Environ Earth Sci (2016) 75:482
DOI 10.1007/s12665-016-5447-2

ORIGINAL ARTICLE

Structural control on drainage network and catchment area geomorphology in the Dead Sea area: an evaluation using remote sensing and geographic information systems in the Wadi Zerka Ma'in catchment area (Jordan)

Taleb Odeh[1] · Richard Gloaguen[2] · Al-Sharifa Hind Mohammad[3] · Mario Schirmer[4,5]

Received: 1 February 2015 / Accepted: 10 February 2016 / Published online: 10 March 2016

Abstract The geology of Jordan is characterized by fault systems with three major trends: (1) NW–SE, the oldest, (2) WNW–ESE, and (3) NNW–SSE, the youngest. The drainage network of the Wadi Zerka Ma'in catchment area, located in the middle of the Dead Sea rift, parallels these structural orientations. A regional transtensive fault, with embedded normal faults, bounds the lower and middle part of the catchment area. The topographic profile of the Zerka Ma'in River exhibits two major knickpoints where it crosses two major embedded normal faults. The second major knickpoint developed as a result of the dramatic lowering of the Lisan Lake water level, a lake that predates the Dead Sea. The decreased water level triggered river incision into the clastic sandstone units of Wadi Zerka Ma'in. We performed a morphotectonic analysis study to investigate how the rock structures control the drainage network and the catchment area geomorphology. According to the transverse topographic symmetry factor (*T*), the catchment area is highly asymmetric. The major basin asymmetry trend is SE-oriented, parallel to the oldest set of fault systems. The catchment area displays a convex hypsometric curve indicating a very recent stage in the geomorphologic cycle. Our study indicates that the Lisan Lake catchment area shrinkage and structures growth controlled and shaped the Wadi Zerka Ma'in catchment area geomorphology. The combined use of a geographic information system (GIS) and remote sensing was shown to be very efficient in unraveling the evolution of the drainage network and catchment area geomorphology.

Keywords Dead Sea · Catchment area · Drainage network · Strike-slip fault · GIS · Remotes sensing · Structural control

Electronic supplementary material The online version of this article (doi:10.1007/s12665-016-5447-2) contains supplementary material, which is available to authorized users.

✉ Taleb Odeh
taleb_odeh@yahoo.com

[1] The Faculty of Natural Resources and Environment, The Hashemite University, P.O. Box 330127, Zarqa 13133, Jordan

[2] Remote Sensing Group, Institute for Geology, TU Freiberg, Bernhard-von-Cotta-Strasse 2, 09596 Freiberg, Germany

[3] Water, Energy and Environment Center (WEEC), The University of Jordan, Amman 11942, Jordan

[4] Department Water Resources and Drinking Water, Eawag - Swiss Federal Institute of Aquatic Science and Technology, Überlandstrasse 133, 8600 Dübendorf, Switzerland

[5] Centre for Hydrogeology and Geothermics (CHYN), University of Neuchâtel, Rue Emile-Argand 11, 2000 Neuchâtel, Switzerland

Introduction

The catchment area is a basic spatial unit in surface water hydrology. However, the geomorphological features of the catchment area such as the drainage network and catchment area asymmetry and similarity have a major influence on the surface water hydrology especially on the run off processes (Rodríguez-Iturbe and Rinaldo 1997; Stephenson 2003; Subramanya 2006; Vivoni et al. 2008; Wade et al. 2012). The interaction between surface deformation and underlying structural geology which was generated by the tectonic movements is defined as tectonic geomorphology. The drainage pattern and the catchment area asymmetry and similarity reflect tectonic geomorphology (Wilson and Dominic 1998; Van der Beek et al. 2002). Therefore, there are several disciplines between structural geology, geomorphology and hydrology, which need to be looked at in combination to fully understand tectonic geomorphology.

The geomorphologies and structural settings of the catchment areas were sparsely studied in Jordan so far. The Wadi Zerka Ma'in catchment area is located on the north-eastern side of the Dead Sea, in Jordan, and spans an area of 272 km^2. It is characterized by a sub-dendritic drainage network with two main trends, N–S and E–W (Odeh et al. 2009a, 2013, 2015) (Fig. 1). A tectonic geomorphological study for Wadi Zerka Ma'in catchment area has not yet been carried out. Therefore, the objectives of this research are the following:

1. A passive structural evaluation of the catchments area.
2. A comprehensive description and characterization of the drainage network.
3. An evaluation of the catchment area asymmetry and similarity.
4. A stream profile analysis of the Zerka Ma'in River.
5. An assessment of the passive structural control on the drainage network and catchment geomorphology using the results of the previous tasks to fully understand the geomorphology of Wadi Zerka Ma'in.

Wadi Zerka Ma'in catchment is a part of the Dead Sea basin. However, the Dead Sea is considered as a

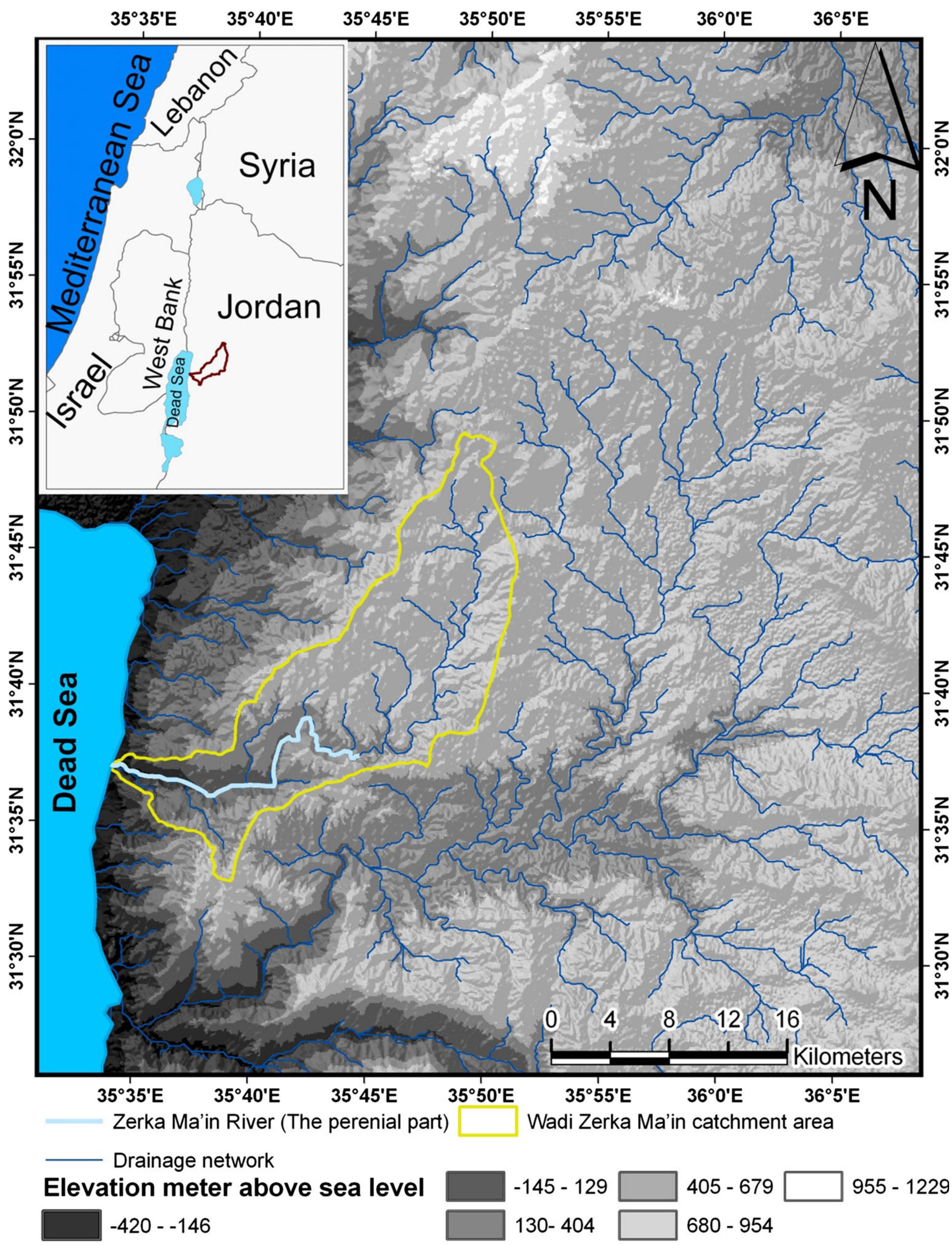

Fig. 1 Location of the study area (north east of the Dead Sea). The study area has a high relief topography where the elevation varies from −420 to 1020 m above sea level (modified after Odeh et al. 2013)

hypersaline lake that is allocated in a pull-apart basin (Horowitz 2001). That basin is part of the Dead Sea transform fault and the lowest place worldwide with an elevation of −421 m above sea level (asl) in 2008. The length of the Dead Sea transform system is about 1000 km (Niemi and Ben-Avraham 1997). This length includes the Dead Sea rift valley. It provides a link between continental divergent and convergent plate boundaries. The fault transform system is with an age of 18 million years (Niemi and Ben-Avraham 1997; Horowitz 2001; Laske et al. 2008).

The two sides of the Dead Sea basin are faulted zones as a result of the Dead Sea pull-apart basin. These sides have a jointed, fractured and massive sandstone in addition to karstic and fractured lime stone that are genetically connected with faults. However, basaltic rock and unconsolidated sediments are also widely distributed (Quennell 1956; Bender 1974; Horowitz 2001; Closson et al. 2010).

The Dead Sea basin is characterized by steep escarpments and complicated morphological units that have not been yet adequately investigated. The land surface of that region has a high relief topography where the elevation difference between the lake and the highlands could be more than 1200 m over a horizontal distance of 15 km (Closson et al. 2010).

Hydrologically, the Dead Sea has a surface water level which is currently dropping at a rate of about 1 m per year as a result of huge evaporation and overexploitation of its tributaries (Salameh and Bannayan 1993; Enzel et al. 2006). The current lowering started 40 years ago, but the sedimentary structures of the basin indicate that the surface water level was dropping during different geological ages in which the Dead Sea lake was much larger than currently (Horowitz 2001; Closson and Abou Karaki 2009; Enzel et al. 2006).

The Dead Sea basin is a unique global study area for evaluating the coupled relationships between basin evolution and groundwater flow. The temporal and spatial distributions of elevations and salinities of groundwaters and lakes are strongly associated to paleo conditions of tectonics, sedimentation, and erosion. Furthermore, climate changes have induced changes in the rift's water mass balance, triggering lake level fluctuations and temporal and spatial changes in lake water salinity (Horowitz 2001; Enzel et al. 2006). The Dead Sea catchment area has special conditions concerning of hydrogeology, hydrology, geomorphology and geology which have a major influence on the generation of the Dead Sea lake (Bender 1974; Niemi and Ben-Avraham 1997; Enzel et al. 2006; Salameh and Al Farajat 2007).

