Hydro-Morphometric Characterization of Wadi Khumal Basin, Western Coast of Saudi Arabia

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ABSTRACT

The aim of this study is to assess the hydro-morphometric and flow characteristics (include: morphology, analysis of drainage patterns, and drainage morphometry) and its influence on hydrology of Wadi Khumal Basin, North Saudi Arabia, which is considered as an additional strategic future water supply for ground water reservoirs and for planning rainwater harvesting and watershed management. For detailed study we used Shuttle Radar Topographic Mission (SRTM) data for preparing Digital Elevation Model (DEM), aspect grid and slope maps, Geographical information system (GIS) was used in evaluation of linear, areal and relief aspects of morphometric parameters. The study reveals that the triangular shape of the Wadi Khumal Basin is mainly due to the guiding effect of Scarp-Radwa Mountains and to many of the the thrusts, faults and dykes that appear in hard and massive metamorphic and igneous rocks which resists weathering processes to give that shape.

Study adopted in hydrological analysis of the Khumal Basin on the model TR-55 to calculate storm runoff volume, peak rate of discharge, hydrographs, and storage volumes required for floodwater reservoirs, where a rainstorm were analyzed its 25 mm, Runoff hydrographs were constructed for four sub-basins of wadi Khumal.

Keywords: Wadi Khumal, Morphometry, Morphology,GIS, hydrology, Red Sea, Saudi Arabia.

INTRODUCTION

The water resources in Saudi Arabia are the essential target of the government planning. Major wadis in Saudi Arabia such as Fatimah, Naaman, and Khulais in Makkah Al-Mukarramah area was studied and taken for coverage this target and which have been developed and used for groundwater supply at the different populations in Saudi Arabia. The groundwater in all areas and wadis in Saudi Arabia is highly decreasing with time due to the scarcity of rain, extensive use for irrigation, domestic and industries. The search for development of new water resources in desert areas is considered among the top priorities in the government policy of Saudi Arabia and as the consumption of water is rising with time due to rapidly growing in population density and scarcity in precipitation with increasing in water evaporation from the earth sand surface. In the mean time most of water supply for all governorates in Saudi Arabia area (more than 90%) is obtained from desalination plants on the Red Sea (El-Khatib, 1980; Sen, 1983; Subyani, 2005).

The drainage basin analysis is an important in any hydrological investigations,like an assessment of groundwater potential, groundwater management, pedology and environmental assessment. Hydrologists and geomorphologist has recognized that a certain relations are most important between runoff characteristics, and geographic and geomorphic characteristics of drainage basin systems. Various important hydrologic phenomena can be correlated with the physiographic characteristics of drainage basins, such as; size, shape, slope of drainage area, drainage density, size and length of the contributories etc (Rastogi et al., 1976).

Many researches and works were studied and applied on the study area at the last several years; Bache and Chevermont (1976), Pellaton (1979), Chevremont and Johan (1981), Hashem (1981), Alshanti (1993), Al Ghamdi (1994), Subyani (2005), Harbi (2008), Nadia et al. (2008), and Fnais (2010). These works concerned on geology, lithology, structural situation, mineralization, and pollution.

Geology, relief and climate are the primary determinants of running water ecosystems functioning at the basin scale (Mesa, 2006). Topography plays an important role in the distribution and flux of water and energy within the natural basins; these include surface water, evaporation, infiltration, heat exchange and other ground-atmosphere interface processes. The quantitative assessment of these processes depends on the topographic configuration of the basin.

Detailed morphometric analysis of a basin is a great help in understanding the influence of drainage morphometry on landforms and their characteristics. The drainage characteristics of Khumal Basin and sub-basins related it, were studied to describe and evaluate their hydrological characteristics by analyzing topographical maps and SRTM data.

The main climate conditions in the study area are completely classified between arid to semi-arid conditions, and the main occupation of the people lives in this area was depends on agriculture and grazing which in turn depends on groundwater, because the surface water resources are scarce. In addition, due to patchy rainfall pattern and uncontrolled abstraction, groundwater levels have declined to deeper levels. Therefore, for these reasons, watershed development schemes become important for developing the surface and groundwater resources in this area, and to prepare a comprehensive watershed development plan, it becomes necessary to understand the topography, erosion status and drainage pattern of the region.

This paper aims to study the hydro-morphometric and flow characteristics of the catchment area of Wadi Khumal Basin. These features include morphology, analysis of drainage patterns, and morphometric analysis.

