Geomorphological Characteristics of Wadi Zabid Basin (Yemen)

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Abstract : *Since topography is one of the principal basin characteristics affecting stream flow, this paper aims to analyze the morphology of the Wadi Zabid basin using the Digital Elevation Model (DEM), which has been developed for the wadi basin. The creation of the DEM enables more understanding of the basin landscape. In addition, the study carried out morphometric analysis of drainage network in order to show the morphometric characteristics of the drainage basin of Wadi Zabid.*

Introduction

Basin morphometry is one of the factors controlling river regimes. Beckinsale (1969) indicates that the morphometry of a basin, which involves the size, shape, stream pattern, and orientation of a drainage basin, has a more decisive influence upon both the regime and its speed of reaction to climatic factors. Therefore, the present study will analyze the morphometric characteristics of Wadi Zabid basin in order to show their influences on the wadi regime.

Study Area

The area of this study is Wadi Zabid basin. The wadi lies in western Yemen and drains into the Red Sea (Fig.1). The wadi basin extends from the mountain ranges (Yemen Highlands) in the east to the Tihama Coastal Plain in the west. It lies between longitude 43° 5′ and 44° 20′ east and latitude 13° 45′ and 14° 30′ north. The wadi starts as a small stream at an elevation of about 2520 m above sea level. With a total length of 212 km, the wadi and its major tributaries drain a drainage basin of 5,257 km^2. The source region of the wadi and some of its tributaries are located on the Yemen Plateau. In the middle reaches, the other main tributaries of the wadi have their sources in the escarpment.

The study area is very heterogeneous in terms of climate. The climate varies from arid in the west to semi-arid in the east with some high elevation areas having sub-humid climate. The main controlling factor for climate is topographical elevations. There is a gradual decrease in the mean values of temperatures from west to east with the rise of elevations. Mean annual temperature varies between approximately 18° C in the highlands and 29.9° C in the Tihama lowlands. Rainfall is highly variable seasonally and annually. During the recorded periods of 30 years (1970–1999), about 58% of the annual rainfall was received during the monsoon season (June to September). Annual rainfall ranges between 385 mm (Al Jerbah station) and 1917.7 mm (Ibb station).

Data Base and Methodology

The topographical sheets of survey of Yemen (1: 50,000 scale), surveyed in 1981, formed the database for this analysis. The variables for the study of morphometric aspects were analyzed using the quantitative geomorphic methods. The parameters worked out include stream order, stream number, bifurcation ratio, stream profiles, basin shape, and drainage density. Further, Digital Elevation Model (DEM) was developed for the wadi basin. The DEM provides a view of the landscape of the basin. Moreover, the DEM has been used to generate profiles. The basin was divided into 8 sub-basins for more detailed analysis (Fig.2). These sub-basins were demarcated and the analyses were carried out for each of them and for the whole Wadi Zabid basin, as well.

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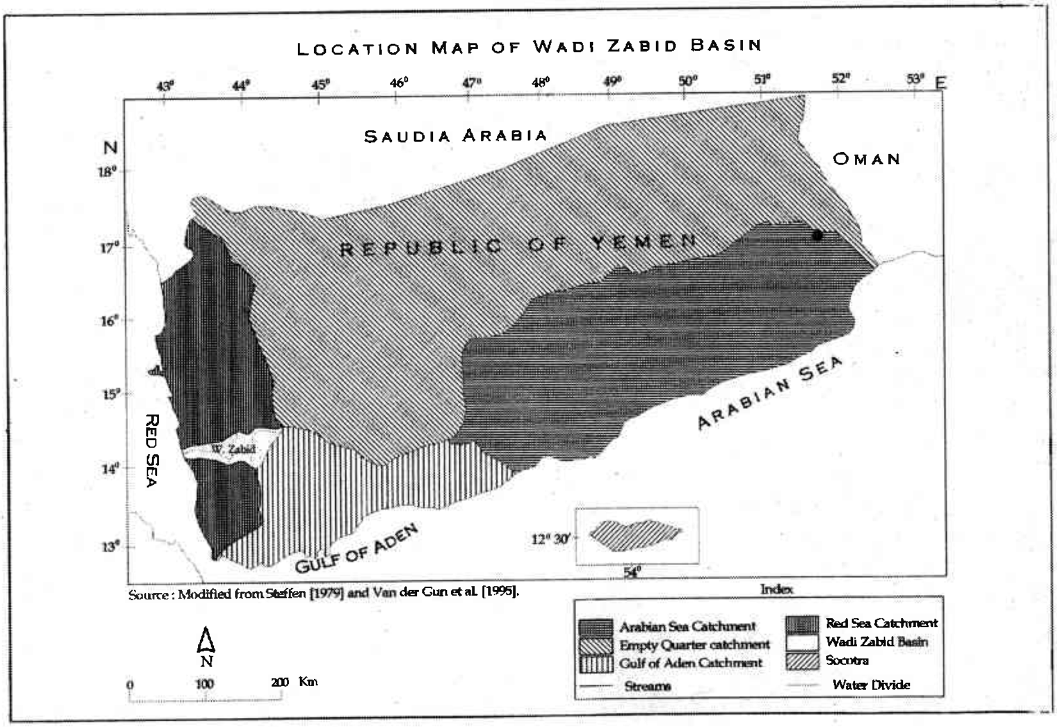

