QUANTITATIVE EVALUATION OF DRAINAGE BASIN CHARACTERISTICS USING GIS BASED MORPHOMETRIC ANALYSIS: A CASE STUDY OF WADI SUDR , SINAI, EGYPT.

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ABSTRACT

Morphometric characteristics of the watershed contain important information regarding its formation and development because all hydrologic and geomorphic processes occur within the watershed. Computing drainage networks within basins and sub-basins can be achieved roughly using traditional methods as field observations and topographic maps or alternatively with advanced methods by Remote Sensing (RS) and Geographical Information System (GIS) from Digital Elevation Models (DEM)**.** Remote Sensing and GIS techniques have been proved to be efficient tools in the delineation and morphometric analysis of drainage basin. Morphometric analysis was performed for Wadi-Sudr, Sinai, Egypt, using Remote Sensing and GIS techniques. Stream ordering was performed to Wadi-Sudr were the highest order was 5th order and the watershed was subdivided into eighteen sub-watersheds. Various morphometric parameters such as linear aspects of the drainage network: stream number (Nu), bifurcation ratio (Rb), stream length (Lu)), areal aspects of the drainage basin: drainage density (Dd), stream frequency (Fs), texture ratio (Dt), infiltration number (If), length of overland flow (Lg), elongation ratio (Re), circularity ratio (Rc), form factor ratio (Rf), and relief aspect: basin relief (H), relative relief (Rhb), relief ratio (Rh), roughness number (HD) of the basin are computed through GIS technique.

Key Words: Sinai, Wadi-Sudr, Remote Sensing (RS), Geographic Information Systems (GIS), Morphometric analysis.

1 INRODUCTION

Flash floods are considered one of the worst weather related natural disasters. Flash floods cause about one third of all deaths, one third of all injuries and one third of all damage from natural disaster. As reported in Egyptian review, about the Assessment of progress in disaster risk reduction. The arid regions exposed to major catastrophic events than humid regions and it increases affected by climate change. Egypt subjected to some torrential rainfall in the north although it lies within the great hot desert belt, which causes flash floods all over Sinai Peninsula. Flash floods in hot deserts are characterized by high velocity and low duration with a sharp discharge peak.(Omran et al., 2011)

Watershed is a natural hydrological entity which allows surface runoff to a defined channel, drainage, stream or river at a particular point. It is the basic unit of water supply, which evolves over time (Shaikh & Farjana, 2015). Morphometric analysis of a watershed provides a quantitative description of the drainage system, which is an important aspect of the characterization of watersheds.(Strahler, 1964)

Computing drainage networks within basins or sub-basins can be achieved using traditional methods such as field observations and topographic maps, or alternatively with remote sensing and Geographical Information System (GIS) using Digital Elevation Models**.** From various researches, we note that it is difficult to examine all drainage networks from field observations due to their extent throughout rough terrain over vast areas. In many studies, the analysis of drainage networks was manually defined from the topographic maps, which is both time consuming and cumbersome. It is better to use a DEM within a GIS environment, and then compare the results with topographic maps. Although the extraction of stream networks using GIS can be done easily, it is still difficult to count stream segments and measure their lengths of different order.

Morphometric parameters of basin have been studied using conventional methods ((Horton, 1945); (Miller, 1953); (Strahler, 1964)). Some of the researchers ((Nautiyal, 1994); (Srivastava et al., 1995); (Srivastava, 1997); (Nag, 1998); (Agarwal,1998); (Biswas et al., 1999); (Shreedevi et al., 2001); (Vittala et al., 2004); (Reddy et al., 2004)) used remote sensing and GIS techniques to demonstrate morphometric analysis and they concluded that remote sensing and geographical information system as powerful tools for studying basin morphometry. Rahaman et al. (2015) used morphological characteristics of sub-watersheds to determine its prioritization using GIS and multi-criteria decision making (MCDM) through fuzzy analytical hierarchy process techniques. Javed et al. (2009), studied the morphometric and land use characteristics for prioritization of sub-watersheds using remote sensing and GIS techniques. Dewidar (2013) used GIS to determine morphometric parameters for Wadi El-Gemal basin, Red Sea coast, Egypt. Abdel-Latif & Sherief (2012) used geographic information systems and remote sensing to extract new drainage network with more details to prepare natural hazard maps of wadi Sudr and wadi Wardan which are nearly perpendicular to the eastern side of the Gulf of Suez, Egypt. (El-Behiry et al., 2006) used quantitative analysis of geo-morphometric parameters to delineate watershed of Wadi Ghoweibba basin in Ain Sukhna area, western side of the Gulf of Suez, Egypt. Shaikh & Farjana (2015) used GIS techniques to study the Eru river Basin, sub watershed of Mahi river, Rajasthan, India. Soni, S.K., S. Tripathi, and A.K. Soni et al. (2013) used Geographical information System (GIS) tools in the drainage delineation in Rachhar nala, Anuppur District of Madhya Pradesh, India. Thankur et al. (2014) computed Morphometric analysis of the Balawal watershed in Jammu Province of Jammu and Kashmir State to evaluate the drainage parameters and basin characteristics.

2 STUDY AREA

2.1 Location

Wadi Sudr is one of South-Western Sinai wadis which is located between latitudes 29o 35' and 29o 55', and longitudes 32o 40' and 33o 20'. Wadi Sudr covers a total area of about 600 km2 and it drains directly in the Gulf of Suez at Ras-Sudr town. This wadi is instrumented by Water Resources Research Institute (WRRI) for Rainfall and runoff measurements since 1989 till now.

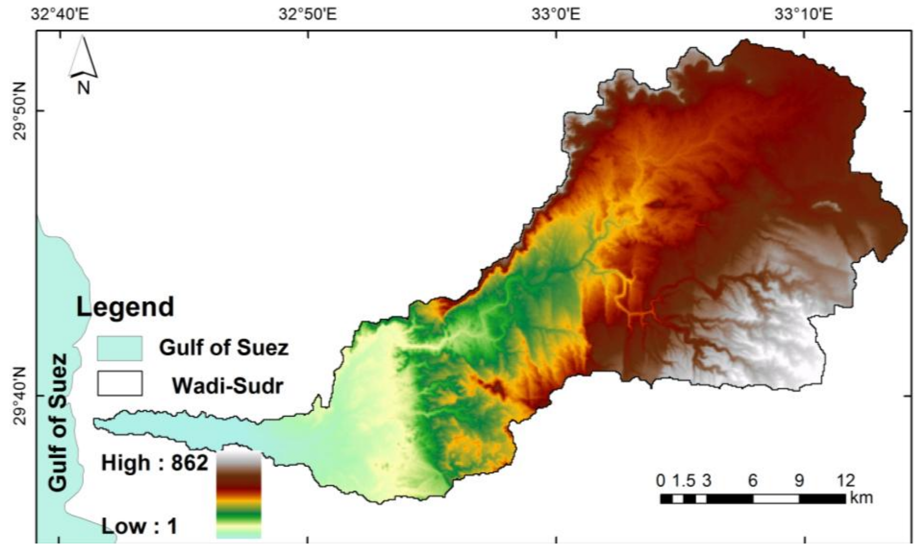

Figure 1. Digital Elevation Model (DEM) of Wadi-Sudr

2.2 Climate conditions

The climatic conditions of the Sinai Peninsula are similar to those, which characterize desert areas in other parts of the world. They include extreme aridity, long hot and rainless summer months and a mild winter. During the winter months some areas of Sinai experience brief but intensity of rainfall that makes Wadi beds overflow and sometimes cause severe flash floods which damage the roadways and sometimes human lives. (Abdel El Aziz, 2013)

Wadi-Sudr has a long summer, from April to October and a short winter from January to March, separated by a transitional period (November-December). Evaporation study in these areas is very important because it is mostly higher than precipitation the values of evaporation depend on some factors such as temperature, relative humidity, wind speed, the cover of plant and solar radiation. So, the amount of evaporation is dependent upon the individual location (Sherief, 2008). Anywhere, the air in the study area is considered arid when the relative humidity is less than 50%, semi-arid when it ranges from 60% to 70% and humid when relative humidity rises up to 70%. So we can consider Wadi-Sudr as semi-arid region.

