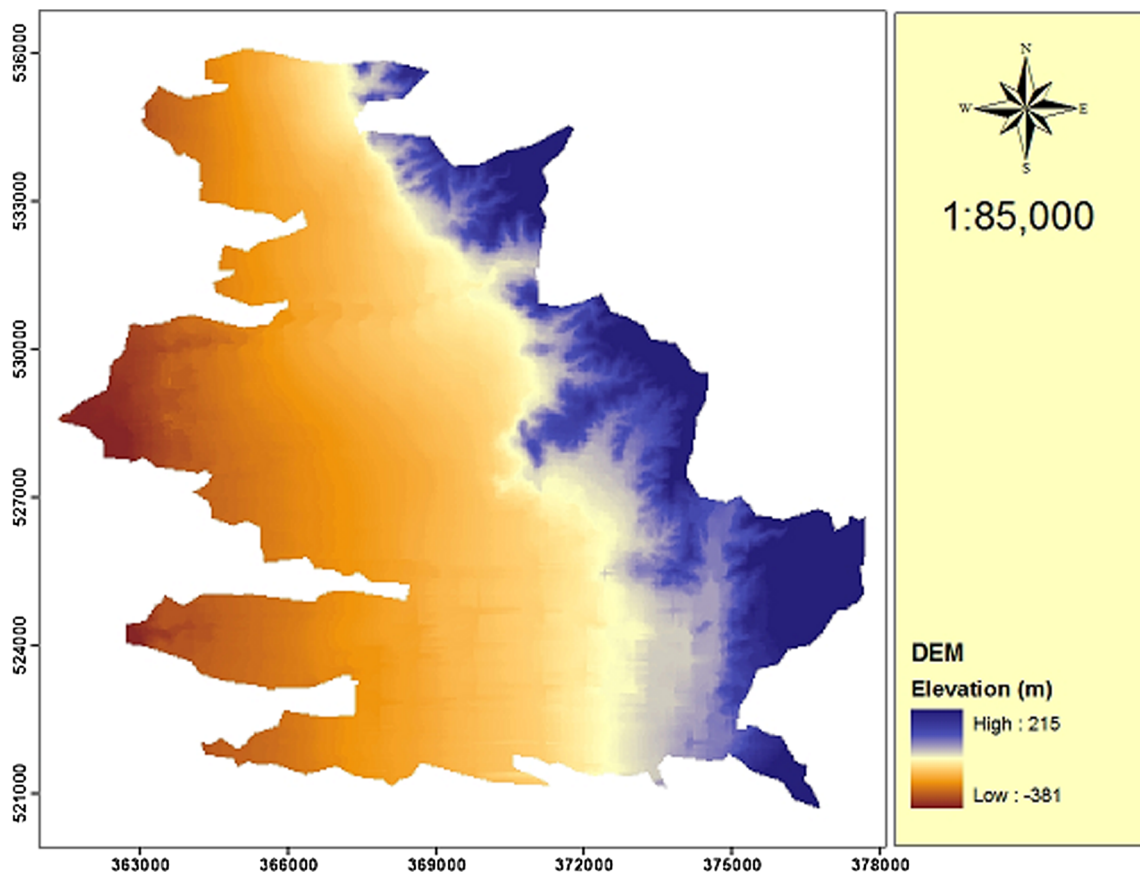
**Fig. 2** Digital elevation model for the study area

Temperature in Jordan Valley may rise in summer up to 45 °C, while the mean annual temperature is about 24 °C. In winter, the temperature may drop to few degrees above zero (Salameh and Bannayan 1993). The relative humidity in the study area is very low with a daily long-term mean of 64 % in the coldest period of the year going down to 27 % in the hottest summer months at 2:00 P.M. (DOM 2010). The potential evaporation in the northern JV is around 2,100 mm/year, and it is gradually increasing to about 2,400 mm/year at shores of the Dead Sea (DOM 2010).

Geological setting

The oldest geological rocks exposed in the southern JV are of Mesozoic age, with younger formations up to Tertiary overlying them (Fig. 3). The exposed rock units in the study area can be summarized as follows:

(a) The Triassic–Jurassic System. This system includes (1) Zerqa Group (Z), which mainly consist of siltstones, limestone, dolomite, and sandstones, and (2) the Lower Cretaceous Kurnub Sandstone (KS), which consists of basal conglomerate or sandstone intercalated with conglomerate layers (Bender 1974).

(b) The Upper Cretaceous system. This system is divided into two main groups according to Quennel (1951); these are (1) The lower Ajlun Group which includes all the marine sediments of Cenomanian–Touronian., and include Naur (A1/2), Fuheis (A3), Hummar (A4), Shuieb (A5/A6), and Wadi El-Sir (A7) formations; (2) the Upper Belqa Group which consists of chalk, limestone, marly chalk, chert, and bituminous limestone, and including Ghudran (B1), Amman (B2), Muwaqqar (B3), and different other rock formations (Bender 1974; McDonald et al. 1965).

The JV floor consists mainly of nonconsolidated alluvial sediments of gravel, sand, shales marls, and clays (Fig. 3). In addition, evaporates that precipitated from the ancestors of the present Dead Sea are found in the form of extensive deposits and lenses, especially in the southern and western part of the Jordan Valley (Bender 1968; Horowitz 1979). Table 1 lists the lithostratigraphic successions in the study area. Different geological groups are outcropping and forming the JV floor in the study area; they are (a) Jordan Valley Group (JV1) represented by Shagur Conglomerates formation, and consisting mainly of well cemented conglomerates with low porosity and permeability, (b) Jordan Valley Group (JV2), consisting of conglomerates, sand, silt, and clayey marl overlying the JV1 with a total thickness of
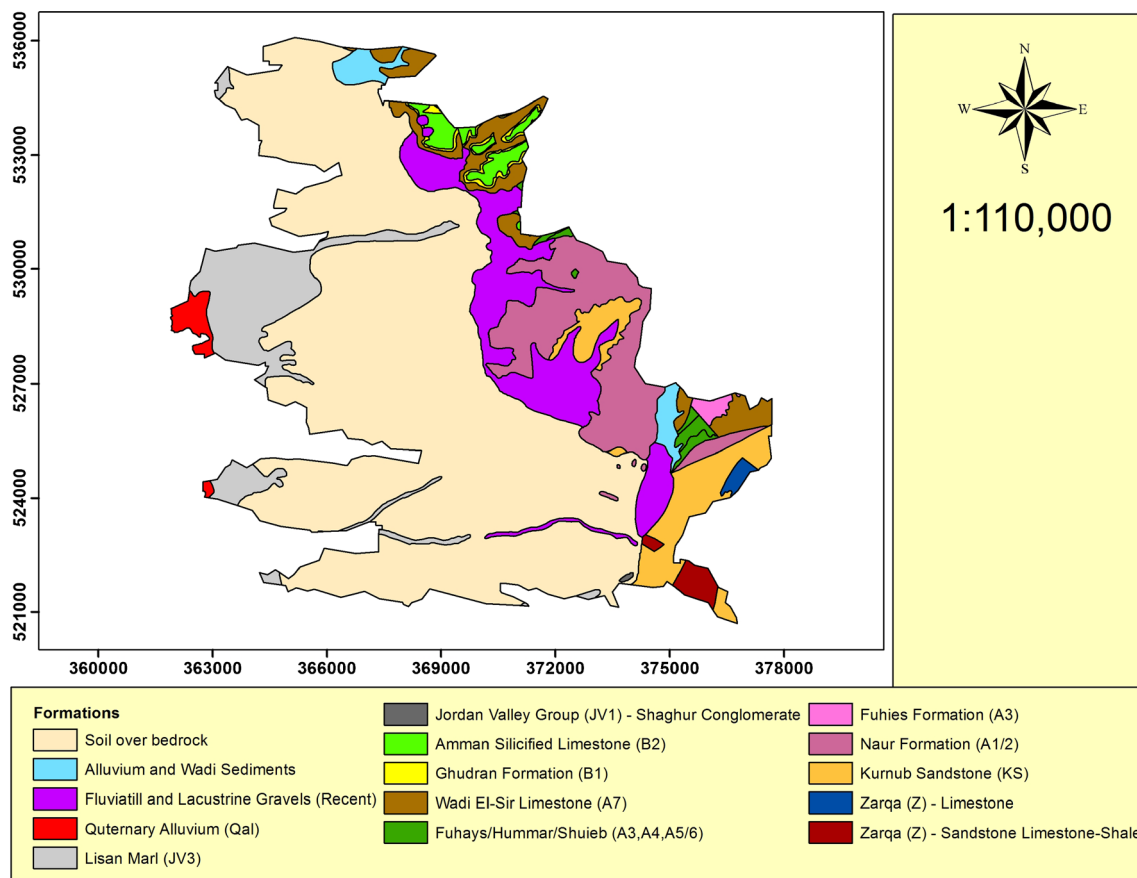
Fig. 3 Geological map of the study area