From a geological perspective, the Arabian-Nubian shield is composed of Pre-Cambrian crystalline basement rocks and crop outs in south-western Jordan (Johnson 1998). This shield underwent several epirogenic activities since Pre-Cambrian time (Bender 1974). This resulted in transgressions and regressions of the Tethys Sea. The geological layers of the Dead Sea basin were deposited during the northwest transgressions and the erosion of the uplifted Arabian-Nubian Shield from the south during the regressions (Andrews 1991). Jurassic and Cretaceous sediments of considerable thickness were laid down and reach up to 4000 m in the southeast of Jordan (Fig. 2) (Flexer 1968; Andrews 1991).

In the Upper Eocene, the Tethys regressed with deposition of fluviatile and lacustrine deposits mainly in the Jordan Rift Valley and Wadi Araba in western Jordan (Horowitz 2001). From the Oligocene to Quaternary basalt flows erupted during volcanic activity in the Harrat Ash Shaam volcanic system, a massive alkaline volcanic field extending from the south of Syria to northwest Saudi Arabia (Bender 1974; BGR 1997).

The fault systems in Jordan have three main trends: (1) NW–SE, the oldest, parallel to the Red Sea and generated simultaneously with rifting (Johnson 1998; Odeh et al. 2010). The Wadi Al Sirhan catchment area has a fault that belongs to this system (Salameh and Al Farajat 2007). The system has been rejuvenated with lock rotation to become oriented WNW–ESE, and produced a shear belt along with (2) a WNW–ESE fault system, which is perpendicular to the Dead Sea transform fault (Garfunkel and Ben-Avraham 1996). The major strike-slip fault of Wadi Zerka Ma'in belongs to this system (Odeh et al. 2009a). Clockwise rotation changed gradually from NW–SE to N–S and led to the formation of (3) a NNW–SSE fault system that is parallel to the Dead Sea transform fault and is the youngest fault system in the study area (Quennell 1956; Garfunkel and Ben-Avraham 1996; Niemi and Ben-Avraham 1997). The regional Dead Sea transform fault experiences ~6 mm of motion per year (Klinger et al. 2000). It connects the divergent plate boundary along the Red Sea with the zone of plate convergence along the alpine orogenic belt in Turkey (Johnson 1998). According to Quennell (1956), the Dead Sea rift valley was generated by two major horizontal movements with a total sinistral movement of 107 km and with a vertical down-throw of ~1500 m. These movements are not older than 14 Ma and not younger than 6 Ma. The Dead Sea represents a pull-apart zone in the Dead Sea transform fault (Bayer 1988; Niemi and Ben-Avraham 1997).

Dead Sea surface water level fluctuations during different periods caused major changes in the river topographic profiles that discharge directly into the sea (Frumkin and Elitzur 2002; Street-Perrott and Harrison 1985). The Dead Sea surface water fluctuations affect the geomorphological characteristics of the catchment areas of those rivers (Street-Perrott and Harrison 1985; Salameh

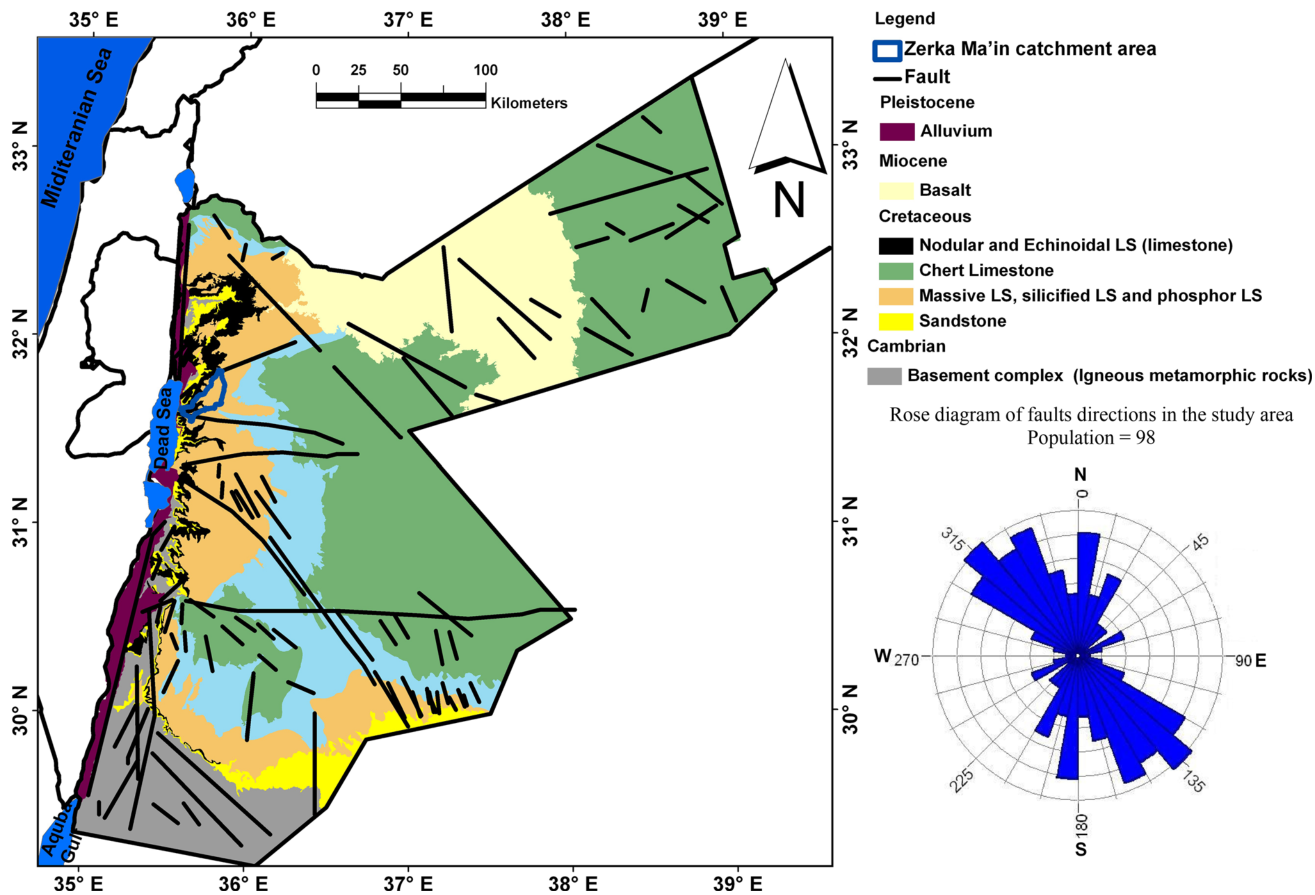

Fig. 2 Geological map of Jordan (modified after Bender 1974). The major fault system direction is in NW–SE direction parallel to the Red Sea

and Al Farajat 2007). It was understood that these fluctuations are due to the paleoclimatic changes, but recently more evidence about geological and geomorphological controls for these fluctuations became evident (Street-Perrott and Harrison 1985; Salameh and Al Farajat 2007; Whipple and Tucker 1999).

In the post-Messinian a maximum ingression of the Mediterranean Sea occurred in the west and generated the Sedom Sea in the Dead Sea rift valley (Fig. 3). However, the Sedom Sea was connected to the Mediterranean Sea by the Yizreel Valley and therefore had 0 m elevation above sea level (Horowitz 2001). Subsequently, the land between the Dead Sea rift and the Mediterranean Sea was uplifted, denying further marine transgressions (Niemi and Ben-Avraham 1997). In the middle Pleistocene, the rift contained three lakes: Al Hula, Kinnert and Samara. However, ~100 ka ago the climate became more and more arid and caused the Lake Samara to shrink and be replaced by the more saline Lisan Lake which was ~180 m below sea level (Horowitz 2001; Salameh and Al Farajat 2007).

The shrinkage of the Lisan Lake led to the formation of the Dead Sea in a pull-apart zone of the Dead Sea transform fault. The Dead Sea had a water level of about −400 m asl 23 ka ago, (Sneh 1996; Niemi and Ben-Avraham 1997). However, according to Salameh and Al Farajat (2007) the shrinkage of the Lisan Lake catchment area from ~170,000 km^2 to the recent Dead Sea catchment area of ~44,000 km^2 was the main reason for that reduced lake level.

The catchment area shrinkage was a result of the eruption and spread of the basalt flows of Jabal Arab Druz (Fig. 4), which together with the resulting deposition of thick rock debris and gravels blocked the pre-basalt drainage system (Lisan Lake catchment area) (Salameh and Al Farajat 2007). These basalt flows and volcanic eruptions together with Jabal Arab Al Drouz are called the Harat Al Sham volcanic system (BGR 1997). The Harat Al Sham volcanic system, which led to the Lisan Lake catchment area shrinkage, took place in six phases (Bender 1968). The first four phases started in the Miocene while the fifth continued into the Pleistocene (Dubertret 1929; Bender 1968). However, the sixth phase started in the Holocene and covered an area much larger than the first previous five phases (Dubertret 1929; Bender 1968; Salameh and Al Farajat 2007). By C14 age determination for organic matter

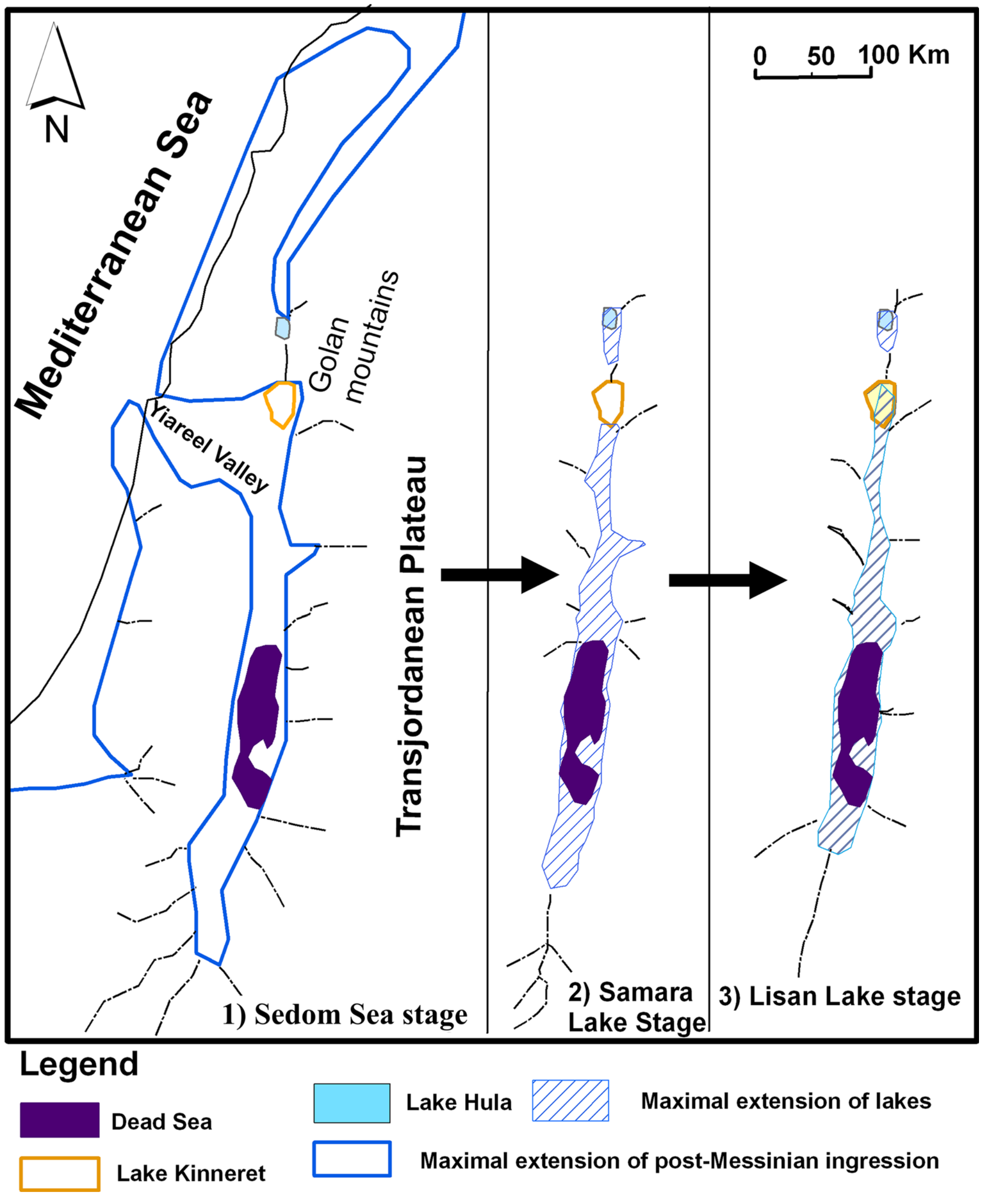

Fig. 3 Lisan Lake stages generation (modified after Horowitz 2001). After Sedom Sea stage three lakes were generated in the rift: Al hula. Kinneret and Samara Lakes, Sedom Sea was connected with the Mediterranean Sea

