ORIGINAL ARTICLE

Hydrological modelling of a heterogeneous catchment using an integrated approach of remote sensing, a geographic information system and hydrologic response units: the case study of Wadi Zerka Ma'in catchment area, north east of the Dead Sea

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Abstract Wadi Zerka Ma'in is the smallest catchment area at the eastern side of the Dead Sea basin and has the largest city in that region. It receives direct groundwater recharge from an area of about 611.25 km^2. Climatically and geomorphologically the region is heterogeneous. These heterogeneities have a major impact on the spatial distributions of the groundwater recharge. We used a Hydrological Response Unit method to investigate the spatial distributions and estimate the amount of groundwater recharge. An integrated approach of remote sensing and a geographic information system was used to feed the hydrological model with the land surface and climatic data. According to our model, it was found that during the last 30 years the average amount of rainfall in the studied area decreased from 275 mm/year to 100 mm/year and the temperature increased from 24.8 to 26.8 °C. These climatic changes had a major impact on the hydrological cycle of the study area by decreasing the runoff of the Zerka Ma'in River and increasing the evapotranspiration. As a result, the groundwater recharge of that catchment decreased during the same time period. It was found that recharge reached a maximum value of 94 million cubic metre (m^3) in 1983, and since 1991 was not exceeding 50 million m^3 per year any more.

Introduction

Surface water scarcity and population growth are increasing the demands of groundwater in the arid and semi-arid regions of the Middle East (Dregne 1991). These demands are increasing the overpumping of groundwater in this area (Konikow and Kendy 2005). As a result, groundwater tables are falling and groundwater quality is deteriorating (Mazor 2004). Therefore, there is a need for a sustainable water management strategy. A groundwater recharge model is a prerequisite of building a transient groundwater flow model that is able to predict the future of the groundwater table levels which will result from groundwater mining (Mazor 2004; Jyrkama et al. 2005; Saraf et al. 2004). However, sustainable groundwater management cannot be achieved without a transient groundwater flow model that is based on groundwater recharge modelling (Kresic 2009).

Jordan has an arid to semi-arid climate and is one of the Middle East countries that are most at threat from water shortage and groundwater pumping (Cook et al. 1989). However, most of Jordan's water demands are supplied by direct groundwater mining because of the limited resources of surface water (Salameh and Bannayan 1993).
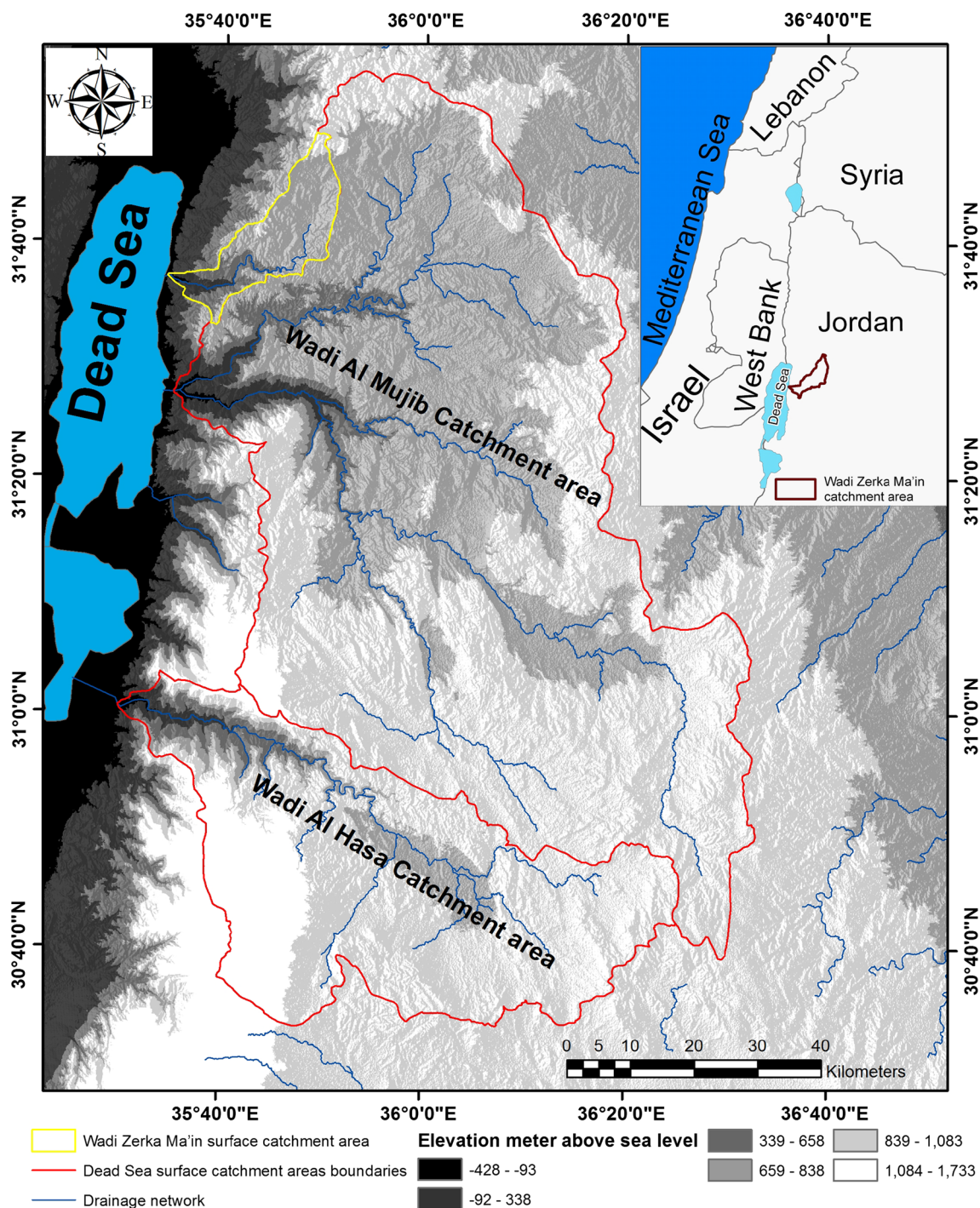
The Wadi Zerka Ma'in catchment area is the smallest catchment area in the eastern Dead Sea region of Jordan (272 km^2, Fig. 1). It has a huge variance in rainfall

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Fig. 1 Location of Wadi Zerka Ma'in catchment. The eastern side of the Dead Sea has three major surface catchments. Wadi Zerka Ma'in catchment is the smallest surface catchment at that side and has (272 km²). However, it has the largest urbanized area and biggest population in the biggest city, so-called Madaba. The Digital Elevation Model (DEM) that has a hill shed effect shows the high relief topography of the area

averages: 100 mm/year in the lowlands to 450 mm/year in the highlands (Salameh and Bannayan 1993). The catchment hosts the city of Madaba which is the largest in that region, with about 150,000 inhabitants, and the fifth largest in Jordan (Department of Statistics 2008).

Madaba's water demands are supplied by groundwater from the Wadi Zerka Ma'in aquifers, with a direct physical boundary area (the model area—subsurface catchment area) of about 611.25 km² (Supplementary Fig. 1, Supplementary Fig. 2). The majority of the
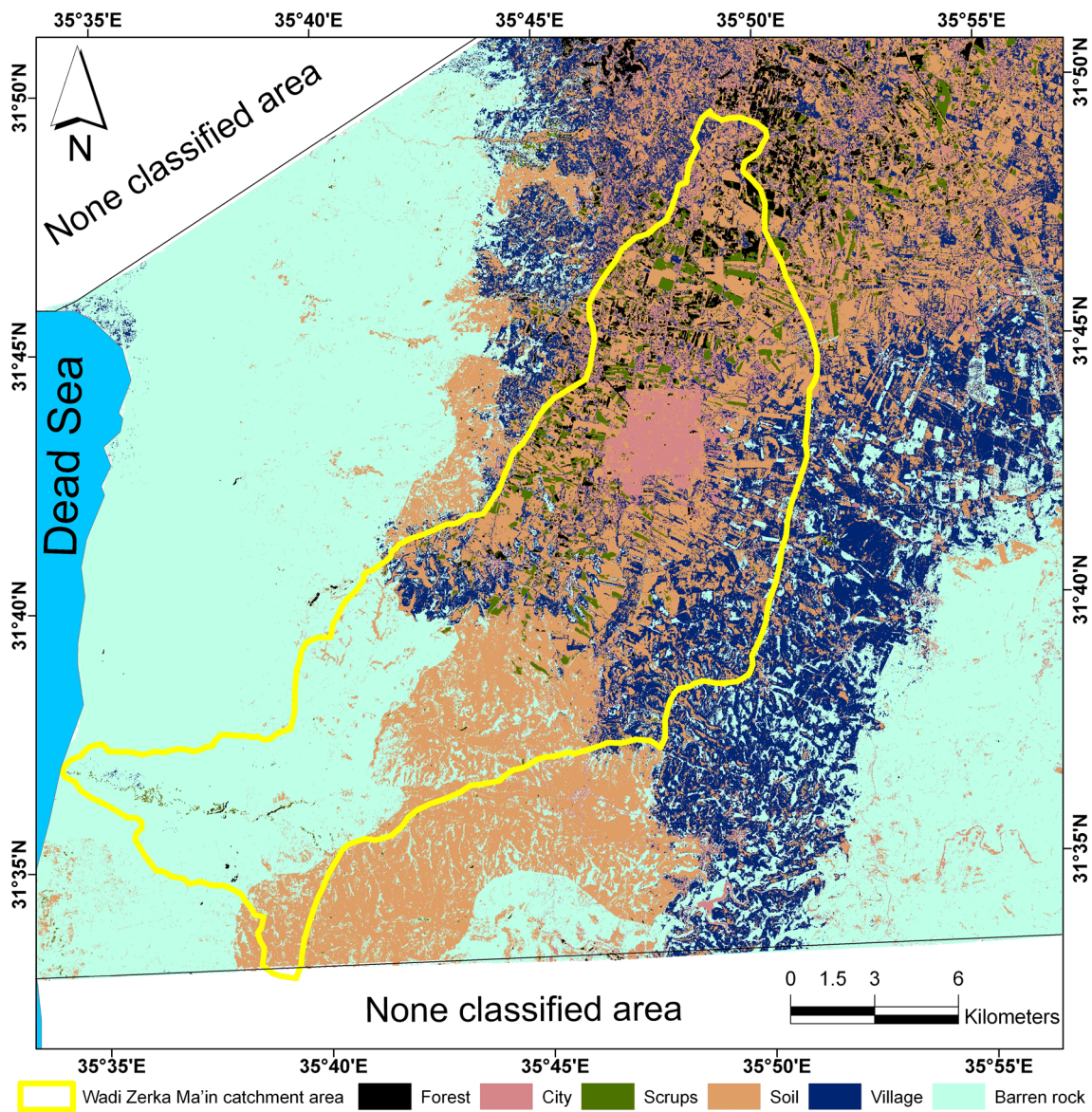
Fig. 2 Land cover of the study area. The urbanized area is concentrated in the upper part of the study area while the lower part is covered mainly by rocks and soil