100 m, and (c) Lisan Marl Formation (JV3) consisting of marls, silty, and sandy marls with gypsum and residuals of halides. It covers more than 70 % the JV floor, (d) Quaternary alluvium deposits (Qal) and alluvial fans, which refer to nonconsolidated colluvial and alluvial deposits developing along the course of the major wadis and foothills of mountains and are composed of lenticular beds of gravel, sand, and calcareous clay.

The major geological structure affecting the JV area is the Dead Sea Transform Fault (DSTF), which can be inferred from geophysical and morphological evidences and from steep tilting of the strata toward the west. It has an overall down throw of 2 km toward the west with left lateral strike–slip fault movement (Quennell 1958). It extends for more than 1,000 km; the total lateral offset is about 107 km (Quennell 1958). The slip rate along the DSTF has been estimated to be 5–8 mm/year (Garfunkel 1981; Ferry et al. 2007). In the JV, it runs along the central part of the JV in its southern area (Dead Sea to Maddi) and at the eastern foothills of the mountains chain in the northern part of JV (Maddi to Tiberias Lake; Salameh 2001). Several minor structures associated with the major fault are found in the JV. They are manifested in offsprings of the major fault, deflections in

drainage streams, and some tensional and compressional east–west trending faults. These can enhance the groundwater movement and recharge processes (Salameh 2001).

Hydrogeology

Groundwater is considered the major water resource in many areas of Jordan and the only water resource in some others. The hydrogeological classification and aquifer system in the study area can be divided into four major aquifers (Table. 2); these are from bottom to top: Zarqa Lower aquifer system, composed of siltstones, limestone, marl, and dolomitic limestone, Lower Cretaceous aquifer system (Kurnub sandstone), Upper Cretaceous aquifer system (A1/2, B2-A7), and the JV aquifer system (shallow groundwater aquifer) (McDonald et al 1965; Bender 1974).

Shallow groundwater aquifer

The groundwater in the study area is mainly found in the Quaternary deposit, which consists of friable sediments that

Table 1 Lithostratigraphic successions in the study area (after Macdonald et al. 1965)

Formation name	Rock type and thickness		Age
Quaternary alluvium (Qal)	Alluvial fans, soil and gravel (0–100) m		Recent (Quaternary)
Jordan Valley–Lisan Marl (JV3)	Gybsiferous marls, blue to black saline shales, conglomerates (40 few hundred meters)		Upper Pleistocene
Jordan Valley group (JV2)	Samra formation, 35 m		Early to Late Tertiary
Jordan Valley group (JV1)	Ubeidiya formation	350 m	Early to Late Tertiary
	Kufranja gravel		
	Abu Habil series		
	Shagur conglomerate		
	Ghor El Kattar F.		
Muwaqqar F. (B3) (are not distributed in the study area)	Balqa	Chalk, Lst, marly chalk, chert, bituminous	Campanian–Danian
Amman F. (B2)	Balqa	Lst, chert, chalk, phosphatic	Campanian
Ghudran F. (B1)	Balqa	Chalk, marl, marly-Lst	Coniacian–Santonian
Wadi El-Sir (A7)	Ajlun	Crystalline Lst, marl, chert	Touranian
Shuieb (A5/A6)	Ajlun	Crystalline Lst, marly Lst,marl	Upper Cenomanian
Hummar (A4)	Ajlun	Crystalline Lst, marly Lst	Up-mid-Cenomanian
Fuheis (A3)	Ajlun	Marl, marly limestone	Lower-mid- Cenomanian
Naur (A1/2)	Ajlun	Lst, chert, marl, (230 m)	Lower Cenomanian
Kurnub (KS)	Ajlun	S.st, calcareous S.st, Dolo, Lst (40 m)	Lower Cretaceous
Zarqa (Z)	Lst, marl, dolomitic limestone, sandstone (50–600 m)		Upper Triassic–Jurassic

were brought in from the eastern side mountains (Salameh 2001). The shallow groundwater aquifer in the study area is subjected to intensive exploitation due to the high agricultural and urbanization activities, which also have gradually led to deterioration in the groundwater quality (Kuisi 1998). The electrical conductivity of the groundwater ranges from <1,000 μS/cm in the eastern part of the study area to more than 3,500 μS/cm in the western part (Kuisi 1998). In addition, overpumping of groundwater during the last few decades has also led to drops in the groundwater table as recorded in different observations wells.

Methodology

Several recent studies have studied the potential zones for groundwater recharge using GIS techniques such as Jothiprakash et al. (2003), Raymond et al. (2009), Yeh et al.

(2009), Ramakrishnan et al. (2009), Chowdhury et al. (2010), and Chenini et al. (2010). In the present study, different dataset types and thematic maps including spatial and nonspatial data in digital form were prepared, gathered, used, and integrated through GIS techniques. The open ended SLUGGER-DQL score model, which was developed by Raymond et al. (2009) to identify the potential sites for artificial recharge and rooftop rainwater harvesting were utilized in the present study. The SLUGGER-DQL algorithm composed of different important geological and hydrogeological parameters for recharge zones sites identification as an outcome of the logic was used in geological studies and ground verification (Raymond et al. 2009). The eight parameters considered in SLUGGER-DQL index model are: slope (S), land use/land cover (LU), geomorphology (G), geology (GE), runoff availability (R), well density (D), water quality (electrical conductivity) (Q), and water levels in the summer season (L) (Raymond et al. 2009). The description and importance of each parameter and its

Table 2 Simplified hydrogeological classification of the aquifers in JV (JICA 1995)

