# GEOSPATIAL ANALYSIS OF THE HYDROLOGICAL CHARACTERISTICS OF NABLUS MOUNTAIN WATERSHEDS IN PALESTINE

**Najeh F. Asmar[1], Jillian Ooi Lean Sim[1] Ahmed Ra'fat Ghodieh[2] & Rosmadi Fauzi[1]**

1. Department of Geography, Faculty of Arts and Social Sciences, University of Malaya, Malaysia.
2. Head of Graduate Department for Human Faculties, An-Najah National University, Palestine

Corresponding email: najehasmar@gmail.com

**ABSTRACT**

Morphometric parameters are the mathematical visualizations of watershed landforms that provide powerful insights into the hydrological processes that drive and shape a watershed. This is especially true for climatically variable regions with complex topographies such as in our study area in the Nablus Mountains. This study aimed to identify the morphometric characteristics of the Nablus Mountains and the spatial distribution of those characteristics. By using the 2008 ALOS PALSAR Digital Elevation Model with a spatial resolution of 12.5 meters for surface and hydrological analysis, eleven main watersheds were recognized and divided into two main drainage systems, i.e. the Mediterranean Sea Drainage System (MSDS) in the west and Dead Sea Drainage System (DSDS) in the east. Morphometric characteristics analyses were performed across linear, areal and relief aspects, resulting in 25 parameters. Drainage density (Dd), bifurcation ratio (Rb), circularity ratio (Rc) and hypsometric analysis (Hs) values were the parameters that most clearly differentiated between western and eastern watersheds. Western watersheds were more elongated in shape, with dense vegetation cover, steep sides and high annual rainfall amounts, and the hypsometric integrals revealed them to be older than those in the east. In contrast, watersheds in the east had high circularity ratio, low vegetation cover and steep slopes, which indicated high susceptibility to flash floods and soil erosion. Thus, soil conservation practices and rainwater harvesting techniques would be better suited for the eastern watersheds and sub-watersheds in the central part of the Nablus Mountains, where slopes are steep and rainfall amounts are high.

**Keywords**: Morphometric, Hypsometric, ALOS PALSAR, GIS, Semi-arid, Nablus Mountains.

## INTRODUCTION

Drainage watersheds represent the most common landforms that reflect the relationship between climate, topography, and geology. These three drivers act in combination to exert an influence on watershed morphology through factors such as rainfall, temperature, vegetation, slope, aspect, and soil type. The spatial variation of these factors likewise produces variation in watershed morphology. Therefore, identifying the morphometric characteristics of watersheds has become a basic aspect of understanding the hydrological processes of a region (Price 2011; Sujatha et al. 2015).

Morphometry is essentially a mathematical description of the earth's surface formations and landforms (Clarke 1966), which can be studied across several aspects: one-dimensional (linear), two-dimensional (areal) and three-dimensional (relief) (Abboud and Nofal 2017; Banerjee et al. 2017; Magesh et al. 2013; Radwan et al. 2017). Horton (1945) was the first scholar to identify some of the morphometric parameters of the drainage basin such as stream order, stream numbers, stream length, drainage density, and drainage texture (Kant et al. 2015; Strahler 1967).

By using morphometric descriptions, analyses of hydrological characteristics, i.e. features that influence surface run-off, have become a key part of studying weathering processes and their resultant landforms in watersheds. For instance, drainage density and stream frequency have been shown to reflect rainfall-runoff processes in a watershed (Magesh et al. 2013). Flood characteristics (peak discharge & duration) have been correlated with the circularity ratio (Rc) and ruggedness number (Rn parameters) (Rahaman et al. 2015; Wani et al. 2018). High values of drainage density, stream frequency, and the bifurcation ratio have a positive relationship with soil erodibility, in contrast with the circularity ratio, and basin shape (Rahaman et al. 2015). Likewise, slope inclination and slope aspect appear to have an effect on vegetation cover in the Nablus Mountains (Ghodieh 2000), which in turn affect infiltration rates and surface runoff. Thus, watershed morphometry provides powerful insights into the hydrological processes that drive and shape it.

Geographical Information Systems (GIS) and Remote Sensing (RS) techniques have proved to be highly effective in producing accurate analyses of watershed characteristics (Ali and Ali 2014; Magesh et al. 2013; Patel et al. 2012; Singh et al. 2014; Waikar and Nilawar 2014; Wani et al. 2018). The spread of free high-resolution satellite imagery has helped in the interpretation of spatial data and its display at high accuracy and low costs (Jafarzadegan and Merwade 2017; Kant et al. 2015; Martin et al. 2005). Based on such techniques, morphometric analyses have been used to prioritize watersheds and to locate check dams (Ratnam et al. 2005), evaluate flash flood hazards and risk assessment (Angillieri 2008; Masoud 2016), make decisions about soil and water conservation (Farhan 2017), calculate peak discharge (Fernandez 2017), interpret drainage parameters for water resource management and sustainable development (Banerjee et al. 2017; Dinagara Pandi et al. 2017), plan for the development of a river basin

(Magesh et al. 2013), and to assess the linkages between morphometric parameters, geomorphological features, and hydrological processes (Ezeh and Mozie 2019; Nongkynrih and Husain 2011). Hence, morphometric characterization has become an essential requirement in surface water management and in planning for the sustainable use of water resources (Al-Saady et al. 2016; Dastorani et al. 2017; Soni 2017).

In regions with highly variable climates such as our study area, morphometric and hydrological characteristics of watersheds bear particular significance. The Nablus Mountains region is classified as semi-humid in the coastal plains, semi-arid in the western slopes, and arid in the eastern slopes of the Jordan Valley. Such variation in its climatic characteristics is a result of high topographic contrasts in elevation, aspect, and slope inclination, all of which have implications on water resources. Palestine suffers from insufficient surface and groundwater sources as a result of annual rainfall variation in time and space, and in increasingly high consumption of groundwater sources (PWA 2013). However, the reverse is also true; extreme rainfall events induce flash floods and lead to the destruction of properties and lives, such as in the case of the flash flood of January 2013 which took three victims and incurred high economic losses (Hawajri 2016). Thus, morphometric and hydrological characteristics can have significant consequences on human livelihoods and well-being in this region.

In this study, we aimed to identify the morphometric characteristics of eleven main watersheds in the Nablus Mountain regions by developing a Digital Elevation Model (DEM) in a GIS. This will provide a better understanding of the hydro-geomorphological processes in arid and semi-arid environments such as in Palestine, which may serve as the basis of performing future rainfall-runoff modelling studies, and in identifying the best possible sites for establishing rainwater harvesting systems and flash flood mitigation.

## STUDY AREA

The Nablus Mountains Series is located in the northern part of the West Bank Mountains. It is located between the Jordan Valley in the east and the coastal plains of the Mediterranean Sea in the west. The Araa watershed and Marj Ibn Amir plain separate the study area from the Carmel mountain range and the Highlands of Galilee in the northwest and the north, respectively. The Nablus Mountains are detached from Jerusalem and the Ramallah Mountains in the south by the Dair-Balout (Sraida) watershed which flows to the Mediterranean Sea basins, and Oja watershed, which flows to the Dead Sea in the east (Figure 1). The study area lies within longitude 34° 56′ 51″ E and 35° 33′ 32″ E, and latitude 31° 54′ 32″ N and 32° 33′ 55″ N, with an estimated area of 3,365 $km^2$. The elevation of the study area rises from 371 meters below sea level in the outlet of the Oja watershed in the Jordan Valley to 1016 meters above sea level in the Qarn Surtba peak, which is located at the southeast of the study area (Figgure 2).

The general landforms of the study area are a result of lifting associated with the Great Rift Valley inception in the Jordan Valley in the Miocene Epoch. The

Nablus Mountains are geologically complex and diverse; folding and faulting formations exist in the south and the north, respectively. Limestone and marl sedimentary formations are a result of the deep sedimentation of the Tethys Sea. Quaternary sedimentary formations were formed by weathering of rocks in the lowlands (Abdlkadeer and Wishahy 1999) (Figure 3 (a)).