groundwater mining in this area is from the upper aquifer which is unconfined (Al Sawarieh 2005). However, there is no numerical hydrological model for that region where the groundwater recharge can be estimated. The heterogeneity of this case study area from both climatic and geomorphological perspectives increases the requirement of a numerical hydrological model that accurately estimates the groundwater recharge (Odeh et al. 2010; Al Sawarieh 2005; Gräbe et al. 2013). Without such a model it would be impossible to achieve a transient groundwater flow modelling that can predict the future groundwater levels as it responds to pumping the groundwater (Mazor 2004). Therefore, the objective of the research was to generate a transient hydrological model that considers the heterogeneity of the catchment area and the spatial distributions of the groundwater recharge. Subsequently, this model can be used for a sustainable groundwater management.

Due to the fact that Jordan has limited hydrological stations that measure the catchment hydrological parameters precisely and accurately, there is data scarcity for the hydrological data that could be used for numerical hydrological modelling (Wu et al. 2011). However, the hydrological field measurements that we carried out for Wadi Zerka Ma'in catchment area gave crucial additional information that made the data set fit to create a model.
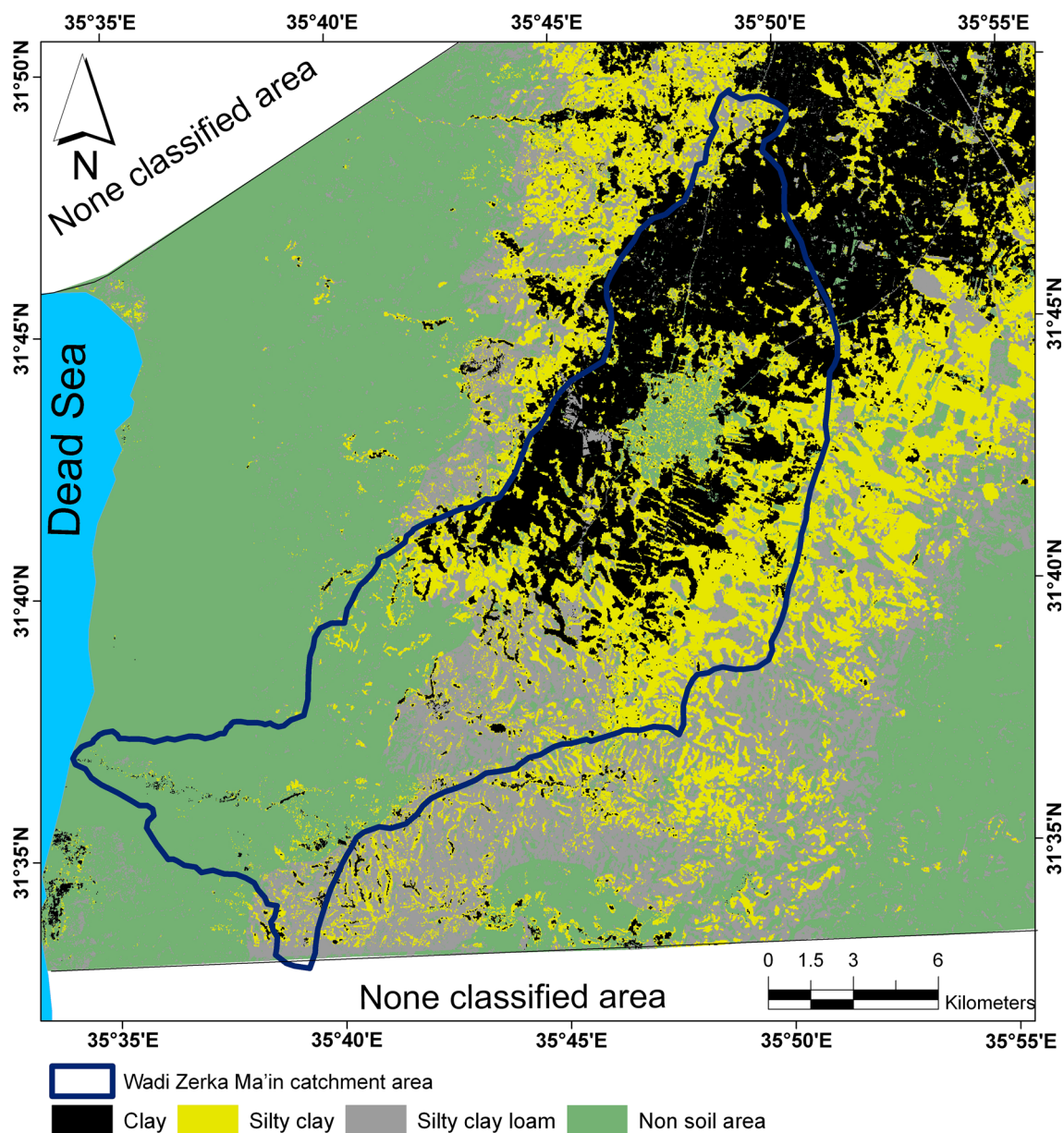
Fig. 3 Soil texture map of the study area. The *upper part* is covered mainly by clay texture where there is the highest amount of rainfall and the area is flat. The *lower part* is covered mainly by rocks where the lowest amount of rainfall occurs

Background information

Land cover

The land cover of the studied area comprises the following (Fig. 2):

1. Urban areas cover about 12 % of the catchment area of Wadi Zerka Ma'in.
2. The Mediterranean forests have limited abundance in the higher land, where the average amount of rainfall per year reaches up to 450 mm, and have an area of

about 6 % of the catchment area. Scrub plants are also sparsely distributed and cover 5 % of the catchment area. The limited vegetation and the forest cover are due to the arid conditions in the catchment area (USDA USDA 1993).

3. Barren rocks cover 35 % of the study area and are described in detail in the geology description.
4. Soil, which covers about 42 % of the study area, is the product of the interaction among the main four soil-forming factors: parent rock, climate, vegetation and topography (Fig. 3) (Scheffer and Schachtschabel

Table 1 Soil textures units and some of their physical parameters

Soil texture	Average thickness (m)	Particulars percent (%)			Field capacity (mm/dm)	Saturated hydraulic conductivity (m/d)
		Clay	Silt	Sand		
Clay (100 samples)	174	55–60	35–40	5–10	15.5	0.12
Silty clay (800 samples)	100	40–50	45–60	5–10	14.5	0.09
Silty clay loam (500 Samples)	150	35–40	45–55	15–20	14.0	0.15

The soil samples were taken from the top 50 cm. The sample analyses were taken from US Department of agriculture (USDA) 1993 database and were used for the supervised classification for Middle infrared bands

2002). Arid and semi-arid region soils have unique properties that distinguish them from soils in humid regions. They have a low level of organic matter, weak to moderate profile development and low biological activity (Dregne 1976). As Wadi Zerka Ma'in catchment is situated within these climate zones, the soil profiles there show a maximum depth of 150 cm in the high plateau area in the upper part of the catchment area, and a minimum depth of 50 cm in the high slope area at the sides of the wadi. The lower part of the catchment area has thin soil layers, of upto 10 cm thickness or only bare rocks (USDA 1993; Cordova et al. 2004). The soil type of the study area (Table 1) is Chromoxerets with more clay in the high land and Camborthids and Torriorthents in the lower part (Shadfan 1983).

Soil plays an important role in facilitating or restricting rainfall water downward movement toward the groundwater table (Santanello et al. 2007). Soil texture is the primary driver in calculations of soil hydraulic behaviour. However, the direct field measurements of the soil hydraulic properties, for both local and regional case studies, are often time consuming and expensive (Hwang 2004). Each soil texture unit has homogenous hydrological parameters. Therefore, a soil texture map is a useful tool to deduce such soil hydrological properties and to have a spatial distribution for the soil hydrological prosperities considering that each soil texture unit has homogeneous hydrological parameters (Santanello et al. 2007). In the study area, silicified limestone rocks are found beneath the soil layer. However, silty clay and silty clay loam are found at the sides of the wadi and their source is the sandstone rock that is outcropping together with the erosion product from the limestone (Cordova et al. 2004).