Fig. 1 : Location Map of Wadi Zabid Basin

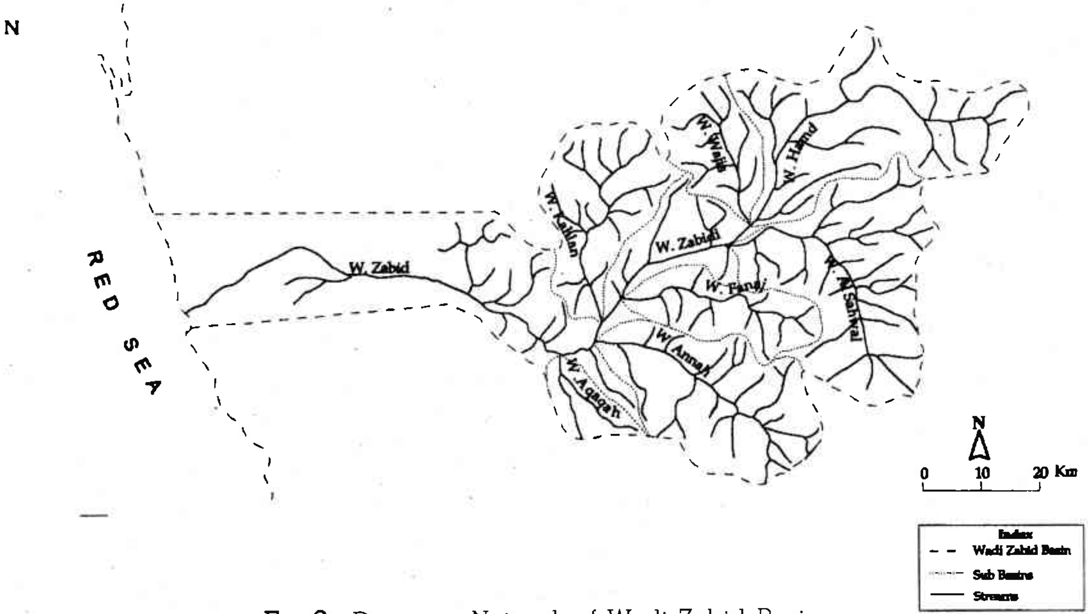

Fig. 2 : Drainage Network of Wadi Zabid Basin

Physiographical Characteristics

Topography is one of the principal basin characteristics affecting stream flow. The relief of the drainage basin affects the rate of water and sediment yield (Gregory and Walling, 1973). The morphological features of the Wadi Zabid basin are largely formed as a result of factors such as the tectonic movements and volcanic activities. The major regional fault systems, the drainage patterns, the alluvial fans, and the aeolian deposits are some of the major features of the basin. Thus, the morphology of the wadi basin is strongly related to the tectonic activities, geological structures as well as lithology.