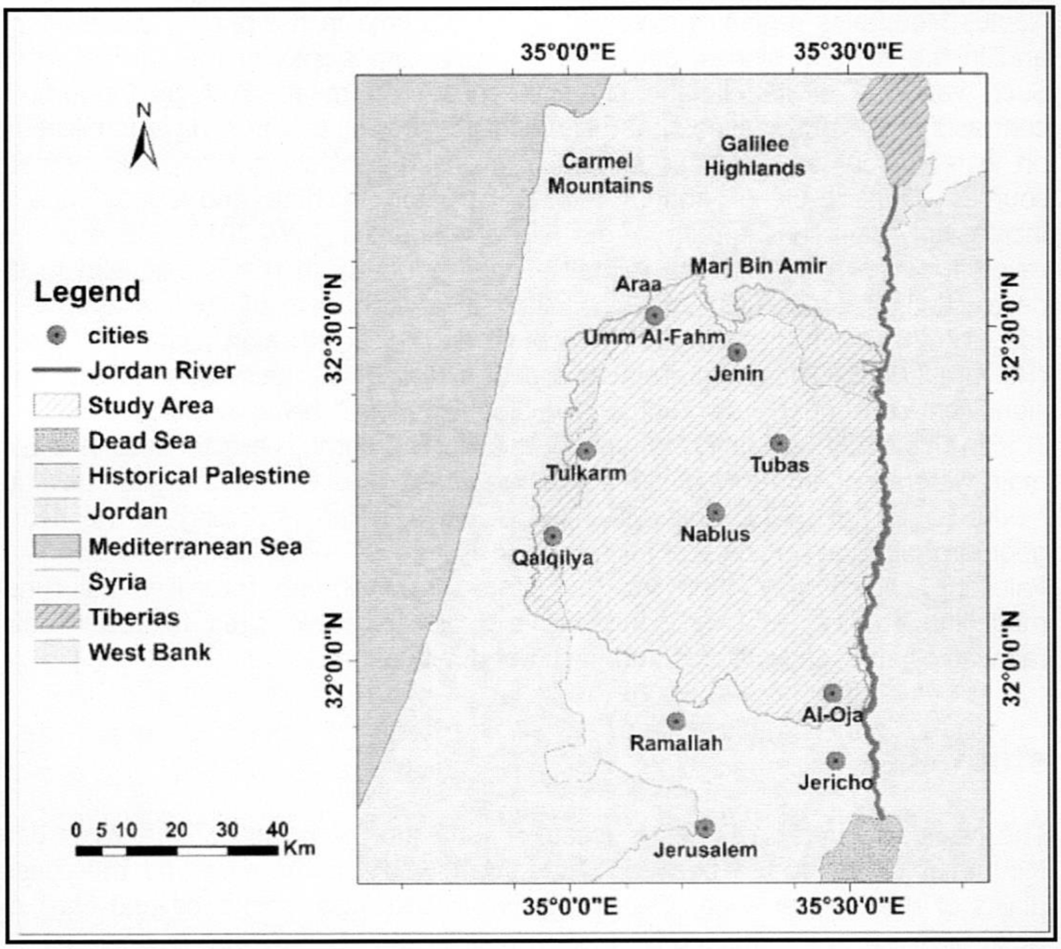


**Figure 1: Nablus Mountains region ( based on data from http://geomolg.ps/).**

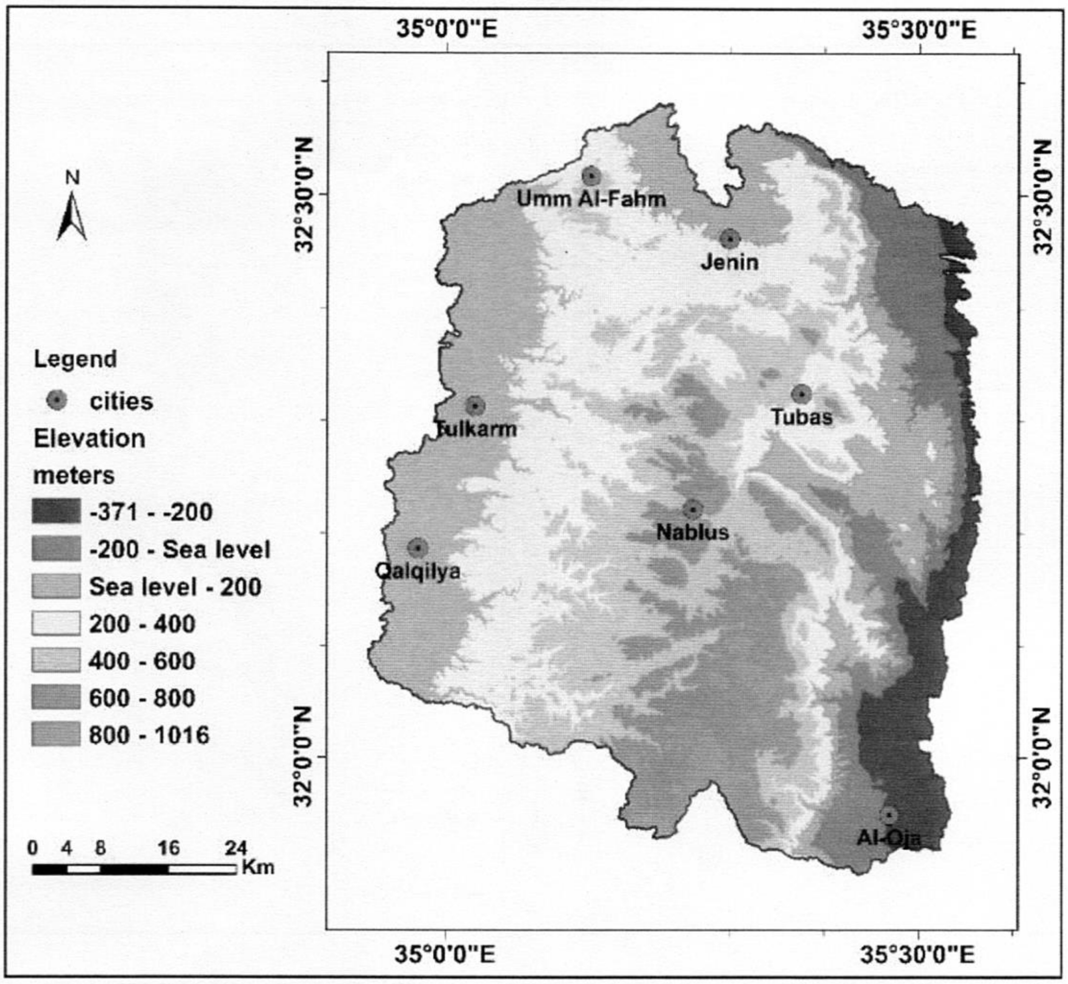


**Figure 2: Elevation map of the study area ( based on ALOS PALSAR DEMS from https://vertex.daac.asf.alaska.edu/ ).**

The Nablus Mountains are characterized as a Mediterranean Climate Region, which has hot summers and moderate rainy winters. The annual precipitation average for the study area ranges between 166 mm/y at the Jericho meteorological station and 739.1 mm/y at the Bidea meteorological station (Figure 3 (b)) (http://www.pmd.ps/viewSeasonRainEng.do).

Human settlements are highly concentrated on the western watersheds, with lower settlement concentration next to the main drainage streams in the eastern watersheds. Likewise, vegetation cover density in the western slopes is much higher than in the eastern slopes, where rainfall average is low and evapotranspiration is relatively high (Ghodieh 2000) (Figure 3 (c)). Moreover, the eastern slopes are much steeper than in the west, which is reflected by the variation of vegetation density and settlement distribution (Figure 3 (d)).

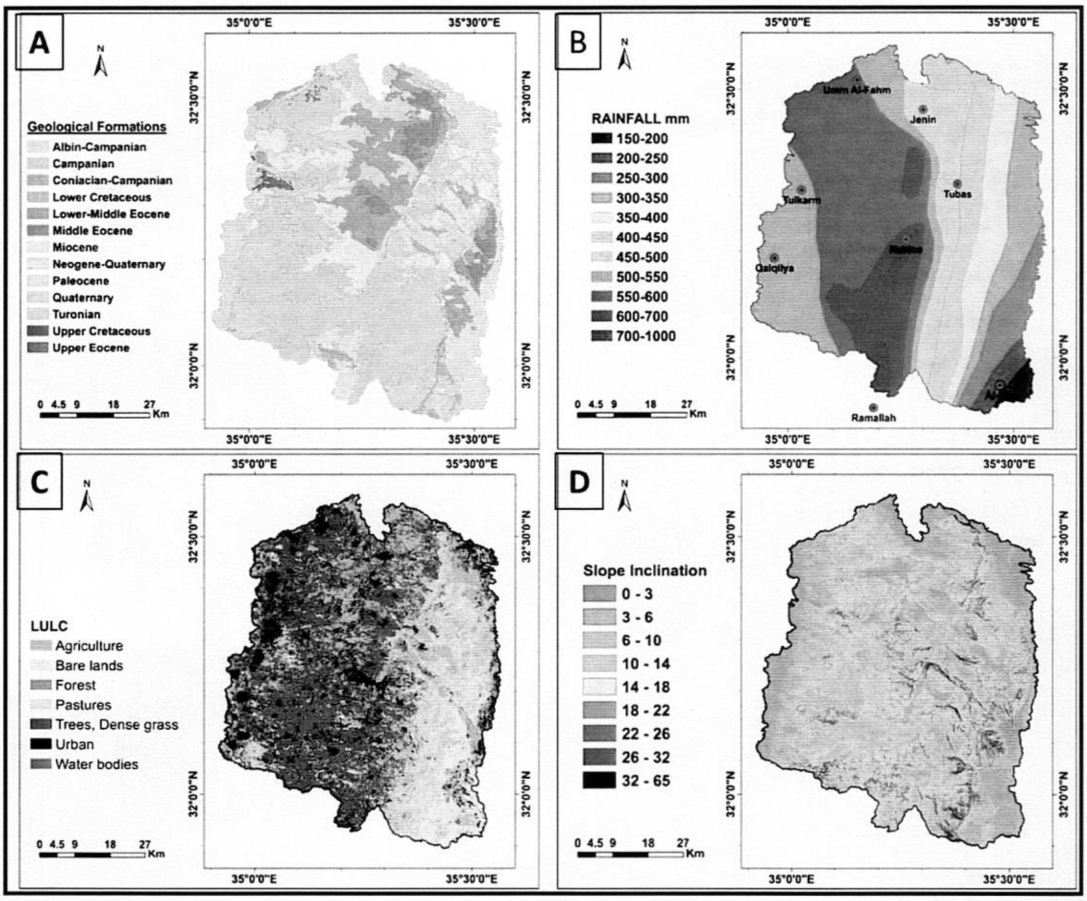


**Figure 3: (A) geological formations, (B) rainfall annual averages , (C) Land Use /Land Cover, and (D) slope inclination (based on ALOS PALSAR DEMS from https://vertex.daac.asf.alaska.edu/ ).**

## MATERIALS AND METHODS

The Geographical Information System software (GIS 10.5) was used to extract the morphometric and topographic parameters of the study area. Two 2008 ALOS PALSAR *(Advanced Land Observing Satellite (ALOS) and The Phased Array type L-band Synthetic Aperture Radar (PALSAR)* Digital Elevation Models (DEMs) with a spatial resolution of 12.5 meters were downloaded from the Alaska Satellite Facility's Vertex data portal (https://vertex.daac.asf.alaska.edu/). These two DEMs were used in GIS 10.5 to cover the Nablus Mountains and projected onto the Palestine_1923_Palestine_Grid coordinate system. The first step of the analysis process was to merge the two DEMs into one mosaic DEM to demarcated the boundaries of the drainagefrom the up-streams to the outlet point of each watershed in the study area. These boundaries were identified by extracting the hydrological parameters (fill, flow direction, flow accumulation, stream order and basin features) and the topographical parameters (slope, aspect, and elevation) by using the Spatial Analyst extension in GIS (Figure 4).

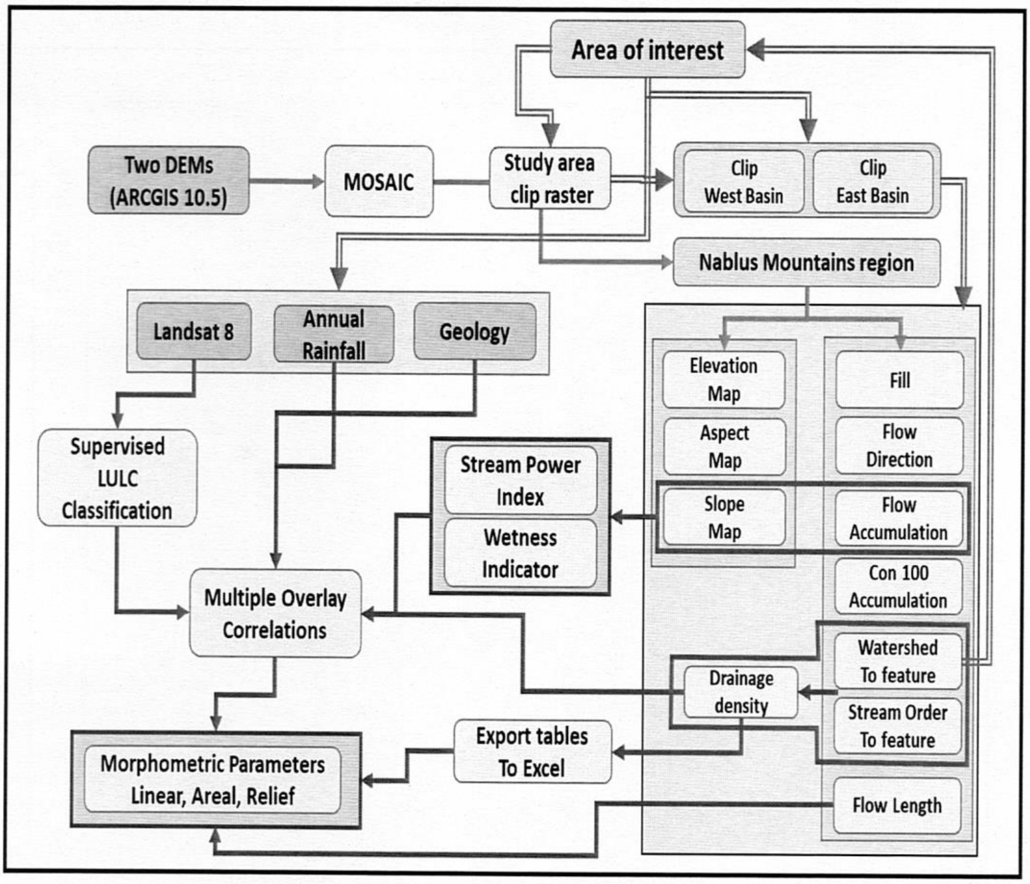


**Figure 4: Methodological framework of the study.**

A geological map of the Nablus Mountains was produced by digitizing geological survey sheet maps of Israel (1:50,000) into feature layers. A rainfall annual average map was generated by using records of the rainfall averages of 28 meteorological stations in the study area. A Land Use/Land Cover (LULC) map was produced by classifying the Landsat-8 satellite image (4/23/2016) of the study area, downloaded from earthexplorer.usgs.gov. The supervised classification approach was used in GIS 10.5 and verified using Google Earth images and field observations.