STUDY AREA

Location

Wadi Khumal is one of the most important wides extended in the study area (Yanbu Governorate) and lies about 40 km from North of Yanbu city (Fig. 1), and it is bounded by Latitudes 24° 10' 26" and 24° 39' 42" N and Longitudes 37° 47' 17" and 38° 10' 51" E. Wadi Khumal is a part of the Scarp-Radwa Mountains, which extends from east to the west perpendicular to the coast of Red Sea and which flows into the coastal plain of Red Sea. The Radwa Escarpment is one of the outstanding landscape features of Hijaz Mountains, while the area is characterized by three physiographic units; the Red Sea coastal plain unit, the hills unit, and the Scarp-Radwa Mountains unit. Finally, Wadi Khumal is located in a relatively small basin drains and catchment area of about 892.6 km2 (Fig. 1).

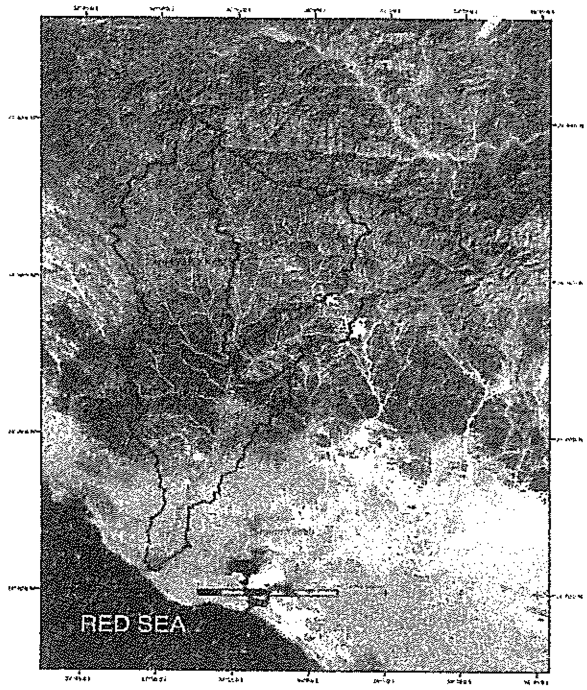


Figure 1: Location TM landsat image of the study area.

Geological Setting

The Arabian Shield is mainly composed of Precambrian crystalline, meta-volcanic and meta-sedimentary rocks with their associated plutonic equivalents, together with Tertiary and Quaternary basalt flows and alluvial sediments which cover part of the Precambrian rocks (Alshanti, 1993) these rocks form the mountain ranges east of the Red Sea coastal plain (Fig. 2).

Precambrian Rocks

The oldest rocks in the study area, which exposed in the Wadi Khumal belong to the Al Hinu Formation which represent an infrastructural unit. The rocks of the Al Hinu Formation are highly deformed and regionally metamorphosed up to amphibolite facies. They include para- and orthoamphibolite, quartzite, feldspathic schist and gnesisses (locally granitized and migmatized) (Harbi, 2008). Kemp et al., (1980) was reported the age of the Al Hinu Formation rocks, older than 780 Ma. Pellaton (1979) indicated that these rocks predate the emplacement of the Wadi Khumal complex and the southern ultramafic-mafic rocks, possibly belong to the Farri Group, or could represent an older basement. The other rocks in the Khumal area can be grouped into two distinct groups: (1) an ophiolitic suite and gabbroic rocks exposed to the southwest of Wadi Mahalah; and(2) Wadi Khumal ultramafic-mafic complex (Harbi, 2008; Fnais, 2010) (Fig. 2).

The ophiolitic mélange suite and the Wadi Khumal ultramafic-mafic complex, which are further intruded by younger granitoid rocks (Post-Khumal intrusions). The younger granitic rocks occupy the southeastern and northwestern parts of the mapped area (Fig. 2). They are of limited distribution and are found as dikes and small intrusive bodies into the ophiolitic rocks, the marginal gabbros and the anorthosites of the Khumal omplex (Harbi, 2008).

The rock sequences in the study area were appearing of metamorphic Precambrian rocks intruded by younger granitic batholiths Plate 1(A) and mafic dykes Plate 1(B) overlain by some basaltic flows and aeolian and marine sediments with alluvial terraces Plate 1(C).