Situated on the Yemen Plateau, the catchment area of Wadi Zabid was strongly influenced by the uplift of this plateau. This tectonic movement started at late Cretaceous and continued during Tertiary (Van der Gun et al, 1995). The tectonic movements generated enormous escarpments that are generally tilted towards the Red Sea Rift. Hence, the vertical movement of the plateau created high relief between the upstream and the downstream areas of the Wadi basin. The escarpment rises to more than 2,000 m ASL. Some peaks on the plateau rise over 3,000 m ASL. The other major effects of the tectonic movements included the regional faults systems and the volcanic activities as well. These volcanic activities resulted in rising the magma that led to the formation of extensive volcanic extrusions in Yemen, including the upper catchment area of Wadi Zabid (United Nations, 1981). This new topography is strongly affecting the slope development as well as the nature of drainage system of the wadi. The western part of the basin (Tihama Plain) was down-faulted several thousand meters. This plain is situated inside the Red Sea Rift valley. The Red Sea rift occurred during the separation of the African and Arabian Plates from the late Oligocene into the Miocene (Young et al, 2000). The out cropping formations in the study area range from Precambrian to Quaternary. Tertiary volcanic rocks (Yemen Volcanics) are dominant in the upper catchment areas, while Quaternary deposits are dominant in the Tihama plain. However, tectonically elevated, old formations are also found as the outcrop in the transition zone (foothills) between the Tihama plain and the eastern catchment area. These formations include Precambrian igneous rock, Upper Jurassic sedimentary rocks (Amran Group–Limestone) and Cretaceous sedimentary rocks (Tawilah Group–Sandstone).

Four distinct physiographical zones can be identified (Fig. 3 -DEM). These include (1) the highland zone (2) central zone (3) foot hill zone and (4) Tihama lowland zone.

The Highlands Zone

The highlands are the result, of block faulting along a north south axis parallel to the Red Sea Escarpment in which large part of the catchment of Wadi Zabid lies. The headwaters of the wadi lie at an elevation of about 3,000 m ASL along the watershed with adjoining catchment (Wadi Rima, Dhamar Basin, Yarim Basin, Wadi Bana, and Wadi Tuban). The landscape of the area is characterised by its rugged and complex topography. The area includes mountain massifs, surrounding the wadi basin, with peaks reaching more than 2,000 m ASL e.g. Jabal (mountain) Arrush (2,895 m), Hisn al Manär (3,200 m), Jabal Rûshi (2,895 m), Jabal Khadrä (2,800 m), Jabal Numan (2,800 m), Jabal Al Hasah (2,960 m), Jabal Nahdän (2,700 m), Jabal Razih (2,680 m), and Bani Muslim (2,480 m). The area is dissected by deep eroded valleys, which are occupied by the drainage system of Wadi Zabid and its tributaries. The north–south profile (Fig. 5-P4) shows that the elevations sharply decrease from an altitude of 2,960 m to 2,240 m and gradually decrease to 2,200 m, then rapidly rise to an altitude of 2,560 m and 2,720 m in the middle portion of the area. Finally the elevation decreases towards the south. The north–eastern part of the area composes of wide plateau, which is cut by the drainage network. Wadi Al Har, one of the main tributaries of Wadi Zabid originates from the eastern part of this area. The slope are steep in the north–east, where the cliffs exist. This situation is reflecting the steep slopes into the streams, thus the runoff quickly gets into the streams channels. It is expected, therefore, that the velocity of the runoff is very high and the streams are carrying heavy load of eroded material. Further, flush flood is expected. In the north, the drainage network of Wadi Khubzah and Wadi Hamd form part of basin. The area is a complex of plateau. The elevation between the low lands and the high lands are 1,500–2,400 m. Other topographical features include hillsides slopes, dissected flat lands, deeply cut wadi courses. In some parts, the plateaus are facing the wadis courses with very steep slopes. High density of drainage system exists due to the characteristics of bedrocks. It has been noted that many first order streams are directly joining the main stream. This indicates that the slopes are very steep. Besides, the contour lines show that there are sharp drops towards the wadis' courses. The situation also indicates that the velocity of the runoff is very high so that the rainwaters reach the stream channels quickly. Hence, the possibility of percolation is very low. Further, the streams are still in their early stage of development. Therefore, it is also expected that the area has been under heavy processes of erosion. As a result the stream will carry large amount of eroded material. Dissected flat lands occurres towards the west in Al Qafr area. This area is highly eroded. Floodplains dominate the landscape in valley zone. The slopes gradually decrease towards the wadis' courses. Second and third stream order are dominant. It is expected that this area may allow some percolation. Southwards in the areas of Al Makhadir and Ibb, the area is represented by two zones, the high plateau (3,000 m and above) in the east and the flood plains (between 1,400-1,600 m) in the west. The plateau faces the low plain with very high relief. Jabal Badan is the eminent peak near Ibb city. The slopes are steep. Deep valleys are carried by the drainage network. The major wadi that runs across the area is Wadi Al Shahwal along with its tributaries. The drainage system has built the alluvial plain. Extensive system of alluvial terraces appears in this area taking advantage of the changing of the slopes levels. The farmers throughout the times have been able to cultivate these terraces. Agriculture depends on different sources of water, such as rain, runoff, and groundwater.