Climatology

Climate is considered as one of the key factors for the groundwater recharge process as a result of its ability to control rainfall and evaporation (Rushton and Ward 1979). However, geomorphology controls the inequalities in the elevation, slope aspect and slope degree of the land surfaces that cause variations in temperature, wind, cloudiness and precipitation. Therefore, the variances in the geomorphological configurations cause climatic differences. The Dead Sea rift valley has strong orographic control on the climatic parameters such as precipitation and temperature (Dayan and Morin 2006; Closson and Karaki 2013; Ezersky et al. 2013) and has thus divided the study area into two major geomorphological and climatological units:

1. The higher land on the top of the catchment area.
2. The lower land which is part of the Dead Sea rift valley.

The average maximum amount of rainfall in the high land reaches up to 450 mm/year while the minimum amount of rainfall in the low land reaches upto 100 mm/year (Fig. 4). The potential evaporation reaches up to 1,600 mm/year in the high land and 1,980 mm/year in the low land (Salameh and Bannayan 1993). According to Köppen (1931), the catchment area of Wadi Zerka Ma'in is classified as an arid and semi-arid region because the potential evaporation exceeds the amount of precipitation. However, the upper part of the catchment area could be classified as a Mediterranean climate zone that is characterized by long, hot, dry summers, and short, cool, rainy winters (US Department of agriculture (USDA) 1993).

Geology

The interaction of climate, geology, morphology, soil physics properties, and vegetation determines the recharge process. Geology, as surface and subsurface condition, controls the groundwater recharge process through controlling the percolation rapidity which is controlled by two main factors: the type of the lithological units and faults abundance (Kresic 2009; Schaffer 2014).

The outcropping rocks of Wadi Zerka Ma'in catchment belong to Palaeozoic, Mesozoic and Cenozoic eras. They are mainly consolidated sedimentary rocks: (1) limestone and phosphorite in the upper part of the catchments area and (2) sandstone in the lower part. However, unconsolidated sediments, Pleistocene gravel, and extrusive
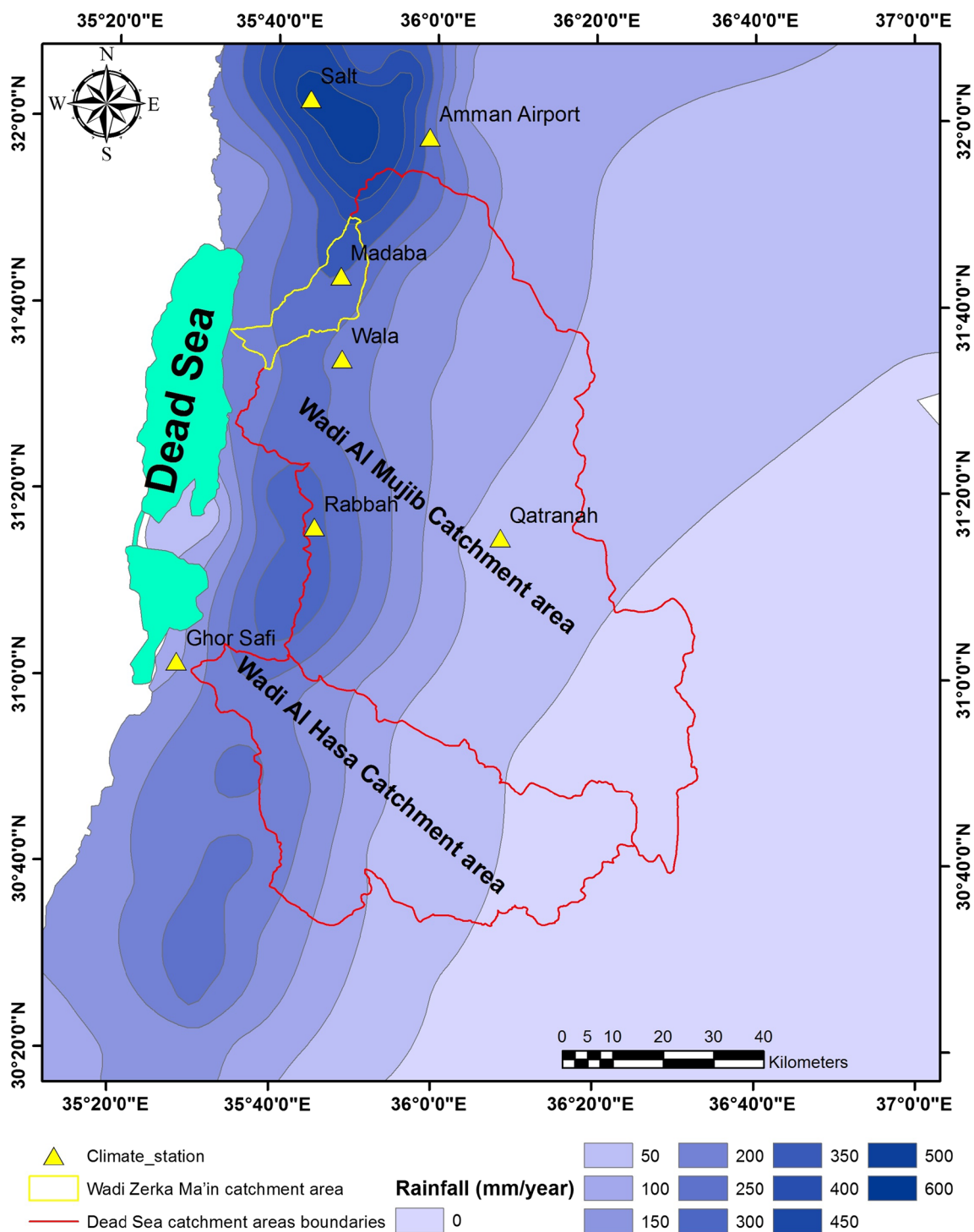
Fig. 4 Rainfall map of the eastern side of the Dead Sea (data source: Meteorological Department 2010). The highest amount of rainfall is found in the high land. The sudden change of the rainfall is due to the topographic dropping of the Dead Sea rift valley

igneous rock, basaltic rock, have limited abundance in the catchment area (Shawabekeh 1998; Odeh et al. 2013); (Fig. 5).

Wadi Zerka Ma'in catchment area is considered as strike faulted catchment area by a major strike slip fault of E–W

direction. However, the catchment is located within the Dead Sea transform fault. As a result of the mentioned regional structures, the local faults, that are mainly strike slip faults, have two major directions similar to the direction of the mentioned regional faults (Odeh et al. 2009):
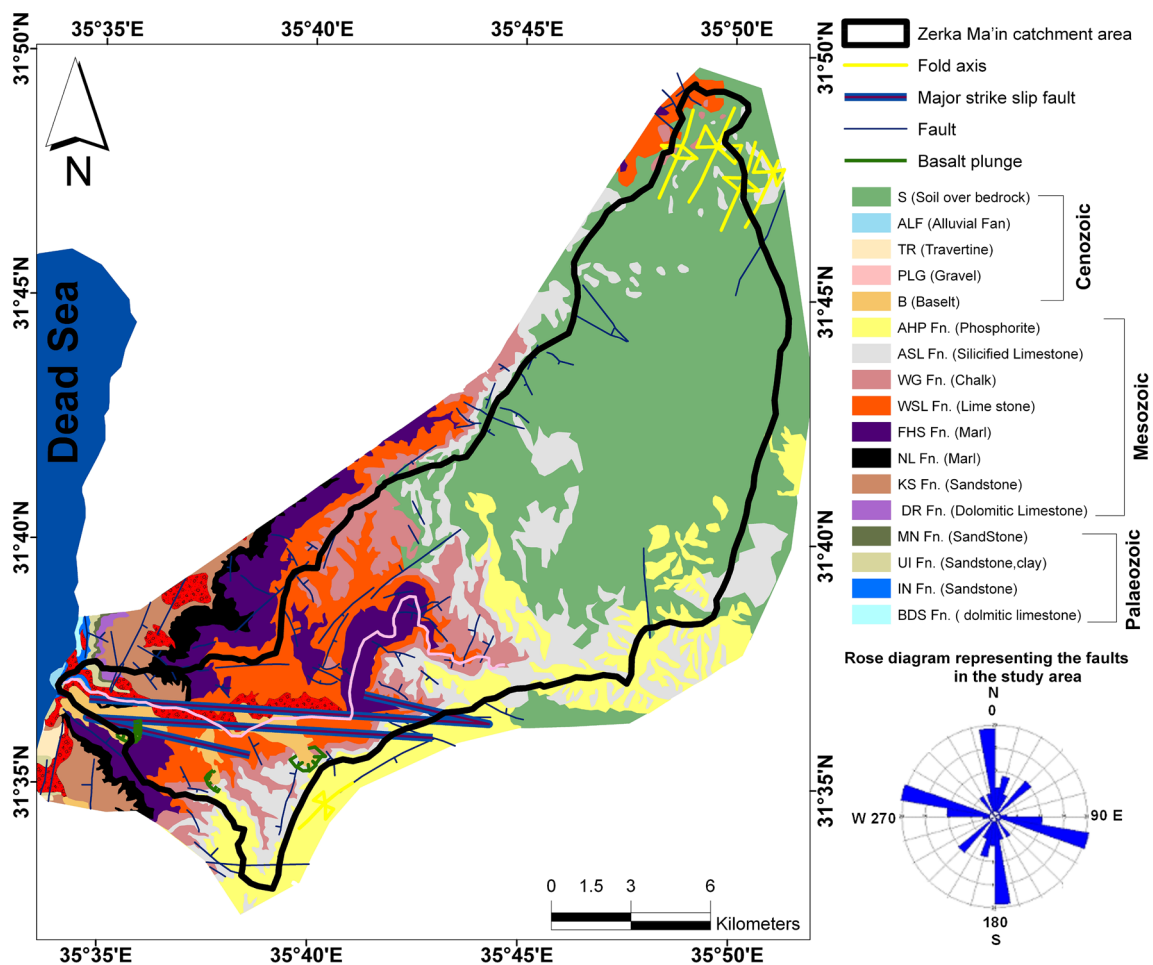
Fig. 5 Geological map of the study area. The lithology of the study area is mainly limestone in the upper part and sandstone in the lower part

1. E–W: the direction of Major Wadi Zerka Ma'in strike slip fault.
2. N–S: the direction of the Dead Sea transform fault.