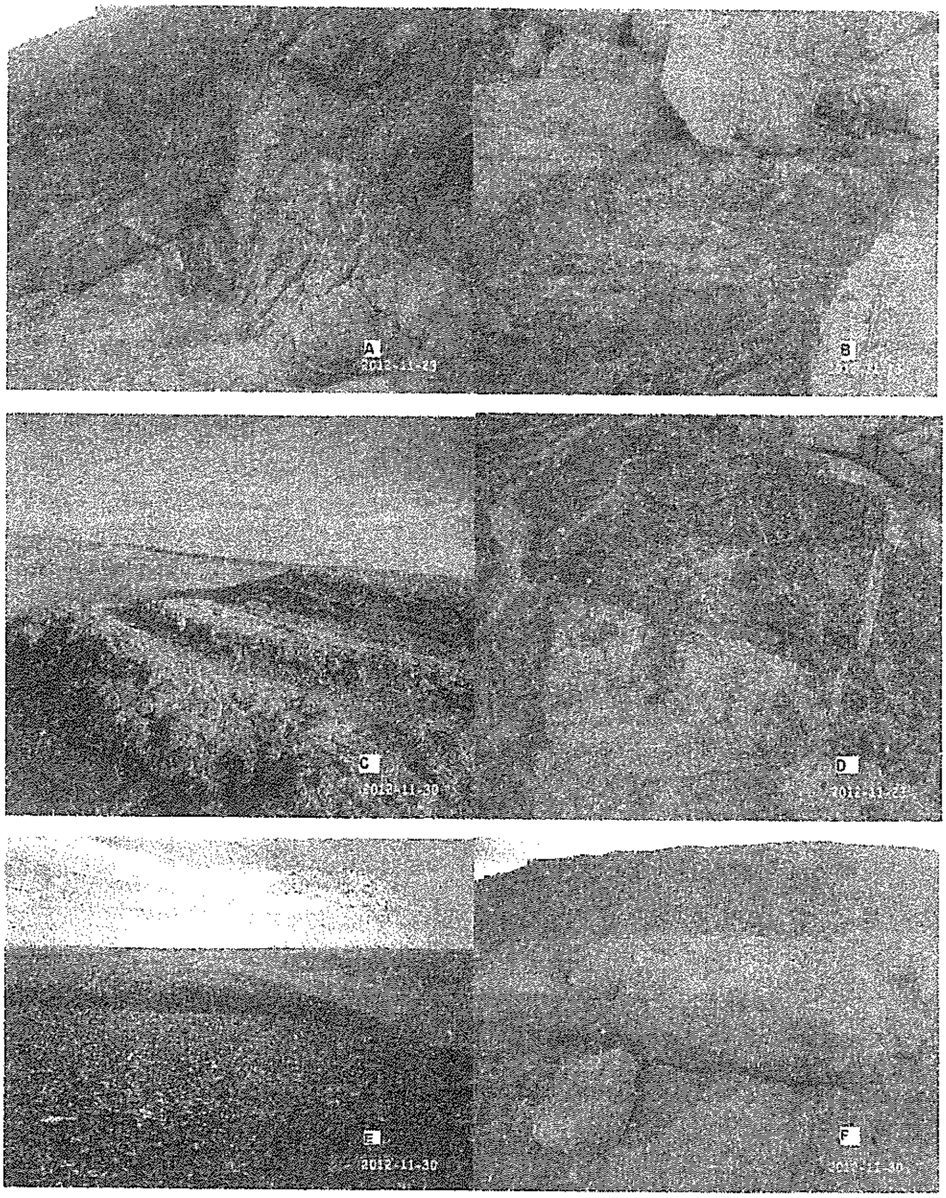


Plate 1:A) Metamorphic rocks lower of younger igneous rocks, B) Mafic dykes intruded granitic rocks, C) Aeolian and marine sediments with alluvial terraces, D) The oldest ultramafic-mafic complex rocks in the study area, E) This soil unit is dark grayish to dark and light brown in color, F) Thickness of the Quaternary deposit in the study area.

In the northwest of the study area, the oldest ultramafic-mafic complex and igneous intrusion rocks consist of adamellitem granodiorite, quartz, and diorite tonalite, with some intrusions appear of gabbro, pyroxenite, and diorite (Nabat Complex) in the middle of Wadi Khumal Basin. This formation is mainly metamorphosed in nature and is located in the upper part of the study area Plate 1(D). These rocks are locally crossed by Tertiary inclined and swarm dykes, and probably rank among the oldest units in the area. This formation was metamorphosed and suffered multiphase deformation during geological time.

Quaternary Deposits

Quaternary deposits in the study area are bounded by and overlie the Precambrian rocks in the western parts of the study area at the mouth of Wadi Khumal on the coast of Red Sea, and at all the body of the wadi from the source to the estuary (Fig. 2).

