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Morphometric Analysis of Wadi Aurnah Drainage System, Western Arabian Peninsula

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Abstract: The analysis of drainage morphometry is usually a prerequisite to the assessment of hydrological characteristics of surface water basin. In this study, the western region of the Arabian Peninsula was selected for detailed morphometric analysis. In this region, there are a large number of drainage systems that are originated from the mountain chains of the Arabian Shield to the east and outlet into the Red Sea. As a typical type of these drainage systems, the morphometry of Wadi Aurnah was analyzed. The study performed manual and computerized delineation and drainage sampling, which enables applying detailed morphological measures. Topographic maps in combination with remotely sensed data, (i.e. different types of satellite images) were utilized to delineate the existing drainage system, thus to identify precisely water divides. This was achieved using Geographic Information System (GIS) to provide computerized data that can be manipulated for different calculations and hydrological measures. The obtained morhpometric analysis in this study tackled: 1) stream behavior, 2) morphometric setting of streams within the drainage system and 3) interrelation between connected streams. The study introduces an imperial approach of morphometric analysis that can be utilized in different hydrological assessments (e.g., surface water harvesting, flood mitigation, etc). As well as, the applied analysis using remote sensing and GIS can be followed in the rest drainage systems of the Western Arabian Peninsula.

Keywords: Hydrology, tributary, stream order, Wadi, Arabian Peninsula.

1. INTRODUCTION

The Arabian Peninsula is situated in arid region where water resources are scarce. This is attributed to the low rainfall rate (i.e. < 200 mm) besides high evaporation. In addition, the influence of current dust storms often hides the geomorphic terrain surface and destroyed surficial hydrological features.

The western coast of Arabian Peninsula is adjacent to the Red Sea, which is a part of the Dead Sea Rift System (DSRS). Along with this system, a curved mega-structure is located and described as the Arabian Shield (Fig. **1**). The geomorphology of this shield composes an elevated region where mountain chains and crests with more than 2000m often exist. The altitude of these chains decreases seaward where the coastal plain is situated and separates the shield from the coast by thick sequence of Quaternary deposits.

The geology of the study area is characterized by dominant Late Precambrian plutonic rocks and Tertiary sedimentary deposits. While, the Cenozoic lavas form extensive fields in the north. The Quaternary surficial deposits occur on different parts of the area, but they are widespread in the coastal plain [1, 2].

Even though, rainfall rate is low and sometimes negligible, yet stream morphology is a unique feature in the Arabian Peninsula. Hence, valleys (Wadis in Arabic) are found to exhibit distinguished morphological patterns. This is a result of recent surface run-off and even some paleo-channels that exit in the area and intersected with recent ones [3].

Wadi Aurnah basin, as a typical hydrologic system in the western part of the Arabian Peninsula, composes a funnel-like shape catchment, with an area of about 3113 km^2. Among this catchment, the Holy Muslim city of Makka Al Mukaramah is situated. This increase the water demand, especially in Hajj pilgrimage.

The catchment of Wadi Aurnah lies between the following geographic coordinates:

39° 12′ 00"E; 40° 18′ 00" E and

21° 01′ 30"N; 21° 35′ 30"N.

The catchment is one of the major five catchments in the central part of the Tihamah-Hijaz (middle part of the Arabian Shield) region. It is bounded from the east by several mountain bench marks. Certainly, Jabal Twayriq (1872 m), Jabal Al Amid (2135m) and Jabal Bared (2337m), Al Tarykah (2402m) and Jabal Al-Adim (2476m).

The area of concern is affected by the Mediterranean climate, which reveals monsoonal rainfall during spring season. Moreover, the Arabian Shield, as an elevated region, composes a barrier parallel to the Red Sea; hence, it condenses cloud masses from west and converts them into rain droplets on the high mountain chains. This, in turn, creates diversity in the geographic distribution of rainfall in the studied area.

According to [4, 5] the average rainfall rate in Wadi Aurnah is 350-400 mm per year. However, recent records show

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Fig. (1). Location map of the study area.

low rate (i.e. between 50 and 200 mm) than the previous. Additionally, remarkable climatic conditions exist, notably the sandy storms and torrential rains. In this view, Arunah Watershed comprises about 880 km^2 of sand desert, which is equivalent to 28% of the whole basin.

The current study was accomplished using several approaches of drainage system analysis. It combines manual sampling and analysis of drainage system followed with the application of recent techniques. In this respect, remotely sensed data was utilized, notably in delineating buried stream and in connecting drainage networks, which are not complete in topographic maps. In addition, GIS was also applied as a helpful tool of data analysis.