There are two properties of the consolidated sediments which control the percolation rate rapidity during the groundwater recharge process in the unconfined aquifer of an arid region: (1) the pore spaces within sandstone and (2) the abundance of the cracked, fissures and solution cavities within a limestone (Davatzes et al. 2005; Micarelli et al. 2006). The limestone unit is highly faulted by the embedded normal faults (Odeh et al. 2010; Shawabekeh 1998). Therefore, it has considerable potential for groundwater recharge. Conversely, the sandstone unit does not have such a potential of groundwater recharge because it is mostly confined by a marly aquiclude layer and its outcropping units are considered as groundwater discharge areas which are located within low rainfall and heavy evaporation zones (Odeh et al. 2009; Al Sawarieh 2005).

Methodology

Computed hydrological modelling is a primary technique for sustainable management of water resources (Bier 2007). It is closely connected to GIS (Geographic Information System) and RS (Remote Sensing). RS can provide multi-temporal and multivariate data of the land surface. GIS offers great capabilities of storage, manipulation, and convergence analysis of the land surface data (Saraf et al. 2004). That synergism between GIS and RS technologies is a major advantage in the use of an integrated approach in the hydrological modelling (Trotter 1991). Therefore, an integrated approach of RS and GIS was used to feed the hydrological model by the land surface data in this study.

The high relief topography of the study area created different geomorphological and climatological units; therefore, Wadi Zerka Ma'in is considered as a heterogeneous catchment area as a results of these units (Odeh et al. 2010; Al Sawarieh 2005). The hydrological response unit
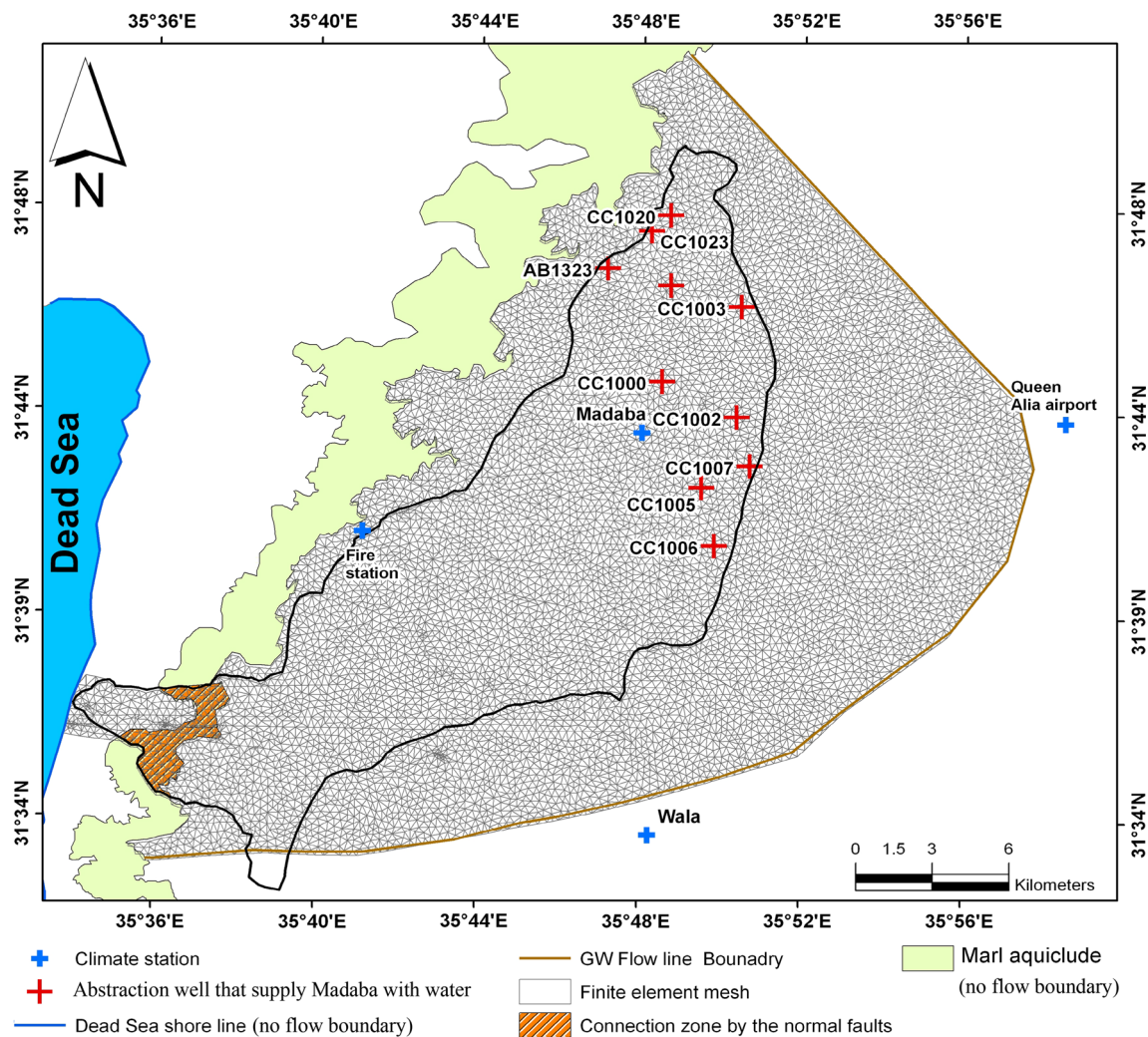
Fig. 6 Finite element mesh for the modelled area. Climate station of Ghour Al Safi locates south of the displayed area

(HRU) is a concept in hydrological modelling and a pre-requisite for modelling such heterogeneous cases (Flügel 1997). According to that concept, the area is subdivided into spatially distributed entities where each entity has spatial physiographic properties (Flügel 1997). Therefore, the catchment area within a physical boundary of the groundwater model is divided using the FeFlow 6 software to super mesh (Fig. 6). The triangles of the finite elements of the super mesh will represent those entities, while the needed spatial physiographic properties will be collected and attributed by an integrated approach of GIS and RS.

Extraction physiographic characterisation layers of the study area

Elevation, slope aspect and slope angle

Digital Elevation Models (DEMs) are a type of GIS raster data that represents any part of the world as a georeferenced regular arrangement of cells. In a DEM, each cell has a value corresponding to its elevation (McMaster 2002). DEMs analyses are widely used for modelling surface hydrology. Those analyses include the automatic delineation of catchment areas, drainage networks extraction, slope angle estimation and slope aspect measuring. The accuracy of a DEM, which is able to replicate the hydrological reality of a catchment, is determined by the cell size (Nikolaus et al. 2006). Therefore, a high-resolution DEM of up to 15 m was extracted from Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) data for our hydrological model (for more details, see Odeh et al. 2009). We used the ASTER image because it has a high spatial resolution (upto15 m) for the infrared and the visible bands in addition to the bands 3N and 3B that are required to extract the high-resolution DEM. These two advantages are not found in the free satellites images such as Landsat (30 m resolution, 7 bands) (Trotter 1991).
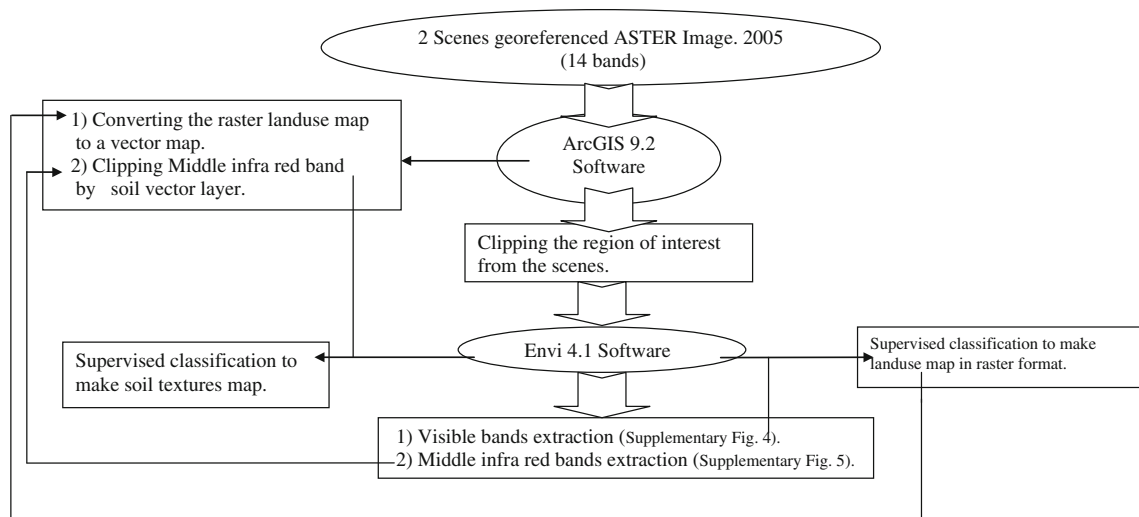
Fig. 7 Flow chart for extracting the landuse and the soil texture maps according to the integrated approach of remote sensing and GIS

Runoff modelling is one of the cardinal components in any groundwater recharge modelling (Maidment 1993; Bier 2007; Kresic 2009). Slope angle and slope aspect calculations are an integral part of any runoff modelling (Nikolaus et al. 2006). As the slope angle increases, the velocity of surface runoff increases. On gentle slopes, water may temporarily pond and later soak in while on steep mountain sides, water tends to move downward more rapidly (Dunne 1977; Pruski and Nearing 2002). Owing to the irregular slope aspect, the runoff takes place in different directions. Components of both slope aspect and angle control the velocity and the volume of the runoff (Maidment 1993). The slope aspect and angle can be easily estimated using ArcGIS 9.3 with the spatial analyst extension. The used algorithm is the quadratic surface algorithm (Srinivasan and Engel 1991). Supplementary Fig. 3 shows the 15-metre DEM from which the slope aspect and angle were extracted. The drainage network and water divide extraction were done according to the hydrology extension (see Odeh et al. 2009).