contained in the lava (4000 years old), it was found that the last lava flow of the Harat Al Sham volcanic system occurred in prehistoric time (de Vries and Barendsen 1954; Bender 1968). According to Salameh and Al Farajat (2007), the major phase of blocking the drainage to Lisan Lake by the basalts and lava flows occurred when the sixth phase basalt flow spread and covered all the five previous phases. After volcanic blocking, the Lisan Lake catchment area was divided into four major catchment areas as follows (Fig. 5):

1. Wadi Al Sirhan (79,608 km^2).
2. Hammad (38,237 km^2).
3. Damascus (9570 km^2).
4. Dead Sea (43,629 km^2).

Methodology

Remote sensing provides a synoptic view for monitoring and change detection analysis of drainage networks (Gong and Xie 2009). A geographic information system (GIS) is a useful tool for the analyses of spatial and temporal parameters detected by remote sensing techniques (Saintot et al. 1999; Odeh et al. 2015). Therefore, an integrated approach of remote sensing and GIS was used to generate digital elevation models (DEMs) that were used for carrying out the geomorphological and structural analyses.

Drainage networks respond rapidly to structural changes (Shahzad et al. 2009). The automated generation of drainage networks from digital elevation models (DEMs) is a

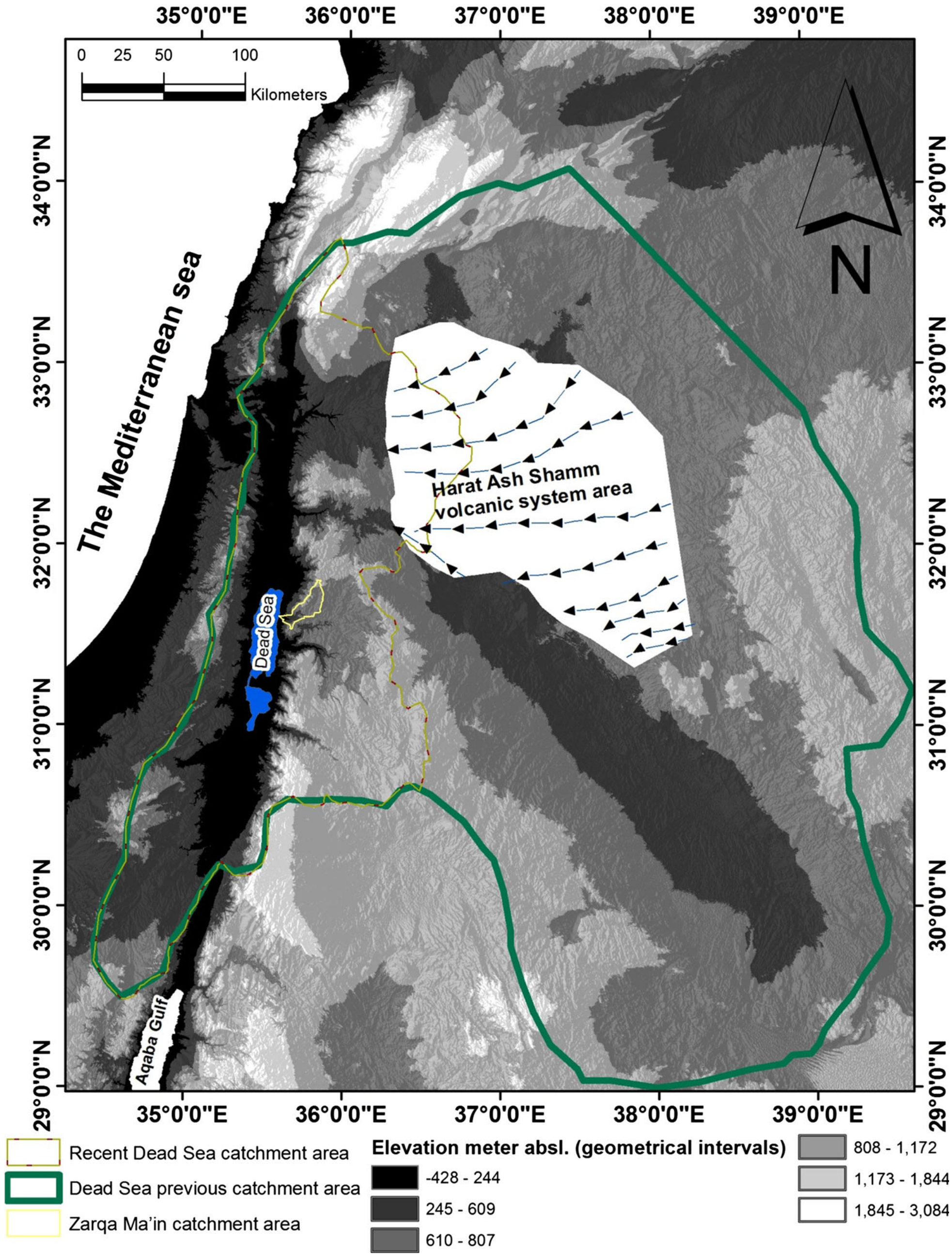

Fig. 4 Pre-basalt catchment area. The *clipped area* represents the Basalt of Harat Al Sham volcanic system including Jabal Arab Al Druz

powerful analytical function in geographic information systems (GIS). DEMs enable earth scientists to obtain geometric characteristics, including numerical descriptions of topographic forms, of the land surface at different scales (Bolongaro-Crevenna et al. 2005). However, extracting a topographic relief is a type of spatial analysis that uses rules of correspondence between real and numerical forms. Wood (1996) used algorithms for numerically describing reliefs with a limited number of morphometric classes. These algorithms specify each morphometric class based on the values of slope and convexity that were calculated from a DEM. Wood's method is according to Evan's hypothesis (1972) which says that the land's surface can be conceptualized as a continuous surface and represented analytically by a second degree polynomial function (Wood 1996; Bolongaro-Crevenna et al. 2005). Remote sensing methods offer a vast array of DEMs with different resolutions to choose from (Wang and Yin 1998). Therefore, an integrated approach that combines remote sensing and GIS was used to extract the drainage network of Wadi Zerka Ma'in. Two different DEM resolutions were used:

1. A DEM of 90 m resolution that covers the regional area and was downloaded from the Shuttle Radar Topography Mission (SRTM) home page.

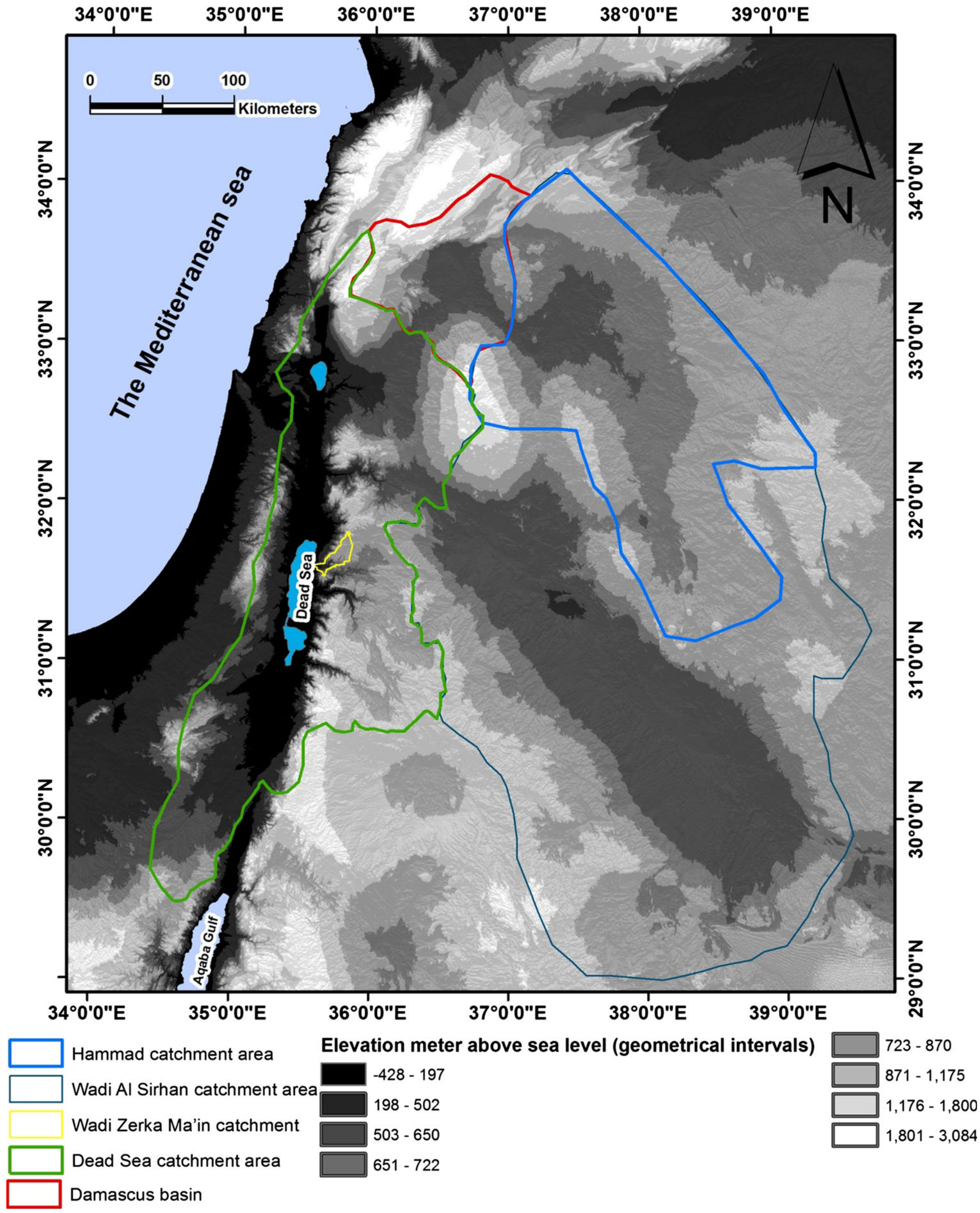

Fig. 5 Dead Sea, Wadi Al Sirhan, Wadi Hammad and Damascus catchment area. The *three catchment areas* were one large catchment area before the late Pleistocene. Wadi Al Sirhan catchment is mainly located in Saudi Arabia, but its extension into Jordan is the closed basin of Al Azraq, which contains separate local depressions that receive flash floods from surrounding hill slopes (supplementary Fig. 1)

2. A DEM of 15 m resolution that covers the study area and was produced from two scenes of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images (Fig. 6a).