The study aims to analyze the major morphometric elements of Wadi Aurnah. It treats the characterization of streams' behavior (e.g. meandering, frequency, etc), their setting with respect to the catchment and their relation to each other (e.g. patterns, junctions, etc). This provides valuable information that can be used in different water and risk management assessments, such as determining flood-prone areas and selecting sites for water harvesting. Additionally, the morphometric analysis can be applied to similar drainage systems in the Arabian Peninsula.

2. MATERIALS AND METHOD

Morphometric analysis of a drainage system requires a delineation of all existing streams and reaches. There are several methods of drainage system delineation, but all follow two procedures. These are the manual and automated system delineation. However, many terrain features may create error while applying stream delineation. For example, in the karstic terrain the, existence of sinkholes creates a problem in stream connectivity and thus identifying water divide becomes tedious. Also, terrain covered by Quaternary deposits (e.g., sand dunes, gravel, etc) often results a distortion in drainage delineation, like in the Arabian Peninsula area.

Drainage system of Wadi Aurnah shows an example of erroneous stream delineation obtained from the available topographic maps**,** which often exists due to the dominance of Quaternary deposits in the low plains and in areas where depressions exist due to the complex geologic structures.

Accordingly, updated stream delineation in this study was carried out for Wadi Aurnah, since the previous obtained maps for this basin reveal erroneous signatures on topographic maps. These are anomalous aspects of drainage behaviour [3], as well as incomplete stream connectivity in some places within the system. Therefore, manual sampling of drainage network was again adopted from topographic maps (1:50000) in combination with computerized tools, certainly the remotely sensed data and Geographic Information System (GIS), which were of great significant in this application.

For the unconnected drainage systems, ASTER satellite images were analyzed using ERDAS Imagine software. These images can provide information on the surface features, and able to detect buried stream networks. This is can be achieved in applying thermal bands with 90m spatial resolution (i.e. capability to distinguish objects on satellite image) in these images. Therefore, bands 10-14 in ASTER images are capable to detect porous terrain the covered by sediments, which is often occupy wet horizons and buried streams.

The applied method in stream delineation was done digitally in GIS (*Arc View* software) system. A number of digital applications were undertaken, including band combination, colour slicing, filtering and related measuring tools. Hence, all tributaries of different extents and patterns were digitized

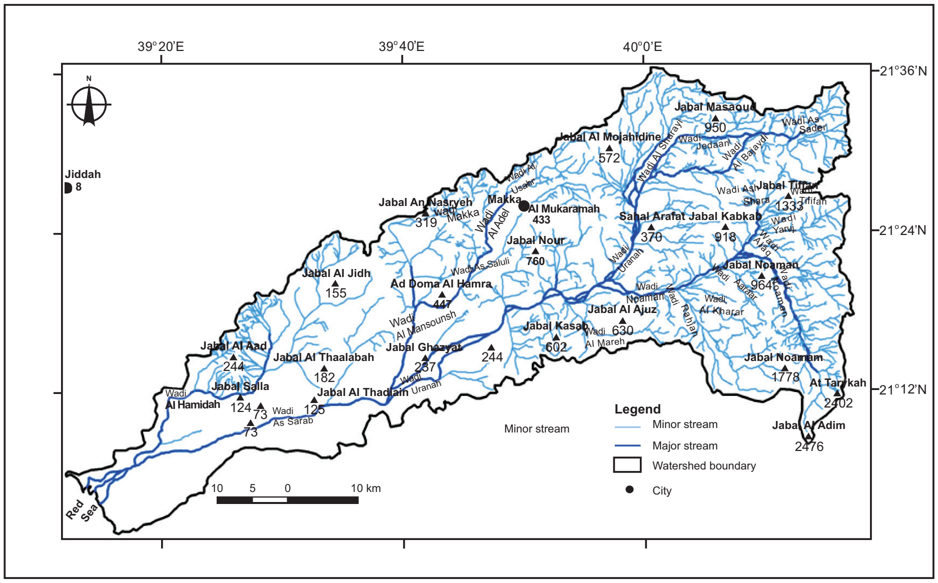

Fig. (2). The drainage basin of Wadi Aurnah.