Land cover

GIS technology has a remarkable capacity to store, retrieve, manipulate and display vast quantities of spatial and attributed data that are used in the hydrological modelling. However, some of the data must be obtained from older maps, such as the land cover data. This problem can be overcome by satellite remote sensing, such as ASTER (Supplementary Fig. 4) and Landsat images (Kam 1995). Landsat images offer a long-time data record but it has low spatial resolution (30 m) and limited spectral bands (7 bands) in comparison with ASTER images (15 m, 14 bands). However, an integrated approach of remote sensing

(RS) and the geographic information system (GIS) was used to feed the model with the land cover data. However, to obtain more accuracy, the supervised classifications of mid infrared bands (Supplementary Fig. 5) were done to investigate the soil texture units after extraction of the soil infra red bands using the soil layer of the land use map. Accordingly, the supervised classification of the mid infrared was done only for soil units to have soil texture maps (Fig. 7).

Overlay physiographic characterisation layers of the study area and its super mesh

GIS performs many tasks for the hydrological modeller such as data manager, pre- and post-processor, and displayer (Saraf et al. 2004). To overlay, physiographic layers are one of the most common processes in GIS during the hydrological modelling. It can create new layers and attribute relations by overlaying the physiographic layers (Coroza et al. 1997). According to the HRU concept, the heterogeneous catchment area is subdivided into cells where each cell is a homogonous unit of elevation slope, aspect and angel degree, soil texture, land cover class and climatological parameters (Fig. 8). The super mesh was converted to HRUs using the overlay method in GIS. However, the climatological parameters will be supplied for each HRU by the hydrological model software automatically.

Hydrological modelling

A water balance equation (Thornthwaite and Mather 1955) is one of the most common methods to estimate the direct groundwater recharge of a catchment area. It has the
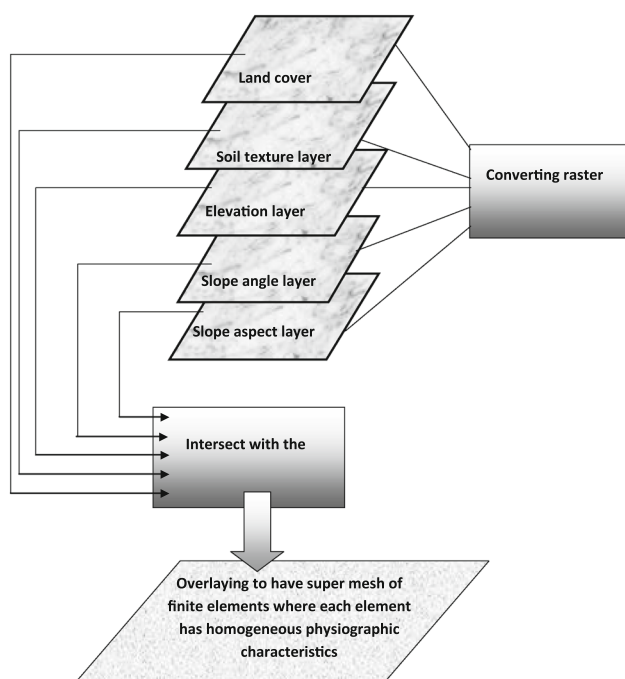
Fig. 8 Flow chart for generating HRUs using the overlay method in GIS. The raster data of the soil, elevation, and slope were converted to vector data in form of a shape file before applying the overlaying method using the ArcGIS software

Table 2 Climate and rain stations for the modelling setup

Location	Parameter	Time period	Unit
Madaba[a]	Climate	1980–2006	Monthly
Fire station[b]	Climate	2008–2009	Monthly
Queen Allia airport[c]	Climate	1980–2009	Monthly
Ghor Safi[a]	Climate	1983–2009	Monthly
Ma'in[a]	Rain	1980–2006	Monthly

Data source: [a]Ministry of Water and Irrigation (open data file: http://www.mwi.gov.jo/Dashboard.aspx). (given in DAISY: www.ufz.de/index.php?de=16882); [c]web source (www.wunderground.com; www.tutiempo.net; http://pc105.narc.affrc.go.jp/metbroker/); [b]own data

advantages of being easy to apply and accounts for all the water entering the hydrological cycle (Lee et al. 2006). The method is essentially a book-keeping procedure which estimates the balance as follows:

$$Gr = P - Ea + \Delta S - Ro \qquad (1)$$

where Gr = groundwater recharge; P = precipitation; Ea = actual evapotranspiration; ΔS = change in soil water storage and Ro = runoff. Five climate stations were used to obtain the available daily rainfall amount and the other climatological data that the Jena Adaptable Modelling System (JAMS) software (Kralisch et al. 2005) used are as follows: Queen Alai airport, Madaba, Ma'in fire station, Wala and Ghour Al Safi stations (Meteorological Department 2010; USDA 1993).

The spatial variability of the groundwater recharge is an important consideration, especially if the case study is heterogeneous geomorphologically and climatologically such as the wadi Zerka Ma'in catchment area (Flügel 1997; Berndtsson and Larson 1987). Most of groundwater recharges estimation methods do not consider the spatial heterogeneity of the catchment areas (Cook et al. 1989). However, the HRU method considers the heterogeneity of the catchment by subdividing the area into triangles where each triangle is a homogenous unit of physiographic parameters and then estimates the groundwater recharge separately. Hence, the catchment area is modelled not as one spatial unit.

JAMS uses a HRU through the water balance estimation. However, JAMS was developed according to the Object Modelling System (OMS) that considers each model component and each item in the water balance equation as independent modules. These modules are coupled by a standardized software interface, JAVA software in case of JAMS, to achieve maximum platform independence (Kralisch et al. 2005). Accordingly, the main technical advantages of using JAMS software as HRUs modelling software are:

- The hydrological process simulation runs technically independent from the spatial representation of the HRUs. This yields a quick speed for simulation running time proportionally to another software which uses the spatial representation during the hydrological simulation.
- JAMS has a capacity to use a largely different configuration of the spatial and temporal data during the hydrological simulation.
- The climatological parameters that are recorded by the climate stations have the ability to distribute automatically and interpolate to all the HRUs.
- The result of the hydrological simulation can be represented by GIS that has a capacity to store, manipulate, and analyse spatially.

Regionalization of climatic data

Regionalization of the five climates station data (Table 2; Meteorological Department 2010) was carried out by the JAMS software for HRUs of the study area. This generalization considered: (1) the distance between the climate stations and the HRUs and (2) the topographic elevation. It is achieved by the following steps:

1. Estimation of the linear regression between the daily climatic data value and the topographical elevation of the stations. The coefficient of determination (r2) and the slope of the regression line (b_H) of this relation is calculated. It is assumed that the MW, which

represents the linear regression value between climatic data and the topographic elevations values, is related linearly to the topographic elevation (H); as follows:

$$MW = a_H + b_H \cdot H \qquad (2)$$

The unknown a_H and b_H are the factors that represent the changes of climatic data values by the topographic elevations values and defined mathematically according to the Gaussian method of the smallest squares as follows:

$$b_H = \frac{\sum_i^n = (H_i - \overline{H})(MW_i - \overline{MW})}{\sum_i^n = 1(H_i - \overline{H})^2} \qquad (3)$$

$$a_H = \overline{MW} - b_H \cdot \overline{H} \qquad (4)$$

The correlation coefficient of the regression (where $\overline{H}$ and $\overline{MW}$ are the mean values of the topographic elevation and linear regressions, respectively) is calculated according to the following equation:

$$\tilde{A} = \frac{\sum_{i=1}^n (H_i - \overline{H})(MW_i - \overline{MW})}{\sqrt{\sum_{i=1}^n (H_i - \overline{H})^2 \cdot \sum_{i=1}^n (MW_i - \overline{MW})^2}} \qquad (5)$$

2. Determining the stations which are closest to each HRU. The number of the station, which needs to be entered during the parameterization, is dependent on the stations spatial network and on the position of the individual stations. The first step is to estimate the distance Dist(i) of each station to the area of interest:

$$Dist(i) = \sqrt{(RW_{Stat(i)} - RW_{DF})^2 + (HW_{stat(i)} - HW_{DF})^2} \qquad (6)$$

where RW is easting of the stations $i \dots n$, or the HRU (DF: Degree of Freedom in the number of the samples); HW is northing of the stations $i \dots n$, or the HRU (DF)

The stations with the closest distance to the HRU are chosen from the distances calculated according to the equation above and are then used for potenzialization with the weighting factor pIDW (IDW = Inverse-Distance-Weighting). Accordingly, those distances are converted to weight distance wDist(i) where the influence of nearby stations increases and that of the more distant stations decreases.

3. Using IDW the weightings of the stations are determined depending on their distances to each HRU. The IDW method is used to consider the horizontal variability of the station data. The estimation is carried out according to the following equation:

$$W(i) = \frac{\left(\frac{\sum_{i=1}^n wDist(i)}{wDist(i)}\right)}{\sum_{i=1}^n \left(\frac{\sum_{i=1}^n wDist(i)}{wDist(i)}\right)} \qquad (7)$$

4. The calculation of the data value for each HRU with the weightings is estimated in the previous steps (Kralisch et al. 2005; Flügel 1997).

Water balance modules

Evapotranspiration The potential evapotranspiration and the actual evapotranspiration of the soil layers were estimated according to the Penman–Monteith method (Monteith 1965) for each HRU that attributed to the requested data of the equation using an overlay method in GIS. However, because the estimation is complicated and time consuming, it was sourced out into the pre-processing part of the modelling. The only parameter that is used in the estimation and extracted during the modelling is the soil moisture. Two evaporation values are estimated for each day as a time period as follows: a day value (index d) and a night value (index n). This distinction is important because of the net radiation balance. The estimation for the day and for the night was done and then summed up.