The southernSinai massif is receiving more an average of 65-100 mm but the precipitation comes almost exclusively in winter and may sometimes occur as snow on the high peaks. The mean annual rainfall ranges between 10.4 mm /year at El-Tur. 15.4 mm / year at Ras Sudr, 21.5 mm / year at Abu Rudeis, and 63 mm /year at St. Catherine, and these amounts indicate that the rain increases toward the east of the study area (St. Catherine). (Sherief, 2008)

2.3 Geological Setting of Wadi-Sudr

The geology of Sinai and Wadi-Sudr has been studied by many authors such as Hammad (1980), Garamoon (1987), Hasanien (1989), Gad (1996), Abdel-Latif & Sherief (2012), Sherirf (2008) and others. According to the previous works and the geologic map of Sinai by the Geological survey of Egypt scale 1:250,000 “Fig. 2”, the geological formation of the study area can be classified as listed below.

Wadi deposits (Quaternary age) are distributed in Wadi floors. Most of these deposits consist of gravels and soft material. However, they differ from one Wadi to another depending of the source of these deposits, the slope angle, and the extent of basin and wideness of Wadis.

Sabkha (Quaternary age) deposits are an Arabic word for salt pan which has become entangled with playa. Sabkha sediments are dominated usually by carbonates, evaporates, fluviatile, aeolian and marine debris and are sometimes cemented with carbonate or gypsum.

Quaternary deposits are represented by Pleistocene and Holocene sediments cover the main channels of studied wadies. These deposits consist mainly of alluvial, wadi and sabkha deposits.

Matulla Formation (Cretaceous age) consists of sandy shales with phosphatic marl and limestone intercalations.

Sudr Formation (Cretaceous age) consists of white colored chalk and dolomitic limestone.

Gharandal Group is represented by: *(i) Sumar Formation* (Lower Miocene age) is represented by gypsiferous yellowish green shale and gray to white intercalation with a thin flint band at the base. *(ii) Uyun Musa Formation* (Middle — Lower Miocene age) consists of green gypseous fossiliferous clays intercalated with sandstones and marls.

Ras Malab Group is represented by: *(i) Kareem Formation* (Middle Miocene age) consists of clastics with interbedded anhydrite and occasional limestone. *(ii) Belaim Formation* (Middle Miocene age) consists of intercalation of evaporates and marl. *(iii) Hammam Phrayuon Formation* (Middle

Miocene age) consists of two main Facies. The first being a calcareous facies consisting of argillaceous limestone with shale and marl interbeds and the second is a shaky facies consisting of shale, marl and sandstone. *(iv) South Gharib Formation* (Upper Miocene age) consists of anhydrite shales and minor sands. *(V) Zayt Formation* consists of evaporates with clastic intercalation.

Extrusive basaltic rocks (Olivine basalt).

Egma Formation (Eocene age) consists of chalky limestone with flint bands and nodules at the base and thin successive chert bands on top.

Esna Formation (Paleocene age) is darkly green shale with grayish yellow marly limestone band in the middle. It overlies the Sudr Formation and is overlain by the Thebes Formation.

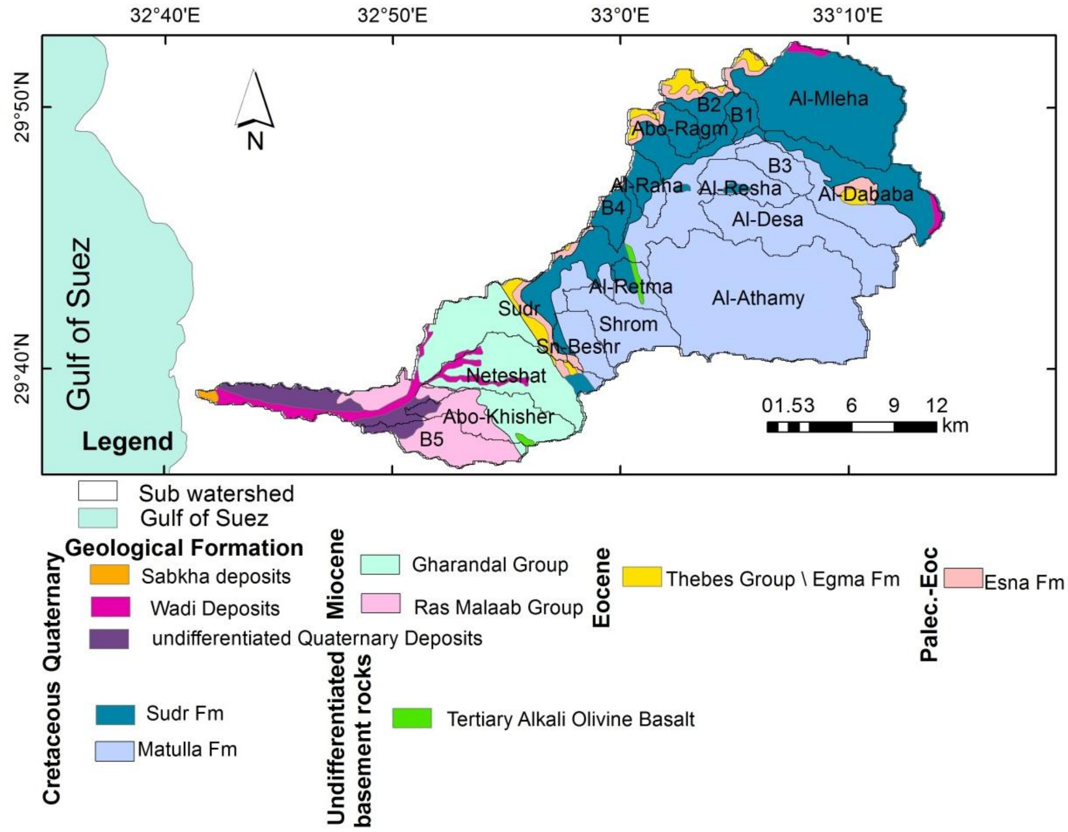

Figure 2. Geological map of the study watershed

2.4 Land use

Wadi-Sudr is one of the most important wadies in Sinai Peninsula. Wadi-Sudr location is opposite to Ras Sudr city which is one of the important tourist cities. Ras Sudr has a 95 km beach coastline which offers waters for swimming and sea sports. The majority of the town and outlying districts are inhabited by Sinai Bedouins who live in the areas of Wadi-Sudr. Ras Sudr itself is made up of two residential areas, bisected by the main north-south road. One side contains local housing for workers; who mainly come from the Nile Delta and the Nile Valley governorates of Egypt. The other contains private villa residences for professionals and second holiday homes whose owners are mainly from Cairo.