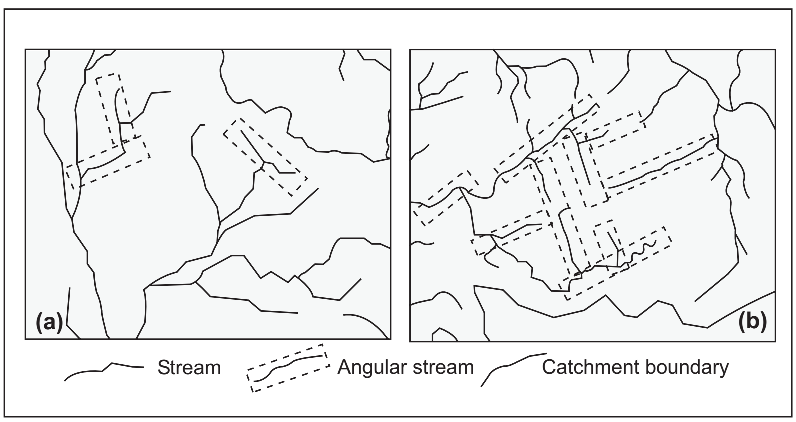

Fig. (3). Examples showing singular and set of angular streams in Wadi Aurnah.

and the catchment boundary was also determined for Wadi Aurnah (Fig. **2**).

3. DATA ANALYSIS AND RESULTS

3.1. Drainage Patterns

The arrangement of streams in a drainage system constitutes the drainage pattern, which in turn reflects mainly structural/ or lithologic controls of the underlying rocks [6].

The area of study encompasses a miscellany of drainage patterns; however, dendritic drainage pattern is the most dominant type and occupies more than 95% of the area. Even though, difference in stream lengths and angle of connection, yet they are in general characterized by a treelike branching system, which is a dendritic drainage pattern that indicates homogenous and uniform soil and rocks [7].

Angular drainage patterns also exist in Wadi Aurnah basin. They appear either as one-set or two-sets of angular streams (i.e. with acute angle of stream connection) to indicate the existence of fault and joint systems (Fig. **3a**), like that in Jabal Kasab area, where joint and fault systems exist (Fig. **3b**).

3.2. Drainage Density (D)

Drainage density is a measure of the length of stream channel per unit area of drainage basin. Mathematically it is expressed as:

$$D = \frac{\Sigma L \text{ (total length of all stream)}}{A \text{ (area of the basin)}}$$

In this study, the drainage density map was obtained using the digital data from the obtained drainage map. This was accomplished using the GIS system (*Arc View* software), which is capable to measure the actual stream lengths and number. Therefore, the drainage system was classified into frames of definite area (i.e. 5kmx5km). This classification depended on the visual density of streams in the area. Hence, the total length of streams in each frame (i.e. 25km^2) was measured using *Arc View* software. The resulted value of total length was plotted in the middle of the frame (Fig. **4**).

Also, for each four neighbouring frames, the average value was again calculated, and then plotted again in the middle of the new resultant frame. After having a number of values (total length/25km^2) in grid arrangement, a contour map could be derived to show the drainage density (Fig. **5**).

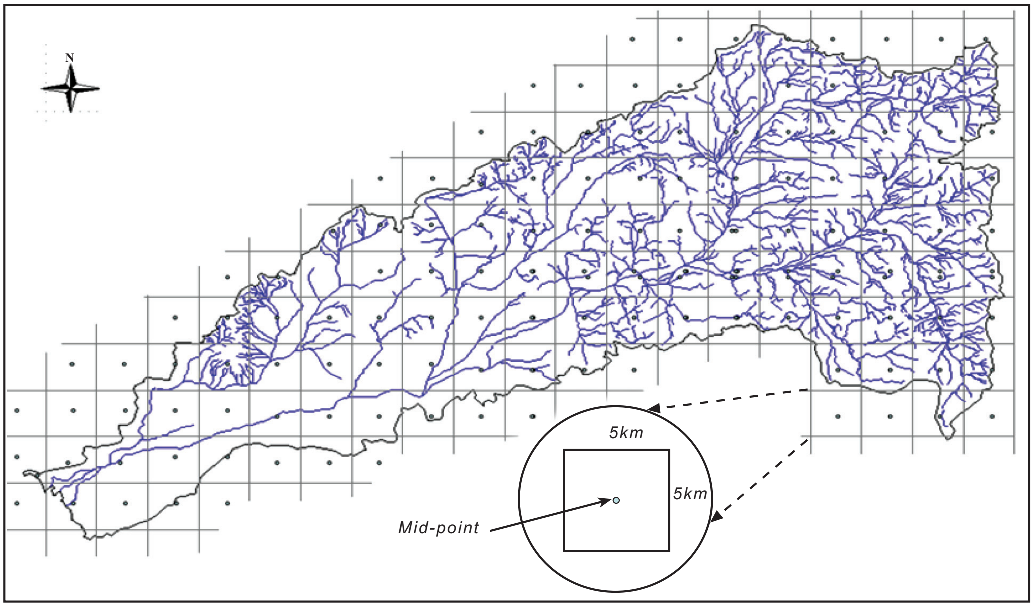

Fig. (4). Classification of Wadi Aurnah into frames to obtain drainage density map.