Soil water The soil water module of Jamas software (Flügel 1997; Kralisch and Krause 2006) consists of two components: (a) infiltration and evapotranspiration (process units) and (b) storage units (middle pore, large pore storage and depression storage). The infiltration estimation is done by applying the following empirical equation:

$$Inf = (1 - soil_{sat}) \times max\,INF\ (mm/d) \qquad (8)$$

where maxINF (maximum infiltration) is in mm/d and defined by the user. The relative saturation deficit of the soil [1—soil saturation ($soil_{sat}$)] is estimated according to the maximum filling storage of the middle and large pores as follows:

$$soil_{sat} = \frac{(MPS_{act} + LPS_{act})}{(MPS_{max} + LPS_{max})} \qquad (9)$$

where MPS_{act} and MPS_{max} are the actual, maximum filling of the middle pore storage; LPS_{act} and LPS_{max} are actual, maximum filling of the large pore storage.

When the amount of water that infiltrates is more than the maximum infiltration rate (maxINF) the surplus water is converted to surface runoff. However, Jamas software considers the effect of the surface gradient at two gradients mainly as follows:

1. Surface gradient greater than 80 % then only 25 % of the precipitation is infiltrated.
2. Surface gradient less than 80 % only 60 % of the precipitation is infiltrated.

The influx in the MPS (MPS$_{in}$) is the result of the infiltrated precipitation (Inf) against its relative storage content (ΘMPS) and a calibration coefficient (Dist coef) that is entered by the user (Kralisch et al. 2005; Kralisch and Krause 2006). Mathematically, MPS$_{in}$ is represented by the following equation:

$$MPS_{in} = Inf \times \left(1 - e^{\frac{-1\times Distcoeff}{\Theta MPS}}\right)[mm] \qquad (10)$$

The infiltrated amount of precipitation water that is not absorbed by the MPS is received by the large pore storage (LPS$_{in}$):

$$LPS_{in} = Inf - MPS_{in} \quad (mm) \qquad (11)$$

The value of the calibration coefficient ranges between zero (when no water can flow into the MPS) and infinite. The discharge from the MPS is represented by the evapotranspiration (ETP), which is calculated from the current storage filling of the MPS and the potential ETP (Kralisch et al. 2005; Flügel 1997).

The percolation water movement (perc) runs in the LPS and is therefore dependent on the amount of the large pores. To estimate the amount of that water, the runoff component needs to be estimated. The runoff is estimated against the relative saturation of the soil (soil$_{sat}$), the actual large storage content (LPS$_{act}$) and a calibration coefficient (LPS$_{out}$) as follows:

$$LPS_{out} = (Soil_{sat})^{LPSout} \times LPS_{act} \quad (mm) \qquad (12)$$

The following allocation of the LPS runoff in the vertical and lateral (inter) flow direction is carried out against the slope and a user-specific calibration factor (LatVertDist) which can take values between zero and infinite. Accordingly, the following two equations are estimated (Kralisch et al. 2005; Flügel 1997; Kralisch and Krause 2006):

$$perc = LPS_{out} \cdot (1 - \tan slope \cdot LatVertdist) \ (mm) \qquad (13)$$

$$Inter = LPS_{out}^{\cdot}(\tan slope \cdot LatVertDist)(mm) \qquad (14)$$

Runoff The retention mechanisms of the runoff were described by the other soil water module. Therefore, with this module only the HRUs influxes and discharges are allocated. The routing of the runoff generation is divided into (a) lateral routing: where the HRU can have several influxes but only one discharge. The order of the HRUs as receiver is specified by the topologic ID of the HRU data set that was generated by the overlay method in GIS. By

that data set, it is also specified which HRUs finally drain as receiving stream.

(b) reach routing: that is for the flow phenomena in the channel and the calculation of the rapidity of flow according to Manning and Strickler (Gauckler 1867). Jamas software applies this equation as follows:

1. Extracting the runoff retention coefficient (Rk). According to the following equation:

$$Rk = \frac{u}{fl} \cdot TA \cdot 3600 \ (-) \qquad (15)$$

The parameter (TA), which needs to be set, is the routing coefficient. It measures the travel time of the discharge which moves from the channel to the runoff after the precipitation event. u is the stream's rapidity flow and (fl) is the flow length.

2. Calculating the rapidity of flow (v_{new}). Where M is a roughness factor, I is the slope of the river bed and Rh is the hydraulic radius as follows:

$$V_{new} = M \cdot Rh^{\frac{2}{3}} \cdot I^{\frac{1}{3}} \ (m^3/s) \qquad (16)$$

The hydraulic radius (Rh) is estimated from the cross-section of the river part where the water flows through (A), flow passage (q), the rapidity of flow (v) and the width of the river (b) as follows:

$$Rh = \frac{A}{b + 2\frac{A}{b}} \ (m) \qquad (17)$$

$$A = \frac{q}{v\text{init}} \ (m^2) \qquad (18)$$

The initial rapidity (v_{init}) of flow is assumed to be 1 m/s, which is then iteratively matched with the new calculated rapidity of flow (v_{new}) until the deviation of both speeds is less than 0.001 m/s. Finally, the discharge of the particular river part (q_{act}) is calculated with the generated runoff retention coefficient (Rk) as follows (Kralisch et al. 2005; Flügel 1997):

$$Discharge = q_{act} \times e^{\left(\frac{-1}{rk}\right)} \quad [m^3/s] \qquad (19)$$

Results and discussions

Direct groundwater recharge is the water added to the groundwater reservoir in excess of soil-moisture deficits and evapotranspiration by direct vertical percolation through the unsaturated zone (Lerner et al. 1990). The chosen hydrogeological boundaries of the arid catchment area of Wadi Zeka Ma'in consider the direct groundwater recharge type. However, the arid catchment areas have a
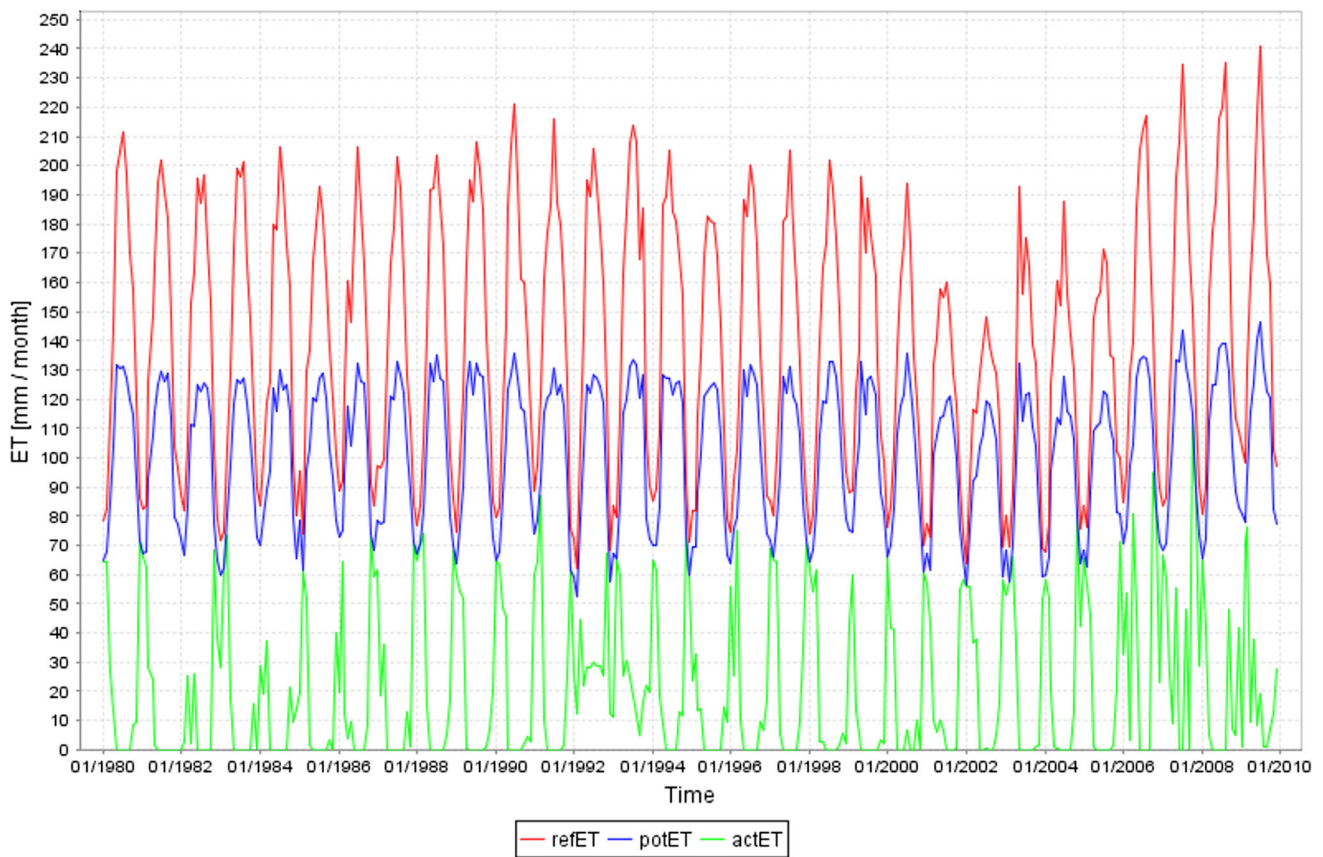
Fig. 9 The actual evapotranspiration (actET) from the soil horizon and the plants cover over the super mesh. The potential evapotranspiration (potET) exceeds the actual one while both of them are more the average reference global evapotranspiration (refET)

potential evapotranspiration on average that exceeds the rainfall. Therefore, direct groundwater recharge generates occasionally on rainfall events of high amount, accumulation of rain water in depressions and streams, and the ability of rain water to escape evapotranspiration by rapid infiltration through the soil media and percolation through cracks, fissures, or pores of the rocks (De Vries and Simmers 2002).