3 MATERIAL AND METHODOLOGY

The main objectives of this work were to extract a new stream network and demonstrate the morphometric analysis of sub-watersheds of the study area. To achieve this work, the following tasks were performed.

3.1 Satellite image collection

Morphological parameters of the study area were extracted using Digital Elevation Model (DEM) with 90m resolution obtained from the SRTM (Shuttle Radar Topography Mission data), which was subsequently enhanced by the topographic contours, spot heights and streams of topo sheet 1:25,000 was exported to a Geographic Information System (GIS) environment (Arc GIS 9.3 software). Maps have been converted to the Universal Transverse Mercator (UTM) and WGS 1984 map projection to be compatible with the different GIS thematic layers.

3.2 Construction of drainage net map

The extraction of drainage network was performed inside the WMS 8.0© software platform using the "Main Drainage Module" then through its sub-modules using the TOpographic PArameteriZation program (TOPAZ) program (AQUAVEO, 2008). A modified version of this program is distributed with the WMS software for the purpose of computing flow directions and flow accumulations for use in basin delineation with DEMs. Sub- watersheds were generated by creating an outlet on a downstream branch, stream network and watershed boundary are generated based on flow direction and stream threshold. After the watershed was delineated, the basin's characters, such as area, basin's slope, maximum flow distance, etc., can be calculated automatically by WMS.

A shape file of drainage network was exported to a Geographic Information System (GIS) environment (Arc GIS 9.3 software) in order to define stream order and calculate the length and number for each stream order for all sub-basines. The stream order was defined by Strahler stream ordering technique (Strahler, 1964). Computing morphometric parameters for sub-watersheds

Morphometric parameters for the delineated watershed area were calculated based on the formula suggested by Horton (1932 & 1945), Strahler (1952 & 1964), Melton (1957), Hagget (1965) Faniran (1968), Schumn (1956) and Miller (1953) are given in "Table 1". Various morphometric parameters which are classified into: (i)linear aspects of the drainage network; stream order (Nu), bifurcation ratio (Rb), and stream length (Lu), (ii) areal aspects of the drainage basin; drainage density (Dd), stream frequency (Fs), texture ratio (Dt), infiltration number (If), length of overland flow (Lg), elongation ratio (Re), circularity ratio (Rc), form factor ratio (Rf), and (iii)relief aspect of the basin; basin relief (H), relative relief (Rhb), relief ratio (Rh), roughness number (HD) of the basin are computed through GIS technique. "Table 1"; illustrates the methodology used for the computation of morphometric parameters.

Table 1. Methodology used for the computation of morphometric parameters

Aspect type	Morphometric Parameters	Formula	Author
Linear	Stream order	Hierarchical Rank	Strahler (1964)
	Bifurcation Ratio (Rb)	Rb = Nu / Nu+1 Where, Nu= Total number of stream segments of order, Nu+1=Number of segments of the next higher order	Schumm (1956)
	Mean Bifurcation Ratio (Rbm)	Rbm = Average of bifurcation ratios of all order	Strahler (1964)
	Stream Length (Lu)	Length of the Stream (km)	Horton (1945)
	Mean Stream Length (Lsm)	Lsm = Lu / Nu, km Where, Lu= Total stream length of a given order (km). Nu= Total number of stream segments of order	Strahler (1964)
	Stream Length Ratio (RI)	RI = Lu / Lu-1 Where, Lu= Total stream length of a given order (u). Lu-1= The total stream length of its next lower order	Horton (1945)
Areal	Drainage Density (Dd)	Dd = (ΣLu /Au) km/km2 Where, Lu=Total Stream length of all orders (km). Au= Area of the Basin (km2)	Horton (1932)
	Drainage Texture(Dt)	Dt = Σ Nu/P Where, Nu= Stream Number. P = Perimeter (km)	Horton (1945)
	Stream Frequency (Fs)	Fs = Σ Nu /Au Where, Nu= number of streams. Au= Basin Area (km2)	Horton (1932)
	Infiltration No. (If)	If = Dd*Fs Where, Dd= Drainage density. Fs= stream frequency.	Faniran (1968)
	Length of Over Land Flow (Lg)	Lg = 1/ Dd×2 Km Where, D = Drainage density (km/km^2).	Horton (1945)
	Form Factor (Rf)	Rf = Au / Lb2 Where, Au=Area of the Basin (km2). Lb=Maximum Basin length (km).	Horton (1932)
	Elongation Ratio (Re)	Re = 2√(Au/π) / Lb Where, Au= Area of the Basin (km2). Lb=Maximum Basin length (km). Π = 3.14	Schumm (1956)
	Circularity Ratio (Rc)	Rc = 4πAu/ P2 Where, Au= Basin Area (km2). P = Perimeter of the basin (km). π = 3.14	Miller (1953)
Relief	Relative Relief (Rhp)	Rhp = H× (100) / P Where, H = Maximum basin relief P = Perimeter of the basin (km)	Melton (1958)
	Relief Ratio (Rh)	Rh = H / Lb max Where, H = Maximum basin relief (km) Lb max= Maximum basin length (km)	Schumm (1956)
	Ruggedness Number (HD)	HD = H×Dd Where, H= Maximum basin relief Dd = Drainage density	Strahler (1956)

4 RESULTS AND DISCUSSION

4.1 MORPHOMETRIC ANALYSIS OF THE BASIN

Morphometric analysis of the study area was computed according to the previous methodology. The analysis made an indication of the drainage characteristics and runoff potentiality in the basin.

4.1.1 Linear Aspects of the Channel System:

Linear Aspects of the channel system include stream order (Nu), bifurcation ratio (Rb), and stream length (Lu). "Fig. 3"; shows the sub-watersheds of Wadi-Sudr and the order of its streams.