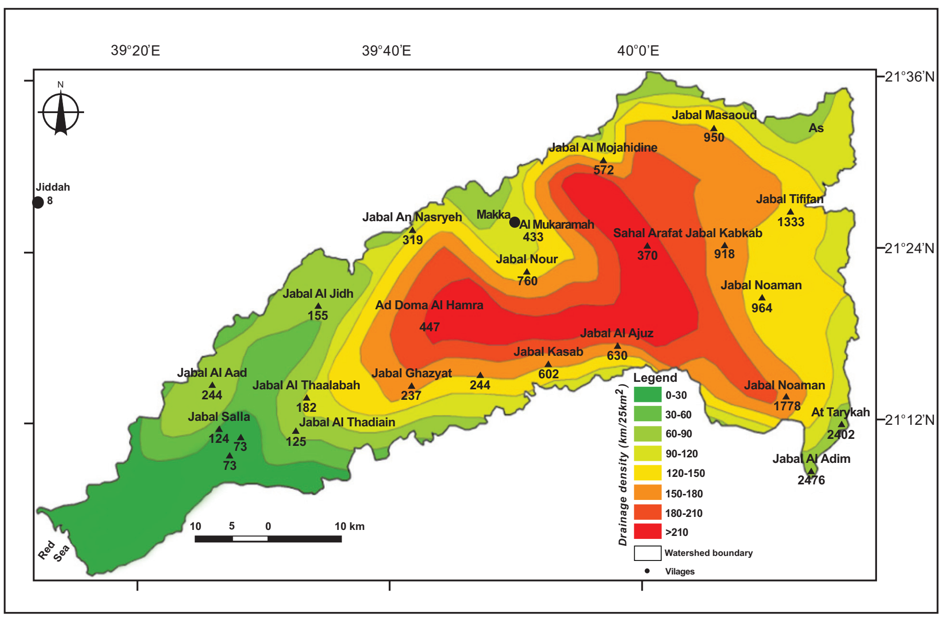

Fig. (5). Drainage density map of Wadi Aurnah.

It was categorized into eight classes with an interval of 30 km.

3.3. Drainage Frequency (F)

A similar mathematical relation to that applied in drainage density, stream frequency was also done by counting the number of streams in a specified area. In the light of this morphometric relation, several workers used stream frequency rather than drainage density (length density). Therefore, some hydrologic studies consider the density of drainage (e.g. Dingman, 1970), while others deal with drainage frequency [8-11].

Stream frequency is expressed by the following equation:

$$F = \frac{\Sigma L \text{ (number of streams)}}{A \text{ (area of the basin)}}$$

Presenting drainage frequency in contour maps was obtained by the same applied approach used in drainage density. However, instead of length, the numbers of streams were counted and put in the mid-point of each frame.

3.4. Meandering Ratio (M_r)

It is calculated to express the ratio between straight to curved lengths of the primary (major) stream within the drainage system. It shows how the real stream length is larger than the straight one, which is indicative to stage maturity. Therefore, the lower meandering ratio is a function of