The main watersheds of the Nablus Mountains are divided into two groups: the Dead Sea Drainage Systems (DSDS) in the east (eastern watersheds) which includes Oja, Faria, Fasayil, Shobash and Maleh watersheds and several sub-watersheds that pour directly into the Jordan River, and the Mediterranean Sea Drainage Systems (MSDS) in the west (western watersheds) which includes Zoumar, Massen, Qana, Ateen, Abo-Nar and Dair-Balout main watersheds and many other sub-watersheds that follow the lower drainage basins into the coastal plain of the Mediterranean Sea (Figure 5). The eastern watersheds are the smaller of the two, at 1,297.2 $km^2$. In contrast, the western watersheds cover an area of 2,067.8 $km^2$.

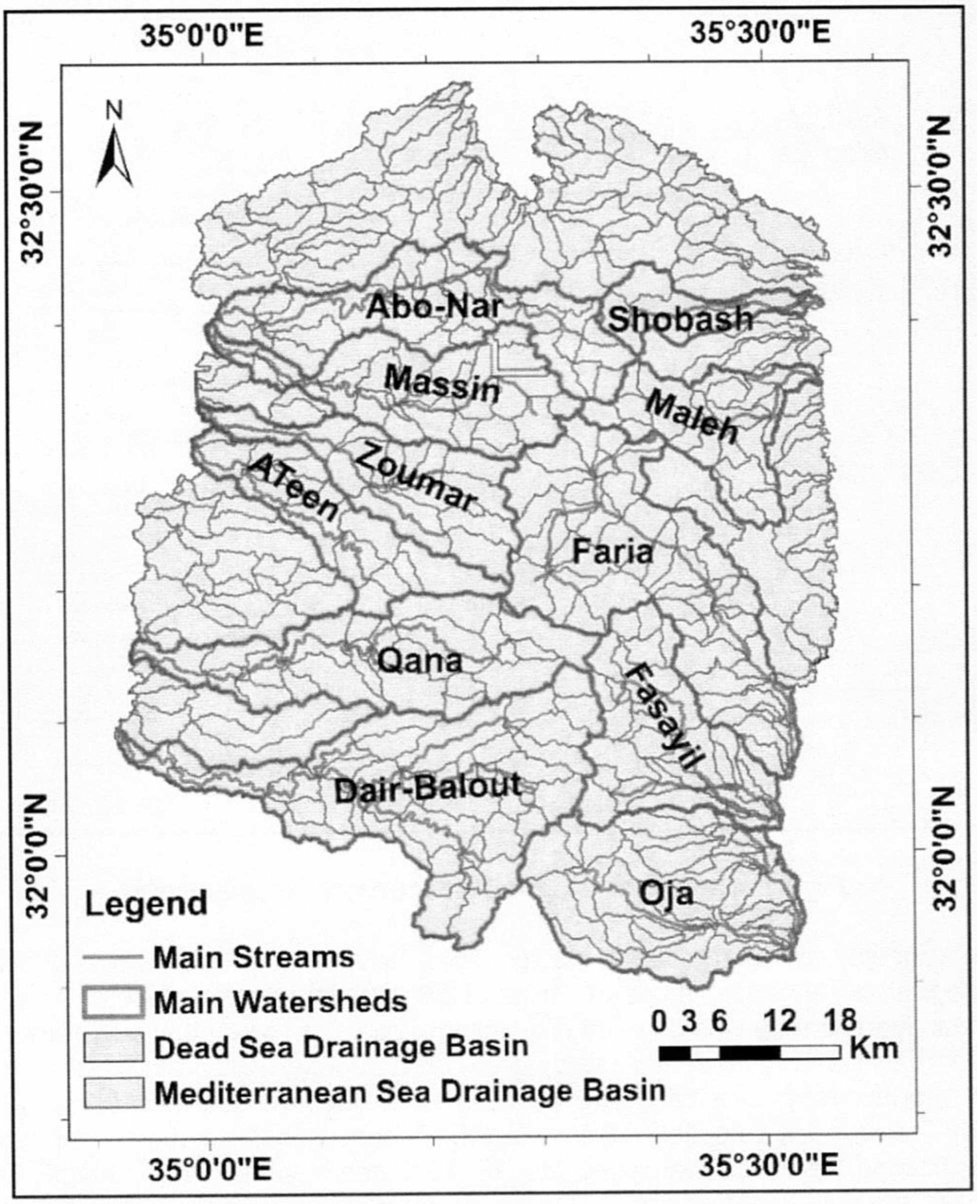


**Figure 5: Main watersheds of the Nablus Mountains (based on ALOS PALSAR DEMS from https://vertex.daac.asf.alaska.edu/)**

Morphometric parameters in this study were categorized into three groups (Table 1):

**One-dimensional aspect (linear parameters)**

Linear parameters reflect topographic landforms and the control of geological structures (Waikar and Nilawar 2014). Stream Order (Su) is a parameter generated by Strahler (1964), whereby the smallest and the first segments are designated as the first order, the second stream order are generated by joining two streams of the first order, the third order from two segments of the second order, and so on. The Con 100 accumulation flow was adopted to assign the first-order streams which means that the first-order stream starts when the number of upslope cells that flow into a certain cell reaches 100 cells. Stream Length Ratio (Rl) is defined as the ratio of the mean length of the streams for a certain order, to the mean length of the streams over the next lower order (Horton 1945). Bifurcation Ratio (Rb) is the ratio of the stream number of any order to the stream number of the next highest order (Strahler 1957). Infiltration Number (If) has a positive relationship with direct runoff (Rai et al. 2017) and is defined as the product of stream frequency and drainage density (Pareta and Pareta 2012). Sinuosity ratio (Si) is defined as the ratio of the longest flow path of the watershed to the watershed's maximum length (Schumm 1963); its values range between 1 and 4, with 1 referring to a perfectly straight line and 4 referring to a highly meandering path. All parameters were derived using the Spatial Analyst extension of GIS 10.5.

**Two-dimensional aspects (areal parameters):**

Areal parameters demonstrate the shape of a watershed, which is a reflection of the watershed perimeter and area (Table 1). Drainage Density (Dd) is the ratio of the cumulative length of all stream orders to that of the watershed surface area (km/ $km^2$) (Horton 1945). Form Factor (Ff) is defined as the ratio of the watershed area to the square of the watershed's maximum length (Horton 1932). The highest value is 0.75, which indicates a perfectly circular watershed (Al-Saady et al. 2016). Circularity Ratio (Rc) is used to outline the watershed form. It is defined as the ratio of the watershed area to the area of a circle, which has the same perimeter as that of the watershed (Miller 1953; Strahler 1964). Elongation Ratio (Re) is defined as the ratio of the diameter of a circle, which has the same area as that of a given watershed to the maximum length of the same watershed (Schumm 1956). Constant channel maintenance (C) is inversely proportional to the drainage density of a watershed and defined as the area of the watershed surface to the total stream length of all orders (Schumm 1956), and Shape Index (Sw) is defined as the ratio of the watershed's maximum length to the watershed area (Horton 1932).

**Three-dimensional aspects (relief parameters):**

Relief parameters describe the vertical dimension of the watershed and express the geomorphological stage and landform features of the drainage watershed

(Table 1). Basin Relief (Bh) is defined as the vertical distance between the highest point (source point) of the watershed and the lowest point (mouth point) of the watershed. It indicates the potential denudation energy (Farhan 2017). Relief Ratio (Rhl) is defined as the ratio of Basin Relief (Bh) to the maximum length of the basin that is parallel to the main channel (Schumm 1956). Dissection Index (Dis) is an embodiment of the vertical denudation or degree of dissection, which explains the stages of landscape development, as well as the morphometric and physiographic attributes of the landscape (Schumm 1956; Singh and Dubey 1994). Ruggedness number (Rn) is a dimensionless number that reveals the unevenness of a surface and implies slopes coarseness and landscape fragmentation (Al-Saady et al. 2016). It is a product of vertical basin relief and drainage density (Strahler 1957).

Hypsometric Analysis (Hs) is a powerful tool to understand the geomorphological stages and geological development of a watershed (Farhan et al. 2016), its tectonic activity, weathering of mass-movement, denudation processes, and direct runoff, which produce a geometrically complex topography (Luo and Harlin 2003; Pareta and Pareta 2012). The hypsometric analysis can be presented as a hypsometric curve alongside the Hypsometric Integral (Hi), which can provide information on the development stages of the landforms. The Hs represents the ratio of the surface mass to the horizontal surface of the watershed (Hurtrez et al. 1999). These are dimensionless numbers that characterize the relationship between the horizontal cross-section of a watershed to its overall relief (Strahler 1957).

Similarly, the Hypsometric Integral (Hi) represents the geological development and geomorphological stages of a watershed (Farhan et al. 2016). Hi and the Erosion Integral (Ei) percentage gives an accurate understanding of the erosion cycle of the basin material. It can be classified into three categories; a value less than 0.30 is considered to be at the old stage or Monadnock, 0.30-0.60 is denoted as a mature or equilibrium stage, and a value above 0.60 is classified as the primary or young stage (Strahler 1952).

Water flow is an extremely erosive power, which can be defined in the stream power index (SPI). It is a ratio of the watershed area against the inclination of the slope of the watershed surface (Moore et al. 1991). It can be interpreted in the GIS calculator as eq 1:

$$SPI= (Ln\ (Flow\ accumulation + 0.001) * ((Slope/100) +0.001) \qquad (1)$$

The Topographical wetness index (WI) highlights the influence of topography on sediments and deposits in the plain surfaces next to the slope toes (Conforti et al. 2011). This indicator can calculated through the GIS raster calculation extension eq 2:

$$WI= (Ln\ (Flow\ accumulation + 0.001) / ((Slope/100) +0.001) \qquad (2)$$

Figure 4 represents the methodology stages of this study which start with the input data (two DEMs) to define drainage boundaries by extracting the hydrological features and identifying each watershed from the up-stream to the outlet points.