Interrelationships between topography and near-surface structure are often recognizable (Wilson and Dominic 1998). Topography can be parsed automatically by manipulating land surface heights within elevations arrayed in DEMs. From a functionality perspective, GIS techniques can efficiently achieve that process through a variety of data visualization approaches, patterns, and spatial analyses (Wang and Yin 1998; El Bastawesy 2007).

The two DEMs were inserted in the GIS. According to the extension hydrology in the ArcGIS 9.3 software, the drainage network was extracted regionally and locally. However, the DEM of 90 m resolution was used to extract the drainage at regional scale while the DEM of 15 m was used to extract the drainage network at local scale. The drainage networks were extracted by the extension of hydrology in ArcGIS 9.3 (Fig. 6b). The first step was removing the holes in the DEMs and then using a D8 flow grid algorithm (O'Callaghan and Mark 1984). This algorithm estimates the flow direction possibilities at each cell towards the eight neighboring cells. The least cost algorithm was used to connect the stream flow directions to generate a continuous network of streams (Shahzad and Gloaguen 2009a). Geometrical classification and hillshade effects were then computed for the raster elevations to

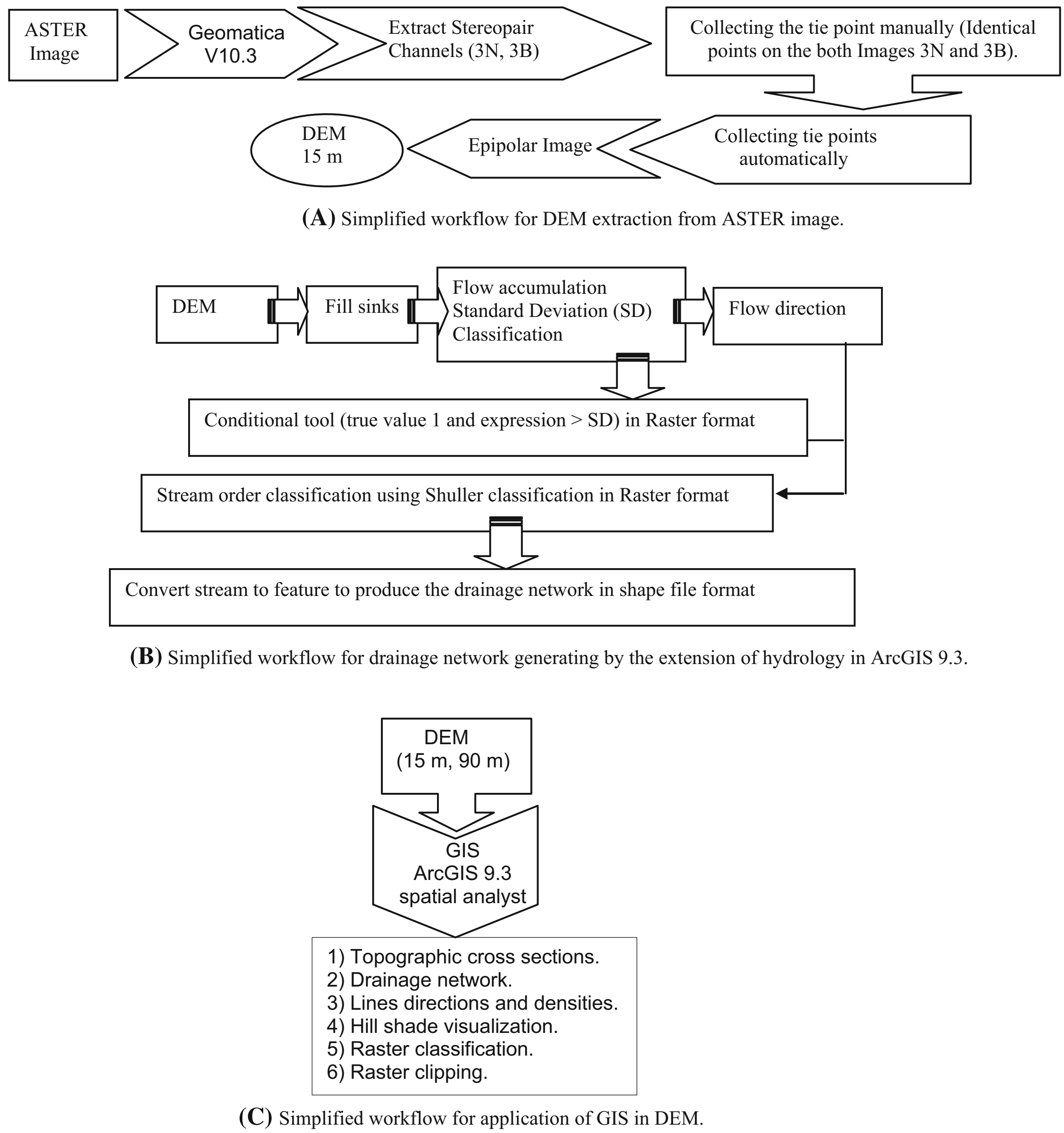

Fig. 6 An integrated approach of remote sensing and GIS. The Digital elevation model (DEM) that is extracted by remote sensing techniques while the spatial analysis of it is done by GIS

parse and visualize the topography using the spatial analyst extension in the ArcGIS 9.3 software (Fig. 6c).

Stream profile analysis is a useful tool in tectonic geomorphology as a diagnostic indicator of factors such as stages of landscape evolution, tectonic uplift or subsidence, variations in rock resistance and base level changes (Wobus et al. 2006; Phillips and Lutz 2008). It is a tool to aid understanding of tectonic–climatic–topographic interactions because river incision into bedrock is a response to tectonic, lake or sea level, and climatic forcing (Whipple and Tucker 1999). Thus, the dynamic of stream power incision (Whipple and Tucker 1999) is represented as follow:

$$\frac{dz}{dt} = U - E \quad (1)$$

where dz/dt denotes the rate of change in the topographic elevation of a river during time. U is the rate of landmass uplifting and E is the rate of erosion. Whipple and Tucker (1999) define the rate of the erosion and generated the following equation:

$$\frac{dz}{dt} = U - KA^m S^n \quad (2)$$

where A is the catchment drainage area, S is its slope and K is its erosion coefficient. The constant of m and

n depends on basin hydrology, hydrologic geometry and the predominant erosion process.

Under dynamic equilibrium conditions (between the sea level and the river incision) dz/dt will be zero. Therefore, the previous equation would be as follows (Hack 1973; Flint 1974; Whipple and Tucker 1999; Snyder et al. 2000; Kirby and Whipple 2001):

$$S = \left(\frac{U}{K}\right)^{1/n} A^{m/n} \quad (3)$$

where the coefficient $(U/K)^{1/n}$ is the steepness of the river profile while m/n is the concavity of the profile.

According to Wobus et al. (2006), the stream power law is represented as:

$$S = k_s A^{-\theta} \quad (4)$$

where the river steepness index k_s equals (U/K) and the concavity index θ equals (m/n). Following Mahmood et al. (2013), we can combine the two Eqs. (3) and (4) and get equation:

$$U = k_{sn}^{n} K \quad (5)$$

where k_{sn} is the normalized steepness index (Flint 1974; Snyder et al. 2000; Whipple 2004). For further explanations on how k_{sn} can be determined, the reader is referred to Wobus et al. (2006). The stream gradient index (Hack 1973) is defined as:

$$\mathrm{SL} = \left({}^{\Delta H}\!/\!_{\Delta L}\right) L \quad (6)$$

where SL is the stream gradient index, $\Delta H/\Delta L$ is the gradient of the stream reach where the index is computed, (ΔH is the drop in the topographic elevation of the reach and ΔL is the length of the reach) and L is the total stream length from the drainage divide to the center of the reach.

There are two methods to evaluate the basin asymmetry: the transverse topographic symmetry factor method (T) and the asymmetric factor method (AF). An asymmetric factor (AF) can be applied over a relative large catchment area (Keller and Pinter 2002). Wadi Zerka Ma'in has a small catchment area, therefore we applied a transverse topographic symmetry factor (T), which evaluates the amount of asymmetry of a river within a catchment area and the variation of this asymmetry. The catchment area midline is the line of symmetry for the catchment. Mathematically, T denotes the ratio of the distance from the catchment area basin midline to the river (Da) and to the catchment area border (Dd) as follows (Horton 1945; Kothyari and Rastogi 2013):

$$T = {}^{\mathrm{Da}}\!/\!_{\mathrm{Dd}} \quad (7)$$

The factor value varies from zero to one, which represents the minimum and the maximum values. Hypsometry refers to the distribution of the land area at different elevations. It has generally been used to infer the stage of geomorphic development and to study the influence of tectonics on topography (Hurtrez et al. 1999). The hypsometric curve is a plot of relative height (h/H) versus relative area (a/A), where: h is the topographic elevation of a given location on the river, H is the total topographic elevation, a is the measurement (in km^2) of the area that is higher in elevation than the point of measurement, A is the total area of the catchment.

Shahzad and Gloaguen (2009a, b) developed TecDEM, a Matlab-based software for estimating and plotting stream profile analysis. We used TecDEM to estimate, extract and visualize stream profiles for the study area using the 15 m DEM that was extracted from the Aster stereopair. The drainage network density is defined as the ratio of the sum of the total stream length divided by the drainage catchment area (Horton 1945; Knighton 1998). It is a spatial measurement of the drainage network geometry because it represents the degree of dissection of the drainage basin by surface streams (Keller et al. 1999). The spatial analyst extension in ArcGIS 9.2 was used to produce a drainage density map for the study area.

Results and discussion

Drainage network and fault directions

The fluvial dissection of the landscape consists of geomorphological units and their included channel ways organized into a system of connections known as a drainage network (Abrahams 1984). Drainage networks represent the type of quantitative regularity that are useful in analyzing both the fluvial systems and the terrains that they dissect (Abrahams 1984). However, The drainage network is a essential hydrological and geomorphical part of the river system (Knighton 1998). According to it, the description of the geometry of landforms could be defined (Abrahams 1984; Knighton 1998). Wadi Zerka Ma'in catchment area has a combination of two drainage network types as follows:

(a) Dendritic drainage network:
Most of the third-order streams in the catchment area of Wadi Zerka Ma'in are in form of dendritic shape as a results of the uniformly resistant geological layers (limestone in the upper and middle part and sand stone in the lower part of the catchment) to erosion. However, this type of drainage network in the study area is recent and generated after the fault systems (Huggett 2007; Odeh et al. 2010).