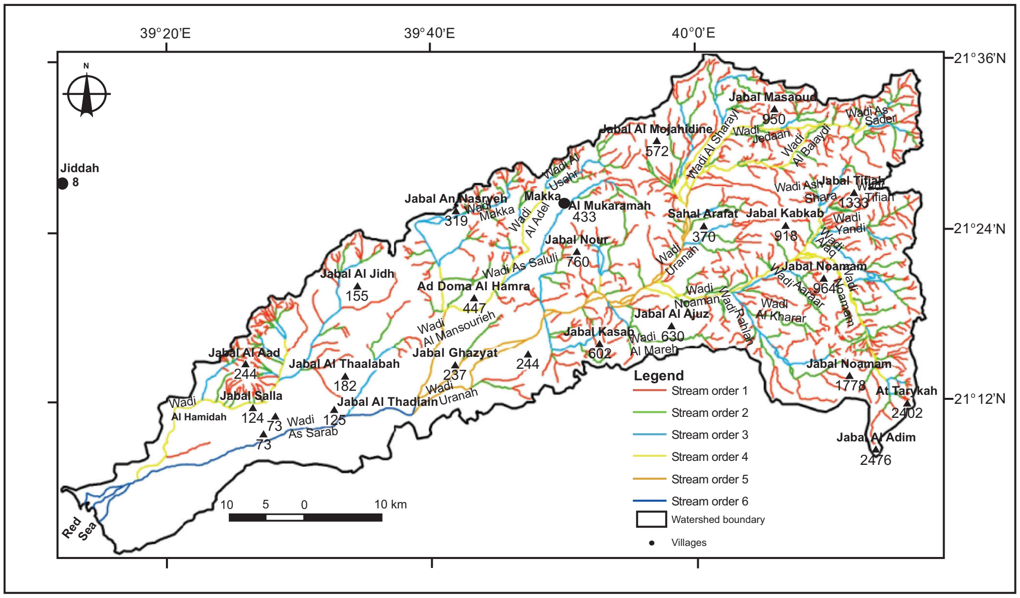

Fig. (6). Stream order map of Wadi Aurnah.

Table 1. Classification of Stream Orders of Wadi Aurnah

Stream Order	Number of Streams	Total Length of Streams (km)
1	2197	1221
2	1900	577
3	694	291
4	483	212
5	188	107
6	37	62
Total	5499	2470

older stream stage and vice versa. Meandering ratio is expressed as:

$$M_r = \frac{Ls \text{ (straight stream length)}}{Lc \text{ (curved stream length)}}$$

Since this relation is applied to the primary watercourse, thus for Wadi Aurnah it was taken from the maximum lengths to calculate both variables (*Ls* and *Lc*). Therefore, the primary course was measured from Jabal Al Adim (2476m), where Wadi Noaman is originated, thus terminated at Wadi As sarab in the coastal zone (Fig. **1**).

Hence, the meandering ratio (M_r) of Wadi Aurnah is:

$$M_r = \frac{123.5}{157.3} = 0.78$$

3.5. Stream Order

Stream order is a method for classifying the relative location of a reach (a stream segment) within the river basin. The applied method followed the procedure that modified by Stahler [12]. Stream order 1 has one connected edge, and then at the confluence of two1st -order streams assigns the downstream reach of order 2, and so on for the rest orders. Wadi Aurnah system has 6-stream orders, and thus a map was obtained using GIS system (Fig. **6**). In addition, the used GIS system enabled calculating the number of reaches in each order (Table **1**).

3.6. Bifurcation Ratio (R_b)

In a simple definition, bifurcation ratio is the ratio between the numbers of stream segments in one order to the number in the next order. Values of R_b typically range from the theoretical minimum of 3 to 5. If R_b is high, thus the flow energy is low, which in turn gives sufficient time for infiltration and groundwater recharge, as well as low probability of flooding and vice versa.

Considering the number of streams of order *i* equal to (N_i), and the number of streams in the next order is N_{i+1}, thus the bifurcation ratio will be calculated as:

$$R_b = N_i/N_{i+1}$$

According to Wadi Aurnah drainage system, the results of bifurcation ratio are shown in Table **2**.

Table 2. Bifurcation Ratio of Wadi Aurnah

Stream Order	Number of Streams	Bifurcation Ratio (R_b)
1	2197	-
2	1900	1.15
3	694	2.73
4	483	1.43
5	188	2.57
6	37	5.08
Average R_b		2.59

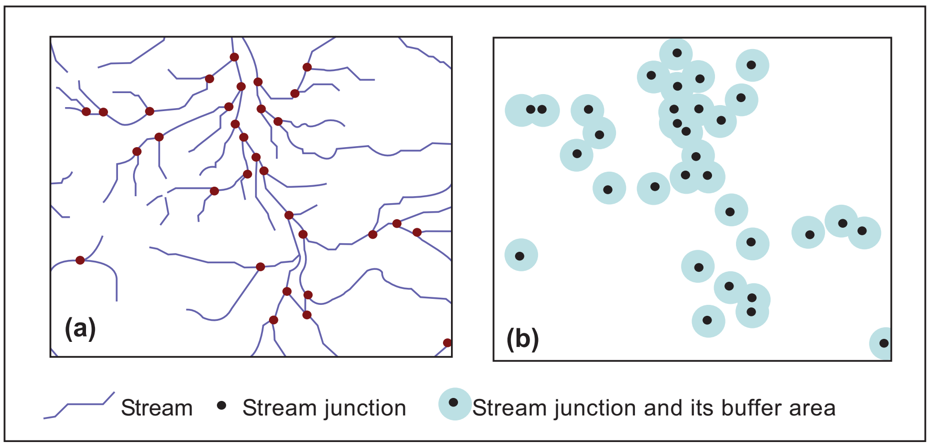

Fig. (7). Example showing the plotting of stream junction and obtaining junction density.