**Table 1: Morphometric parameters and calculation methods**

| Morphometric Parameters | Formula/ Definition/Methods | Reference |
|---|---|---|
| **Linear Parameters** | | |
| Stream order (Su) | Hierarchical order | (Strahler 1964) |
| Stream Number (Nu) | ----- | (Horton 1945) |
| Stream Length (Nl) | Length of the Stream (km) | |
| Stream length Ratio (Rl) | Rl=Nl/Nl-1; where, Nl-1=Stream length of next lower order. | |
| Bifurcation Ratio (Rb) | Rb = Nu / Nu+1 Where, Nu+1= Number of segments of the next higher order. | (Schumm 1956) |
| Infiltration Number (If) | If=Fs*Dd. Where, Fs= Stream Frequency, Dd = Drainage density. | (Faniran 1968) |
| Length of Over Land Flow (Lof) | Lof = 1/ 2Dd. | (Horton 1945) |
| **Areal Parameters** | | |
| Drainage Density (Dd) | Dd =L/A. Where, L=Total length of Stream, A=Area of the Watershed (km/ km2). | (Horton 1945) |
| Drainage texture (Dt) | Dt=Nu/P. Where Nu= Total number of stream, p= perimeter of the watershed. | |
| Stream Frequency (Fs) | Fs = Nu /A. Where, Nu= Total number of Stream. | |
| Drainage intensity (Di) | Di = Fs/Dd. | (Faniran 1968) |
| Texture ratio (T) | T=N1/P. Where, N1= Total number of first order stream. | (Horton 1945) |
| Form Factor (Ff) | Ff = A / (Lb) Where, Lb=Maximum Basin length. | (Horton 1932) |
| Circularity Ratio (Rc) | Rc = 4ðA/ P2. Where, , ð = 3.14 | (Miller 1953) |
| Elongation Ratio (Re) | Re= 2√ (A/ð) / Lb. | (Schumm 1956) |
| Constant channel maintenance (C) | 1/Dd. | (Horton 1945) |
| Shape index (Sw) | Sw = 1/Ff. | (Horton 1932) |
| **Relief Parameters** | | |
| Basin Relief (Bh) | Vertical Distance between the lowest and highest point in watershed in meters. | (Schumm 1956) |
| Relief Ratio (Rhl) | Rhl=Bh/Lb; where, Lb= Basin length in km. | |
| Dissection Index (Dis) | Dis = Bh/Ra, where, Ra = absolute relief. | (Singh and Dubey 1994) |
| Ruggedness number(Rn) | Rn=Bh*Dd. | (Schumm 1956) |
| Hypsometric Analysis (Hs) | Hs = (a/A)/(h/H); Where a/A = relative area, h/H = relative elevation | (Strahler 1957) |
| Hypsometric Integrals (Hi) | HI = (E mean–E min)/(E max–E min); Where E =elevation | (Strahler 1952) |

## RESULTS AND DISCUSSION

Morphometric analysis of the Nablus Mountains showed that the Mediterranean Sea Drainage System had high values of stream frequency (Fs) and mean bifurcation ratio (mRb), and low values of drainage density (Dd) and infiltration numbers (If) in comparison to the Dead Sea Drainage System. This indicates that the western drainage basin has gentler slopes, lower relief, and lower runoff rates. Such morphometric characteristics are compatible with the denser vegetation cover and higher infiltration capacity previously found in the west (Ghodieh 2000; Khalaf and Donoghue 2012). On the other hand, the high drainage density values, steeper slopes, and higher direct runoff of the Dead Sea Drainage System in the east are more typically associated with its sparse vegetation cover and lower infiltration capacity (Chopra et al. 2005). These findings matched well with the land cover and the topographic maps of the study area (Ghodieh 2000).

The hypsometric integrals (Hi) indicate that both the eastern and western sides of the study area are in the primary stage of geomorphic development (Figure 6). The erosion integral (Ei) variance between the Dead Sea Drainage System and the Mediterranean Sea Drainage System was low, at 37.32% and 35.34%, respectively.

The high variation in land cover, relief, and general slope between the eastern and western drainage systems appear to have limited impact on the morphometric parameters (Hypsometric Integrals (Hi) and Erosion Integrals (Ei)). This may be due to the spatial distribution in rainfall amounts which have a direct impact on vegetation cover density (Ghodieh 2000). For instance, vegetation cover density decreased from west to east in a similar way as rainfall amounts (Figure 3 (b)). It is possible that low rainfall amounts that fall across the eastern slopes have yielded moderate vegetation cover and erosion rates in the areas of the first-order stream.

The high elevation interval in the eastern watersheds is 1,378 meters from the up-stream point to the outlet point in Oja watershed, which reinforces our earlier point about the steepness of the slopes here in comparison to the west. Similar, the vertical interval of 970 meters in the western Dair-Balout watershed indicates that these are gentler slopes (Table 2).

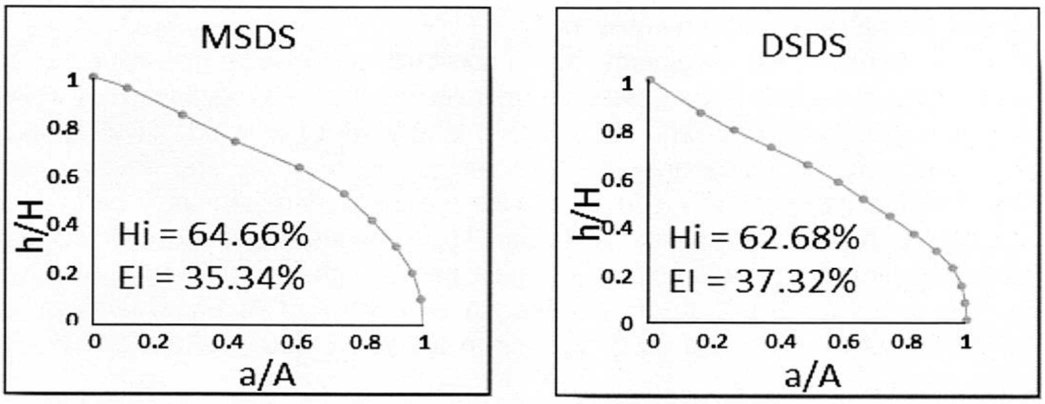


**Figure 6: Hypsometric curve (Hs), hypsometric integral (Hi) and erosion integral (EI) of the Mediterranean Sea Drainage System (MSDS) and the Dead Sea Drainage System (DSDS) in the Nablus Mountains.**

**Table 2: Morphometric parameters of the eastern and western basins.**

| **Stream order** | **Mediterranean Sea Drainage System** | | **Dead Sea Drainage System** | |
|---|---|---|---|---|
| | **Stream Number** | **Stream Length(km)** | **Stream Number** | **Stream Length (km)** |
| 1 | 25699 | 4784.1 | 15644 | 2992.4 |
| 2 | 11108 | 1893.3 | 6963 | 1407.5 |
| 3 | 6243 | 1076.6 | 4114 | 827.7 |
| 4 | 3712 | 558.8 | 1949 | 385.2 |
| 5 | 1796 | 252.8 | 1241 | 222.4 |
| 6 | 1704 | 247.6 | 577 | 87.5 |
| 7 | 261 | 38.7 | 265 | 35.8 |
| Total | 50523 | 8851.9 | 30753 | 5958.5 |
| Area ($km^2$) | 2,067.8 | | 1,297.2 | |
| Drainage Density | 4.28 | | 4.6 | |
| Stream Frequency | 24.43 | | 23.71 | |
| Mean/Bifurcation Ratio | 2.57 | | 1.99 | |
| Infiltration Number | 104.6 | | 109.1 | |
| Max Elevation (m) | 1016 | | 1016 | |
| Min Elevation (m) | 46 | | -371 | |
| Hypsometric Integrals | 64.66% | | 62.68% | |

## Linear morphometric parameters

**Stream order (Su)** segments are important parameters to visualize and understand hydrological processes in drainage watersheds because they reflect the geological structures and topographic landforms of a region. The drainage watersheds in the study area were classified into five, six and seven orders. Stream-order was positively correlated with basin size, wherein small basins such as Shobash have lower stream order while larger basins such as Dair-Balout have higher stream order (Table 3). The largest basins with up to seven orders were the Oja and Dair-Balout streams. Although Shobash and Ateen watersheds are relatively smaller, they had up to six stream orders for both western and eastern watersheds (Table 3) and (Figure 7).

The **stream number (Nu)** is recognized as the total number of stream segments for each stream order. For both western and eastern watersheds, the first order number included 51% of the total streams in the study area, while the second and the third orders included 22% and 13%, respectively (Figure 7). Horton (1945) stated that the stream number has an inverse linear relationship with the stream order. The inverse relationship is true for the Nablus Mountains, where the highest values of the stream number belonged to the first order. However, the linear relationship between the stream number and stream order was not clear for most basins in the study area. This result may be an expression of the control exerted by geologic structures and topographic variations of high relief and steep slopes (Rai et al. 2017).

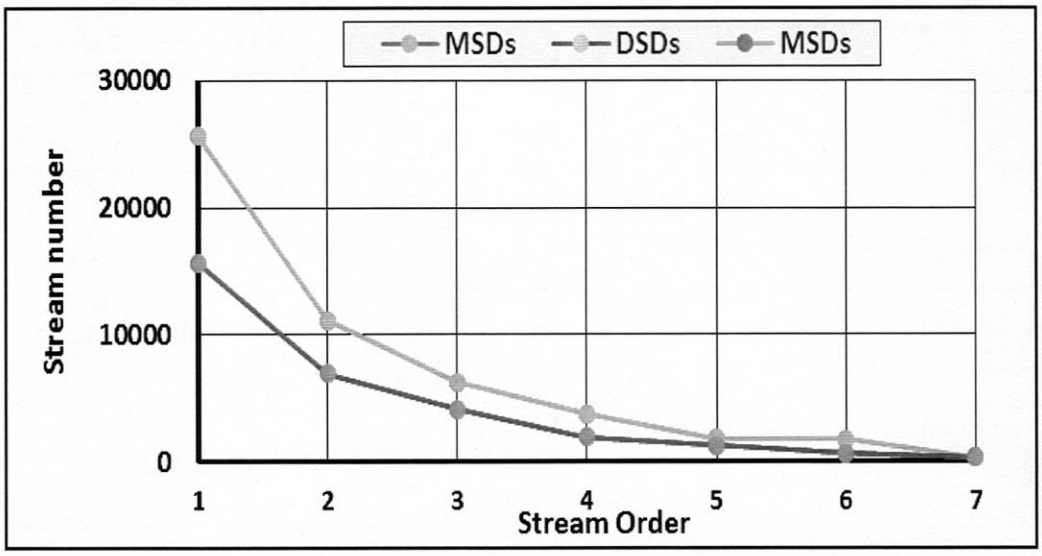


**Figure 7: Stream number and stream order of the Mediterranean Sea Drainage System (MSDS) and Dead Sea Drainage System (DSDS) in the Nablus Mountains.**

**The Total Stream Length (Nl)** for each stream order revealed the impact of the surface runoff characteristics, which are linked to topographic and geologic structures. There were a relatively high number of first order streams in the study area and thus, the high NI values for these order streams were higher than the rest. The smaller length of streams may be an indicator of steep slopes and fine geologic textures (Waikar and Nilawar 2014). However, the length of the total stream of the higher orders is longer than those of the lower orders as a result of the elongated shape of the main watersheds, geology and expansion of the upper sub-watersheds of the drainage watersheds. For instance, in Qana watershed, the total length of the fifth-order was 27.5 km, and in the sixth-order was 43.2 km. The stream length ratio is the ratio of the mean stream's length of a given order, to the next lower order (Horton 1945). The mean stream length ratio for the main drainage watersheds ranged between 0.93 to 1.07 in Massin and Fasayil watersheds, respectively. The stream's length ratio for the sixth order ranged between 0.69 and 1.94 for the Faria and Massin watersheds, respectively. The low values of stream length ratio indicate the late mature stage of geomorphic development of the watersheds in the study area (Pareta and Pareta 2012).