Geological formation (group)	Hydrogeological classification	Lithology	Thickness (m)
Mio-Pli-Quaternary	Aquifer/aquiclude	Sand/limestone/clay/ conglomerates	10–400
Amman-Wadi Sir (B2-A7)	Upper Cretaceous aquifer	Limestone/Chert	50–>350
Ajlun (A1-6)	Upper Cretaceous Aquifer	Sandy limestone/sandstone	120
Kurnub (KS)	Lower Cretaceous system	Sandstone	50–300
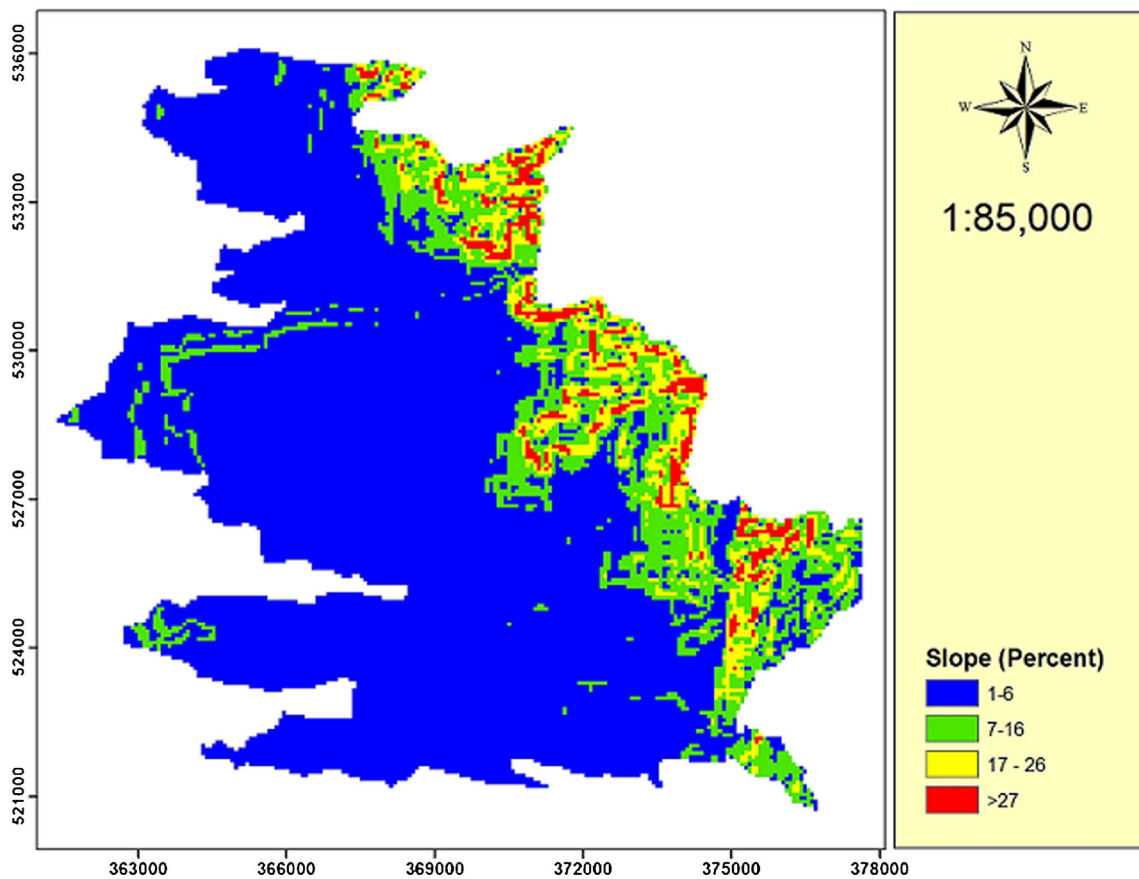
Fig. 4 Slope model in percent

effective weight in the model index is described and discussed below in details.

Results and discussion

Preparation of thematic maps

(a) Slope model (S): the slope of topography surfaces refers to the variability of land surface. It is considered one of the most important parameters controlling the infiltration process of groundwater into the subsurface; thereby, it is an indicator for the suitability for groundwater recharge. Information related the slope parameter was derived from the digital elevation model (DEM) (Fig. 2). The DEM was obtained by Shuttle Radar Topographic Mission with cell size of 90 m, which has been downloaded from Consultative Group for International Agriculture Research. It was possible with the aid of ArcGIS9.2 tools to calculate the slope model in percent for the investigated area (Fig. 4). The slope or gradient controls the surface runoff, as there is more topographic gradient as it produce a higher runoff and less recharge. Consequently, areas of higher slopes are

given a lower rate and areas of lower slopes are given high rates in SLUGGER-DQL index model (Raymond et al. 2009). Slopes in the study area ranged from 1 to 80 %. More than 65 % of the study area was found to have a slope <6 % (Fig. 4). Table 3 shows the rating scores of the slope parameter, and Fig. 10a shows the spatial distribution of the classified scores of the slope in the study area

(b) Land use/LU: land uses/covers are highly influence the behavior of water flow on terrain surfaces and the recharge process (Al Saud 2010). Several parameters are used to describe this influence such as: soil types and thicknesses, urban, bare rock, vegetation cover, and agriculture (Su 2000). Each parameter affects the water recharge in a different and complicated manner. For instance, soil deposits with highly clay content cause decreases in water infiltration and, thus, prevents efficient recharge of groundwater (Al Saud 2010). In contrast, clay-free soils enhance the recharge process. In addition, the vegetation cover plays a significance role in this respect, the higher the vegetation cover, the higher the evapotranspiration, which implies less chance for infiltration (Darwich et al. 2003). In addition, agricultural lands benefit from the return recharge due to irrigation.

Table 3 Rating sores for different SLUGGER-DQL parameters and their corresponding weights (modified after Raymond et al. 2009)

Slope (S)

Class	Slope in percent (%)	Rating (S)	Weight (W)
1	1–6	1.25	2
2	7–16	0.75	
3	17–26	0.5	
4	>27	0.25	
Land use/land cover (LU)			1
1	Agriculture, vegetation	0.40	
2	Built-up	0.10	
3	Urban, bare rock	0.20	
4	Open	0.25	
5	Hills	0.05	
Geomorphology (G)/landform			1
1	Hill	0.20	
2	Plateau	0.30	
3	Plain	0.50	
Geology (GE)/rock type			1
1	Alluvium	0.75	
2	Massive limestone	0.15	
3	Marl, clay	0.10	
Runoff availability (R)			1
Class	Runoff in percentage	Rating (R)	
1	11–13	0.10	
2	14–16	0.20	
3	17–20	0.30	
4	>21	0.40	
Well density (D)			1
Class	Number of wells (km^2)	Rating (D)	
1	>100	0.40	
2	61–99	0.25	
3	31–60	0.20	
4	11–30	0.10	
5	0–10	0.05	
Electrical conductivity (quality of water) (Q)			1
Class	Electric conductivity (μS/cm)	Rating (Q)	
1	<250	0.75	
2	250–750	0.25	
3	751–2,250	0.15	
4	>2,250	0.05	
Depth to groundwater (mbgl) (L)			2
Very deep	>16.1	0.80	
Deep	12.1–16	0.60	
Moderate	8.1–12	0.30	
Shallow	4.1–8	0.20	
Very shallow	0–4	0.10	

Table 4 Land use/land covers classes

No.	Class	Area (km^2)	% of total area
1	Urban and bare rocks	128.1	74.4
2	Rain-fed vegetables, cereal	13.1	7.6
3	Irrigated nondeciduous trees	8.7	5.1
4	Natural vegetation, Steppe	1.6	1.0
5	Irrigated vegetable, cereal	14.4	8.4
6	Irrigated fruit trees	6.1	3.5
7	Water bodies	0.2	0.1

the land use/land cover and pattern of their spatial distribution is a very important and is a prerequisite in selecting a suitable site for groundwater recharge as well it controls the surface run off (Ramakrishnan et al. 2009). The raw digital data about land use/cover map for the study area were obtained from the Ministry of Water and Irrigation (MWI 2010) as extracted from analysis of Landsat imagery ETM+ images. The collected information as well as field observations were used to validate and to identify the signatures representing various land use classes. It was possible to classify the investigated area into seven major classes based on the land uses (Fig. 4). These classes, their areas, and the ratio of each class relative to the total surface area are listed in Table 4. The rating scores of land uses/cover are given in Table 3. Figure 10b shows the spatial distribution of the classified scores of LU of the study area (Fig. 5).