A common quantitative method of analyzing drainage basins, and then cited the "*Law of stream number*" [13] is expressed by the following equation:

$$N_u = R_b^{s-1}$$

Where N_u is the number of streams of order u, R_b is the bifurcation ratio and s is the highest order of the basin. For Wadi Aurnah, R_b will be:

$$N_u = 2.59^{6-1} = 116.5$$

3.7. Stream Junction Density (Jr)

The connection between streams is a significant relation to obtain the stream morphomety in a drainage system. Nevertheless, rarely this relation is used by geomorphologists; however, they often consider only the number of tributaries as indicative function to water infiltration property.

It is obvious that the diversity in the number of junctions between streams can specify a tight hydrological property. Therefore, the higher ratio of connection between streams is almost attributed to several reasons with a special emphasis to the terrain property itself, and more certainly to the non-homogeneity of the exposed lithology, complicated structures, and steep sloping terrain.

In this study, the stream junction, also described as "nodes" was plotted using the GIS system. Hence, for each node (stream junction) a buffer zone was drawn in order to attain the overlapped influence between neighboring nodes. Therefore, a map showing different junction density was derived (Fig. **7**).

Accordingly, areas with high stream junction density were determined in Wadi Aurnah basin. They are concentrating in areas where complex geological structures are located, and certainly in terrains with extensive fracture systems. Therefore, the high density of stream junction indicates zones with high infiltration rate, and thus water recharges easily at these zones and percolate into aquiferous rock formations.

3.8. Dominant Flow Direction

Even though, the dominant flow direction of streams is of great hydrologic importance, yet this morphometric relation is rarely found in many studies. The dominancy of flow in a specific direction is indicative to land mass orientation of the basin terrain. However, in large-scale drainage system (like Wadi Aurnah), often there is more than one prevailing dominant flow direction. This in turn, compels classifying the basin into a number of sub-catchments as shown in Fig. (**8**).

The dominant flow direction can be achieved by establishing rosette-diagrams, in which the direction and even the length of each stream can be plotted for each sub-catchment. This can provide significant information if sub-catchments with major stream courses are considered (almost 4^{th} order and above).

Fig. (**8**) shows the obtained diagrams for the dominant surface run-off directions for the six sub-catchments in the

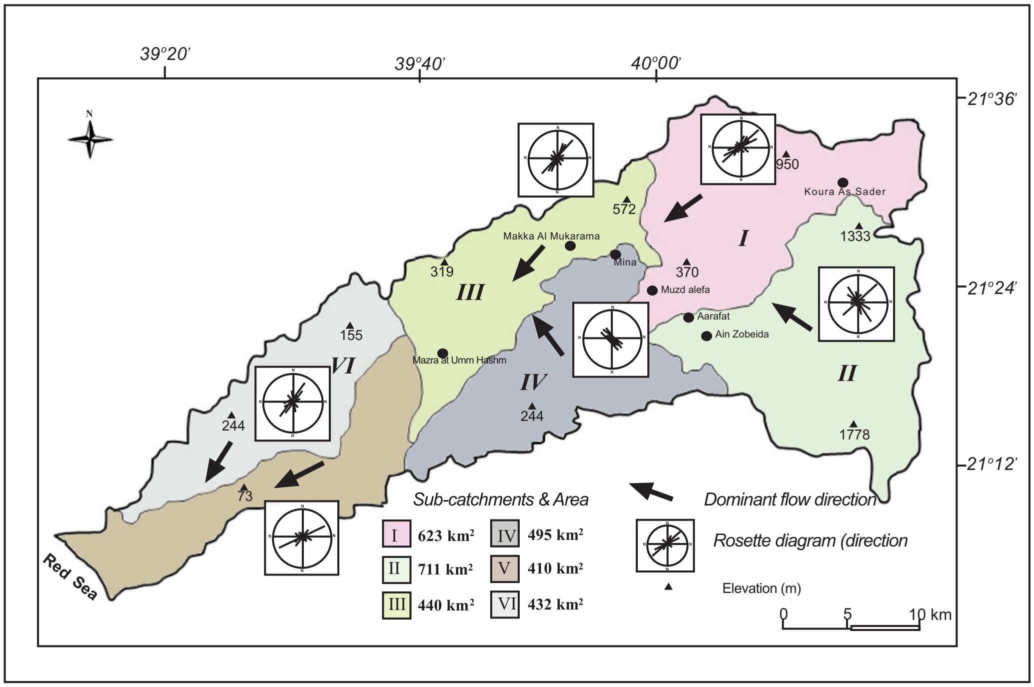

Fig. (8). Sub-catchments of Wadi Aurnah and the dominant flow directions.