(b) Rectangular drainage network:
Most of the first- and second-order streams in the

studied area are of this type. It is the oldest drainage network in the study area. It represents a perpendicular drainage network of streams with tributaries and main streams joining at angles. It is less regular than trellis drainage networks and is controlled mainly by the faulting systems in the study area (Huggett 2007; Odeh et al. 2009a).

The geomorphological units and geological structures of a catchment control the overland flow processes as a results of controlling the length and the direction of drainage network flow over the land surface unit (Sreedevi et al. 2012; El Bastawesy et al. 2013; Odeh et al. 2015). Therefore, the analysis of a drainage network quantitatively is important to understand the hydrological and environmental interactions over a catchment area. Furthermore, the drainage network has interactions with the geological processes which determine the stream orders, stream lengths, stream flow directions and catchment areas shapes (Kaliraj et al. 2014).

The study area is part of the Dead Sea rift valley that is considered as an active tectonic region with complicated geological systems (Horowitz 2001; Shtober-Zisu et al. 2008). In tectonically active regions most of the drainage network reflects the interaction between surface processes and the growth and propagation of underlying faults (Ribolini and Spagnolo 2008). Figure 7 shows that most of the drainage networks are of rectangular type. However, the directions of Wadi Zerka Ma'in catchment area rectangle drainages follow the NNE–SSW fault system that is parallel to the Dead Sea transform fault, and the WWN–EES fault system that is normal to the Dead Sea transform fault. However, the effects of the NW–SE faults are limited and found mostly in the upper part of the catchment area. The influence of the oldest fault system on the drainage network has degraded within geological times (Odeh et al. 2009b).

Influence of a regional strike-slip faulting on the Zerka Ma'in River profile

The regional strike–slip fault of Wadi Zerka Ma'in cuts through the middle and lower parts of the catchment area and is associated with normal faults. Therefore, it is considered as a transtensive strike-slip fault (Fig. 8) (Odeh et al. 2010). A knickpoint is a steep reach in a stream topographic profile that creates a localized sharp incision (Gardner 1983). It is a response either of the resistance differences of lithological layers to the denudation process, a reaction to fault displacement, or a disequilibrium steepening in response to a relative base level fall (Tucker and Slingerland 1994; Bishop et al. 2005). Four normal faults are located in the Wadi Zerka Ma'in River with four complimentary knickpoints (Fig. 9). The first major one is located at a distance of 34 km from the source, with a vertical lowering of 200 m. The second major one is located 44 km from the source with a vertical lowering of 100 m. The rapid drop of the Dead Sea water level after the Lisan Lake stage enhanced river incision in the clastic sandstone units, so the fourth knickpoint developed as a result of disequilibrium with the Dead Sea water level.

Catchment areas that are influenced by uplifting processes are marked by a convex river profile and high steepness index (k_{sn}) values (Knighton 1998, Van der Beek et al. 2002). Figure 10 A shows that the studied area has four steepness indices (k_{sn}) that are generated in four stages as follows:

1. $k_{sn} = 0.73$ with concavity index (θ) of 0.56 as a result of anticlinal uplift with slight embedded normal fault effect in the top of the catchment area.
2. $k_{sn} = 51.40$ and $\theta = 1.74$ as a result of the first major knickpoint which is caused by the first normal fault.
3. $k_{sn} = 62.04$ and $\theta = 1.54$ as a result of the second major knickpoint which is caused by the second normal fault.
4. $k_{sn} = 544.03$ and $\theta = 1.18$ as a result of a slight embedded normal fault effect that was developed by river incision after the Lisian Lake stage.

The Hack stream gradient (SL) (Hack 1973) index is a valuable tool for evaluating the vertical surface deformation component (Troiani and Della 2008). The sensitivity of the index to changes in the stream permits evaluation of the relationships between tectonic activity, rock resistance and topography (Keller and Pinter 2002). It was found that there are four major stream gradient indices that occurred with changing steepness indices. The effects of the normal fault in vertical deformation are shown by the SL = 994 and SL = 3092 (Fig. 10b).

Catchment area hypsometry and asymmetry

The hypsometric curve is a dimensionless graph of area-altitude distribution. It describes the total size of the catchment area relative to topography (Ohmori 1993). The runoff components are a function of the basin hypsometric curve. A relatively little eroded (convex) basin shows higher total runoff that is more dominated by subsurface processes, while a relatively more eroded (concave) basin has less total runoff with a higher fraction of surface response (Vivoni et al. 2008; Rodríguez-Iturbe and Valdes 1979). According to the geomorphic cycle, a convex curve

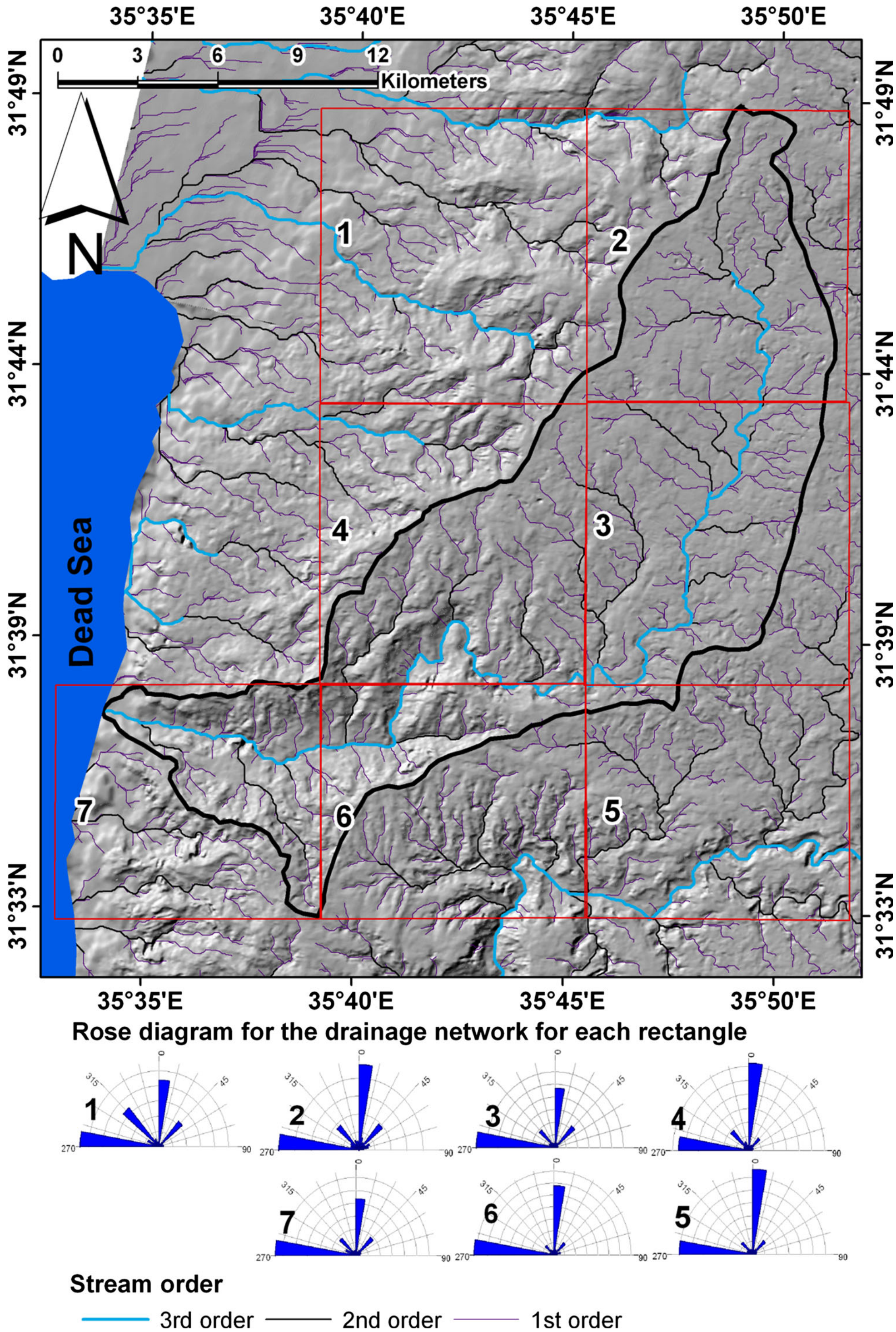

Fig. 7 Drainage network directions in the study area. The study and the surroundings area were divided into seven *rectangles* to investigate the drainage network spatially. The *rose diagrams* were generated for each *rectangle* alone. The major directions of the drainage network are similar to the major directions of the major fault systems

indicates a young stage and s-shaped curves a mature and old stage (Strahler 1952; Ohmori 1993).

Figure 11 shows the hypsometric curve of Wadi Zerka Ma'in. The catchment area has a high convexity, indicating an early stage in the geomorphic cycle. The normal faults within the major strike-slip fault led to an uplifting which generated the convexity. A high convexity generates high total runoff that is denominated by subsurface processes more than from surface ones. The hypsometric integral value indicates the young stage (disequilibrium stage) of the catchment area with undissected landscapes that change continuously as a result of erosion activities (Phillips and Lutz 2008; Kaliraj et al. 2014). The erosion process of the catchment area represents interactions of the drainage