(c) Geomorphology (G): landform features originated by the action of weathering, water flowing, tectonic, and erosion processes over time. Landforms in their various types influence the recharge and runoff pattern of water in different manners Raymond et al. (2009). They effect the distribution of soil type, texture, thickness, physical, chemical, and biological characteristics of soil, and the availability and residence time of recharge water in soils. Therefore, landforms should be considered independently while selecting the favorable sites for groundwater recharge. The study area consists of a limited range of landforms (Fig. 6); these include (a) flat plain deposits comprising the western part of study area, which consists mainly of Quaternary unconsolidated alluvium deposits, conglomerates, clay, and marl, form 73.4 % of the total area, (b) the Plateau area that concentrated along a narrow zone in the central portion of the study area consisting of fluviatile and lacustrine gravel, limestone, and wadi sediments forming 10.9 % of the total area, and (c) hill-slope terrains lying along the most eastern portion of the study area mostly comprised of colluvial deposits of fractured limestone, sandstone and chert forming (15.7 %) of the total area. The rating scores of different landform features are given in Table 3 and Fig. 10c
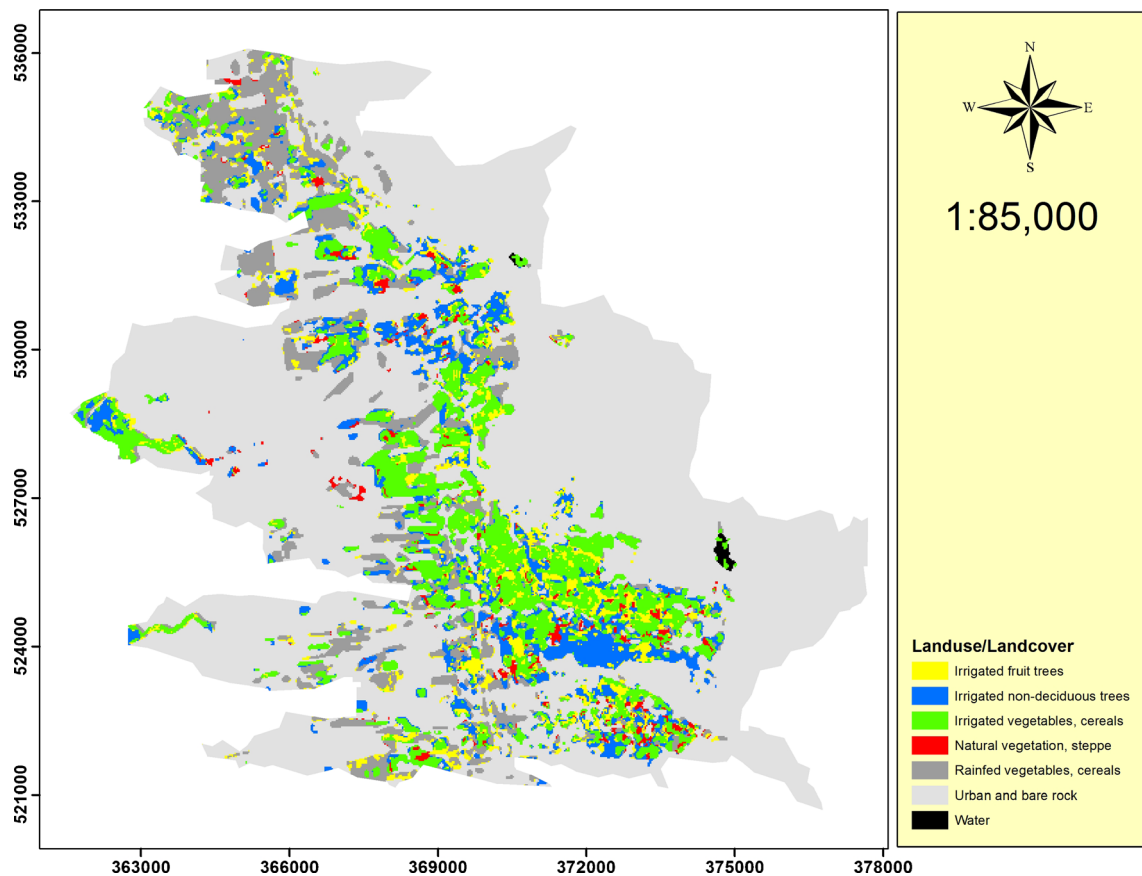
Urbanization affects groundwater recharge significantly, as it introduces new mechanisms and modifies the existing one (Seiler and Gat 2007). Information about

Fig. 5 Land use/land cover map of the study area

shows the spatial distribution of the classified scores of geomorphology for the study area.

(d) Geology (GE): as discussed earlier, different rock types were found in the study area (Fig. 3). Based on the lithological and hydrogeological characteristics of rock types in the study area, the highly porous and permeable formation is given higher score for a site potential of groundwater recharge (Table 3). Figure 10d shows the spatial distribution of the classified scores of geology (GE) for the study area.

(e) Well density (D): during the last fourth decades, several wells have been dug in the study area for the extraction of groundwater for agricultural and domestic uses. Currently, there are about 160 unequal distributed productive wells in the study area. The yield capacity of these wells ranges from a few cubic meters to about 400 m³/day (WAJ 2010). The potential site for groundwater recharge is affected by the spatial and geographical distribution of wells, as well as water abstraction structures and their density in the study area. The higher the density of abstraction wells per land area, the greater is the site potential for groundwater recharge, resulting in lowering the water table and increasing the thickness of recharge zone (Raymond et al. 2009). Therefore,

areas having higher well densities are expected to have larger drops in water table; hence, they are given higher scores for their potential to groundwater recharge (Table. 3). The well-density model (Fig. 7) was determined using GIS techniques, by placing the 1×1 km² grid on the well distribution map and counting the number of abstraction groundwater structures per square kilometer. Figure 10f shows the spatial distribution of classified well density scores.