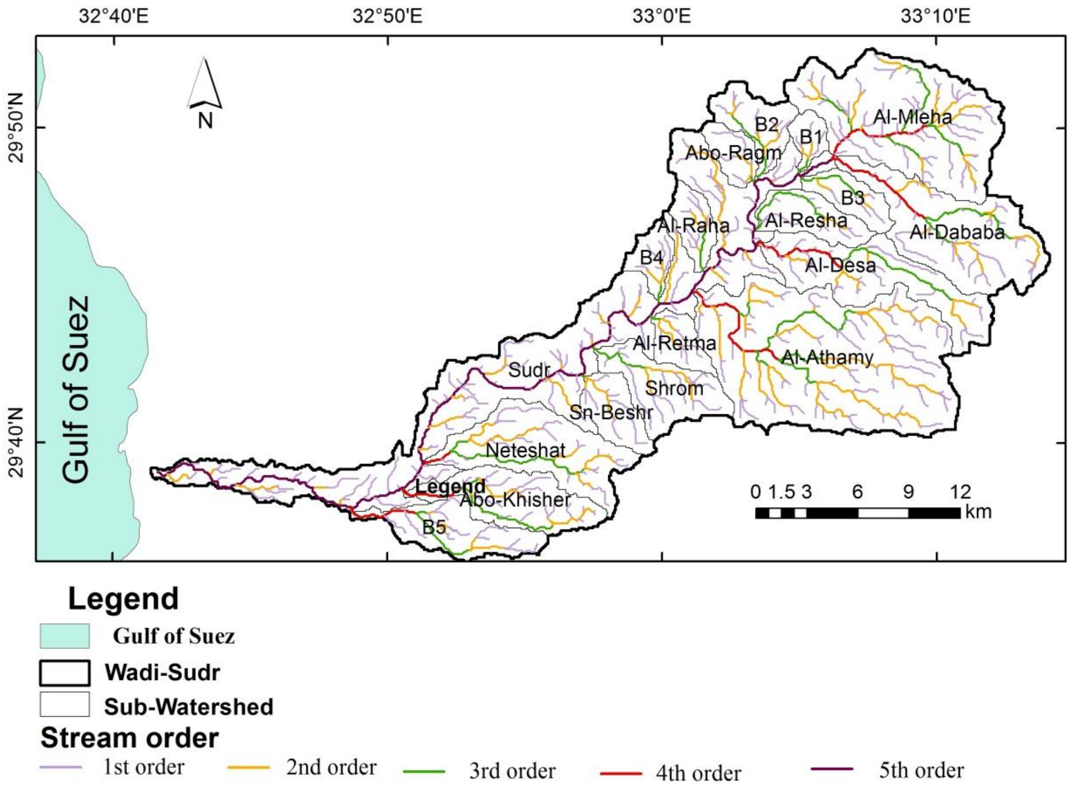

Figure 3. Wadi-Sudr sub-watersheds and their streams orders

Stream Order & Stream Number (Nu)

Computing of stream orders is the first step in drainage network analysis, following a system introduced by Horton (1945) and slightly modified by Strahler (1952). The stream order is a dimensionless value and is directly proportional to the area of the contributing watershed, to the channel dimensions and to the stream discharge.

According to strahler, first order streams are having no stream tributaries and that flows from the stream source. A second-order segment is created by joining two first-order segments, a third-order segment by joining two second order segments, and so on. There is no increase in order when a segment of one order is connected by some other lower order as showing in "Fig. 4".

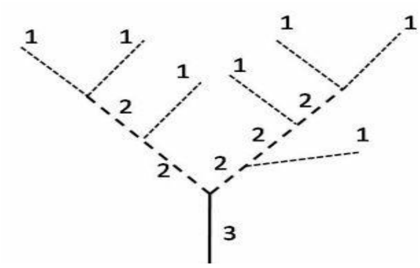

Figure 4. Strahler Ordering System (Strahler, 1964)

For correct calaulation of stream segments number, the stream line previously extracted have to be similar to the definition of stream segments of Strahler, which didn't match the definition of segments in ArcGIS. In ArcGIS a stream segment is defined from a confluence of a tributary to the next confluence, while according to Strahler; a tributary of lower order would not split a stream segment of higher order. For instance, as shown in "Fig. 4"; according to Strahler's definition there would be only two segments of order two; whereas, ArcGIS would define five different segments of this order.

Stream Number (Nu) is the number of stream segments of various orders. Wadi-Sudr; there are 618 streams linked with 5th order of streams sprawled over an area of 601.611 km². the number of streams from each order were observed; 473, 107, 30, 7, and 1 for the first, second, third, fourth, and five order respectively. "Table 2" indicated that Wadi-Sudr contains main stream of 5th order. The watersheds ELMleha, Al-Dababa, Al-Desa, Al-Athamy, Abo-Khisher, Neteshat and B6 had 4th streams order covering an area of 69.598, 47.677, 38.813, 112.866, 26.55, 37.913 and 21.442 Km² respectively. The watersheds Al-Resha, Abo-Ragm, Al-Raha, Al-Retma, Shrom, Sn-Beshr, B1, B2, B3, B4 and B5 had 3rd streams order covering an area of 14.378, 8.072, 8.831, 8.837, 22.703, 12.667, 5.349, 13.95, 10.074, 7.559 and 21.442 Km² respectively. It was noticed that there was a decrease in stream frequency as the stream order increases.

Bifurcation ratio (Rb)

Bifurcation ratio is defined by Schumm (1956), as the ratio between the total number of stream segments of one order to that of the next higher order in a drainage basin. Bifurcation ratio controlled by drainage density, stream entrance angles, lithological characteristics, basin shapes and basin areas (Shaikh & Farjana, 2015). Strahler (1964) demonstrated that the bifurcation characteristically ranges between 2.0 and 5.0 for watersheds in which the geologic structures do not distort the drainage pattern. Elongated Basins have high bifurcation ratio and permit the passage of runoff over an extended period of time, so they have more chances to feed the ground water. Basins of low bifurcation ratio are circular in shape, allowing the runoff to pass in a short time forming a sharp peak of runoff.(Omran, 2013)

Strahler (1964) stated that the theoretical minimum possible value of 2 is rarely approached under natural conditions, therefore, all the results of bifurcation ratio in Wadi-Sudr were more than or equal 2. Bifurcation ratio of Wadi-Sudr sub basin ranged from 2 to 6.5 indicating that the geologic structures did not distort the drainage pattern. Bifurcation ratio for Wadi-Sudr was 4.421, 3.567, 4.286 and 7 for 1st, 2nd, 3rd and 4th stream order. The ratio values for different successive basins will vary slightly, so we usually used a mean bifurcation ratio.The mean bifurcation ratio values of different sub-watersheds showed variation from 1.5 to 3.262 as showing in "Table 2". The mean bifurcation ratio of Wadi-Sudr was 3.855 indicating that the geologic structures do not distort the drainage pattern.

Stream Length (Lu)

Stream length is the length of all the streams having order U (Horton, 1945). Areas with large slopes and fine texture has smaller lengths of streams. Longer lengths indicate flatter gradients of streams. Actually, the streams of first order resemble the mountainous surface which is characterized by a steep slope. These streams are short, obstructive, fast flowing and join quickly to form the streams of the second order, whereas the streams of higher order always record a higher mean length

(Omran, 2013) .With the help of GIS software the number of streams of various orders in the basin is counted and their lengths are measured. We noted that the total length of stream segments is maximum in first order streams and decreases as the stream order increases "Table 2".

Strahler (1964) stated that mean Stream length is a dimensional property revealing the characteristic size of components of a drainage network and its contributing watershed surfaces. Mean stream length is the total stream length divided by the number of segment of that order. It could be observed that there were deviations in mean stream length for the highest and lower order of Main-Sudr sub-watershed. The mean length value was 0.806 km at the 1st stream order, while at the 5th order is 63.102. The deviation might have resulted from the change in topographic elevation and the slope of the area where it is covered by basement rocks. Horton (1945) defined stream length ratio as the ratio of the average stream length of order (u), to average stream length of the next lower order (u-1). Stream length ratio for sub basin varied from 0.035 to 3.191. Stream length ratio for Wadi-Sudr varied from 0.487 to 1.560.