The source of Wadi Khumal deposits are of continental origin, which is accumulated from recent wadi deposits from sands and gravels with little appears of conglomerate and arkosic sandstones at a middle part of wadi system. While in the alluvial plain these deposits start to overlap and mix with marine sediments and soils in the coastal zone, which is accumulated from recent reefal or subreefal limestone and distribution of low and high level terraces, which are, composed from pebbles boulders with light and black tarnish. There is a general agreement among several authors that the coastal plain including both alluvial and marine deposits belongs to the Quaternary period (Brown et al., 1963; Al Sayari and Zölt, 1978).

Alluvial deposits consist of unconsolidated sand, silt, and gravel deposited in the wadi channels and out washed plains. They also occur as a spread deposits along Wadi Khumal and as fan deposits close to the Red Sea shore as well as at the foot of the coastal hills. This soil unit is dark grayish to dark and light brown in color Plate 1(E), due to the basic igneous rocks source of this soil and to tarnished granodioritic gravels distribution on the surface. The average thickness of these deposits increases from one meter in the upstream of the wadi to more than 20 meters in the downstream near the main coast of Red Sea Plate 1(F).

Geological Structure

The recent geological studies have shown that the Arabian Shield has been affected by orogenic episodes and a younger major faulting system. These uplift and faulting have resulted in steep escarpment facing down with torrents such as in deep valleys and then flow more slowly across the coastal plain, and frequently reach the Red Sea (Subyani, 2005, Harbi, 2008). The dikes trend