study area, which is usually found to be in the NE-SW direction

3.9. Density & Frequency/Bifurcation Ratio (D/R_b & F/R_b)

The relationship between bifurcation ratio and drainage density/or frequency is a simplified morphometric relation. It is a tool helps assessing flood-prone areas as well as to determine groundwater potential zones. This relation is usually established graphically between D/R_b and F/R_b, thus compared to dedicated illustrations obtained by Al-Shamy [14] for this purpose. In this study, this relation could be achieved since detailed data is available for each sub-catchment (Table **3**).

Applying this relation separately to each sub-catchment will provide accurate information on flood estimation and recharge potential, rather applying it to the whole system. In order to evaluate this relation, a number of variables must be primarily calculated for each sub-catchment (Table **4**).

The obtained illustrations for D/R_b and F/R_b were plotted on semi-log papers. Each illustration contains two curves, thus divided the area into three zones A, B and C (Fig. **9**). According to Al-Shamy [14], these zones are described as follows:

- Zone A: low flood probability and high recharge property
- Zone B: high flood probability and low recharge property
- Zone C: moderate to high flood probability and moderate recharge property.

The resulting graphics show that all sub-catchments, except number IV, are located in zone C, and thus characterized by moderate to high flood probability and moderate water recharge property. Only the sub-catchement number IV shows low flood probability and high recharge property, since it is located in zone A (Fig. **9**). In addition, the sub-catchments number I and II are close to zone B, which are supposed to be influenced partially by high flood probability and low water recharge.

4. CONCLUSION AND DISCUSSION

Usually, morphometric analysis of drainage system is prerequisite to any hydrological study. Thus, determination of stream networks' behavior and their interrelation with each other is of great importance in many water resources studies.

This study focuses on the analysis of principal morphometric elements. It treats Wadi Aurnah catchement, located in the western part of the Arabian Peninsula, in arid region and demand for water is extremely urgent. However, the morphomerty of the basin was previously studied using different conventional procedures and tools of analysis. Hence, this study utilized new space techniques of remote sensing and GIS system for data extraction and manipulation. Therefore, stream networks and their measures, as well as and catchment boundary, were accurately delineated.

As a descriptive morphometric criterion, the drainage patterns were investigated from topographic maps (1:50000) and correlated to the existing geologic structures. Additionally, drainage density and frequency were analyzed following empirical procedures using GIS with high precision to measure the total length and number of streams. The obtained maps show that the middle part of Wadi Aurnah basin includes the highest density of drainage system, which exceeds 150km/km^2 (Fig. **5**). The same approach of analysis was applied to drainage frequency, and both criteria are often utilized while assessing the infiltration capacity and recharge property of terrain [15, 16].

Table 3. Major Hydrologic Variables of the Sub-Catchments in Wadi Aurnah

Sub-Catchment	Area (km^2)	Stream Order	Number of Streams	Length of Streams (km)
I	623	1	524	685.6
		2	224	320.2
		3	76	102.8
		4	80	147.6
		5	20	42.1
		Total	924	1298
II	711	1	554	792.1
		2	248	373.6
		3	86	161.7
		4	64	138.2
		Total	952	1466
III	440	1	282	309.1
		2	146	165.6
		3	50	123
		4	28	70.3
		5	12	27
		Total	518	695
IV	495	1	210	298
		2	90	167.9
		3	40	71
		4	4	5.15
		5	38	132.8
		6	4	4.6
		Total	386	680
V	410	1	20	26.5
		2	12	18.8
		3	8	24.5
		4	2	1.4
		5	6	1.2
		6	24	118.7
		Total	72	191
VI	432	1	286	335.2
		2	108	116
		3	40	76.7
		4	20	68.8
		Total	454	597

Meandering ratio was another analyzed morphometric property in this study. The resulting value (i.e. 0.78) shows a slight meandering ratio between the straight and curved length of the primary watercourse in the basin. This exhibits a relatively mature stage of streams development.