(f) Water quality (electrical conductivity) (Q): electrical conductivity (EC) of water is related to its total dissolved solids contents. Therefore, it is a very useful indicator for water quality. The EC is controlled by different factors such as the lithological composition (rock type), point-source pollutants, some processes such as evaporation, evapotranspiration, infiltration, precipitation, dissolution in addition to the path of water movement from the source until the aquifer, and the rock–water interaction processes (Venkateswarlu 1996). Therefore, the EC is a good indicator to the velocity of groundwater as well as to the residence time that permit to dissolve more ions. In general, lower values of EC indicate that the groundwater movement is rapid. Accordingly, area with high EC values are given lower rating score in relation to potential
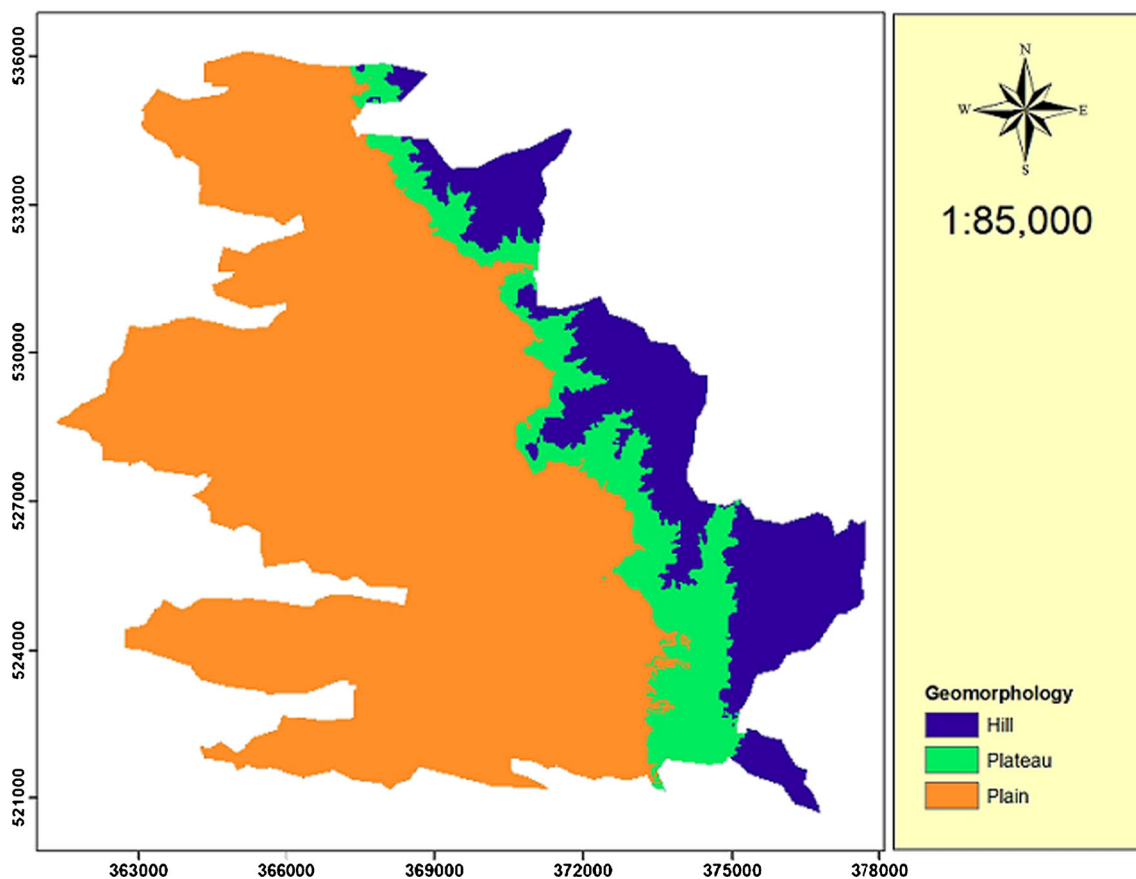
Fig. 6 Geomorphologic and landform features of the study area

groundwater recharge, and the area of low EC values are given higher rating scores (Raymond et al. 2009) (Table 3). The spatial distribution of EC values in the study area is shown in (Fig. 8). Figure 10g shows the spatial distribution of classified scores of EC in the study area.

(g) Depth to groundwater (L): the depth to groundwater is defined as the distance from the ground surface to the water table (Chitsazan and Akhtari 2009). Deeper water levels in wells during summer seasons indicate at considerable water extraction and the area can be considered as a favorable site for recharge. Thus, high scores values (Table. 3) were given for deeper water level (Raymond et al. 2009). The data about the depth to groundwater were obtained by subtracting the water table level from the elevation of well site and averaging over the last 5 years (2006–2010). Data from 160 wells in the study area were used to prepare the depth to groundwater map (Fig. 9). It can be seen from Fig. 9 that the depth to groundwater is variable and ranges from a few meters in the western part to more than 16 m in the middle to eastern part of the study area (Fig. 4). Figure 10h shows the spatial distribution of classified scores of depth to groundwater parameter in the study area.

(h) Runoff available (R): runoff is defined as that part of precipitation as well as any other flow contribution, which appear in surface streams of either perennial or intermittent form (Gupta 1979). There are many factors affecting the surface runoff, some of them pertaining to precipitation characteristics such as its type, duration, intensity, and soil moisture. Beside other parameters that describes the physical characteristic of the basin such as land use, area, shape, slope, elevation, and drainage system (Gupta 1979). The primary objective of any artificial recharge project is to harvest as much runoff water as available. Thus, the higher the runoff water, the greater the water availability for recharge. Accordingly, areas having higher surface runoff are given higher scores (Table 3). Runoff maps for the investigated area were calculated as percentage of rainfall. The rainfall map, which was obtained from MWI (2010), was converted into a raster map through GIS. Based on the slope classes and associated runoff coefficients obtained from the Ministry of Water and Irrigation (MWI 2010). The runoff map was obtained by multiplying the rainfall in each cell by the runoff coefficient. Figure 10e shows the spatial distribution of runoff scores in the study area.
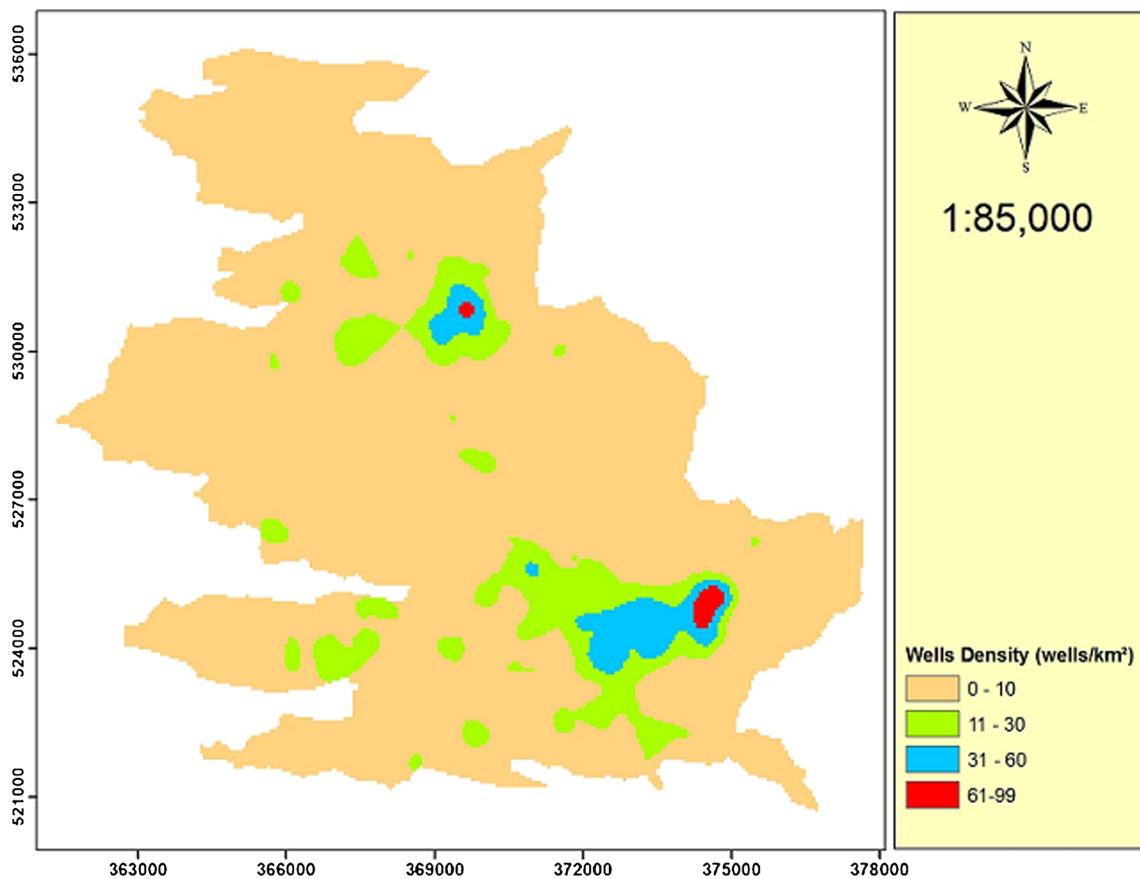
Fig. 7 Well-density model of the study area