Table 2. Stream Order, Stream Number and stream length

Stream Order	Main-Sudr sub-Watershed			Abo-khisher sub-watershed			Neteshat sub-watershed		
	Stream Length (Lu)(km)	Mean Stream Length	Stream Length Ratio	Stream Length (Lu) (km)	Mean Stream Length	Stream Length Ratio (Rl)	Stream Length (Lu)(km)	Mean Stream Length	Stream Length Ratio
1 st	85.382	0.806	0.000	17.798	0.809	0.000	20.304	0.677	0.000
2 nd	33.916	1.696	0.397	8.179	1.363	0.460	13.900	1.986	0.685
3 rd	-	-	-	8.424	4.212	1.030	10.768	5.384	0.775
4 th	-	-	-	3.894	3.894	0.462	1.750	1.750	0.163
5 th	63.102	63.102	0.000	-	-	-	-	-	-
Stream Order	Shrom sub-watershed			Al-Athamy			El-Mleha sub-watershed		
	Stream Length (Lu) (km)	Mean Stream Length (Lsm)(km)	Stream Length Ratio (Rl)	Stream Length (Lu) (km)	Mean Stream Length (Lsm)(km)	Stream Length Ratio (Rl)	Stream Length (Lu) (km)	Mean Stream Length (Lsm)	Stream Length Ratio (Rl)
1 st	19.596	1.633	0.000	61.790	0.782	0.000	52.179	0.884	0.000
2 nd	5.928	2.964	0.303	53.384	3.140	0.864	18.854	1.347	0.3612
3 rd	4.083	4.083	0.689	18.277	3.655	0.342	14.948	2.990	0.793
4 th	-	-	-	8.881	8.881	0.486	7.281	7.281	0.487
5 th	-	-	-	-	-	-	-	-	-
	Al-Dababa sub-watershed			Al-Resha sub-watershed			Al-Desa sub-watershed		
Stream Order	Stream Length (Lu) (km)	Mean Stream Length (Lsm)(km)	Stream Length Ratio (Rl)	Stream Length (Lu) (km)	Mean Stream Length (Lsm)(km)	Stream Length Ratio (Rl)	Stream Length (Lu) (km)	Mean Stream Length (Lsm) (km)	Stream Length Ratio (Rl)
1 st	25.625	0.657	0.000	8.298	0.638	0.000	23.657	0.739	0.000
2 nd	12.434	1.554	0.485	2.111	1.056	0.254	9.356	1.559	0.396
3 rd	9.511	4.755	0.765	6.736	6.736	3.191	8.911	4.455	0.952
4 th	6.769	6.769	0.712	-	-	-	6.226	6.226	0.699
	Al-Retma sub-watershed			Beshr sub-watershed			Al-Raha sub-watershed		
Stream Order	Stream Length (Lu) (km)	Mean Stream Length (Lsm)(km)	Stream Length Ratio(Rl)	Stream Length (Lu) (km)	Mean Stream Length (Lsm)(km)	Stream Length Ratio (Rl)	Stream Length (Lu) (km)	Mean Stream Length (Lsm) (km)	Stream Length Ratio (Rl)

1 st	6.909	0.987	0.000	10.331	1.148	0.000	6.849	0.761	0.000
2 nd	3.859	1.929	0.559	4.128	2.064	0.399	3.334	1.111	0.487
3 rd	0.507	0.507	0.131	0.143	0.143	0.035	2.505	2.505	0.751
4 th	-	-	-	-	-	-	-	-	-

	B1 sub-watershed			B2 sub-watershed			B3 sub-watershed		
Stream Order	Stream Length (Lu) (km)	Mean Stream Length (Lsm)(km)	Stream Length Ratio (Rl)	Stream Length (Lu) (km)	Mean Stream Length (Lsm)(km)	Stream Length Ratio (Rl)	Stream Length (Lu) (km)	Mean Stream Length (Lsm) (km)	Stream Length Ratio (Rl)
1 st	3.947	0.789	0.000	8.448	0.603	0.000	4.938	0.549	0.000
2 nd	2.274	1.137	0.576	4.128	1.032	0.489	2.791	0.930	0.565
3 rd	1.141	1.141	0.502	4.939	4.939	1.197	4.241	4.241	1.520
4 th	-	-	-	-	-	-	-	-	-

	Abo-Ragm sub-watershed			B4 sub-watershed			B5 sub-watershed		
Stream Order	Stream Length (Lu) (km)	Mean Stream Length (Lsm)(km)	Stream Length Ratio (Rl)	Stream Length (Lu) (km)	Mean Stream Length (Lsm)(km)	Stream Length Ratio (Rl)	Stream Length (Lu) (km)	Mean Stream Length (Lsm) (km)	Stream Length Ratio (Rl)
1 st	6.720	0.960	0.000	6.588	0.824	0.000	17.772	1.367	0.000
2 nd	2.455	1.228	0.365	2.760	1.380	0.419	5.059	1.0118	0.285
3 rd	0.334	0.334	0.136	1.022	1.022	0.370	5.150	2.575	1.018
4 th	-	-	-	-	-	-	4.280	4.280	

Stream Order	Main-Sudr sub-Watershed		Abo-khisher subwatershed		Neteshat sub-watershed		Shrom sub-watershed	
	Stream. (Nu)	Bifurcation Ratio (Rb)	Stream No.(N)	Bifurcation Ratio (Rb)	Stream No.(Nu)	Bifurcation Ratio (Rb)	Stream No.(Nu)	Bifurcationatio (Rb)
1 st	106	5.300	22	3.667	30	4.286	12	6
2 nd	20	0.000	6	3	7	3.5	2	2.000
3 rd	-	-	2	2	2	2	1	0.000
4 th	-	-	1	0.000	1	0.000	-	-
5 th	1	0.000	-	-	-	-	-	-
Mean (Rm)	1.767		2.167		2.447		2.667	

Stream Order	Al-Athamy sub-watershed		El-Mleha sub-watershed		Al-Dababa sub watershed		Al-Resha sub-watershed	
	Stream No.(Nu)	Bifurcation Ratio (Rb)	Stream No.(Nu)	Bifurcation Ratio (Rb)	Stream No. (Nu)	Bifurcation Ratio (Rb)	Stream No.(Nu)	Bifurcation Ratio(Rb)
1 st	79	4.647	59	4.217	39	4.875	13	6.5
2 nd	17	3.400	14	2.800	8	4.000	2	2
3 rd	5	5.000	5	5.000	2	2.000	1	0.000
4 th	1	0.000	1	0.000	1	0.000	-	-
5 th	-	-	-	-	-	-	-	-
Mean (Rm)	3.262		3.004		2.719		2.833	

Stream Order	Al-Desa sub-watershed		Al-Retm sub-watershed		Beshr sub- watershed		Al-Raha sub- watershed	
	Stream No.(Nu)	Bifurcation Ratio (Rb)	Stream No.(Nu)	Bifurcation Ratio (Rb)	Stream No. (Nu)	Bifurcation Ratio (Rb)	Stream No.(Nu)	Bifurcation Ratio (Rb)
1 st	34	5.667	7	3.500	9	4.500	9	3.000
2 nd	6	3.000	2	2.000	2	2.000	3	3.000
3 rd	2	2.000	1	0.000	1	0.000	1	0.000
4 th	1	0.000	-	-	-	-	-	-
5 th	-	-	-	-	-	-	-	-
Mean (Rbm)	2.667		1.833		2.167		1.500	

Stream Order	B1 sub- watershed		B2 sub- watershed		B3 sub- watershed		Abo-Ragm sub-	
	Stream No.(Nu)	Bifurcation Ratio (Rb)	Stream No.(Nu)	Bifurcation Ratio (Rb)	Stream No. (Nu)	Bifurcation Ratio (Rb)	Stream No.(Nu)	Bifurcation Ratio (Rb)
1 st	5	2.500	14	3.500	9	3.000	7	3.500
2 nd	2	2.000	4	4.000	3	3.000	2	2.000
3 rd	1	0.000	1	0.000	1	0.000	1	0.000
4 th	-	-	-	-	-	-	0	-
5 th	-	-	-	-	-	-	-	-
Mean (Rbm)	1.500		2.500		1.500		1.833	