Central Zone

In this area four main landscape features can be recognized. These are the steep slopes, dissected pediment surfaces, rugged topography with narrow v–shaped valleys and wadi courses. Several peaks exist in the area. Jabal Utman and Jabal Razin (2,800 m) represented the source zone of Wadi Wajis. Several series of dykes and cliffs exist in the middle of the area. The geological structure and the topographical features play major role in controlling the drainage systems. Steep slopes are in the rugged areas where the high mountains and the cliffs occur. Slopes are very steep. The deep and narrow V–shaped valley created by the drainage systems indicate that these drainage systems are still in the early stage of development. Thus, great amount of the water energy is spent on the erosion processes. As a result, the streams have brought enormous amount of sediments. In addition, serious flush–floods are expected which have to be taken in to consideration for any future water development and management. The high density of the stream network is reflecting the steep slopes of the area. Flood–plains exist where the gentle slopes occur. Here the wadis are spreading out and they have been able to build the alluvial plains by the eroded material, which is brought from the surrounding mountains. Due to the steep slopes, it is expected that the opportunity of percolation will be low in this area, while in the flood-plains, the chance of percolation may be high. These plains present high density of cultivated lands. The large terrace farming system that

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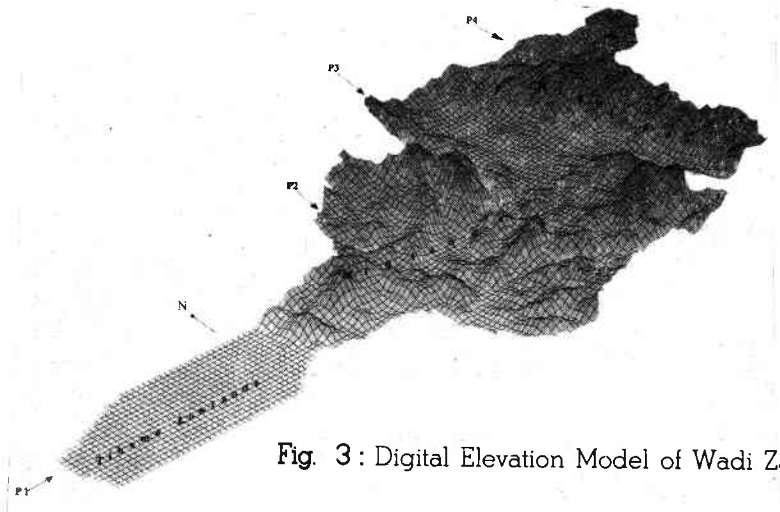