Data integration through GIS

As discussed above, each thematic map provides certain information about the groundwater recharge potential zones. In order to get all collected information unified, it is essential to integrate these data in appropriate factors. The integration of various thematic maps has been carried out through application of GIS. Various thematic maps were reclassified based on weights assigned in Table 3 and integrated using the "Raster Calculator" function in spatial analysis module within GIS environment. The weights assigned (ranking system) for the different layers have considered according to Raymond et al (2009). The weighting system contains three significance parts: weight, range, and ratings. In this system, each factor of SLUGGER-DQL has been assigned a relative rate ranging from 0.05 to 1.25 (Table 3). The most significant factor has a weight of 2 and the least significant has a weight of 1. The recharge potential index is obtained by summing the pixel values for each area that resulted from multiplying the ratings with its appropriate SLUGGER-DQL factor weight (Table. 3) using a simple arithmetic expression given by Raymond et al (2009) through raster calculator of spatial analysis module:

$$SLUGGER - DQL = S_W \times S_R + LU_W \times LU_R + G_W$$
$$\times G_R + GE_W \times GE_R + R_W$$
$$\times R_R + D_W \times D_R + Q_W \times Q_R$$
$$+ L_W \times L_R \tag{1}$$

where the subscript W denotes to factor weight and R denote to its rating. Higher SLUGGER-DQL Index values correspond to high potential of groundwater recharge. The groundwater potential recharge zones are classified based on the total SLUGGER-DQL scores as follows: 0–2, respects areas of low recharge potential; 2–4, represents areas of moderate recharge potential; 4–6, those areas with high recharge potential; and >6, are assigned for areas with very high recharge potential (Raymond et al 2009).

Groundwater recharge potential map (SLUGGER-DQL index model)

Figure 11 shows the derived map representing zones of different potentials for groundwater recharge in the southern Jordan valley (SLUGGER-DQL index). The map is generated by
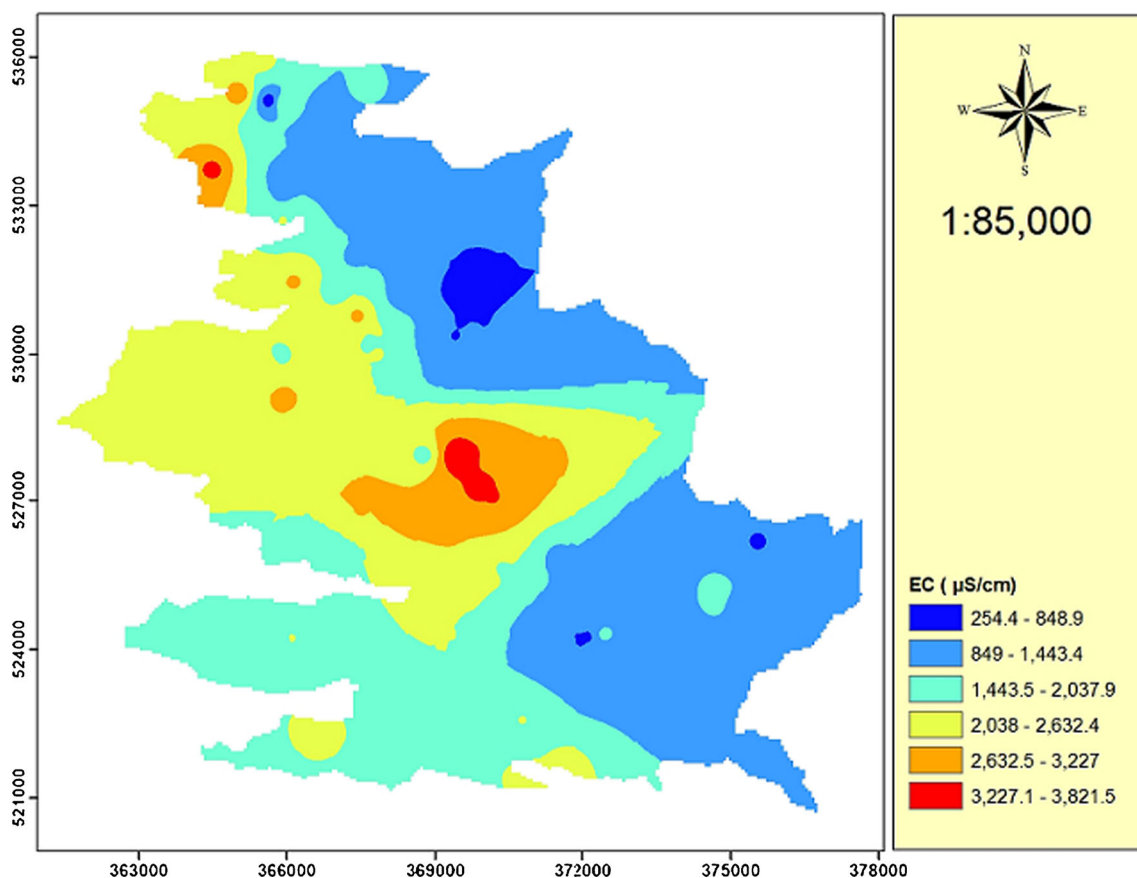
Fig. 8 Electrical conductivity map of the study area

integration of different components, extracted from various dataset sources. The extent of various zones as a percentage of the total area can be summarized as following: 70.8 % of the study area was classified as high potential, 18.7 % moderate potential, and 10.5 % low potential for groundwater recharge. It was found according to Fig. 11 that the moderate to high groundwater recharge potential zones are concentrated along the central part of the study area due to the distribution of alluvium stratum composed of gravel, sand, and conglomerate in addition to irrigated lands with high infiltration ability. The most eastern region is of less importance due to its relatively steep slopes.

Sensitivity analysis

The main objective of sensitivity analysis is to assess the influence of rating values and assigned weights to each parameter on the results of recharge potential. This helps hydrogeologists to judge the significance of subjective elements (Gogu and Dassargues 2000).

Performing sensitivity analysis was described by many authors and applied for different modeling studies (Gogu and Dassargues 2000; Napolitano and Fabbri 1996 and others), where the model index is computed several times,

by the removal of one parameter in each step. In this study, SLUGGER-DQL index maps were computed eight times, and in each time, one parameter was removed.