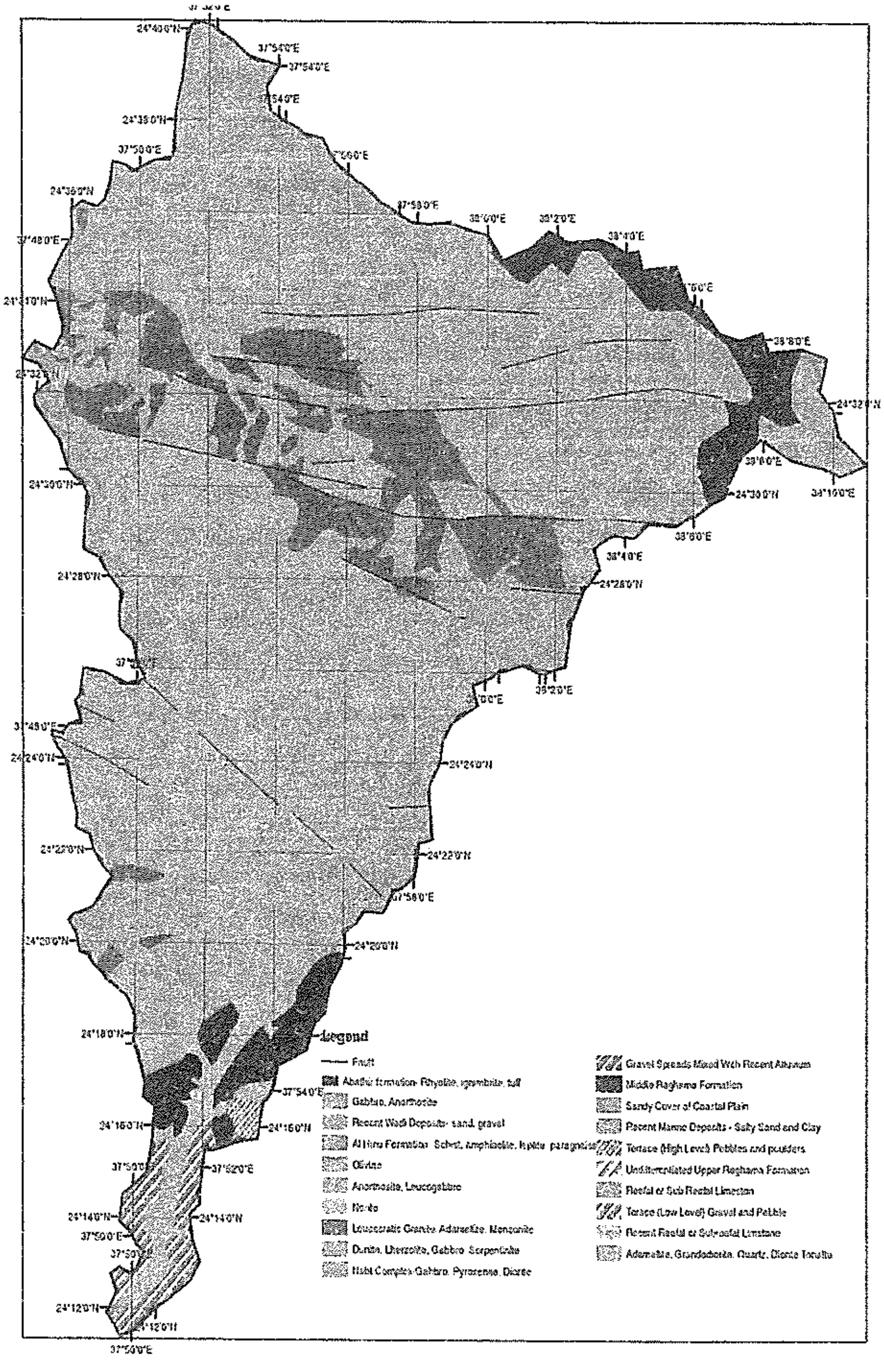


Figure 2: Geological and structural map of Khumal Basin.

mainly in the north-west direction (Subyani, 2005). The most important structural elements recorded in the study area were faults, which show the following main trends; NW-SE, NE-SW, E-W (ENE) and N-S (NNW). The ENE-WSW to E-W trend represents one of the main tectonic trends crossing the Neoproterozoic basement complex in the Arabian-Nubian Shield. ENE-WSW direction exhibits right lateral strike-slip sense (Fig. 2), which could be observed in the field and traced on the SPOT data (Harbi, 2008).

MATERIALS AND METHOD

Geographic information systems (GIS) are computer-based systems for storing, retrieving, manipulating and displaying spatial data (Sabins, 2000) in the sciences of geology, geography, environment, etc. The applications of GIS in hydrology and water resource studies fall into two main categories; informational and analytical, it also the principal softwares were used in this study; ILWIS3 and WMS Aquaveo.

The drainage characteristics of Khumal Basin and sub-basins were studied to describe and evaluate their hydrological characteristics by analyzing topographical map and SRTM data. The climate conditions of the study area located within arid and semi-arid regions. While the main occupation of the Bedouin peoples in this area is the grazing. In addition, they depend on groundwater at usual works and daily life style, because the surface water resources are scarce. Moreover, due to erratic rainfall pattern and uncontrolled abstraction, groundwater levels have declined to deeper levels. Therefore, watershed development schemes become important for developing the surface and groundwater resources in these areas. To prepare a comprehensive watershed development plan, it becomes necessary to understand the topography, erosion status and drainage pattern of the region.

For the purpose of detailed morphometric analysis, SRTM data used for preparing DEM map slope and aspect maps. GIS was used to evaluate the Linear, Areal and Relief morphometric parameters.

SRTM data and GIS techniques (ILWIS3 and WMS Aquaveo, version 8.3) were used to calculating and analysis of hydro-morphometric data because it is quick and fast, accurate, and inexpensive way. In addition, an attempt has been made to utilize SRTM data and the interpretative techniques of GIS to find out the relationships between the morphometric parameters and hydrological parameters.

MORPHOLOGY

The physiographical setting of Wadi Khumal Basin can be divided into three main zones: the Red Sea coastal plain, the hills, and the Scarp-Radwa Mountains. The Red Sea coastal plain zone is a flat strip of land, and it has a width of about 5 km in the study area, it also bounded inland by the small rigid hills (Plate). This zone of study area from Red Sea Coast is a depositional surface, principally a coral reef and sabakhah deposits, while the sediments inland towards the foothills, it consists of alluvial deposits and aeolian sands (floodplain) (Plate). While, the elevation of coastal plain area is varies from sea level to 100 m.a.s.l.

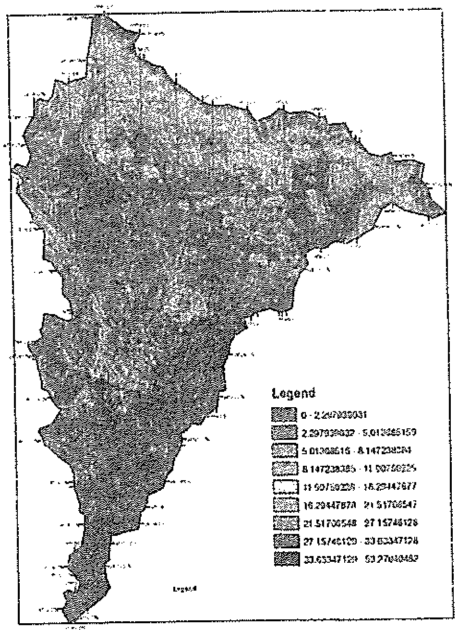
The hills zone is a vast peneplain sloping slightly to the west of the Scarp Mountains toward of Red Sea Coast. It consists mainly of

Pleistocene terrace (gravel and pebble) and Raghma Formation (Miocene), of complex heterogeneous conglomerate with arkosic sandstone rocks (Fig. 2). The elevation of these hills varies from 150 to 500 m.a.s.l.