Fig. 3 : Digital Elevation Model of Wadi Zabid Basin

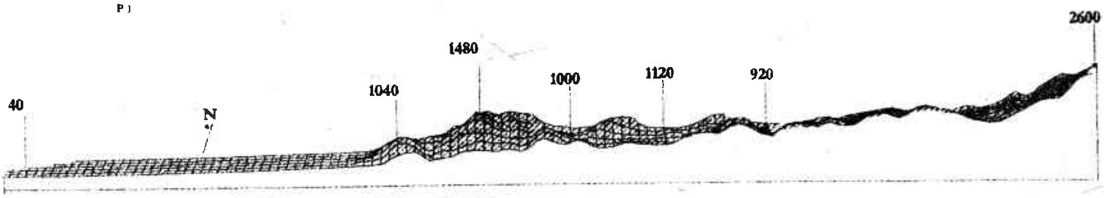

Fig. 4 : Profile - East to West

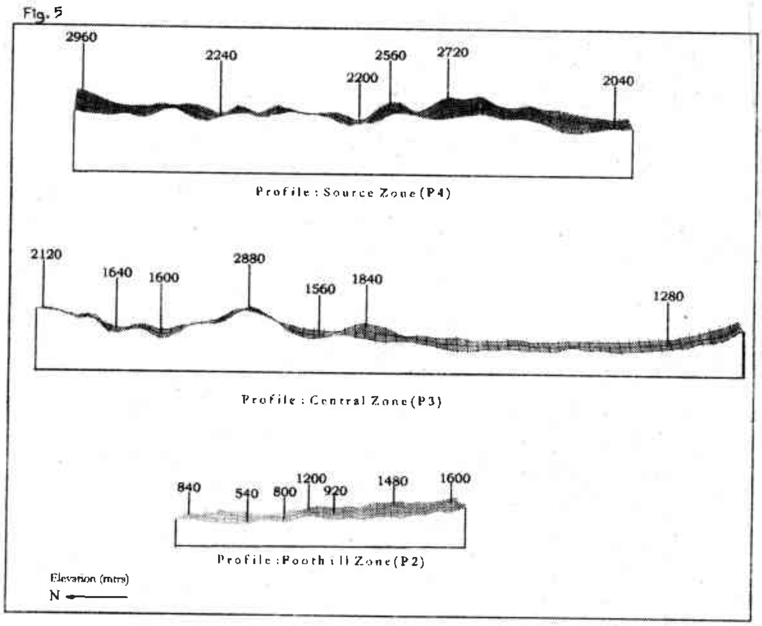

Fig. 5 : Profile - Source Zone (P 4) , Profile-Central Zone (P 3), Profile - Fothill Zone (P 2)

exist in the area and elsewhere, help in reducing the rate of the runoff. The north south profile (Fig. 5 P3) shows that the elevation decreases from more than 2,000 m in the north, where Wadi Wajis and Wadi Kahalan (two of the main tributaries of Wadi Zabid) rise, to more than 1,280 m toward south where the flood plains exist. The high use of elevations presented by the profile refer to the high peaks, while the low elevations refer to the valleys and the flood plains. In general, the area is composed of strongly dissected rugged mountainous zone in the north that reaches elevations over 2,000 m and gently sloping southern zone with medium to low elevation. As a result, high density of the stream network appears in the steep slopes of the area, while low density exists where the gentle slopes occur.

Foothill Zone

This area is the extension of the mountain front towards the Tihama Coastal Plain in the west. The landscape of the area is influenced by the uplift of the Yemen Plateau and down faulted Tihama Plain. These tectonic activities created this transition zone. Geologically, the out-crop formations in this area, as mentioned earlier, compose of igneous and sedimentary rocks. Due to their strong resistance against erosion, the hard rock stands as high peak mountains, while the sedimentary rocks are extensively eroded. The north–south cross profile (Fig.5 P2) shows that the elevation generally rises from altitude of 540 m in the north to 1,600 m in the south. The topographical features include series of ridges, representing local water divides, transition foothills, rugged mountain area, flat areas and flood–plains. Several mountain peaks appear in the area. For example, Jabal Adf (1,280 m) in the north–east, Jabal Huqamh (1,320 m) and Jabal Qrdan (1,051 m) in the north, Jabal Ras (1,440 m) in the south and Jabal Dubas (1,080 m) in the south–west. In this area, all the main tributaries of Wadi Zabid meet and generate the big wadi locally called Wadi Al Zabidi. The erosion is high in this area. Therefore, wide wadis courses exist along with the flood plains. In the areas where the flood plains exist, the slope is gradually decreasing towards the stream channels. As a result, the chance of percolation in these areas is high. The recharge of the ground water is expected to be good. The Wadi Zabid enters the Tihama Plain through a narrow basaltic gap near Al–Kolah village. In the west of this zone, the pediment occurs on the boundary zone between foothills and the Tihama Coastal Plain. This pediment area was formed by the retreat of the mountains under the effect of extensive fluvial erosion. The formation of the Red Sea Rift by the divergent and subsidence movements in early Tertiary was also one of the important factors in the generation of the pediment as well as the Tihama Coastal Plain (Yossef and Abdu, 1990). High density of stream network appear in the foothill zone.