In order to assess the influence or sensitivity of removing one parameter, Lodwik et al (1990) define a map-removal sensitivity measure that represent the sensitivity associated with removing one or more maps .This measures (Sp_i) can be expressed as:

$$Sp_i = \left| \frac{V_i}{N} - \frac{Vp_i}{n} \right| \tag{2}$$

where:

|	
Sp_i	sensitivity of SLUGGER-DQL (for the ith cell), associated with removal of one map of parameter (p)
V_i	SLUGGER-DQL index computed from Eq. (1) for the ith cell
Vp_i	SLUGGER-DQL index for the ith cell without considering parameter (p) (S, LU, G, GE, R, D, Q, and L)
N	number of parameters used in obtaining the SLUGGER-DQL index (eight maps)
n	number of parameters used in obtaining the SLUGGER-DQL index for each of the cells after removing one parameter (p) (seven maps).
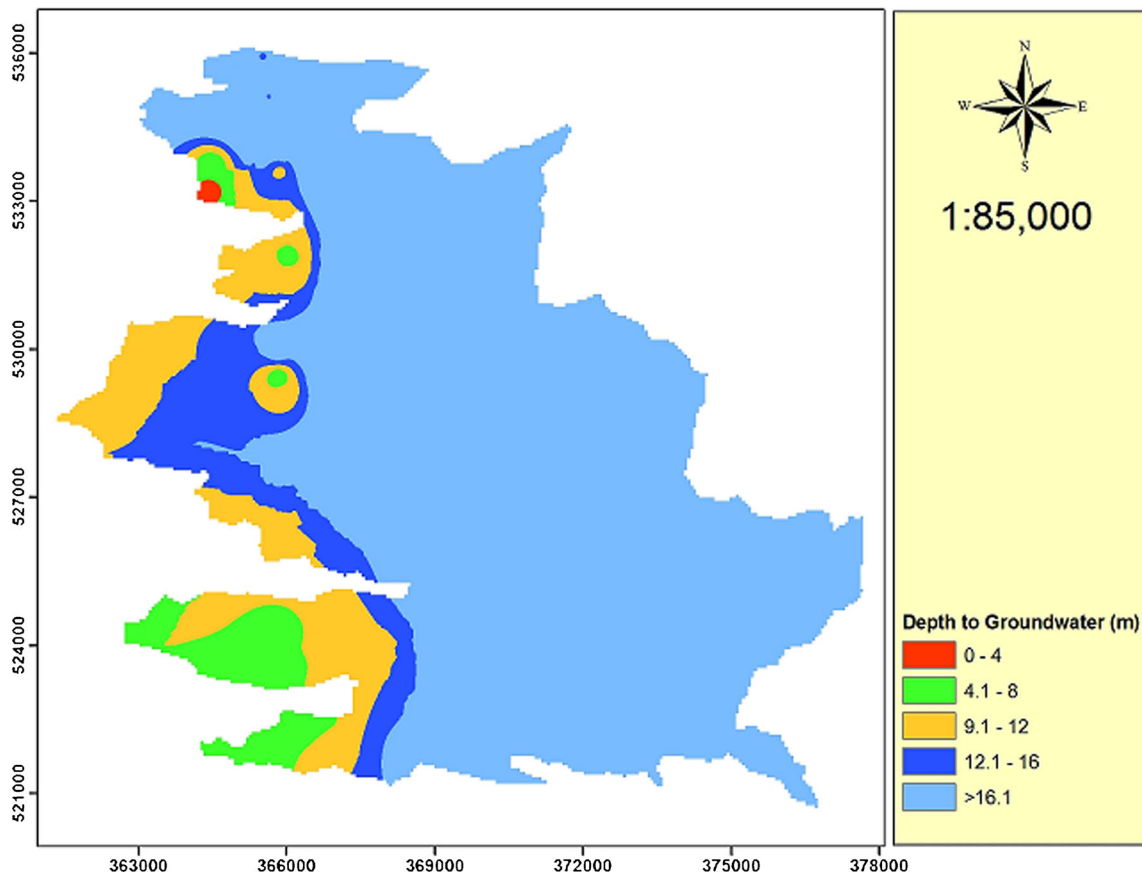
Fig. 9 Depth to groundwater map

Table 5 shows the statistics on the sensitivity of removing one SLUGGER-DQL parameter on the obtained index values.

As can be noticed from this table, the most sensitive parameters to SLUGGER-DQL index were "S" parameter, which is
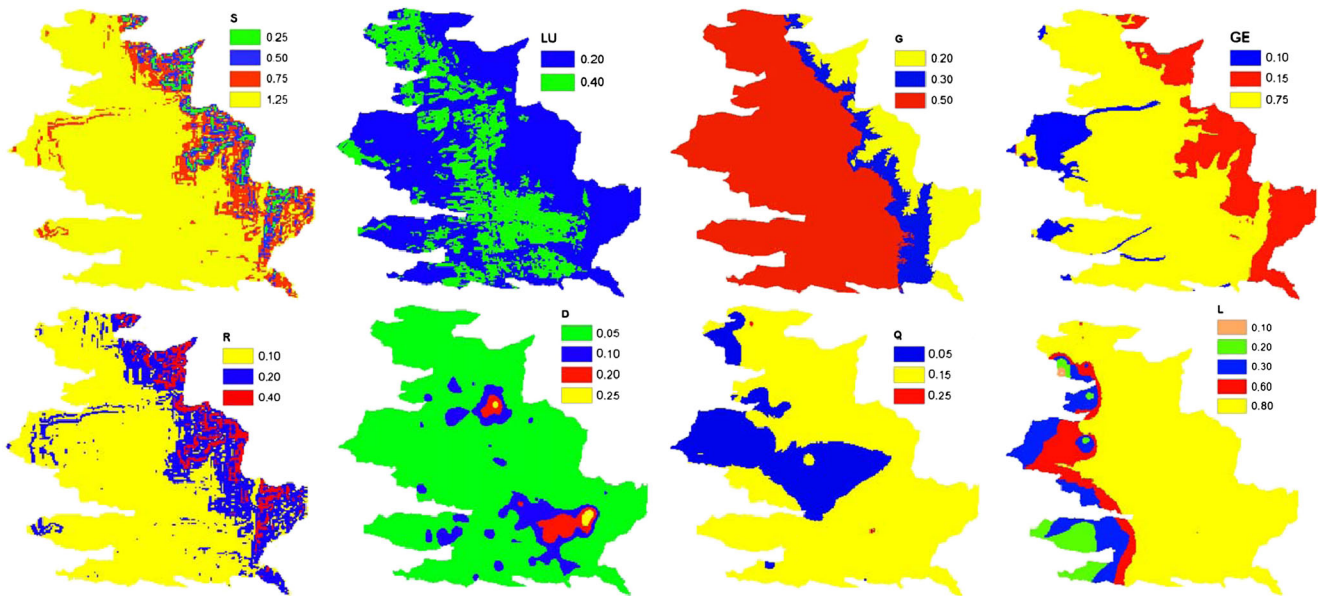