Stream Order	B4 sub- watershed		B5 sub- watershed	
	Stream No.(Nu)	Bifurcation Ratio (Rb)	Stream No.(Nu)	Bifurcation Ratio (Rb)
1 st	8	4.000	13	2.600
2 nd	2	2.000	5	2.500
3 rd	1	0.000	2	2.000
4 th	-	-	1	0.000
5 th				
Mean (Rbm)	2.000		1.775	

4.2.1 Areal Aspects of the Drainage Basin

Drainage Density (Dd)

Drainage density was introduced by Horton (1945); as the ratio of total stream length within a basin to the basin area. It gives an idea about the physical properties of the underlying rocks in the study area. It is a measure for the degree of fluvial dissection and is influenced by numerous factors, among which resistance to erosion of rocks, infiltration capacity of the land, and climatic conditions rank high .(Thorp, 2012)

A drainage density varies from less than 5 km/km^2 for watersheds where slopes are gentle, low rainfall, and permeable, fractured, highly jointed bed rock under dense vegetative cover, and low relief. On other hand, values of more than 500 km/km^2 are possible where rocks are impermeable, slopes are steep, mountainous relief, sparse vegetation and high rainfall (Shaikh & Farjana, 2015). Medium drainage density indicates medium surface runoff, moderate impermeable sub-surface material, moderate sparse vegetation, steep to high relief and well developed network.(Soni et al., 2013)

According to “Table 3” drainage density varied from 0.998 to 1.860 Km^{-1} for Al-Dababa and B3 sub-watershed respectively with an average of 1.321 km^{-1}. Drainage density value for Wadi-Sudr is 1.302 km^{-1} indicating gentle slopes, low rainfall, and permeable, fractured, highly jointed bed rock.

Stream frequency (Fs)

Horton (1932) defines Stream frequency as the number of streams per unit area. Stream frequencies primarily depend on lithology of the basin and the texture of drainage network (Shaikh & Farjana, 2015). Basins of high stream frequency and density value have more possibilities for flood initiation. Stream frequency does not give direct indication to the quantity of runoff. However, it could be used in determining the drainage density which could not be estimated directly from available data, but it could give good indication with other parameters, such as drainage density, about the potential runoff risk zones.(Saad et al., 1980)

It can be observed from “Table 3” that; Higher values of drainage frequency were found in Al-Raha, B1, B2, B3, B4, Abo-Khisher, Al-Mleha, Al-Resha and Al-Retma sub-watersheds, which also have the higher value of Dd, which indicates that the Fs increases with the increase in Dd indicating more hazards they may cause. Drainage frequency for sub-watersheds varies from 0.661 to 1.496 km^{-2}. with an average of 1.079 km^{-2}. Drainage frequency value for Wadi-Sudr is 1.027 km^{-2}.

Texture Ratio (Dt)

Drainage texture was introduced by Horton (1945); as the total number of stream segments of all orders per perimeter of that area. It is one of the important concepts of geomorphology which means that the relative spacing of drainage lines. Drainage textures were classified by Smith (1950) into five classes, very coarse (< 2), coarse (2 - 4), moderate (4 - 6), fine (6 - 8) and very fine (> 8). The drainage texture depends upon a number of natural factors such as climate, rainfall, vegetation, rock and soil type, infiltration capacity, relief, and stage of development.(Smith, 1950)

A fine texture was produced when The rocks were soft or weak unprotected by vegetation , whereas massive and resistant rocks cause coarse texture. Drainage texture for all sub-watersheds varied from 0.491 to 1.574 in Shrom and Al-Athamy sub-watershed respectively with an average of 0.799 which indicates very coarse Drainage texture. Drainage texture for sudr main watershed is 2.939 indicating coarse Drainage texture.

Infiltration Number (If)

Faniran (1968) defined the infiltration number of a watershed as the product of drainage density and stream frequency and given an idea about the infiltration characteristics of the watershed. It gives an idea about the infiltration characteristics of the basin that reveals the impermeable lithology and higher relief. The higher the infiltration number the lower will be the infiltration and consequently the higher will be surface runoff. This leads to the development of higher drainage density.(Masoud, 2015)

Infiltration number for all sub-watershed varied from 0.862 to 2.4. The higher values of infiltration number were observed in Abo-Khisher, Al-Mleha, Al-Retma, Al-Raha, Al-Retma, Abo-Ragm, B1, B2, B3, B4, B5 sub-watersheds, which also had the higher values of drainage density, indicating a high runoff possibility and low groundwater recharging potentiality. Other sub-watersheds had low values of infiltration number indicating the high groundwater recharging possibilities by runoff water.

Form Factor Ratio (Rf)

Horton (1932) defined Form factor as the ratio of the area of the basin to the square of the length of the basin. Horton proposed this parameter to predict the flow intensity of a basin of a defined area. For perfectly circular basin the value should be greater than 0.78. Smaller the value, the basin will be more elongated. Therefore, higher value of form factors, the basin shape more circular and vice-versa (Shaikh & Farjana, 2015). Sudr sub-watershed had less Form factor of 0.0684 indicating elongated shape. El-Mleha sub-watershed had high Form factor of 0.647 indicating semi-circular shape. Form factor of Wadi-Sudr 0.203 indicating that the basin will have a flatter peak of flow for longer duration. Flood flows of elongated and elongated circular basins are easier to be managed than that of the circular basins.(Elewa et al., 2012)

Circularity Ratio (Rc)

Circularity Ratio is defined by Miller (1953) as the ratio of the area of the basins to the area of circle having the same circumferences as the perimeter as the basin. It is influenced by the length and frequency of streams, geological structures, land use, land cover, climate and slope of the basin (Soni et al., 2013). The value of circularity ratio generally changes from 0 (a line) to 1 (circle). The higher the value of circularity ratio, more the circular shape of the basin and vice versa (Shaikh & Farjana, 2015). Main-Sudr sub-watershed had less circularity ratio of 0.04 indicating elongated shape. Abo Ragm sub-watershed had the maximum circularity ratio of 0.454 indicating less elongated shape. Circularity Ratio for Wadi-Sudr was 0.171 indicating elongated shape.

Elongation Ratio (Re)

The elongation ratio is determined according to Schumm (1956), as the ratio of the diameter of a circle of the same area as the basin to the maximum basin length. High Re values indicate that the areas are having high infiltration capacity and low runoff. The values of elongation ratio generally vary from 0.6 to 1.0 over a wide variety of climate and geologic types. Values close to 1.0 are typical of regions of very low relief, whereas values in the range 0.6 to 0.8 are usually associated with high relief and steep ground slope (Strahler, 1964). These values can be grouped in to three categories namely (a) circular (> 0.9), (b) oval (0.9 to 0.8), (c) less elongated (< 0.7). (Iqbal et al., 2013)

Elongation ratio for sub-watersheds varied from 0.295 to 0.907. El-Mleha sub-watershed had elongation ratio of 0.907 indicating circular shape. Main-Sudr sub-watershed had lower elongation ratio of 0.295 indicating elongated shape. Abo Ragm, B1 and B2 sub-watersheds have elongation ratio of 0.721, 0.71 and 0.719 respectively indicating slightly elongated shape. The other sub-watersheds have elongation ratio less than 0.7 indicating less elongated shapes. Elongation ratio of Sudr main watershed is 0.508 indicating elongated shape. Watersheds having circular to oval shape allow quick runoff, and result in a high peaked and narrow hydrograph. While, elongated watersheds allow slow disposal of water, and result in a broad and low peak hydrograph. (Singh et al., 2003)

Length of Overland Flow (Lg)

The length of overland flow is determined according to Horton (1945); as half of reciprocal of drainage density. It is length of water over the ground before it gets concentrated into definite stream channels. Overland flow across the ground surface to the nearest channel is defined as surface runoff. Basins of long overland flow induce high infiltration and have low risk of flash flooding. On the other hand, basins of short overland flow have high flooding possibility with high risk of flash flooding (Omran, 2013). Length of Overland Flow varied from 0.269 to 0.501 km for B3 and Al-Dababa sub-watersheds respectively. Length of overland flow for Wadi-Sudr was 0.384 km.