Tihama Lowlands Zone

This zone extends between the mountain from (foothills) in the east and the Red Sea in the west (Fig 3). The Tihama Plain is formed as a result of the tectonic movement. The land surface of the plain is flat to slightly undulating. It rises gently from the Red Sea to an altitude of more than 200 m (Fig 4). The coast is characterised by clay formations. Sandy plain extends as sand bank along the coast. Toward the east, alluvial fans are dominant.

Drainage Network Analysis

The drainage system of Wadi Zabid basin is strongly influenced by factors such as tectonic activities, geological structures, lithology, and topographical features. The uplift of the Yemen Plateau generated the great escarpment in the eastern part of the basin. The escarpment is generally tilted towards the Red Sea rift. This situation created high relief within short distances between the Yemen Plateau and Red Sea valley. Hence the general direction of the flow is towards the Red Sea. The rate of the runoff increases due to the huge differences of relief between the upstream and the downstream areas of Wadi Zabid. The regional faults system controls the drainage network, particularly that of the main wadi (7^{th} order) and some of the sixth and fifth order streams. The lithology of the basin has also affected the drainage system. For instance, the common drainage patterns that can be recognized are dendritic and sub–dendritic, reflecting the homogeneous character of sub–surface lithology of the basin.

The following is the analysis of the morphometric aspects of the basin. The parameters worked out include stream order, stream number, bifurcation ratio, stream length, basin length, basin area, circularity ratio, and drainage density. The different morphometric parameters determined for entire Wadi Zabid basin and the sub–basins have been shown in table (1).

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Table 1 : Some Quantitative Analysis of Wadi Zabid Basin

Basin	Stream Order	Stream Number	Bifurcation Ratio	Stream Length (km)	Basin Length (km)	Basin Area (km^2)	Circularity Ratio	Drainage Density (km/km^2)
Wadi	1	5462	—	3776.78	212	5257	0,38	2,4
Zabid	2	1257	4.35	2635.07				
	3	256	4.91	2638.08				
	4	59	4.34	3363.12				
	5	16	3.69	223.13				
	6	4	5.33	56.28				
	7	1	4.00	54.28				
			Mean=4.4					
1. Annah	1	659	5.1	1898.82	53.6	591.2	0.48	3.21
	2	145						
	3	32						
	4	8						
	5	1						
2. Al Fanaj	1	386	4.7	908.65	51.8	283.7	0.41	3.20
	2	86						
	3	21						
	4	3						
	5	1						
3. Al Sahwal	1	796	3.9	1889.95	57.0	788.0	0.38	2.40
	2	171						
	3	35						
	4	9						
	5	3						
	6	1						
4. Hamd	1	1479	4.4	2626.55	88.0	827.6	0.37	3.17
	2	341						
	3	64						
	4	13						
	5	4						
	6	1						

Table 1 : continued

Sub-basin	Stream Order	Stream Number	Bifurcation Ratio	Stream Length (km)	Basin Length (km)	Basin Area (km²)	Circularity Ratio	Drainage Density (km/km²)
5. Wajis	1	262	4.1	624.1	39.7	213.9	0.50	3.00
	2	54						
	3	13						
	4	3						
	5	1						
6. Kahalan	1	639	3.8	1773.43	56.0	458.7	0.52	3.87
	2	160						
	3	37						
	4	10						
	5	2						
	6	1						
7. Aqaqah	1	141	5.5	538.28	21.0	128.5	0.51	4.19
	2	34						
	3	4						
	4	1						
8. Al Zabidi	1	1100	3.6	2496.92	47.5	646.0	0.18	3.86
	2	266						
	3	50						
	4	12						
	5	4						
	6	2						
	7	1						