The **Bifurcation Ratio (Rb)** reflect watersheds with an elongated or circular shape (Morisawa 1985). Previous studies have shown that the mean Rb values in general range between 3 and 5, which indicates that there is a weak or negligible geological control in the watersheds (Pareta and Pareta 2012; Radwan et al. 2017; Strahler 1957). Low values of Rb reflect watersheds with an elongated shape, while higher values reflect watersheds with a circular shape (Morisawa 1985). In this study, Zoumar and Faria watersheds had the lowest Rb for the fifth and sixth orders (0.5), which reflected the elongated shapes of these watersheds. Meanwhile, Oja and Fasayil watersheds showed a high value of Rb value for the sixth order (14.13 and 81, respectively). These high values reflected the nearly circular shapes of these watersheds. These watersheds (Oja and Fasayil ) show higher values of the mean Rb for all orders, at 4.03 and 14.95, respectively. The eastern watersheds have higher Rb values than the western watersheds due to steep slopes, low vegetation cover and circular shape such as in Fasayil and Oja watersheds.

**The Infiltration number (If)** plays an important role in understanding and assessing the infiltration characteristics of the watersheds. Higher values of the infiltration number in a watershed reflect lower infiltration capacity and higher runoff. Therefore, direct surface runoff is directly proportional to the infiltration number (Rai et al. 2017). Table (3) shows the watersheds with high values of infiltration numbers, such as the Massin (158.49), which can be interpreted to mean that it has low infiltration capacity, high runoff values, and soil erosion probability. On the contrary, in the Dair-Balout watershed, the If value is 90.21 which means low direct runoff and high infiltration capacity.

The **Sinuosity ratio (Si)** is defined as the ratio of the longest flow path of the watershed to the watershed's maximum length (Schumm 1963). Its values range between 1 and 4. Drainage watershed with a Si value of less than 1.5 is defined as a sinuous watershed; a Si value of more than 1.5 implies a meandering watershed (Ezeh and Mozie 2019; Pareta and Pareta 2012). The Si values for the main watersheds in the study area ranged between 1.04 and 1.55 for Qana and Faria, respectively. This indicated that all of the main watersheds were classified as sinuous except Faria, which was meandering (Table 3).

**Table 3: Linear morphometric parameters of the main watersheds.**

| Main watersheds | Stream order | Stream Number | Stream Length (km) | Mean Stream length Ratio | Mean Bifurcation Ratio | Length of Over Land Flow | Infiltration Number | Sinuosity ratio |
|---|---|---|---|---|---|---|---|---|
| Dair-Balout | 7 | 9125 | 1362.9 | 1 | 1.74 | 0.14 | 90.21 | 1.55 |
| Qana | 6 | 6274 | 979.7 | 0.98 | 1.76 | 0.12 | 103.33 | 1.04 |
| Zoumar | 6 | 3765 | 628 | 0.96 | 1.73 | 0.12 | 100.63 | 1.37 |
| Ateen | 6 | 3409 | 530.1 | 1 | 1.75 | 0.13 | 101.85 | 1.42 |
| Massin | 6 | 4506 | 1220.8 | 0.93 | 1.67 | 0.08 | 158.49 | 1.3 |
| Abo-Nar | 6 | 5052 | 941.7 | 0.98 | 1.78 | 0.11 | 108.19 | 1.51 |
| Oja | 7 | 6017 | 1166 | 0.97 | 4.03 | 0.11 | 98.08 | 1.32 |
| Fasayil | 7 | 4551 | 818.2 | 1.07 | 14.95 | 0.11 | 109.98 | 1.4 |
| Faria | 7 | 7935 | 1540.3 | 0.95 | 1.85 | 0.11 | 112.61 | 1.55 |
| Maleh | 6 | 2889 | 516.8 | 0.98 | 1.85 | 0.12 | 93.52 | 1.48 |
| Shobash | 5 | 1349 | 252.6 | 0.99 | 1.65 | 0.12 | 91.41 | 1.49 |

## Areal morphometric parameters

**Drainage density (Dd)** is the most important of the areal morphometric parameters. It is usually linked to land cover, terrain, and soil properties. High Dd values are normally associated with impermeable and weak surface materials, low vegetation cover, and high relief terrains (Rasool et al. 2011; Waikar and Nilawar 2014) as well as high runoff surfaces (Omolabi and Fagbohun 2019). The Dd results of the main watersheds in the Nablus Mountains ranged between 3.67 and 6.55 for the Dair-Balout and Massin watersheds, respectively. In this study, the Dd values of the eastern watersheds were higher than that of the western watersheds (Table, 4). In a previous study, high Dd values were correlated with high runoff and erosion rate values (Bagyaraj et al. 2011) (Figure 8). The Dd values of the western watersheds showed that they had more infiltration capacity and dense vegetation cover than of the eastern ones. The high Dd values of the Massin watershed was attributed to the high intensity and length of the first order segments in the Sanour flooded plain which occupied 21 $km^2$ of the basin.

**Constant channel maintenance (C)** is influenced by land cover, relief, permeability, and geological structures. Massin and Dair-Balout watersheds had the two most extreme values of 0.15 and 0.27, respectively. This range falls between what is typically known as low constants, and thus indicate low permeability and high surface runoff, as well as very steep slopes. These represent the typical characteristics of the eastern slopes.

**Circularity ratio (Rc)** reflects the watershed form. In Ateen and Oja watersheds, the circularity ratios were 0.15 and 0.49, respectively, which are elongated shapes. This has previously been associated with the geologic structure, relief, land cover and slope (Soni 2017). Meanwhile, Hajam et al. (2013) pointed out that the circularity ratio is also influenced by stream order, length and frequency, more so than slope conditions. Also, a high circularity ratio may be linked to the maturity stage of landforms (Ali and Ali 2014). Based on this, Oja and Fasyail watersheds are in the mature stage with Rc values of 0.49 and 0.35, respectively. Watersheds with low circularity values are assumed to be young watersheds, with a delayed time in reaching peak flow and high flood duration (Rai et al. 2017). Conversely, high circularity ratio associated with large areas such as the Oja watershed which ismore likely to experience successive flash floods with a higher peak of flow in shorter durations. The Rc values ranged from 0 to 1; with 0 indicating a perfect line and 1 indicating a perfect circle. The literature is unclear about what defines Rc classes as being high or low (Ali and Ali 2014; Pareta and Pareta 2012; Rai et al. 2017; Rasool et al. 2011; Singh et al. 2014).