According to daily observations of five climate stations the climatological parameters were measured (Fig. 6). The average rainfall and temperature for the last 30 years of the studied area are presented in the Supplementary Figs. 6 and 7. They show that the rainfall average in the studied area decreased in the last 30 years from 275 mm/year to 100 mm/year while temperatures increased from 24.8 to 26.8 degree as a result of climatic changes in the Mediterranean region (Trondalen 2009). Such climatic changes affect the runoff and the evapotranspiration, and therefore the groundwater recharge (Bouraoui et al. 1999). To evaluate that effect, a hydrological model was developed according to Jamas software in three steps as follows:

(a)   Model initialization for 1 year.

(b)   Model calibration, parameter optimization and sensitivity analysis for the soil water module were processed using the available soil physical data. However, the overland flow model calibration was carried out according to the direct field measurement of Zerka Ma'in river discharge.

(c)   Model validation, according to chloride mass balance method, was carried out by running the model for the complete 30 years. The detailed procedure was described by Rödiger et al. 2014.

Figure 9 shows that the potential evapotranspiration mostly exceeds the actual evaporation which is a common climatic condition for the arid regions. The climate change for the last 30 years has led to increased evapotranspiration potential from 130 mm/month to 148 mm/month; as a result of increased temperatures and the subsequent decreased groundwater recharge due to the increased actual evapotranspiration.

The simulated hydrograph of Wadi zerka Ma'in River for the last 30 years (Fig. 10) shows that the flash flood of the river was decreasing from 37.5 m^3/s to less than 2 m^3/s, as a maximum value. This is a result of the decreased
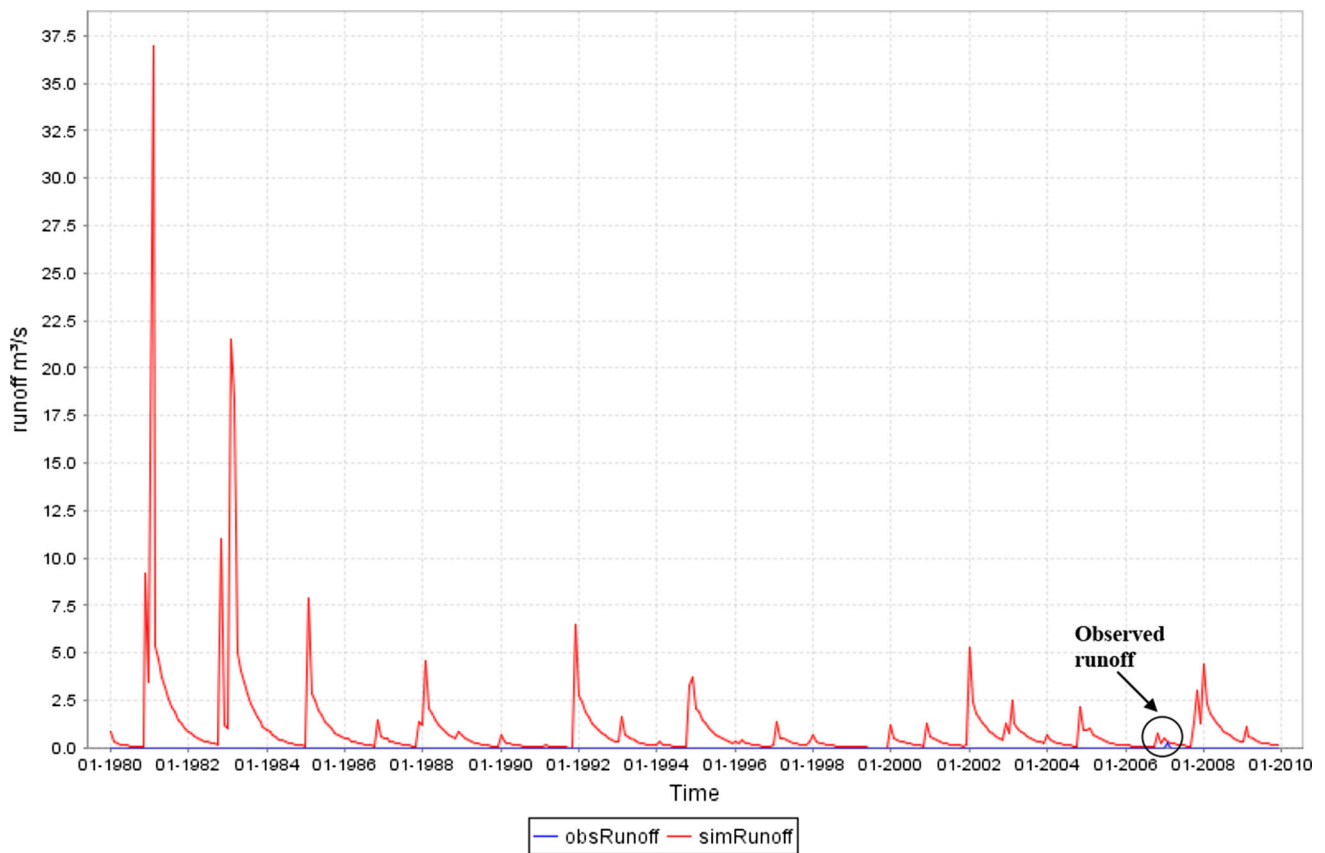
Fig. 10 The modelled hydrograph of Zerka Ma'in River. The river discharge is mostly flash flood (SimRunoff) and the observed value (obsRunoff) represents a direct field measurement of site NO.1 (Supplementary Fig. 7) in the year 2007. No other measurements are available. There are no data for calibrating the runoff modelling therefore we used the field measurements of Zerka Ma'in River flow in the winter of 2007

rainfall. The overland flow is controlled by the urbanized area. When the urbanized area of the catchment becomes larger the overland flow is increasing. However, Madaba city is the only urbanized area in the study area. It has currently an area of about 34 km^2 which means about 6 % from study area and as long as we go back in the time the percent become smaller because the urbanized area becomes smaller. Therefore, we considered that the changes in the land use during those 30 years are negligible and there is no irrigation water system in this catchment area that can affect the groundwater recharge system because Jordan (including Madaba) depends mainly on the Jordan Valley as area for agricultural activities where there is a considerable irrigation system (Cordova et al. 2004; Odeh et al. 2009; Salameh and Bannayan 1993). The model that we constructed is mainly to investigate the spatial distribution of the groundwater recharge. However, the influence of the land use and land cover changes on groundwater recharge in form of scenarios needs detailed classifications from Landsat images that offer a long-time data image record (Santanello et al. 2007).

The climate change is the only factor that has a direct influence on the groundwater recharge fluctuations in our case. Zerka Ma'in River discharge data are unavailable. Therefore, field flow measurements (Supplementary Fig. 8) were carried out for the Zerka Ma'in River during flash floods to roughly calibrate the modelled hydrograph, by modifying the soil physics parameters. In the upper part of the Wadi most of the springs are equal or below 6th magnitude (63–630 mL/s) (Salameh and Bannayan 1993); therefore, the river has no remarkable base flow and most of its discharge is flash flood. On the other hand, the groundwater level in the lower part of the catchment area is higher than the river level; hence, the river is a losing stream in the upper part and is slightly improved to a gaining stream in the lower part.

Climatologically, the studied area is heterogeneous since there is a sharp difference in the rainfall distribution where it reaches up to 450 mm/year in the upper part of the catchment and 100 mm/year in the lower part. The distribution of potential evapotranspiration exhibits a similar pattern as rainfall but with a bigger difference. It reaches

**Table 3** Land cover parameters of the hydrological simulation

Land cover/ subclasses	Surface resistance of the land cover (s/m) (literature)	Leaf area index (m²/m²) (literature)
Impervious areas (dense + light)	10	–
Shrubs	102–323	3–5
Forest	118–667	1–13
Soil	60–1000	1–4
Rocks	70	–

up to 2,000 mm/year in the upper part and 4,000 mm/year in the lower part (Cordova et al. 2004).

From a geomorphologic prospective, the catchment area is considered as heterogeneous too. The underlined geological structures had a major influence in the geomorphic characteristics of Wadi Zerka Ma'in. This is indicated by the two major trends of the drainage network, N–S and E–W, and by the high asymmetry and low similarity value

(Odeh et al. 2010) which control the slope aspect and angle; and hence the runoff (Table 3) as well as the groundwater recharge distributions (Beven 2001; Srinivasan and Engel 1991).