4.3.1 Relief Aspect of the Drainage Basin

Maximum basin relief (H)

Maximum basin relief is the maximum vertical distance between the lowest and the highest points of the basin (Sangle & Yannawar, 2014). Main-Sudr sub-watershed had highest relief of 740.2 m whereas B3 sub-watershed had lowest relief of 158 m. For Wadi-Sudr the maximum elevation in is 862 m and minimum elevation is 1 m. Therefore, the average basin relief value in the study area was 861 m AMSL.

Relief Ratio (Rh)

Relief Ratio is defined by Schumm (1956) as the ratio of total relief of watershed and horizontal distance along the longest dimension of the basin parallel to the principal drainage line. It measures the overall steepness of a drainage basin and is an indicator of the intensity of erosion processes operating on the slopes of the basin (Soni et al., 2013). Relief ratios varied from 0.0178 to 0.089 for Main-Sudr and B4 sub-watersheds respectively. Also, relief ratio for Wadi-Sudr is 0.016.From "Table 3", it had been observed that there were a high degree of correlation between high relief, high stream channel slopes high, drainage frequency and high stream frequency indicating high discharges in short duration.

Relative Relief (Rhp)

Schumm (1956) defined relative relief as the ratio of maximum basin relief (H) to perimeter of the basin. Relative relief varied from 0.359 to 2.531 for Main-Sudr and B4 sub-watersheds respectively. Relative Relief for Sudr main watershed was 0.41.

Ruggedness Number (HD)

Ruggedness Number was defined by Strahler (1956); as the product of the maximum watershed relief and drainage density. Ruggedness Number for sub-watersheds varied from 0.242 to 1.006 for Sudr and Al-Resha sub-watersheds respectively and 0.661 for Wadi-Sudr. High values of drainage density and maximum basin relief indicates extremely high values of HD.

Table 3. Morphometric areal and relief aspects of Wadi-Sudr sub-watersheds

Sub-Watershed	Drainage Density (Dd) km^{-1}	Drainage Texture (Dt)	Stream Frequency (Fs) km^{-2}	Infiltration Number (If)	Length of Overland Flow (Lg) km	Elongation Ratio (Re)	Circularity Ratio (Rc)	Form Factor (Rf)	Total Relief (m)	Relief Ratio (Rh)	Relative Relief (Rhp)	Ruggedness Number (HD)
Main-Sudr	1.359	0.617	0.946	1.285	0.368	0.295	0.039	0.068	720.2	0.0167	0.359	1.01
Abo-khisher	1.442	0.816	1.168	1.684	0.347	0.481	0.230	0.182	347	0.0287	0.912	0.501
Neteshat	1.232	0.884	1.055	1.300	0.406	0.541	0.232	0.230	473	0.0369	1.045	0.583
Shrom	1.304	0.491	0.661	0.862	0.383	0.581	0.306	0.265	413	0.0446	1.353	0.539
Al-Athamy	1.261	1.574	0.904	1.140	0.397	0.691	0.338	0.375	557	0.0321	0.860	0.702
El-Mleha	1.340	1.557	1.135	1.521	0.373	0.907	0.340	0.647	275.1	0.0265	0.542	0.369
Al-Dababa	0.998	0.049	1.049	1.046	0.501	0.557	0.264	0.244	262	0.0187	0.550	0.261
Al-resha	1.193	0.697	1.113	1.327	0.419	0.600	0.343	0.283	203	0.0285	0.884	0.242
Al-Desa	1.241	0.787	1.056	1.310	0.403	0.474	0.180	0.177	417.9	0.0282	0.802	0.518
Al-Retma	1.276	0.589	1.132	1.444	0.392	0.644	0.385	0.326	282	0.0542	1.661	0.360
Beshr	1.153	0.608	0.947	1.092	0.434	0.652	0.408	0.334	378	0.0614	1.914	0.436
Al-Raha	1.437	0.735	1.472	2.115	0.348	0.614	0.356	0.296	403	0.0738	2.278	0.579
Abo-Ragm	1.178	0.669	1.239	1.459	0.424	0.724	0.453	0.412	314	0.0709	2.099	0.370
B1	1.376	0.592	1.496	2.058	0.363	0.710	0.368	0.396	239	0.065	1.769	0.329
B2	1.256	0.804	1.362	1.710	0.398	0.719	0.314	0.406	305	0.052	1.291	0.383
B3	1.860	0.685	1.291	2.400	0.269	0.587	0.351	0.270	158	0.0259	0.832	0.294
B4	1.365	0.651	1.448	1.975	0.366	0.648	0.334	0.330	428	0.0892	2.531	0.384
B5	1.505	0.589	0.979	1.474	0.332	0.446	0.212	0.159	235	0.0201	0.659	0.354

4.2 Prioritization of sub-watersheds

The morphometric parameters in the linear, areal and relief aspects as discussed above were used for prioritization of sub-watersheds for runoff water harvesting potential sites. For linear aspects of the drainage network we chose mean bifurcation ratio (Rbm), but for areal aspects of the drainage basin drainage density (Dd), stream frequency (Fs), texture ratio (Dt), infiltration number (If), length of overland flow (Lg), elongation ratio (Re), circularity ratio (Rc) and form factor ratio (Rf) were selected. Basin relief (H), relative relief (Rhb), relief ratio (Rh) and roughness number (HD) were selected for relief aspect of the basin. Geometric characteristics of sub-watershed were taken in consideration such as basin area (BA), basin length (BL) and basine slope (Bs).

The prioritizations of sub-watersheds were done in the environment of GIS using Weighted Spatial Probability Model (WSPM). Each of morphometric parameters layers were converted into raster format and reclassified by the ‘‘Spatial Analyst’’ extension tool to five classes very high, high, moderate, low, very low “Table 4”. Some parameters were directly proportion to runoff potentiality such as; drainage density (Dd), stream frequency (Fs), texture ratio (Dt), infiltration number (If), elongation ratio (Re), circularity ratio (Rc), form factor ratio (Rf), basin relief (H), relative relief (Rhb), relief ratio (Rh), roughness number (HD), basin area (BA) and basine slope (Bs). Other parameters were inversely proportional to runoff potentiality such as; basin length (BL), length of overland flow (Lg) and bifurcation ratio (Rb). The resultant map could classify the area into five runoff potentiality classes ranging from very low to very high classes “Fig. 5”.