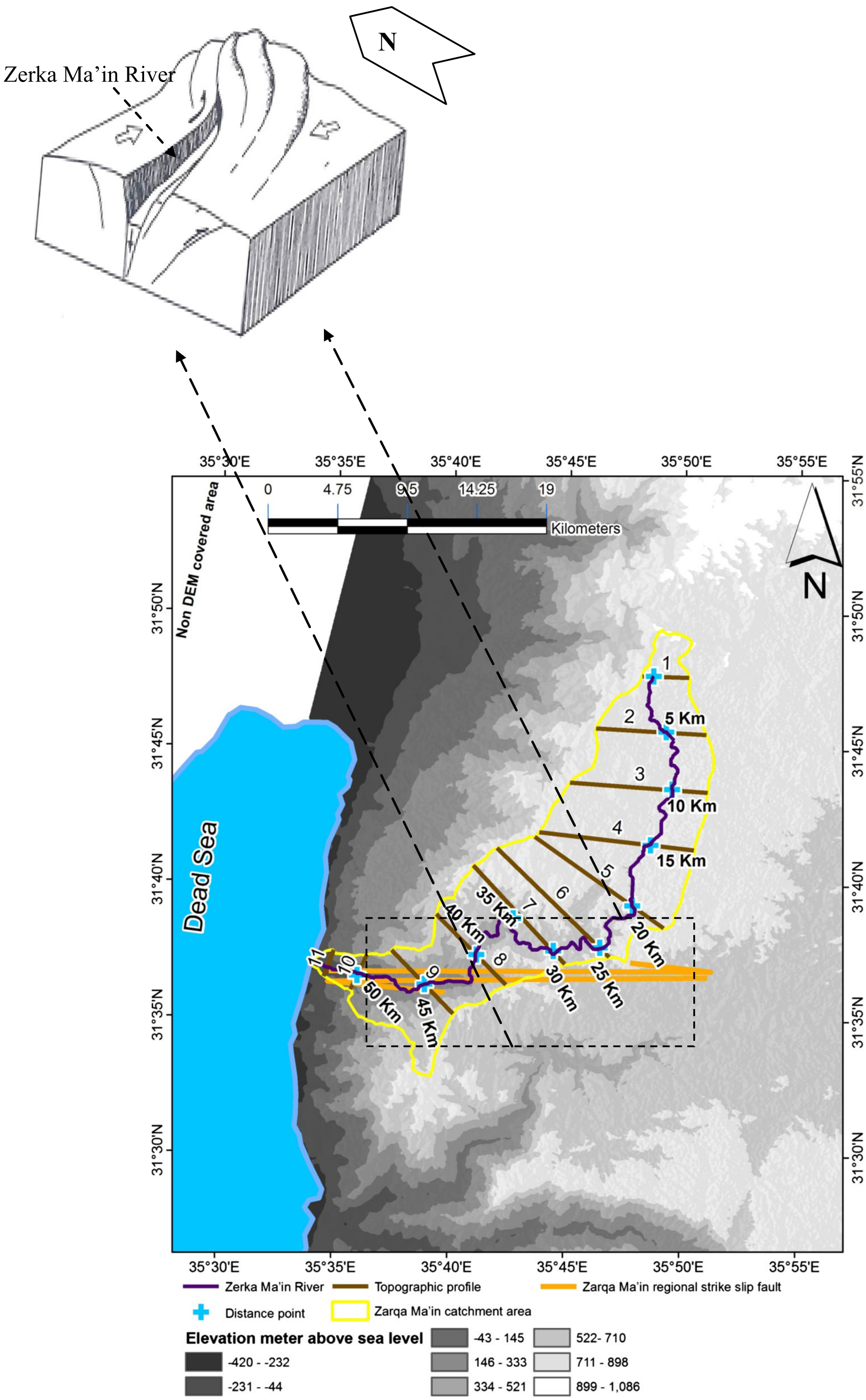

Fig. 8 Location of the topographic profiles and a transtensional zone of the major strike-slip fault in the Wadi. There is negative (Tulip) structure-transtensional zone within the Wadi. The embedded normal faults are within the transtensional zone

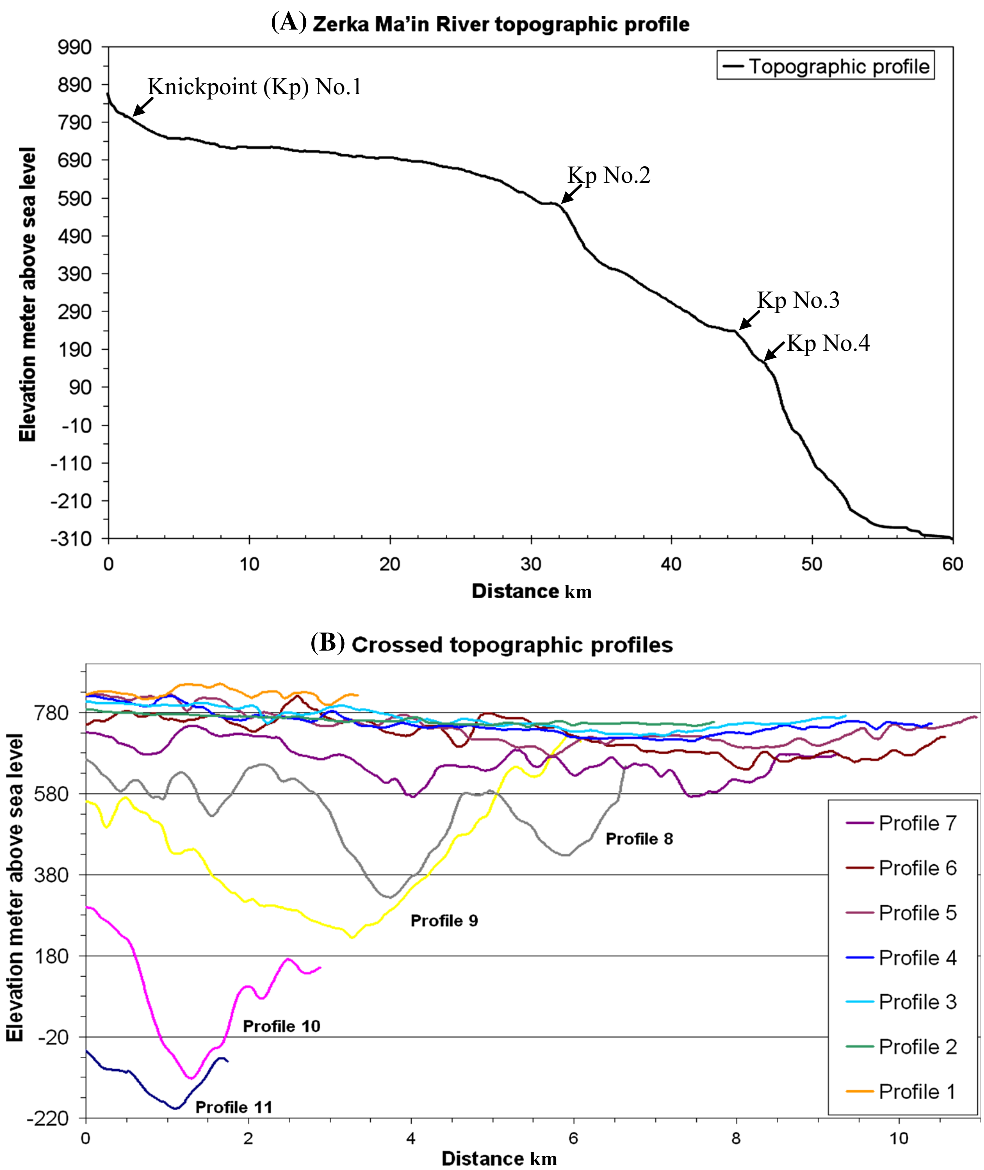

Fig. 9 The topographic profiles show four topographical lowering stages (knickpoints) as a result of the displacements the embedded normal faults within the transtensional zone of the major strike-slip fault. The locations of the crossed topographic profiles are shown in Fig. 8. However, at the end of the Zerka Ma'in River topographical profile there are three small topographical droppings that are correlated with the recent Dead Sea water level decrease

network with the geomorphological landforms (Kaliraj et al. 2014). The anomaly index values at the beginning of the curve indicate the topographical and lithological influences on the formation of the drainage system, especially along the high altitude areas in the northern part of the catchment area (Hurtrez et al. 1999; Kaliraj et al. 2014).

A transverse basin asymmetry vector denotes the direction and degree to which a river deviates from the basin midline. It creates important map-scale data for a neo-tectonic assessment and permits the delineation of geomorphic domains of stream migration that are related to tilted fault blocks (Garrote et al. 2006). Catchment areas that are associated with strike-slip faults, like the case of Wadi Zerka Ma'in, are asymmetrical. This is because of the geomorphological changes that occurred during horizontal faulting (Ben-Avraham 1991). Figure 12 shows that the Wadi Zerka Ma'in catchment is a strike-slip faulted area that displays a strong left asymmetry and is highly influenced by the NW–SE fault system, the oldest in the region (Odeh et al. 2010). The second major trend of the asymmetry arrows is parallel to the strike-slip fault of Wadi Zerka Ma'in and the third trend is parallel to the Dead Sea transform fault. Thus, the trends of the asymmetric arrows parallel those of the fault systems.

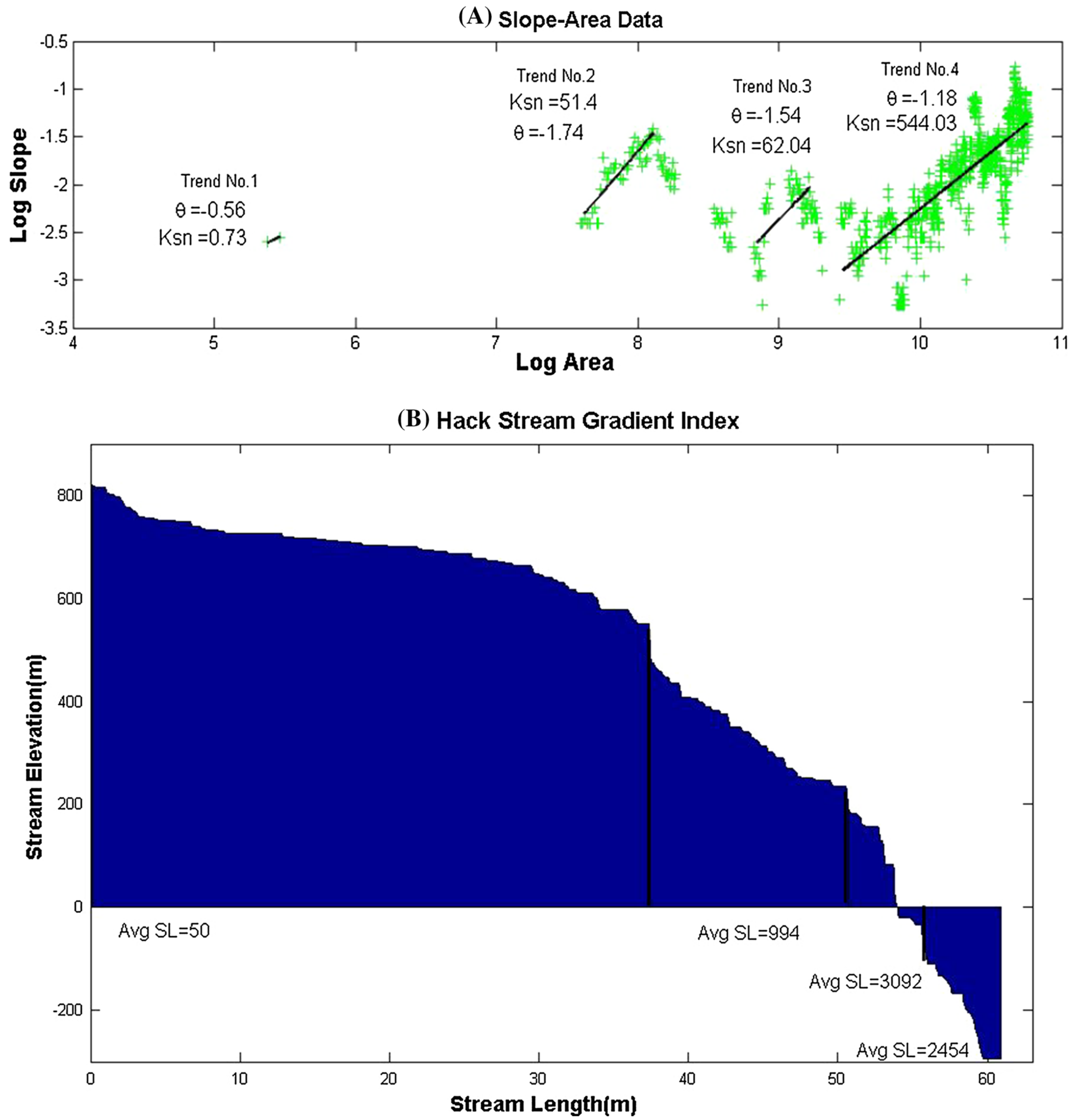

Fig. 10 Stream profile analysis of Wadi Zerka Ma'in River. The four trends in the log slope–log area diagrams are associated with the four knickpoints of Zerka Ma'in River. In addition, the Hack stream index diagram shows four major gradients as a result of the knickpoints