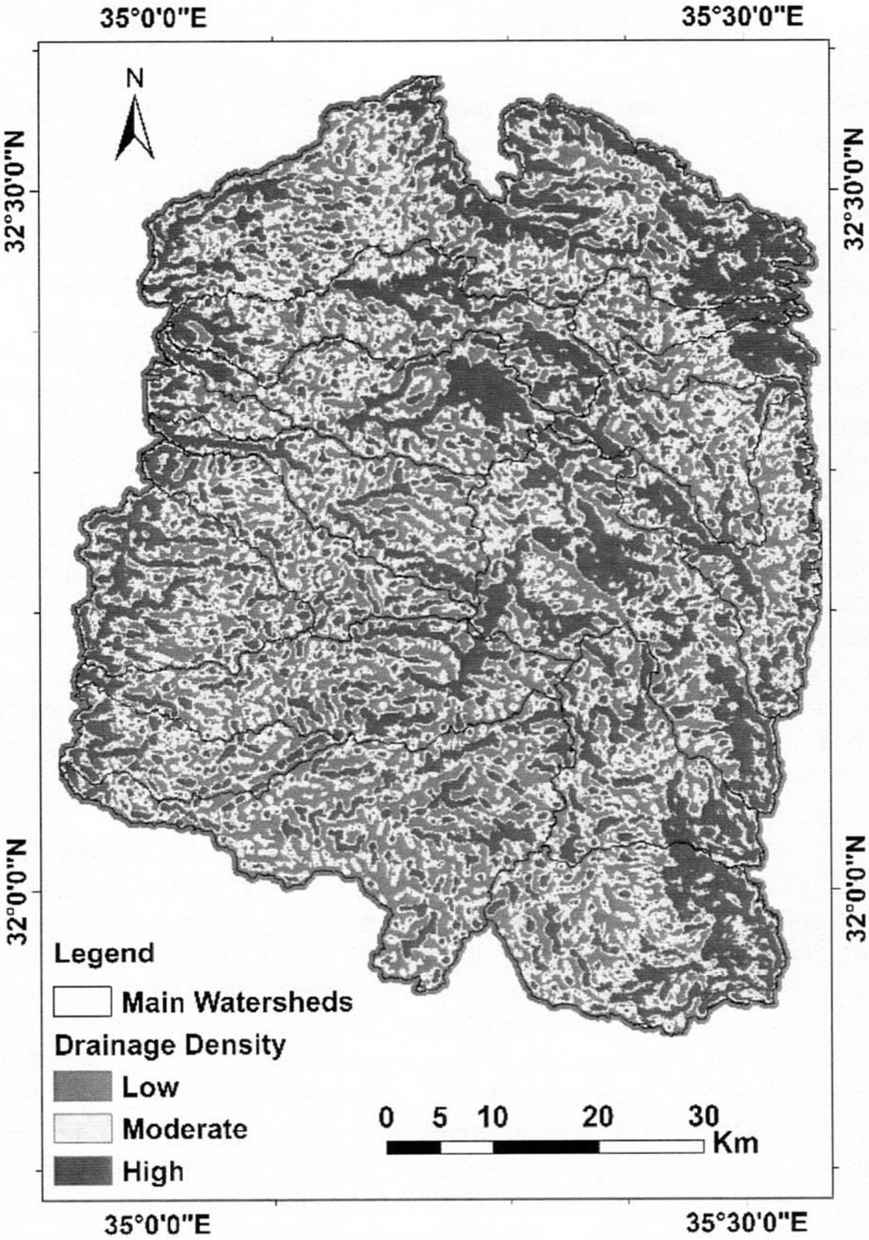


**Figure 8: Drainage density map (based on ALOS PALSAR DEMS from** https://vertex.daac.asf.alaska.edu/**).**

**Table 4: Areal morphometric parameters of the main watersheds.**

| Main Watershelds | Area ($km^2$) | Stream Frequency | Circularity Ratio | Drainage Density | Drainage texture | Texture ratio | Form Factor | Constant channel maintenance | Elongation Ratio | Shape index |
|---|---|---|---|---|---|---|---|---|---|---|
| Dair-Balout | 371.3 | 24.58 | 0.22 | 3.67 | 62.93 | 31.92 | 0.22 | 0.27 | 0.6 | 4.55 |
| Qana | 243.9 | 25.72 | 0.24 | 4.02 | 55.08 | 27.96 | 0.15 | 0.25 | 0.72 | 6.67 |
| Zoumar | 153.1 | 24.53 | 0.22 | 4.1 | 39.88 | 20.22 | 0.16 | 0.24 | 0.7 | 6.25 |
| Ateen | 133.2 | 25.59 | 0.15 | 3.98 | 32.53 | 16.94 | 0.15 | 0.25 | 0.72 | 6.67 |
| Massin | 186.3 | 24.19 | 0.24 | 6.55 | 45.48 | 23.41 | 0.18 | 0.15 | 0.67 | 5.56 |
| Abo-Nar | 209.7 | 24.09 | 0.19 | 4.49 | 42.89 | 21.74 | 0.16 | 0.22 | 0.71 | 6.25 |
| Oja | 267.45 | 22.5 | 0.49 | 4.36 | 72.63 | 36.82 | 0.44 | 0.23 | 0.43 | 2.27 |
| Fasayil | 184.77 | 24.63 | 0.35 | 4.43 | 56.2 | 28.54 | 0.34 | 0.23 | 0.48 | 2.94 |
| Faria | 329.45 | 24.09 | 0.26 | 4.68 | 63.46 | 32.08 | 0.25 | 0.21 | 0.56 | 4 |
| Maleh | 126.35 | 22.86 | 0.27 | 4.09 | 37.93 | 19.2 | 0.29 | 0.24 | 0.52 | 3.45 |
| Shobash | 61.05 | 22.1 | 0.25 | 4.14 | 24.24 | 12.33 | 0.16 | 0.24 | 0.7 | 6.25 |

**The Elongation Ratio (Re)** is the inverse of the circularity ratio. Re classes ranged from those less elongated (0.7-0.8) to moderately elongated (0.5-0.7), followed by more elongated (<0.5) forms (Pareta and Pareta 2012). The low Re values indicate that the watersheds were characterised by high relief and steep slopes (Farhan 2017), with low infiltration capacities as well as high runoff and high susceptibility to soil erosion and sediment load (Rai et al. 2017). In the study area (Table 4), the Abo-Nar, Qana, and Ateen classified as less elongated watersheds (0.7-0.8). Meanwhile, the Faria, Massin, Dair-Balout and Maleh watersheds were moderately elongated (0.5-0.7). However, the Oja and Fasayil watersheds were highly elongated (<0.5), characterised by high relief and steep slopes that are typically associated with increased runoff rate and soil erodibility.

The Re has implications on flood occurrences, in that runoff and flash flood events in elongated watersheds can be mitigated and controlled with greater ease than those in circular watersheds that are characterized by high peaks flow and low durations or shorter lag time.

The **Form factor (Ff)** is the ratio of the watershed area to the maximum length of the watershed (Horton 1932). The lowest values of the form factor were for the Ateen and Qana (0.15), which implied that they had elongated shapes with lower peak flows that occur for longer durations (Waikar and Nilawar 2014). The Oja watershed form factor value was 0.44 which is the highest, implying a strong tendency toward a circular shape in the study area watersheds, with peak flows seen over shorter durations.

**The Shape index (Sw)** can be used to discriminate erosion and flood prone areas (Rather et al. 2017). It is the inverse of the form factor (table 1). The shape index values of the main watersheds in the study area range between 2.27 in the Oja and 6.67 in Ateen and Qana watersheds. The high values of Sw like Ateen and Qana depict longer lag time and weak flood discharge peaks and a low likelihood for erosion, while the low values of the shape index such as in Oja and Fasayil indicate that these are watersheds with much shorter lag time and are highly prone to erosion and flash floods (Al-Saady et al. 2016; Altaf et al. 2013; Rather et al. 2017).

**The texture ratio (T)** is the ratio between the streams numbers of the first order to the watershed perimeter (Horton 1945). The texture ratio is influenced by the underlying lithology, relief, and infiltration capacities (Demoulin 2011; Reddy et al. 2002). The values of the texture ratio for all watersheds were high, and ranged between 11.94 and 36.82 for the Ateen and Oja areas, respectively. These indicated a complex terrain relief, with chopped slopes and rough surfaces that resulted in the presence of fragile slope materials, which will cause serious soil degradation issues (Farhan 2017).

**Drainage texture (Dt)** findings for the selected watersheds were compatible with the texture ratios (Table 4); the drainage texture and texture ratio values were high because of the high segmentation and high stream numbers in the steep slopes which produced coarse slope surfaces.

The **Stream frequency (Fs)** is defined as the total number of all streams of all orders per watershed area (Horton 1945). All watershed basins in the study area showed high stream frequencies, which reflected steep surfaces, moderate vegetation cover, impermeable surface and high runoff rates (Al-Saady et al. 2016) (Table 4).

## Relief morphometric parameters

**Basin Relief (Bh)** is an indicator of the potential denudation energy in the watershed (Farhan 2017). High basin relief values are susceptible to soil erosion (Bagyaraj et al. 2011). The Basin Relief for the entire study area was at 1,016 meters above sea level (asl). The western watersheds range between 46 and 1016 meters, while the eastern watersheds relief range between -371 meters below sea level (bsl) and 1016 meters (Table 5). The highest values for the basin relief were in the eastern watersheds because the watershed mouths were located below sea level in the Jordan Valley, which is the lowest drainage elevation in the world.

**Table 5: Elevation areas of the Mediterranean Sea Drainage System (MSDS) and the Dead Sea Drainage System (DSDS).**

| Elevation range (m) | MSDS | DSDS |
|---|---|---|
| < -300 | 0 | 0.02 |
| -300 - -200 | 0 | 0.14 |
| -200 - -100 | 0 | 0.1 |
| -100 - 0 | 0 | 0.12 |
| 0 - 100 | 0.1 | 0.12 |
| 100 - 200 | 0.17 | 0.09 |
| 200 - 300 | 0.16 | 0.08 |
| 300 - 400 | 0.18 | 0.08 |
| 400 - 500 | 0.14 | 0.08 |
| 500 - 600 | 0.09 | 0.07 |
| 600 - 700 | 0.07 | 0.05 |
| 700 - 800 | 0.05 | 0.03 |
| 800 - 900 | 0.03 | 0.01 |
| 900 - 1016 | 0.01 | 0.01 |

**The Relief Ratio (Rhl)** has a major influence on flood pattern and sediment volume. In addition, it is an indicator of the slope characteristics of the watershed surface. Table 6 shows high values of relief ratio (> 40) for the eastern watersheds (Oja, Fasayil, Faria, Maleh and Shobash) as opposed to the western watersheds (Dair-Balut, Qana, Zoumar, Ateen, Massin, and Abo-Nar) (< 30). This indicates that the eastern watersheds are characterized by steep surfaces and low vegetation density, as well as exposure to denudation. The western watershed has a moderate density of vegetation cover and has a less steep surface (Ghodieh 2000) because of the lower relief ratio (Rai et al. 2017).

**The terrain ruggedness index (Rn)** is a product of the vertical basin relief and drainage density. This dimensionless index is a combination of slope steepness and length. It reveals surface unevenness (Selvan et al. 2011). High ruggedness values of above 6 indicated the presence of extremely rugged and highly fragmented landscapes (Al-Saady et al. 2016), while low ruggedness values of less than 1 indicate terrain that is almost level. Similarly, it implies that a primary-age stage exists for the basin's development (Soni 2017). The Mediterranean Sea Drainage System watersheds have low Rn values due to gentle slope inclinations and surface relief as compared to the Dead Sea Drainage System watersheds. Table 6 shows that the Abo-Nar watershed had the lowest Rn value (2.97) and the Oja watershed had the highest Rn value (6.05). Therefore, it can be concluded that the high Ruggedness Number values correlated positively with the circular form of the watersheds which are more prone to flash floods with a low time of concentration.

**Dissection Index (Dis)** explains the stages of landscape development (Singh and Dubey 1994). Dis estimates varied between 0.85 and 0.97 for Shobash and Oja watersheds, respectively. In general, the higher Dissection index value revealed that the watershed is much more dissected.

**Hypsometric analysis (Hs)** and the hypsometric curve and integral Hi values reflect the geomorphological dissection stage of the watershed and relative landform age (Al-Saady et al. 2016). In Figure 9, the Oja, Massin, Abo-Nar, and Ateen watersheds fall into the category of the primary or young stage of hypsometric integral Hi values above 60%, which are highly vulnerable to erosion, while the other watersheds fall into the mature stage because of the hypsometric integral values are less than 60% which are less susceptible to soil erosion (Pareta and Pareta 2012).

**Stream power index (SPI)** reflects the relationship between slope inclination and the potential power of running water on carrying sediments (Conforti et al. 2011). High values of the stream power index indicate a high potential of denudation (Kakembo et al. 2009). The eastern slopes, which have steep surfaces, showed much more susceptibility to erosion than the western slopes (Figure 10 (a)). It can be concluded that the Dead Sea Drainage System watersheds have much more potential for erosion. This possibly due to their low density vegetation cover, low infiltration capacity, high relief and high runoff rates.

**Topographical wetness index (WI)** is the ratio of slope inclination to the contributing area of runoff water and thus, reflects topographic control on the hydrological processes. The study area has been known to suffer from several devastating flood incidents in the past (Lahlabat 2013). A humidity indicator layout map showed the areas that are prone to flood recurrences (Figure 10(b)), with the Oja watershed shown to repeatedly experience flood incidents. This is related to its circular form, high ruggedness number and high steep relief, making it susceptible to flash floods. A similar observation was seen for the Zoumar watershed in the winter of 2012. A heavy storm claimed three victims as a result of a flash flood in the low lands (Hawajri 2016).

## CONCLUTION

Morphometric characteristics is a quantitative analysis performed to understand the impact of rainfall-runoff processes and geology on watershed landforms. GIS and RS Techniques have shown to be useful in terms of extracting the linear, areal and relief aspects of the morphometric and hydrologic characteristics of the Nablus Mountains watersheds by using a DEM approach. In this study, the analysis was carried out with 25 parameters across eleven main watersheds. It has been shown that there is a significant variation between the Mediterranean Sea Drainage System watersheds (Dair-Balout, Qana, Ateen, Zoumar, Massin and Abu-Nar) and the Dead Sea Drainage System watersheds (Oja, Fasayil, Faria, Maleh and Shobash). The latter watersheds were characterized by high circularity ratio, low vegetation cover and steep slopes, which indicated high susceptibility to flash floods and soil erosion.