The Scarp-Radwa Mountains zone is characterized by a knife-edge ridges and deep canyons. These high relief mountains are mainly located in Alnagaf area, such as Alghrab and Alkharas Mountains where the Wadi Khumal starts. While the elevation of Radwa Mountain increases from 1000 to 1700 m.a.s.l.

Slope analysis is an important parameter in geomorphic studies, and slope elements, in turn are controlled by the climatomorphogenic processes in the area having the different rocks of varying resistance. An understanding of slope distribution is essential as a slope map provides data for planning, settlement, mechanization of agriculture, deforestation, planning of engineering structures, morphoconservation practices, etc (Sreedevi et al. 2005).

In this study, slope map was prepared based on SRTM data and were converted into slope and aspect grids using Arc GIS method. Slope grid is identifying as "the maximum rate of change in value from each cell to its neighbors", using methodology described in Burrough (1986). The Khumal watershed area slope varies from 0° to 53.5° with a mean slope of 6.34° and Slope Standard Deviation 4.33°. A high degree of slope is noticed in the Eastern and northeastern parts of the Wadi Khumal Basin (Fig. 3). Aspect grid (Fig. 4) is identifying as "the down-slope direction of the maximum rate of change in value from each to its neighbors" (Gorokhovich, 2006).



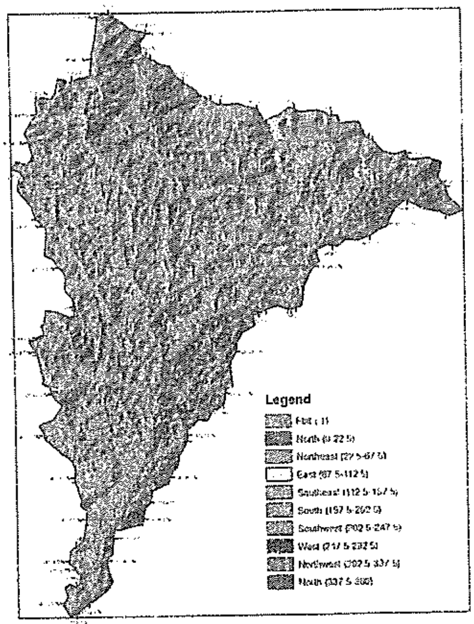
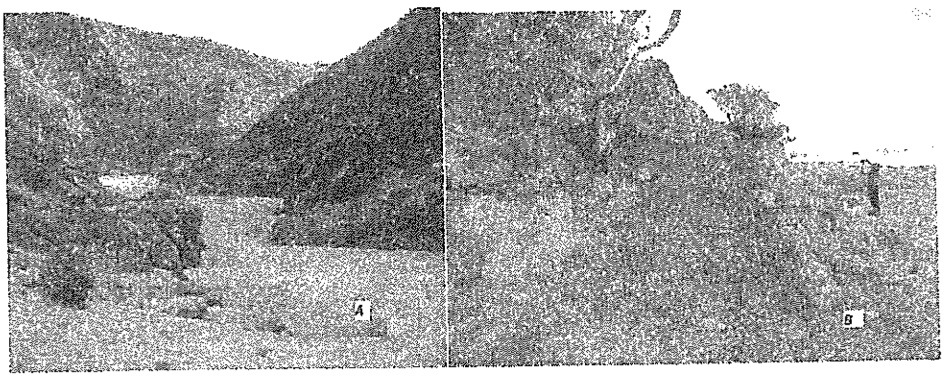


Figure3 Slope map of Khumal Basin Figure 4 Aspect grid map of Khumal

During the field study was observed that the upper regions of the Wadi Khumal Basin affected by a many fractures and joints, and spread of the rocky terraces. Canyons spread in the supreme waterway objects at many areas in the Wadi Khumal Basin and which prevent behind it large quantities of boulders and large rock masses (Plate 2-A).