Exposition

Stream Order and Stream Number

Horton (1945) devised the "Laws of drainage composition". The first is the law of stream numbers. According to Waugh (1996) this law of stream number states that within a drainage basin a constant geometric relationship exists between stream order and stream number. Therefore, if the number of segments in a stream order are plotted on a semi–log graph against the stream order, then the resultant best fit line will be straight. This has been done in figure (6a, b & c) These figures show the relationship between stream order and the number of streams. The figures show negative correlations between stream order and stream number. As the stream order increases, the number of streams decreases. Figure 6.a shows straight–line relationship. However, in Figures 6.b and 6.c the stream numbers do not show straight–lines relationships. The sets of the points show a marked up–concavity at the middle and lower end, indicating that the geological structures of the basin have great effects on the drainage systems.

Bifurcation Ratio

Horton (1932) defined bifurcation ratio as the mean of the ratios of the number of streams of an order to the number of streams of the next higher order. The mean bifurcation ratio computed for the entire Wadi Zabid Basin is 4.4. The bifurcation ratio for the sub–basins ranges from 3.6 up to 5.5. Strahler (1964) pointed out that bifurcation ratios characteristically range between 3.0 and 5.0 for watersheds in which the geological structures do not distort the drainage pattern.

Fig. 6.a

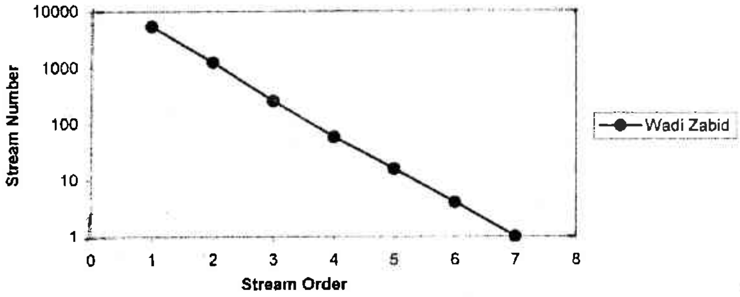

Fig. 6.b

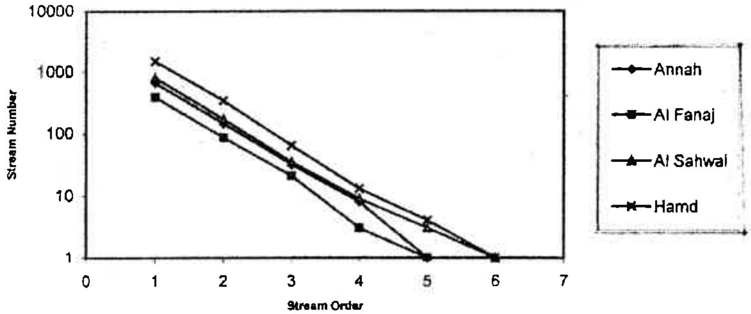

Fig. 6.c

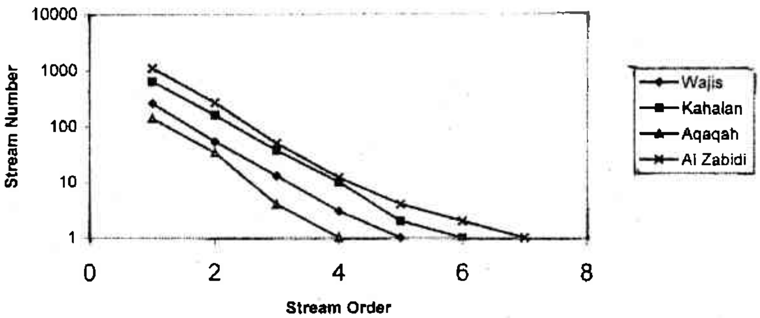

Fig. 6 : Relationship of Order-Number of Streams of Wadi Zabid Basin and Sub-basins

All sub–basins of Wadi Zabid fit between these two bifurcation ratios values, except Wadi Aqaqah. These high values of bifurcation ratios are expected in highly dissected basins. Wadi Aqaqh with the high value of 5.5 clearly indicates the great influence of geological structures on the drainage basin. The wadi is located on the foothills zone. This area was highly influenced by the tectonic activities.