Table 4. Ranges of input criteria used for the WSPM

Watershed RWH Criteria	Very High	High	Moderate	Low	Very Low
Mean bifurcation ratio (Rbm)	2.568-2.434	2.434-2.309	2.309-2.180	2.180-2.050	2.050-1.921
Drainage density (Dd)(km^{-1})	1.356-1.340	1.340-1.325	1.325-1.304	1.304-1.288	1.288-1.271
Drainage frequency (Fs)(km^{-2})	1.491-1.316	1.316-1.167	1.167-1.039	1.039-0.923	0.923-0.666
Drainage texture (Dt)(km^{-1})	1.568-1.353	1.353-1.138	1.138-0.922	0.922-0.707	0.707-0.492
Form factor ratio (Rf)	0.628-0.517	0.517-0.406	0.406-0.296	0.296-0.185	0.185-0.073
Elongation ratio (Re)	1.00-0.90	0.90-0.80	0.80-0.70	0.70-0.50	0.50-0.20
Circularity ratio (Rc)	0.414-0.341	0.341-0.268	0.268-0.195	0.195-0.122	0.122-0.049
Overland flow distance (Lg)(m)	434.479-414.727	414.727-399.699	399.699-386.352	386.352-372.940	372.940-358.260
Basin infiltration number (If)	1.845-1.591	1.591-1.532	1.532-1.493	1.493-1.449	1.449-1.260
Relative	2.212-1.432	1.432-1.357	1.357-1.272	1.272-	1.154-

relief (Rhb)				1.154	0.695
Relief ratio (Rh)	0.072-0.049	0.049-0.046	0.046-0.043	0.043-0.400	0.400-0.026
Roughness number (HD)	0.933-0.846	0.846-0.699	0.699-0.552	0.552-0.405	0.405-0.258
Basin Area (BA)(km^2)	118.613-74.315	74.315-56.274	56.274-38.453	38.453-21.633	21.633-7.909
Basin Length (BL)(m)	44089.242-30944.363	30944.363-20944.248	20944.248-13719.938	13719.938-8800.215	8800.215-3718.642
Basin Slope (BS)(m/m)	0.189-0.132	0.132-0.104	0.104-0.083	0.083-0.063	0.063-0.035

From the resultant map, the very high and high basin area classes occupied the eastern parts of study area including Abo-Ragm, Al-Raha, B1, B2 and B4 sub-watersheds and some parts of Al-Arhamy and Al-Mleha. Those sub-watersheds had high drainage density (Dd), stream frequency (Fs), infiltration number (If), elongation ratio (Re), circularity ratio (Rc), form factor ratio (Rf), basin relief (H), relative relief (Rhb), relief ratio (Rh), roughness number (HD) and basine slope (Bs) proving their positive relationship with runoff potentiality. In addition they had low basin length (BL), overland flow distance (Lg) and mean bifurcation ratio (Rbm) proving their negative relationship with runoff potentiality.

On the other hand, the very low and low basin area classes occupied Al-Dababa and B5 sub-watersheds and some parts of Al-Desa, Abo-Khisher, shrom, B3 and main-sudr sub-watersheds. Those sub-watersheds had low drainage density (Dd), stream frequency (Fs), infiltration number (If), elongation ratio (Re), circularity ratio (Rc), form factor ratio (Rf), basin relief (H), relative relief (Rhb), relief ratio (Rh), roughness number (HD) and basine slope (Bs) and high basin length (BL), overland flow distance (Lg) and mean bifurcation ratio (Rbm).

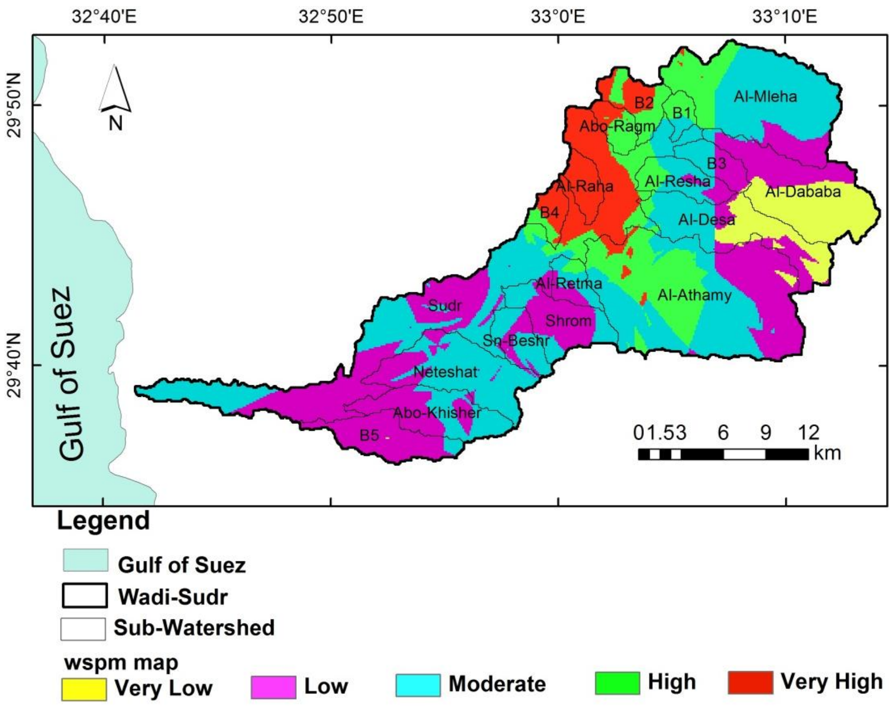

Figure 5. WSPM map showing runoff potential areas in wadi Sudr.

5 SUMMARY AND CONCLUSION

Morphometric analysis of a watershed provides a quantitative description of the drainage system, which is an important aspect of the characterization of watersheds. With the help of GIS software, the number of streams of various orders in the basin is counted and their lengths are measured. Wadi-Sudr had 618 streams linked with 5^{th} order of streams sprawled over an area of 601.611 km² and was subdivided into 18 sub-watersheds. It is noticed that the total length of stream segments is maximum in first order streams and decreases as the stream order increases. The bifurcation ratio values indicated that the geologic structures do not distort the drainage pattern.

Drainage density value for Wadi-Sudr indicated gentle slopes, low rainfall, and permeable, fractured, highly jointed bed rock. High value of drainage frequency and drainage density indicating more hazards they may cause. Drainage texture for all sub watersheds values was less than two indicating very coarse drainage texture. Drainage texture for Wadi-Sudr was 2.939 indicating coarse drainage texture. The higher values of infiltration number were observed in Abo-Khisher, Al-Mleha, Al-Retma, Al-Raha, Al-Retma, Abo-Ragm, B1, B2, B3, B4, and B5 sub-watersheds, which also has the higher values of drainage density, indicating a high runoff possibility and low groundwater recharging potentiality. Al-Mleha sub-watershed is more circular in shape. Abo-Ragm, B1 and B2 are less elongated in shape. All other sub-watersheds are elongated in shape.

The prioritizations of sub-watersheds for runoff water harvesting potentiality were done using Weighted Spatial Probability Model (WSPM). From The resultant map, the very high and high basin area classes occupied the eastern parts of study area including Abo-Ragm, Al-Raha, B1, B2 and B4 sub-watersheds and some parts of Al-Arhamy and Al-Mleha. The very low and low basin area classes occupied Al-Dababa and B5 sub-watersheds and some parts of Al-Desa, Abo-Khisher, shrom, B3 and main-sudr sub-watersheds.

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