Those geomorphological and climatic heterogeneities led to the spatial distribution of the groundwater recharge presented in Fig. 11. It shows the highest amount of groundwater recharge in the upper part of the studied area where the rainfall amount is maximum (i.e. reaching up to 450 mm/year), while the lower part is the minimum (i.e. 100 mm/year). However, the low recharge zone in the upper part of the catchment area is due to the urbanized area of Madaba city where the amount of the runoff is high (Butler and Davies 2000) and hence the amount of groundwater recharge is low. The asymmetry of the catchment area generates a rift zone in the northern middle part with high slope angles (Odeh et al. 2009). That rift area has a zone of low recharge amounts due to the large runoff converted water by the high slope angles (Cheng et al. 2008). The southern middle part of the catchment
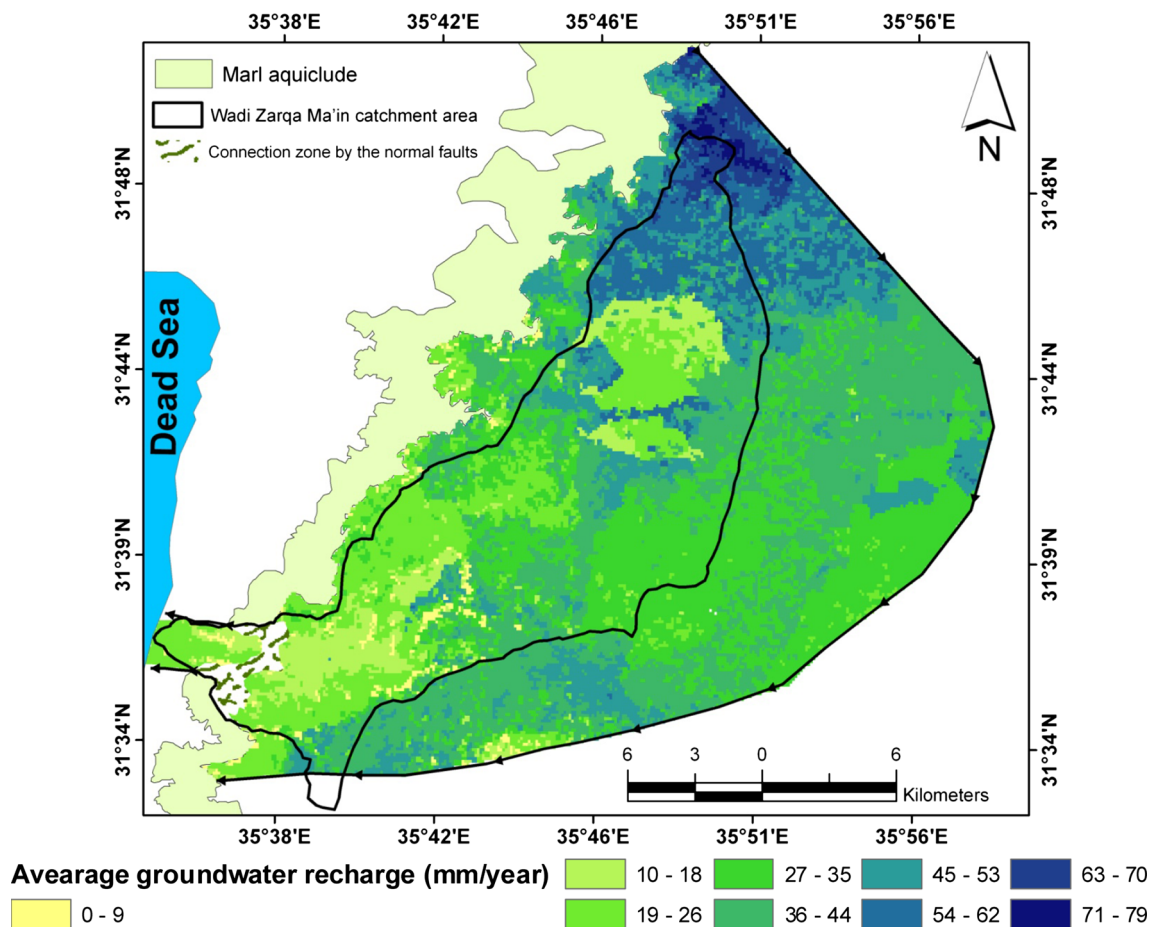
Fig. 11 The spatial distribution of the groundwater recharges (average values of 30 years). The low value of recharge in the lower part of the studied area is due to the low amount of precipitation while in the

upper part this is due Madaba city with large sealed areas where the runoff is high

Groundwater recharge volume
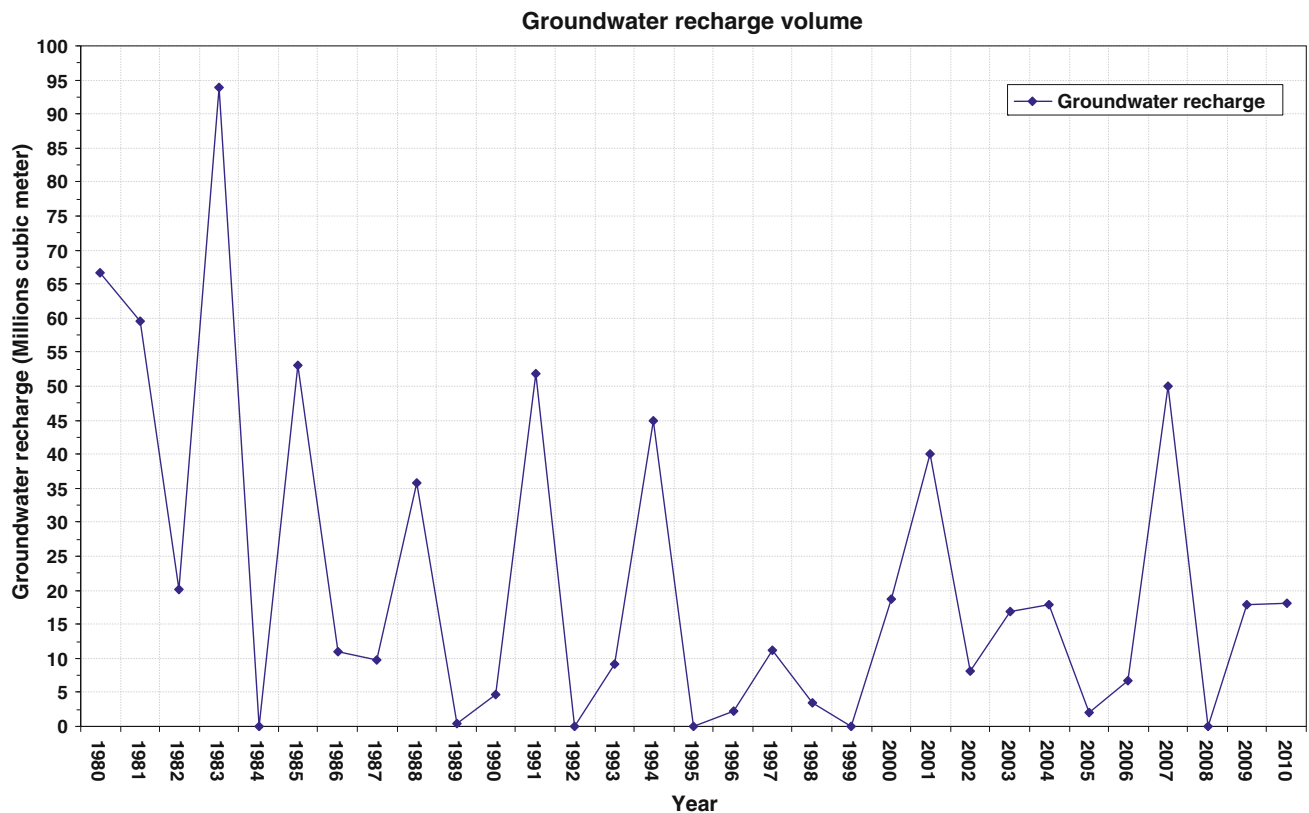
Fig. 12 The amount of groundwater recharge for 30 years. The general trend of groundwater recharge is decreasing as a result of decreasing rainfall due to climatic changes

area has lower slope angles and therefore lower runoff and higher groundwater recharge in comparison to the northern middle part (Cheng et al. 2008; Butler and Davies 2000).

The climatic change affects surface water runoff obviously through changes in the major long-term climate variables such as temperature and precipitation (Jones et al. 2005, Pruski and Nearing 2002). The hydrological cycle is related to climate change through the direct interaction with surface runoff, evapotranspiration, and rainfall. Increasing the rainfall is a factor for increasing the runoff while the temperature is a factor too for increasing the evapotranspiration (Jones et al. 2005). Quantifying the impact of climate change on groundwater resources requires an accurate estimation of groundwater recharge which is a result of rainfall minus the runoff and the evapotranspiration (Holman 2006). The HRUs consider the heterogeneity of the catchment area in the groundwater recharge modelling and therefore obtain an accurate estimation for the groundwater recharge (Flügel 1997). The average yearly value of the groundwater recharge (Supplementary Fig. 9) multiplied by the area of the super mesh (611.25 km^2) gave the yearly quantities of groundwater. Figure 12 shows that the groundwater recharge quantities fluctuate almost regularly; while there is a peak of

groundwater recharge every 2 years. However, the general trend of groundwater recharge is decreasing as a result of decreasing rainfall and the increased temperatures which consequently increase evapotranspiration. During the last 30 years, the maximum recharge value of about 95 million m^3 occurred in 1983 while after 1991 the groundwater recharge quantity does not pass the 50 million m^3 as a result of the climatic change with decreasing rainfall and increased temperatures.

Conclusions

The geomorphologic variations have a major influence on the spatial distribution of the groundwater recharge. This is according to the controlling factors of (a) the drainage network and hence runoff distribution and (b) the distributions of temperature and rainfall, as a result of topographical elevations, and hence the actual evapotranspiration. Furthermore, the regional climatic changes of the Mediterranean region have a major influence on a long-time period of the hydrological cycle of Wadi Zerka Ma'in. According to our study of Wadi Zerka Ma'in catchment hydrological cycle we found the following:

- Wadi Zerka Ma'in catchment area receives a direct groundwater recharge within a physical boundary that generates an area of about 611.25 km^2.
- The study area is heterogeneous from a geomorphological and climatic prospective which leads to a spatial distribution of groundwater recharge.
- The HRU method in groundwater recharge modelling has a great capacity to estimate and represent the spatial distribution of groundwater recharge of the heterogonous study area.
- As a part of regional climate changes and according to our model, the rainfall average decreased in the last 30 years from 275 mm/year to 100 mm/year while the temperature increased from 24.8 to 26.8 degree in the study area.
- There is a decreasing trend of groundwater recharge as a result of the regional climatic changes.
- The groundwater recharge quantities fluctuate almost regularly where every 2 years there is a peak of groundwater recharge.
- It was found during a time period of 30 years that the maximum value of groundwater recharge was 95 million cubic metres in 1983 while after 1991 it does not exceed 50 million m^3 per year as a result of climatic change with decrease in rainfall and increase in temperature.

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