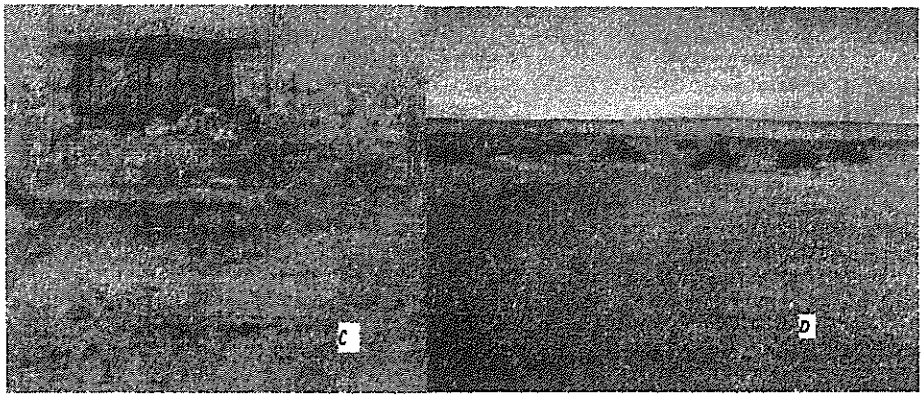


Plate 2: Different morphology features distribution at Khumal Basin (A) Canyon,(B)low-rise river terraces,(C)groundwater extraction and (D)Nebak forms

MORPHOMETRIC ANALYSIS

The shape of the stream network in the Wadi Khumal Basin reflects the hydrologic processes that prevail in the area and in turn determines the potential efficiency of the basin. The network characteristics also strongly reflect the climate, lithology, topography, and the geologic structure of the basin.

Certain characteristic of the drainage basins reflect hydrologic behavior and are, therefore, useful, when quantified, in evaluating the hydrologic response of the basin. These characteristic relate to either the physical drainage basins of channels. Physical characteristic of the drainage basins include drainage area, basin shape, and basin slope. Channels characteristic include channel order, channel length, channel slope and drainage density (Sheklar et al. 2011).

Based on the drainage orders, the Khumal Basin has been classified as forth order basin to analyze linear, relief and areal morphometric parameters (fig 5), different morphometric features have been defined for the drainage network (Strahler, 1952; Doornkamp and King, 1971; Gregory and Walling, 1973; and Maidment, 1993). These features are as shown in Table 1.

DATA ANALYSIS AND RESULTS

1- Drainage Patterns

There is many-encountered drainage patterns such as dendritic, trellis, barbed, rectangular, distribution on the surface of the earths depend on the

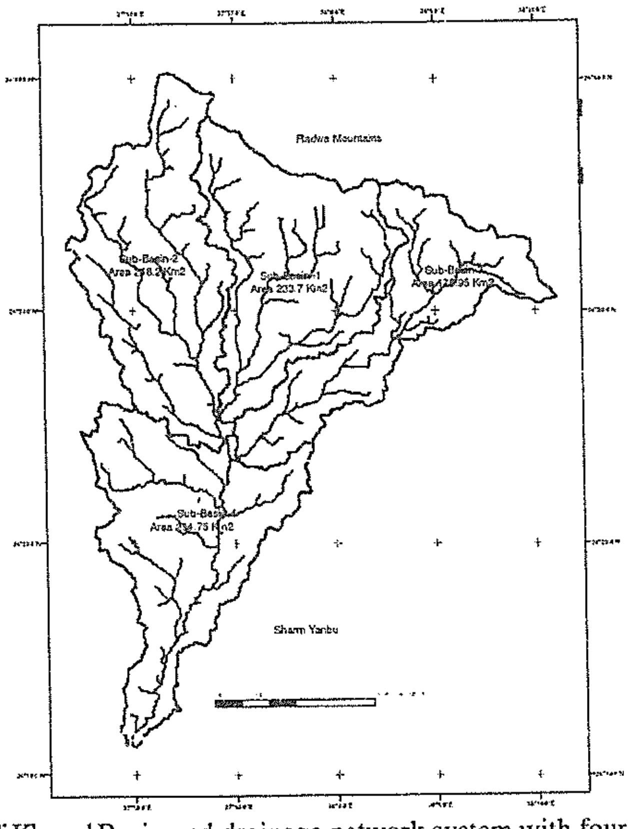


Figure 5: Wadi Khumal Basin and drainage network system with four sub-basins.

types of rocks. The rock types, structure, weathering, and rainfall intensity mainly affect these patterns. A network streams of the

Khumal Basin is characterized by irregular branching of tributary streams in different directions . The host rocks are mainly composed of massive igneous rocks (massive and very hard granite with some distributions of dioritic and rhyolitic rocks) with a complexity of metamorphic rocks, composed from intrusions of megmatite bodies, which are very resistant. These features have resulted in a dendritic drainage pattern (Fig. 5).