Conclusion

The geomorphological features of the catchment areas are developed simultaneously by the growth of tectonic structures. Therefore, the structural geology of the wadis can be evaluated by an investigation of their geomorphological characteristics. The presented case study of Wadi Zerka Ma'in catchment area represents a particular combination of disciplines between structural geology, geomorphology and hydrology. We summarize our findings as follows:

- The regional strike-slip fault of Wadi Zerka Ma'in has two major embedded normal faults that cause two major topographic lowerings (knickpoints) along the Zerka Ma'in River: (1) 34 km from the source with a lowering of 200 m, (2) 44 km from the source with a lowering of 100 m.
- The rapid decrease of the Lisan Lake water level enhanced the development of the second major topographic lowering by enhancing the river incision.
- The catchment area of Wadi Zerka Ma'in is asymmetrical due to the NW–SE fault system, the oldest faults system. The asymmetric arrows have the same trends as this fault system.
- The hypsometry curve shows that the catchment area is convex. This is a result of the embedded normal faults within the regional strike-slip fault. The catchment area

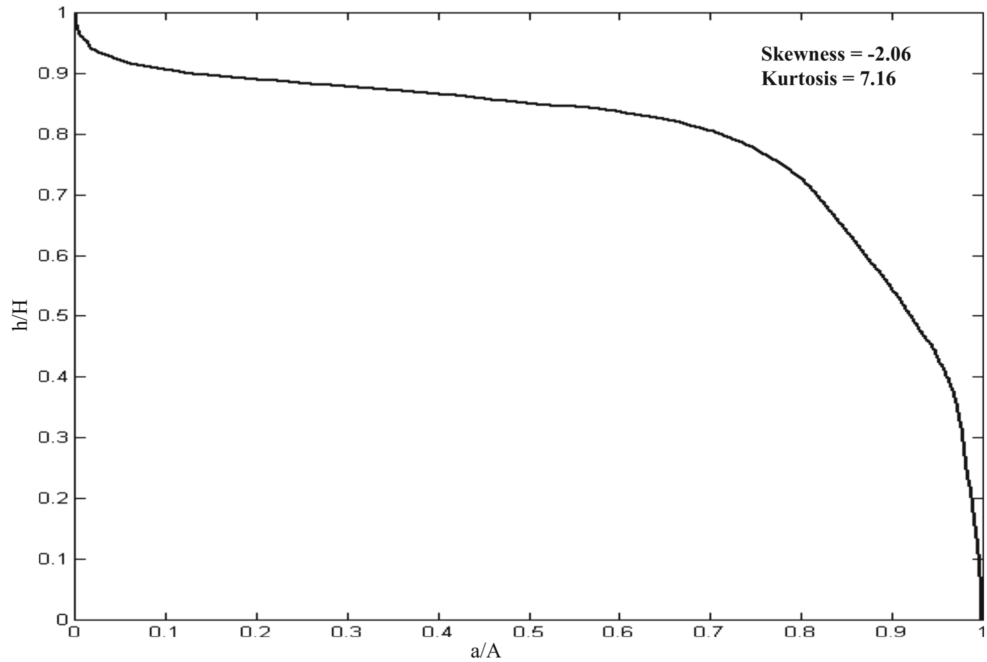

Fig. 11 Hypsometry plot as an indicator of basin similarity. The *concaving up of the diagram* indicates the catchment is a recent basin as a result of the major strike-slip fault

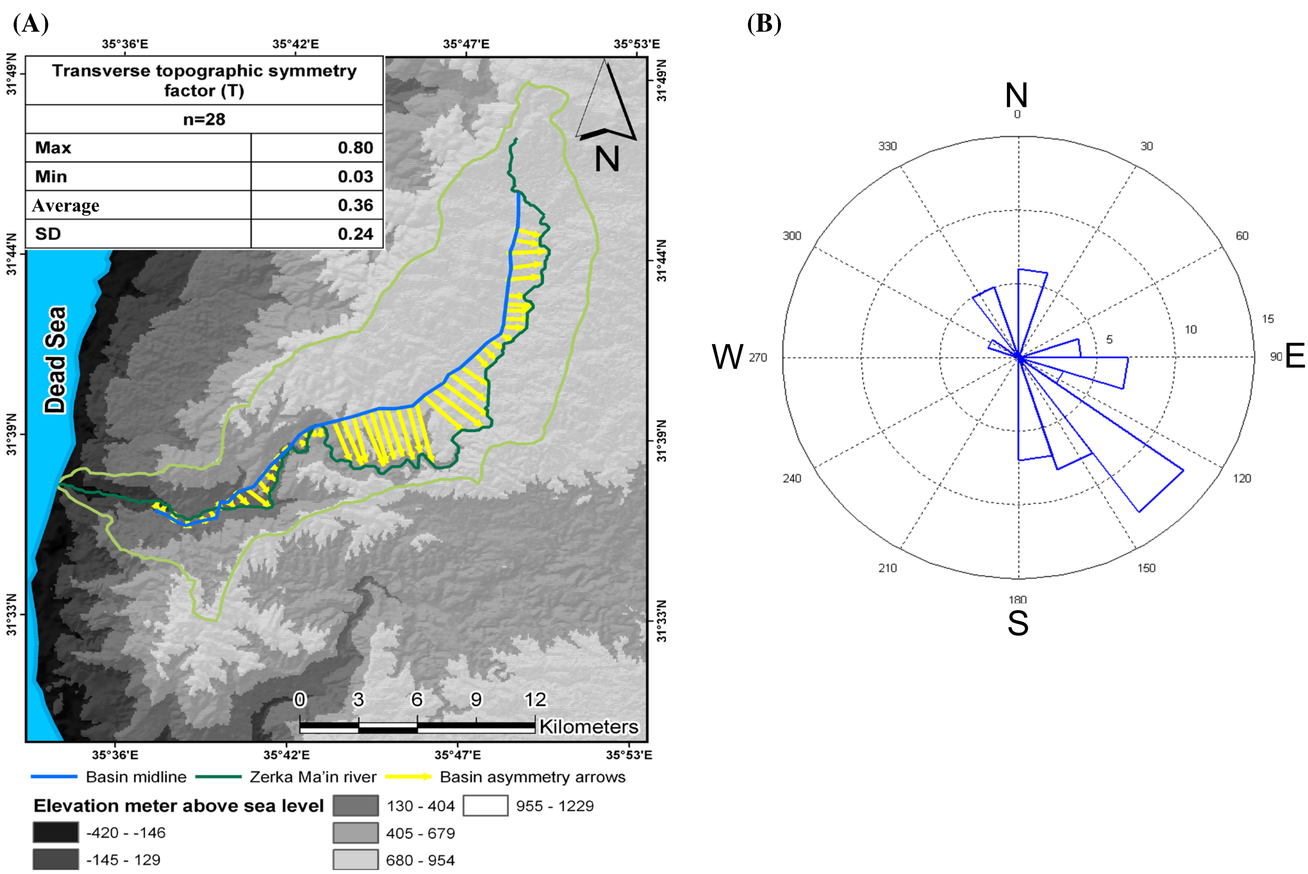

Fig. 12 Basin asymmetry similarity: **a** Basin asymmetry arrows. **b** Basin asymmetry rose diagram. The major trend of the basin asymmetry arrow is similar to the major trend of the oldest fault system in Jordan, NW–SE faults (Fig. 2). The catchment asymmetry is generated mainly because of these faults

of Wadi Zerka Ma'in is in an early stage of the geomorphic cycle.
- It was found that the drainage network follows the same direction of the fault systems.
- The catchment area asymmetry is more influenced by the oldest fault system.
- The combination of GIS and remote sensing with stream profile analysis provides an excellent tool for the structural evaluation of wadis.
- Further tectonic geomorphology studies are needed for the Dead Sea catchment areas to understand the Dead Sea drainage network system and the surrounding catchment areas.

The Dead Sea catchment area has a lag of studies that combine the disciplines of geomorphology, structural geology and hydrology although there has been considerable work in each topic individually. Our study achieved a conceptual model for a combined analysis of structural geology and geomorphology and subsequently evaluated the effect of the geomorphic shape on the hydrological system of the catchment area.

The integrated approach of remote sensing and geographic information systems was applied intensively on the aspects of hydrological and environmental modeling of the Dead Sea basin. Our research is distinguished by applying this approach on the geomorphological evaluation. Furthermore, our study presents a new geo-visualization of the Dead Sea origin by manipulating different DEM resolutions.

The difficulties that we faced are mostly correlated with data scarcity. There are no hydrograph data for the Zerka Ma'in River. Such data would help to better understand the hydrological system. The borehole data are limited to understand the subsurface geology of the study area in addition to the fact that there are no geophysical data that offer a better understanding for the structure of the wadi.

We do recommend to extend our study to all catchments of the Dead Sea basin and to evaluate the hydrological system of the Dead Sea in terms of geomorphological properties. We do believe that future projects in the Dead Sea basin should combine more the disciplines of geology, hydrology and geomorphology.

Acknowledgments We are thankful to the editorial board and the four anonymous reviewers who improved the manuscript. We would like to thank the German Academic Exchange Service (DAAD—Deutscher Akademischer Austausch Dienst) and the Federal Ministry of Education and Research (BMBF—Bundesministerium für Bildung und Forschung; Grant FKZ 02-WM 0848) for the financial support. We thank Adam Szulc (TU Freiberg, Germany) for reviewing the manuscript.

References

Abrahams D (1984) Channel networks: a geomorphological perspective. Water Resour Res 20:161–188

Andrews J (1991) Palaeozoic lithostratigraphy in the subsurface of Jordan. Nat Resour Auth Geol Bull 2, Amman, p 75

Bayer J (1988) Wadi Araba und Jordantal, Ein tektonischer Graben und zugleich Blattverschiebung. Nat Mus 118:33–45

Ben-Avraham Z (1991) Development of asymmetric basins along continental transform faults. Tectonophysics 215:209–220

Bender F (1968) Geologie von Jordanien. Gebrueder Borntraeger, Berlin

Bender F (1974) Geology of Jordan. Contribution of the regional geology of the earth. Borntraeger, Berlin, p 196

Bundesanstalt für Bodenforschung und Rohstoffe (BGR) (1997) Investigations of the regional basalt aquifer system in Jordan and Syria, E/ESCWA/ENR/1, Hannover,p 60

Bishop P, Hoey TB, Jansen JD, Artza IL (2005) Knickpoint recession rate and catchment area: the case of uplifted rivers in Eastern Scotland. Earth Surf Proc Land 30:767–778

Bolongaro-Crevenna A, Torres-Rodríguez V, Sorani V, Frame D, Ortiz MA (2005) Geomorphometric analysis for characterizing landforms in Morelos State, Mexico. Geomorphology 67:407–422

Closson D, Abou Karaki K (2009) Human-induced geological hazards along the Dead Sea coast. Environ Geol 58:371–380

Closson D, Abou Karaki N, Hallot F (2010) Landslides along the Jordanian Dead Sea coast triggered by the lake level lowering. Environ Earth Sci 59:1417–1430

De Vries HL, Barendsen GW (1954) Measurement of age by the carbon-14 technique. Nature 174(4442):1138–1141