Ordering of streams and bifurcation ratio were also diagnosed in this study. Therefore, the numbers of each order as well as total length were calculated using *Arc View* GIS software. These two morphometric properties are integral variables for further hydrologic assessment. However, they are necessary to identify the run-off through the existing

Table 4. Principal Morphological Variables of Wadi Aurnah

Sub-Catchment #	Stream Orders	Total Length *(km)*	Total Number *(n)*	Area *(km²)*	*D*	*F*	R_b	D/R_b	F/R_b	Basin Assessment*
I	5	1298	924	623	2.08	1.48	2.56	B^+	C	C
II	4	1466	952	711	2.06	1.34	2.15	B^+	C	C
III	5	695	518	440	1.57	1.17	2.24	C	C	C
IV	6	680	386	496	1.37	0.77	4.84	A	A	A
V	6	191	72	410	0.46	0.17	1.55	C	C	C
VI	4	596	454	432	1.37	1.05	2.45	C	C	C

*According to Al-Shamy (1992).

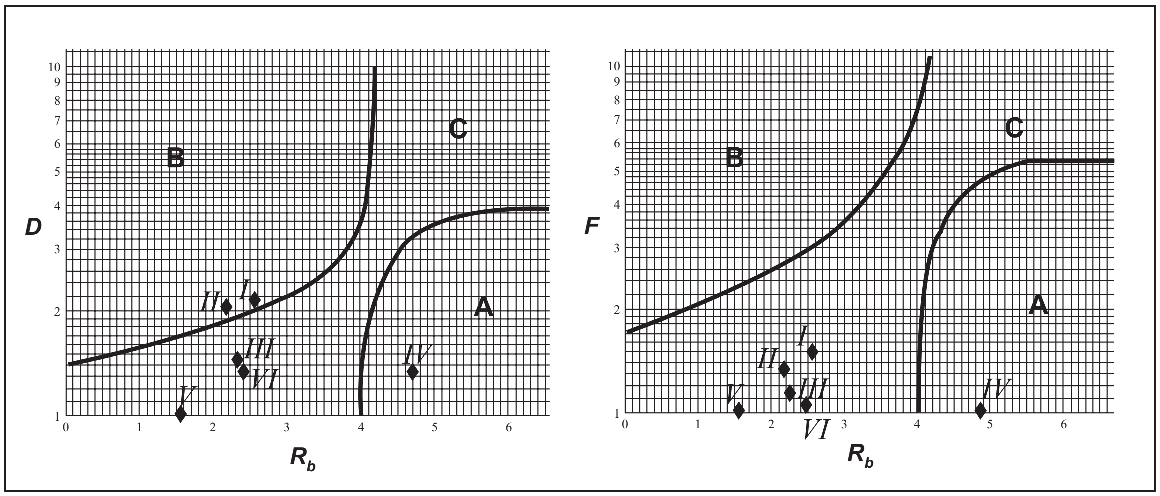

Fig. (9). Assessment of the sub-catchments to floods and recharge property.

stream networks. This provides information on flood-prone areas, surface water (i.e. run-off) velocity and thus the lag time for evaporation and recharge rates.

Moreover, connection (junction) behavior between streams was identified. It is a rarely used morphometric property, but high junction density is indicative to intensive geologic structures, which in turn helps identifying high infiltration zones among which groundwater can be recharged.

Additionally, Wadi Aurnah basin was classified into six sub-basins (sub-catchments) depending on stream networking. This classification can be also done at smaller scale depending on the purpose of any optimum study. For each sub-catchment, the area, number of streams and their orders were calculated and major flow directions was also determined using rosette-diagrams (Fig. **8**).

The existing sub-catchments are characterized by moderate to high flooding probability with anticipated moderate recharge property, except sub-catchment number IV. This can be attributed mainly to the geological setting of the area [1] including structures and lithologies. The intensive faulting systems in the basin divided it into different terrain blocks, where flooding is anticipated between these blocks. These fault systems uplifted/subsided different terrain floors in the basin [18]. However, diversity in the geomorphic setting of sub-catchments exists and influences the response to flooding events. This is obvious since the sub-catchment number IV shows an opposite flow direction with respect to the rest sub-catchments (Fig. **9**), which is in turn, slowdown water flow energy.

Following the same used approach in this study, as well as applying the new morphometric relations (e.g. presentation of drainage frequency, junction density, etc) at small-scale, is recommended to be done in the basin, notably nearby the major cities with large human activities, which have witnessed flooding events, as well as experiencing water scarcity, like that in Makka Al Mukaramah.

The used approaches in this study include a comprehensive morphometric analysis that can be applied for any drainage system elsewhere. They introduce the major elements needed to assess water resources and their hydrologic regime, thus it is recommend to apply similar studies to the rest systems in the Arabian Peninsula.

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