Meanwhile, the Mediterranean Sea Drainage System watersheds in the west had an elongated shape, dense vegetation cover, steep sides and high annual rainfall amounts (windward side of the Nablus Mountains). In this study, the Drainage density values of the eastern watersheds were higher than that of the western watersheds, which underscores the idea that flash floods and soil degradation are more likely to occur in the eastern watersheds than in the western watersheds. Variation in the morphometric characteristics of the eastern and the western watersheds reflect their respective topographic and climatic conditions. Thus, geospatial analysis of the morphometric and hydrological characteristics of watersheds has provided useful insights into where and how to address the most pressing problems of erosion and water supply in this region. What this means in applied terms is that soil conservation practices and rainwater harvesting techniques which would reduce the magnitude of flash floods are better suited to be located in the eastern watersheds and the sub-watersheds in the central part of the Nablus Mountains, where slopes are steep and rainfall amounts are high.

**Table 6: Relief aspect morphometric parameters of the main watersheds.**

| Main watersheds | Basin Relief (m) | Max Elevation (m) | Min Elevation (m) | Relief Ratio | Dissection Index | Ruggedness number | Hypsometric Integrals |
|---|---|---|---|---|---|---|---|
| Dair-Balout | 969 | 1016 | 47 | 23.6 | 0.95 | 3.56 | 43.24% |
| Qana | 826 | 872 | 46 | 20.8 | 0.95 | 3.32 | 51.45% |
| Zoumar | 895 | 941 | 46 | 29 | 0.95 | 3.67 | 58.10% |
| Ateen | 831 | 881 | 50 | 28.1 | 0.94 | 3.31 | 64.86% |
| Massin | 716 | 766 | 50 | 22.1 | 0.93 | 4.69 | 52.25% |
| Abo-Nar | 661 | 710 | 49 | 18.3 | 0.93 | 2.97 | 62.33% |
| Oja | 1387 | 1016 | -371 | 56.2 | 0.97 | 6.05 | 62.22% |
| Fasayil | 1230 | 866 | -364 | 53 | 0.96 | 5.45 | 51.22% |
| Faria | 1275 | 941 | -334 | 35.4 | 0.94 | 5.96 | 55.45% |
| Maleh | 986 | 710 | -276 | 47.4 | 0.87 | 4.03 | 53.55% |
| Shobash | 970 | 710 | -260 | 50.3 | 0.85 | 4.01 | 52.17% |

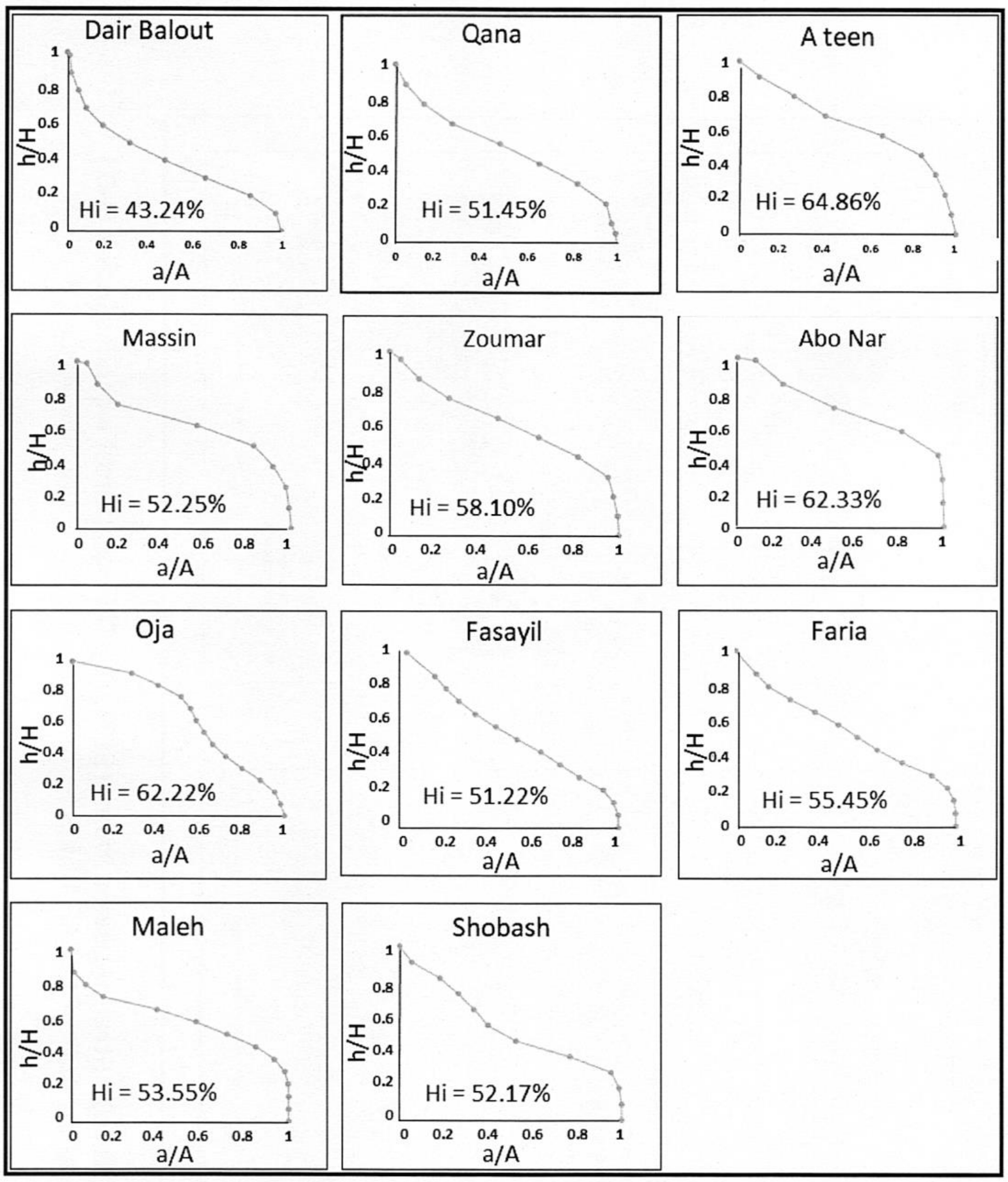


**Figure 9: Hypsometric curves and Hypsometric Integral of the main watersheds.**

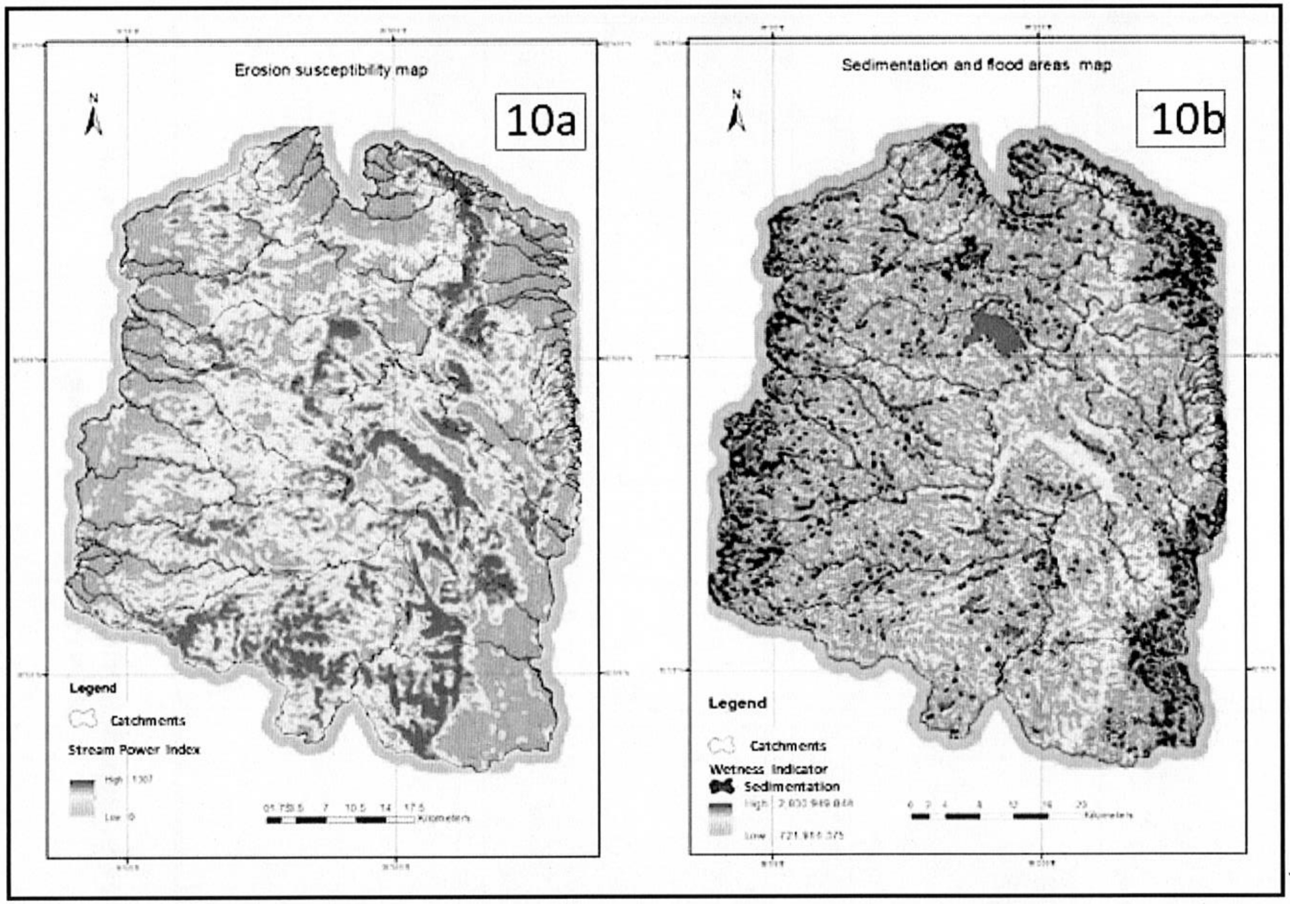


**Figure 10 (a): Stream power index (SPI), (b) Topographical wetness index (WI) (based on ALOS PALSAR DEMS from https://vertex.daac.asf.alaska.edu/ ).**

**Acknowledgments**
The authors express their gratitude to the editorial board and reviewers for their contribution to improving the quality of this paper.