Basin Shape and Circularity

Basin shape is the result of geomorphological processes within a particular basin. It has a significant impact on runoff. It has long been accepted that a circular basin is more likely to have a shorter time lag and a higher peak flow than an elongated basin (Waugh, 1996). The dimensionless circularity ratio has been applied in order to determine the shape of the entire Wadi Zabid basin and sub–basins.

Miller (1953) defined circularity ratio as the ratio of basin area to the area of a circle having the same perimeter length as the basin. According to Strahler (1964), "long narrow basins with high bifurcation ratios would be expected to have attenuated flood–discharge periods, while rotund basins of low bifurcation ratio would be expected to have sharply peaked flood discharge." In the study area the circularity ratio is found to be between 0.18 (in Wadi Al Zabidi) and 0.52 (in Wadi Kahalan). From the circularity values obtained for the 8 sub–basins, Wadi Al Zabidi (0.18) was found to be more elongated than the other basins. Wadi Kahalan, Aqaqah and Wajis, which have the circularity values of 0.52, 0.51 and 0.50 respectively, are found to be less elongated. While, the other sub–basins that have circularity values ranging from 0.37 to 0.48 are found to be less circular. Further, the entire Wadi Zabid Basin which circularity value of 0.18 was also found to be less circular. The Wadi Zabid Basin takes a triangle shape with its apex in the west.

Drainage Density

Horton (1932) defined drainage density as the length of streams per unit of drainage area. According to Waugh (1996), drainage density tends to be highest in areas where the land surface is impermeable, where slopes are steep, where rainfall is high and prolonged, where vegetation cover is lacking. Given the fact that the study area, is characterised by steep slopes, and sparse vegetation. It would be expected that the drainage density might range from high to moderate.

Strahler (1957), described drainage density values less than 5.00 as coarse, between 5.00 and 13.7 as medium, between 13.7 and 155.3 as fine, and greater than 155.3 as ultra–fine. Based on this classification, the Wadi Zabid and its sub–basins have a coarse drainage density as values are less than 5.00. Coarse values, according to Gregory and Walling (1973), are frequent in areas of permeable rocks and low rainfall intensities. It is observed that the drainage density varies from a minimum of 2.40 (in Wadi Al Sahwal sub–basin) to maximum of 4.19 (in Wadi Aqaqah sub–basin) among the sub–basins of the Wadi Zabid Basin.

Conclusion

The morphological features of Wadi Zabid basin are largely formed as a results of the tectonic movement; Volcanic activities during the Tertiary and Quaternary Periods; the major faults systems; the drainage patterns; the terrace system; the alluvial fans; the coastal Aeolian deposits are name of the district features of the wadi basin. The out cropping formations range from Precambrian to Quaternary. The land surface varies from low relief coastal areas (Tihama Plain) in the west to high mountains (Western Escarpments) in the east.

The Digital Elevation Model (DEM) provides a great view of the landscape topography of the Wadi Zabid basin and helps in generating the profiles, which are helpful in showing the topographical variabilities that occur in these cross-sections. The morphometric analysis shows that the geological structure and lithology have great influence on the drainage pattern. The regional faults control some of the streams channels. The common drainage patterns that can be recognized are dentritic and sub-dentritic reflect the homogenous character of the subsurface lithology. The stream order for the Wadi Zabid has been found to be seventh. The Wadi Zabid and its sub-basins have a coarse drainage density with values less than 5.0. The values of the bifurcation ratio obtained for the entire Wadi Zabid basin and for the sub-basins range from 3.6 to 5.5, indicating that the drainage basins are highly dissected. From the circularity values obtained for the 8 sub-basins, Wadi al Zabidi was found to be more elongated than the other basins. Further, the entire Wadi Zabid basin with circularity value of 0.38 was found to be less circular. The Wadi Zabid basin takes a triangular shape with its apex in the West.

In general there is sharp relief towards the wadis courses. This situation indicates that the velocity of the runoff is very high, so that the rain waters reach the streams' channels quickly. Hence, the possibility of percolation is very low. The streams are still in their early stage of development. Therefore, great amount of the water energy is spent on the erosion process. As a result, the streams will carry large quantities of eroded material. In addition, serious flash-floods are expected which have to be taken into consideration for any future development and management.

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