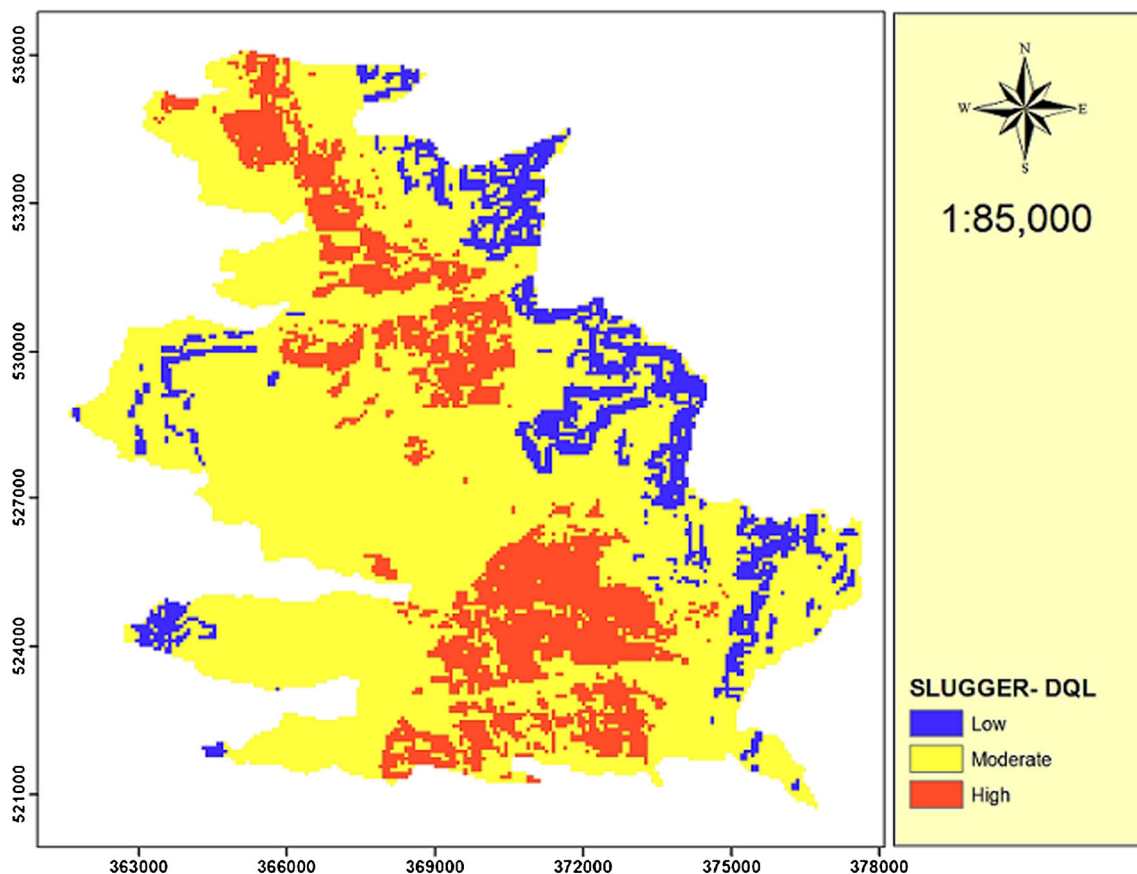**Fig. 10** Spatial distribution of SLUGGER-DQL index parameters scores

Fig. 11 SLUGGER-DQL index

the slope percent with a mean value of 22.93. The sensitivity of the geology parameter "GE" was the lowest; with a mean value of 0.98.

In order to assess the magnitude of the variation created by removal of one parameter, the variation index Vap_i was computed. This index measures the effect of removing one parameter and is given by the following expression according to (Gogu and Dessargues 2000):

$$Vap_i = \frac{V_i - Vp_i}{V_i} \qquad (3)$$

where:

Vap_i variation index of the removal parameter p (S, LU, G, GE, R, D, Q, and L).

V_i SLUGGER-DQL index for the ith cell computed Eq. (1), and

Vp_i SLUGGER-DQL index of the ith cell after removing one (p) parameter (S, LU, G, GE, R, D, Q, and L).

The negative value of variation index means that removal of the parameter increases the SLUGGER-DQL index values, thereby reducing the calculated index model (Gogu and Dassargues 2000). In our case, the obtained values are positive which means that the SLUGGER-DQL index was

Table 5 Statistics on sensitivity to removing one SLUGGER-DQL parameter

Parameter of sensitivity	Min	Max	Mean	SD
S	0.63	36.88	22.93	7.07
LU	0.27	15.36	6.09	3.15
G	0.09	14.91	4.52	2.83
GE	0.00	7.86	0.98	2.19
R	0.00	17.14	7.86	3.71
D	0.00	17.86	8.08	4.43
Q	0.00	17.59	7.54	3.91
L	0.00	2.73	12.04	6.36

Table 6 Variation index of the excluded SLUGGER-DQL parameter

Variation index	Min	Max	Mean	SD
S	−0.03	0.69	0.43	0.09
LU	−0.12	0.27	0.06	0.07
G	−0.12	0.31	0.10	0.07
GE	0.02	0.20	0.12	0.04
R	−0.12	0.27	0.04	0.08
D	−0.17	0.19	0.03	0.07
Q	−0.17	0.21	0.04	0.08
L	−0.06	0.59	0.29	0.11

Table 7 Statistical analysis of the effective weight

Variation Index	Assigned weight	Assigned weight percent	Mean effective weight (Wp_i) (%)	Standard deviation (Wp_i) (%)	Mean effective weight percent (Wp_i)
S	2	20	0.42	0.09	42.4
LU	1	10	0.05	0.01	5.1
G	1	10	0.08	0.02	8.1
GE	1	10	0.11	0.05	11.1
R	1	10	0.03	0.02	3.0
D	1	10	0.01	0.01	1.0
Q	1	10	0.02	0.01	2.0
L	2	20	0.27	0.08	27.3

reduced by removing one parameter of SLUGGER-DQL model and thereby increasing the calculated index. Table 6 shows the variation index of the excluded SLUGGER-DQL parameter.

One last factor that should be analyzed is the effective weight (Wp_i). According to Napolitano and Fabbri (1996), each parameter contributes with an effective weight to the final index map. It can be calculated based on the following expression:

$$Wp_i = \frac{Xr_i - Xw_i}{V_i} \times 100 \quad (4)$$

where:

Wp_i effective weight
Xr_i rating values given for each parameter (p)
Xw_i weights for the parameter p assigned in the cell (i), and
V_i SLUGGER-DQL index for the ith cell as computed from Eq. (1).

Table 7 shows the statistics of the calculated effective weights or variability for each SLUGGER-DQL parameters. As can be noticed from this table, the parameters runoff (R), well density (D) and water quality (Q) show the lowest effective weights. Furthermore, the effective weight for each parameter differs from the theoretical weight assigned by SLUGGER-DQL method. This difference is highly noticed in the slope percent parameter (S) and depth to groundwater (L). This implies that the theoretical weight of this parameter should be revised for computing the SLUGGER-DQL index.

Conclusions

The main objective of this study was mapping the potential groundwater recharge zones in the southern part of JV. In order to achieve this goal, GIS was used to investigate the groundwater recharge potential in the southern Jordan Valley using various spatial and non-spatial data sets such as DEM, slope, land use/cover, geology, geomorphology, runoff, well density, EC, and depth to water table. These data sets were

gathered, stored and organized in GIS environment for subsequent and further analyses. The methodology adopted in this study is based on the open-ended SLUGGER-DQL score index, which was developed by Raymond et al (2009) to identify the potential sites for artificial recharge and the rooftop rainwater harvesting for the purpose to improve the groundwater resources in the JV. The various thematic maps were prepared, classified, weighted, and integrated in a geo-referenced form using GIS. The final produced map shows the potential groundwater recharge zones of importance for the planning of artificial groundwater recharge using surface water. The investigated area has been categorized into three broad zones; these are 70.8 % of high potential; 18.7 % of moderate potential; and 10.5 % of low potential. The moderate to high potential zone were found along the central part of the study area due to the presence of alluvium deposits and lands of high infiltration ability. In order to validate the SLUGGER-DQL index model of groundwater recharge potential zones, sensitivity analysis was performed to assess the influence of rating values and assigned weights to each parameter on the outcome of the analysis. It was found that the slope parameter (S) is the largest sensitive parameter to SLUGGER-DQL index, followed by L, D, Q, R, LU, and G, and the lowest sensitive parameter is the geology parameter (GE). Moreover, the parameters R, D, and Q showed the lowest effective weights (Table 7), and it was also found that the effective weight for each parameter differs from the theoretical weights assigned by SLUGGER-DQL model.

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