## REFERANCES

Abboud IA, Nofal RA (2017) Morphometric analysis of wadi Khumal basin, western coast of Saudi Arabia, using remote sensing and GIS techniques Journal of African Earth Sciences 126:58-74

Abdlkadeer A, Wishahy S (1999) Geology of Palestine, the West Bank and the Gaza Strip. Palestinian Hydrology Group, , Palestine

Al-Saady YI, Al-Suhail QA, Al-Tawash BS, Othman AA (2016) Drainage network extraction and morphometric analysis using remote sensing and GIS mapping techniques (Lesser Zab River Basin, Iraq and Iran) Environmental Earth Sciences 75:1243

Ali U, Ali SA (2014) Analysis of drainage morphometry and watershed prioritization of Romushi-Sasar catchment, Kashmir Valley, India using remote sensing and GIS technology International Journal of Advanced Research 2:5-23

Altaf F, Meraj G, Romshoo SA (2013) Morphometric analysis to infer hydrological behaviour of Lidder watershed, Western Himalaya, India. Geography Journal 2013

Angillieri MYE (2008) Morphometric analysis of Colangüil river basin and flash flood hazard, San Juan, Argentina Environmental geology 55:107-111

Bagyaraj M, Gurugnanam B, Nagar A (2011) Significance of morphometry studies, soil characteristics, erosion phenomena and landform processes using remote Sensing and GIS for Kodaikanal Hills, a global biodiversity hotpot in Western Ghats, Dindigul District, Tamil Nadu, South India Research Journal of Environmental and Earth Sciences 3:221-233

Banerjee A, Singh P, Pratap K (2017) Morphometric evaluation of Swarnrekha watershed, Madhya Pradesh, India: an integrated GIS-based approach Applied Water Science 7:1807-1815

Chopra R, Dhiman RD, Sharma P (2005) Morphometric analysis of sub-watersheds in Gurdaspur district, Punjab using remote sensing and GIS techniques Journal of the Indian Society of Remote Sensing 33:531

Clarke JI (1966) Morphometry from maps Essays in geomorphology 252:235-274

Conforti M, Aucelli PP, Robustelli G, Scarciglia F (2011) Geomorphology and GIS analysis for mapping gully erosion susceptibility in the Turbolo stream catchment (Northern Calabria, Italy) Natural hazards 56:881-898

Dastorani MT, Kohzad B, Sepehr A The role of rainwater harvesting techniques on preparation of water required for vegetation in arid and semi-arid regions. In: 37th IAHR World Congress, 2017.

Demoulin A (2011) Basin and river profile morphometry: a new index with a high potential for relative dating of tectonic uplift Geomorphology 126:97-107

Dinagara Pandi P, Thena T, Nirmal B, Aswathy M, Saravanan K, Mohan K (2017) Morphometric analyses of Neyyar River Basin, southern Kerala, India Geology, Ecology, and Landscapes:1-8

Ezeh CU, Mozie AT (2019) Morphometric analysis of the Idemili Basin using geospatial techniques Arabian Journal of Geosciences 12:208

Faniran A (1968) The index of drainage intensity-A provisional new drainage factor Australian Journal of Science 31:328-330

Farhan Y (2017) Morphometric Assessment of Wadi Wala Watershed, Southern Jordan Using ASTER (DEM) and GIS Journal of Geographic Information System 9:158

Farhan Y, Elgaziri A, Elmaji I, Ali I (2016) Hypsometric analysis of Wadi Mujib-Wala watershed (Southern Jordan) using remote sensing and GIS techniques International Journal of Geosciences 7:158

Fernandez OM (2017) Morphometric analysis of river basins using GIS and remote sensing of an Andean section of Route 150, Argentina. A comparison between manual and automated delineation of basins Revista Mexicana de Ciencias Geológicas 34:150-156

Ghodieh ARf (2000) An evaluation of satellite remote sensing for crop area estimation in the West Bank, Palestine. Dissertation, Durham University

Hajam RA, Hamid A, Bhat S (2013) Application of morphometric analysis for geo-hydrological studies using geo-spatial technology–a case study of Vishav Drainage Basin Hydrol Current Res 4:2

Hawajri O (2016) Natural disasters and complex humanitarian emergencies in the occupied Palestinian territories Emergency and Disaster Reports, 3 (1)

Horton RE (1932) Drainage-basin characteristics Eos, transactions american geophysical union 13:350-361

Horton RE (1945) Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology Geological society of America bulletin 56:275-370

Hurtrez JE, 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 Surface Processes and Landforms 24:799-808

Jafarzadegan K, Merwade V (2017) A DEM-based approach for large-scale floodplain mapping in ungauged watersheds Journal of Hydrology 550:650-662

Kakembo V, Xanga W, Rowntree K (2009) Topographic thresholds in gully development on the hillslopes of communal areas in Ngqushwa Local Municipality, Eastern Cape, South Africa Geomorphology 110:188-194

Kant S, Meshram S, Dohare R, Singh S (2015) Morphometric analysis of Sonar sub-basin using SRTM data and geographical information system (GIS) African Journal of Agricultural Research 10:1401-1406

Khalaf A, Donoghue D (2012) Estimating recharge distribution using remote sensing: a case study from the West Bank Journal of Hydrology 414:354-363

Lahlabat LOB (2013) Rainfaill-Runoff Analysis of Wadis Contributing to the Dead Sea: Wadi Og as a case study. Dissertation, An-Najah National University.

Luo W, Harlin JM (2003) A THEORETICAL TRAVEL TIME BASED ON WATERSHED HYPSOMETRY 1 JAWRA Journal of the American Water Resources Association 39:785-792

Magesh N, Jitheshlal K, Chandrasekar N, Jini K (2013) Geographical information system-based morphometric analysis of Bharathapuzha river basin, Kerala, India Applied Water Science 3:467-477

Martin PH, LeBoeuf EJ, Dobbins JP, Daniel EB, Abkowitz MD (2005) Interfacing GIS with water resource models: A state-of-the-art review JAWRA Journal of the American Water Resources Association 41:1471-1487

Masoud M (2016) Geoinformatics application for assessing the morphometric characteristics' effect on hydrological response at watershed (case study of Wadi Qanunah, Saudi Arabia) Arabian Journal of Geosciences 9:280

Miller VC (1953) quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain area, Virginia and Tennessee Technical report (Columbia University Department of Geology); no 3

Moore ID, Grayson R, Ladson A (1991) Digital terrain modelling: a review of hydrological, geomorphological, and biological applications Hydrological processes 5:3-30

Morisawa M (1985) Rivers: form and process Geomorphology texts

Nongkynrih JM, Husain Z (2011) Morphometric analysis of the Manas river basin using earth observation data and Geographical Information System International Journal of Geomatics and Geosciences 2:647-654

Omolabi PO, Fagbohun BJ (2019) Mapping suitable sites for water storage structure in the Sokoto-Rima basin of northwest Nigeria Remote Sensing Applications: Society and Environment 13:12-30

Pareta K, Pareta U (2012) Quantitative geomorphological analysis of a watershed of Ravi River Basin, HP India International Journal of Remote Sensing and GIS 1:41-56

Patel DP, Dholakia MB, Naresh N, Srivastava PK (2012) Water harvesting structure positioning by using geo-visualization concept and prioritization of mini-watersheds through morphometric analysis in the Lower Tapi Basin Journal of the Indian Society of Remote Sensing 40:299-312

Price K (2011) Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review Progress in physical geography 35:465-492

PWA (2013) Status report of water resources in the occupied state of palestine-2012 Palestinian Water Authority

Radwan F, Alazba A, Mossad A (2017) Watershed morphometric analysis of Wadi Baish Dam catchment area using integrated GIS-based approach Arabian Journal of Geosciences 10:256

Rahaman SA, Ajeez SA, Aruchamy S, Jegankumar R (2015) Prioritization of sub watershed based on morphometric characteristics using fuzzy analytical hierarchy process and geographical information system–A study of Kallar Watershed, Tamil Nadu Aquatic Procedia 4:1322-1330

Rai PK, Mohan K, Mishra S, Ahmad A, Mishra VN (2017) A GIS-based approach in drainage morphometric analysis of Kanhar River Basin, India Applied Water Science:1-16

Rasool Q, Singh VK, Singh U (2011) The evaluation of Morphmetric characteristics of Upper Subarnarekha Watershed drainage basin using geoinformatics as a tool, Ranchi, Jharkhand International Journal of Environmental Sciences 1:1924-1930

Rather MA, Kumar JS, Farooq M, Rashid H (2017) Assessing the influence of watershed characteristics on soil erosion susceptibility of Jhelum basin in Kashmir Himalayas Arabian Journal of Geosciences 10:59

Ratnam KN, Srivastava Y, Rao VV, Amminedu E, Murthy K (2005) Check dam positioning by prioritization of micro-watersheds using SYI model and morphometric analysis—remote sensing and GIS perspective Journal of the Indian Society of Remote Sensing 33:25

Reddy GO, Maji A, Srinivas C, Velayutham M (2002) Geomorphological analysis for inventory of degraded lands in a river basin of basaltic terrain using remote sensing and GIS Journal of the Indian Society of Remote Sensing 30:15-31

Schumm SA (1956) Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey Geological society of America bulletin 67:597-646

Schumm SA (1963) Sinuosity of alluvial rivers on the Great Plains Geological Society of America Bulletin 74:1089-1100

Selvan MT, Ahmad S, Rashid S (2011) Analysis of the geomorphometric parameters in high altitude glacierised terrain using SRTM DEM data in Central Himalaya, India ARPN Journal of Science and Technology 1:22-27

Singh P, Gupta A, Singh M (2014) Hydrological inferences from watershed analysis for water resource management using remote sensing and GIS techniques The Egyptian Journal of Remote Sensing and Space Science 17:111-121

Singh S, Dubey A (1994) Geoenvironmental planning of watersheds in India. Chugh,

Soni S (2017) Assessment of morphometric characteristics of Chakrar watershed in Madhya Pradesh India using geospatial technique Applied Water Science 7:2089-2102

Strahler AN (1952) Hypsometric (area-altitude) analysis of erosional topography Geological Society of America Bulletin 63:1117-1142

Strahler AN (1957) Quantitative analysis of watershed geomorphology Eos, Transactions American Geophysical Union 38:913-920

Strahler AN (1964) Quantitative geomorphology of drainage basin and channel networks Handbook of applied hydrology

Strahler AN (1967) Quantitative geomorphology, Encyclopedia of Geomorphology, R W FAIRBRIDGE _ Reinhold Book Corp, New York 3:898-912

Sujatha ER, Selvakumar R, Rajasimman U, Victor RG (2015) Morphometric analysis of sub-watershed in parts of Western Ghats, South India using ASTER DEM Geomatics, Natural Hazards and Risk 6:326-341

Vieceli N, Bortolin TA, Mendes LA, Bacarim G, Cemin G, Schneider VE (2015) Morphometric evaluation of watersheds in Caxias do Sul City, Brazil, using SRTM (DEM) data and GIS Environmental earth sciences 73:5677-5685

Waikar M, Nilawar AP (2014) Morphometric analysis of a drainage basin using geographical information system: a case study International Journal of Multidisciplinary and Current Research 2:179-184
Wani MB, Ali SA, Ali U (2018) Flood Assessment of Lolab Valley from Watershed Characterization Using Remote Sensing and GIS Techniques. In: Hydrologic Modeling. Springer, pp 367-390