Dubertret L (1929) Etudes des regions Volcaniques du Huran, du Djabal Druse et du diret et Touloul. Rev Geogr Pyhs Geol Dyn 2(4):275–321 **[Paris]**

El Bastawesy M (2007) Influence of DEM source and resolution on the hydrographical simulation of Wadi Keed catchment, Southern Sinia, Egypt. Egypt J Rem Sens Space Sci 9:68–79

El Bastawesy M, Ali R, Al Harbi K, Faid A (2013) Impact of the geomorphology and soil management on the development of waterlogging in closed drainage basins of Egypt and Saudi Arabia. Environ Earth Sci 68:1271–1283

Enzel Y, Agnon A, Stein M (2006) New frontiers in Dead Sea paleoenvironmental research. Geological Society of America, Boulder, p 401

Evans S (1972) General geomorphology, derivatives of altitude and descriptive statistics. In: Chorley RJ (ed) Spatial analysis in geomorphology. Harper and Row, New York, pp 17–90

Flexer A (1968) Stratigraphy and facies development of the Mount Scopus Group in Israel and adjacent countries. Isr J Earth Sci 17:85–114

Flint J (1974) Stream gradient as a function of order, magnitude, and discharge. Water Resour Res 10:969–973

Frumkin A, Elitzur Y (2002) Historic Dead Sea level fluctuations calibrated with geological and archaeological evidence. Quat Res 57:334–342

Gardner W (1983) Experimental study of knickpoint and longitudinal evolution in cohesive, homogeneous material. Geol Soc Am Bull 94:664–672

Garfunkel Z, Ben-Avraham Z (1996) The structure of the Dead Sea basin. Tectonophysics 266:155–176

Garrote J, Cox T, Swann C, Ellis M (2006) Tectonic geomorphology of the Southeastern Mississippi Embayment in northern Mississippi, USA. Geol Soc Am Bull 118–9:1160–1170

Gong J, Xie J (2009) Extraction of drainage networks from large terrain datasets using high through put computing. Comput Geosci 35:337–346
Hack T (1973) Stream-profile analysis and stream-gradient index. J Res US Geol Surv 1:421–429
Horowitz A (2001) The Jordan Rift Valley. Ballkema, Rotterdam, p 730
Horton R (1945) Erosional development of stream and their drainage basin: hydrophysical approach to quantitive morphology. Geol Soc Am Bull 56:275–370
Huggett R (2007) Fundamentals of geomorphology. Routledge, New York, p 447
Hurtrez E, Sol C, Lucazeau F (1999) Effect of drainage area on hypsometry from an analysis of small-scale drainage basins in the Siwalik Hills (central Nepal). Earth Surf Proc Land 24:799–808
Johnson P (1998) Tectonic map of Saudi Arabia and adjacent areas. Technical report USGS-TR-98-3, p 2
Kaliraj S, Chandrasekar N, Magesh NS (2014) Morphometric analysis of the river Thamirabarani Sub-Basin in Kanyakumari District, South West Coast of Tamil Nadu, India, using remote sensing and GIS. Environ Earth Sci 73:7375–7401
Keller EA, Pinter N (2002) Active tectonics: earthquakes and landscape. Prentice-Hall, Upper Saddle River, p 362
Keller E, Gurrola L, Tierney T (1999) Geomorphic criteria to determine direction of lateral propagation of reverse faulting and folding. Geology 27:515–518
Kirby E, Whipple X (2001) Quantifying differential rock-uplift rates via stream profile analysis. Geology 29:415–418
Klinger Y, Avouac JP, Dorbath L, Abou Karaki N, Tisnerat N (2000) Seismic behavior of the Dead Sea fault along Araba valley (Jordan). Geophys J Int 142:769–782
Knighton D (1998) Fluvial forms and processes. Edward Arnold, New York, p 380
Kothyari G, Rastogi K (2013) Tectonic control on drainage network evolution in the Upper Narmada Valley: implication to neotectonics. Geogr J. doi:10.1155/2013/325808
Laske G, Weber M, The DESERT Working Group (2008) Lithosphere structure across the Dead Sea Transform as constrained by Rayleigh waves observed during the DESERT experiment. Geophys J Int 173:593–610
Mahmood A, Batool H, Waheed Z, Akhtar A, Masood A (2013) Investigation of neotectonics along Hazara Kashmir syntaxis through remote sensing and GIS analysis. Int J Recent Dev Eng Technol 1(3):61–67
Niemi T, Ben-Avraham Z (1997) The Dead Sea: the lake and its setting. Monographs on Geology and Geophysics Press 36, Oxford University, pp 326–336
O'Callaghan J, Mark D (1984) The extraction of drainage networks from digital elevation data. Comput. Vision Graph 28:323–344
Odeh T, Gloaguen R, Schirmer M, Geyer S, Rödiger T, Siebert C (2009a): Exploration of Wadi Zerka Ma'in rotational fault and its drainage pattern, Eastern of Dead Sea, by means of remote sensing, GIS and 3D geological modeling. In: Proceeding of SPIE Europe's international symposium on remote sensing (ERS09), vol 7478, Berlin, p 11
Odeh T, Salameh E, Schirmer M, Strauch G (2009b) Structural control of groundwater flow regimes and groundwater chemistry along the lower reaches of the Zerka River, West Jordan, using remote sensing, GIS, and field methods. Environ Geol 58:1797–1810
Odeh T, Gloaguen R, Schirmer M, Geyer S, Rödiger T, Siebert C (2010) Investigation of catchment areas migrations through a Sinstral and Dextral Strike Slip Faults: the case study of Zerka Ma'in and Al Hasa catchment areas, east of the Dead Sea in Jordan. In: Proceedings of the 4 ASME/WSEAS international conference on geology and seismology (GES'10), Cambridge, ISBN: 978-960- 474-160-1, pp 120–126
Odeh T, Geyer S, Rödiger T, Siebert C, Schirmer M (2013) Groundwater chemistry of strike slip faulted aquifers: the case study of Wadi Zerka Ma'in aquifers, north east of the Dead Sea. Environ Earth Sci 70:393–406
Odeh T, Rödiger T, Geyer S, Schirmer M (2015) 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. Environ Earth Sci 73:3309–3326. doi:10.1007/s12665-014-3627-5
Ohmori H (1993) Changes in the hypsometric curve through mountain building. Geomorphology 8:263–277
Phillips J, Lutz D (2008) Profile convexities in bedrock and alluvial streams. Geomorphology 102:554–566
Quennell AM (1956) The structural and geomorphic evolution of the Dead Sea Rift. Q J Geol Soc Lond 114:1–18
Ribolini A, Spagnolo M (2008) Drainage network geometry versus tectonics in the Argentera Massif (French–Italian Alps). Geomorphology 93:253–266
Rodríguez-Iturbe I, Rinaldo A (1997) Fractal River Basins: chance and self-organization. Cambridge University Press, New York, p 564
Rodríguez-Iturbe I, Valdes J (1979) The geomorphologic structure of the hydrologic response. Water Resour Res 15:1409–1420
Saintot A, Angelier J, Chorowicz J (1999) Mechanical significance of structural patterns identified by remote sensing studies: a multiscale analysis of tectonic structures in Crimea. Tectonophysics 32:187–218
Salameh E, Al Farajat M (2007) The role of volcanic eruptions in blocking the drainage leading to the Dead Sea formation. Environ Geol J 52:519–527
Salameh E, Bannayan H (1993) Water Resources of Jordan—present status and future potentials. Friedrich Ebert Stiftung, Amman
Shahzad F, Gloaguen R (2009a) Understanding tectonics from digital elevation model, part 1: drainage network preparation and stream profile analysis. Comput Geosci 37:250–260
Shahzad F, Gloaguen R (2009b) Understanding tectonics from digital elevation model, part 2: surface dynamics and basin analysis. Comput Geosci 37:261–271
Shahzad F, Mahmood S, Gloaguen R (2009) Drainage network and lineament analysis: an approach for Potwar Plateau (Northern Pakistan). J Mt Sci 6:14–24
Shtober-Zisu N, Greenbaum N, Inbar M, Flexer A (2008) Morphometric and geomorphic approaches for assessment of tectonic activity, Dead Sea Rift (Israel). Geomorphology 102:93–104
Sneh A (1996) The Dead Sea Rift: lateral displacement and down faulting phases. Tectonophysics 263:277–292
Snyder N, Whipple K, Tucker G, Merritts D (2000) Landscape response to tectonic forcing: DEM analysis of stream profiles in the Mendocino Triple junction region, Northern California. Geol Soc Am Bull 112:1250–1263
Sreedevi D, Sreekanth D, Khan H, Ahmed S (2012) Drainage morphometry and its influence on hydrology in an semi arid region: using SRTM data and GIS. Environ Earth Sci 70:839–848
Stephenson D (2003) Water resources management. Taylor and Francis, The Netherlands, p 323
Strahler A (1952) Hypsometric (area-altitude) analysis of erosional topography. Geol Soc Am Bull 63:1117–1253
Street-Perrott A, Harrison P (1985) Lake levels and climate reconstruction. In: Hecht AD (ed) Paleoclimate analysis and modeling. Wiley, New York, pp 291–340
Subramanya K (2006) Engineering hydrology. Tata McGraw-Hill, New Delhi, p 392

Troiani F, Della M (2008) The use of the Stream Length-Gradient index in morphotectonic analysis of small catchments: a case study from Central Italy. Geomorphology 102:159–168

Tucker E, Slingerland L (1994) Erosional dynamics, flexural isostasy, and long-lived escarpments: a numerical modeling study. J Geophys Res 99:12229–12243

Van der Beek P, Champel B, Mugnier L (2002) Control of detachment dip on drainage development in regions of active fault-propagation folding. Geology 30:471–474

Vivoni R, Benedetto F, Grimaldi S, Eltahir E (2008) Hypsometric control on surface and subsurface runoff. Water Resour Res 44:12502–12512

Wade AJ, Smith SJ, Black ECL, Brayshaw DJ, Holmes PAC, El-Bastawesy M, Rambeau CMC, Mithen SJ (2012) A new method for the determination of Holocene palaeohydrology. J Hydrol. doi:10.1016/j.jhydrol.2011.10.033

Wang X, Yin Z (1998) A comparison of drainage networks derived from digital elevation models at two scales. J Hydrol 210:221–241

Whipple X (2004) Bedrock rivers and the geomorphology of active orogens. Annu Rev Earth Planet Sci 32:151–185

Whipple X, Tucker E (1999) Dynamics of the stream-power river incision model: implications for height limits of mountain ranges, landscape response timescales, and research needs. J Geophys Res 104:17661–17674

Wilson T, Dominic J (1998) Fractal interrelationships between topography and structure. Earth Surf Proc Land 23:509–525

Wobus W, Whipple X, Kirby E, Snyder P, Johnson J, Spyropolou K, Crosby BT, Sheehan D (2006) Tectonics from topography: procedures, promise and pitfalls. In: Willett SD, Hovius N, Brandon MT, Fisher DM (eds) Tectonics, climate and landscape evolution. Geological Society of America Special Paper 398: Penrose Conference Series, pp 55–74

Wood D (1996) The geomorphologic characterization of digital elevation models. PhD Dissertation, University of Leicester, UK