2- Stream Order

Stream order is a method for classifying the relative location of a reach of a stream segment within the river basin. The applied method followed the procedure that modified by Stahler (1964). In Stahlar system, all streams, which have no tributaries, are known as first-order streams. When two first-order streams are joined together, they form a second-order stream,

and so on. The upper stream network of Khumal Basin is denser starting from high steep slopes of Radwa Mountainous Ridge to flat and wide area on the coast of Red Sea. In the middle and downstream networks of the Khumal Basin are lighter due to low relief. In general, Khumal Basin has the fifth-order stream, which means that the Khumal Basin have a moderate potential of discharge. Figure 6 which appears the order of Wadi Khumal system, which classified as fifth-stream orders, and the map was obtained using GIS system.

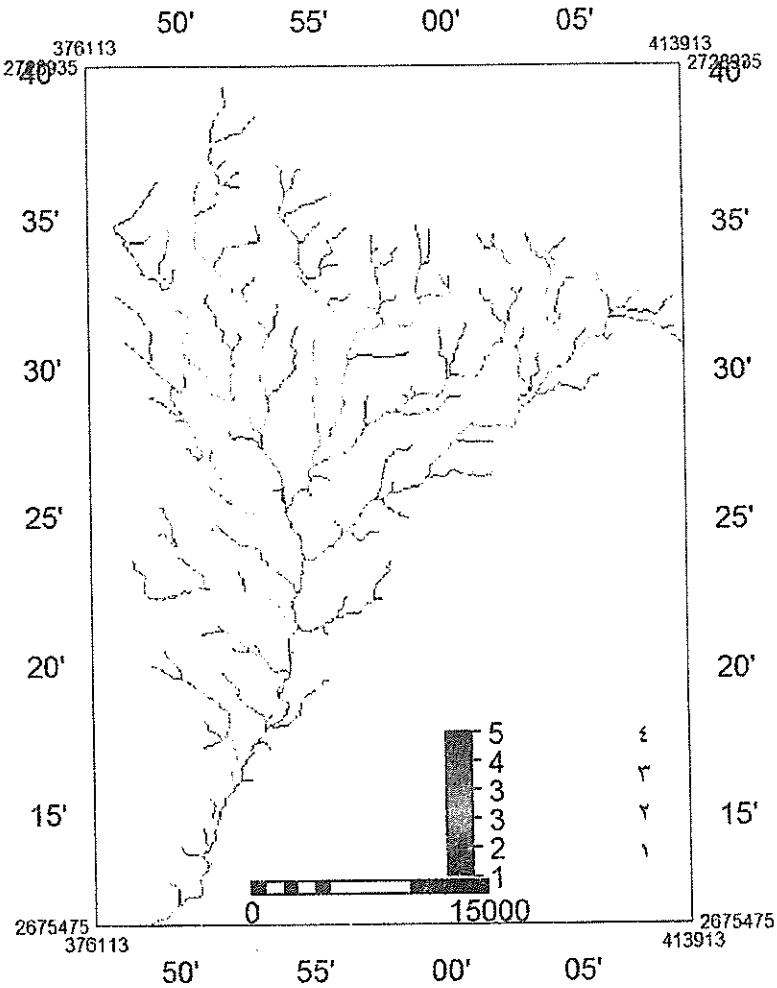


Figure 6: Drainage pattern of the Wadi Khumal Basin with stream network orders

3- Drainage Density (D_d)

The drainage density (D_d) is a very important variable to explain the climatological, geological, and topographical features of the basin, because it affects the actual and potential basin discharge. In addition, it is a positive correlation between drainage density (D_d) and rainfall parameters (Montgomery and Dietrich, 1989; Tucker and Bras, 1998). While Abrahams (1984) showed that, several climatic factors simultaneously affect on drainage density in a complex way. Generally, field observations shows that the high drainage density is favored in arid regions with sparse vegetation cover as also in temperate and tropical regions subjected to frequent heavy rains (Melton, 1957; Strahler, 1964; Toy, 1977; Morisawa, 1985).

Slope gradient and relative relief are the main morphological factors controlling drainage density. Strahler (1964) noted that low drainage density (D_d) is favored where basin relief is low, while high (D_d) is favored where basin relief is high.

The combined role of relief and climate on (D_d) has also been investigated by Kirkby (1987), suggesting that the relationship between (D_d) and relief depends on the dominant hill slope processes. He predicts a positive relationship for semi-arid environments and an inverse one for humid climate. Gardiner (1995) showed that greater drainage densities are generally associated with impermeable rocks. Drainage density (D_d) for the basin was found by dividing the total length *(Ct)* by the area *(A)* of the basin as an equation 1:

$$D_d = Ct / A \quad (1)$$

Table 1, shows the drainage density (D_d) for whole basin of the study area

Table 1: Morphometric Parameters distribution of Wadi Kumal Basin

parameters	**Sub-basin I**	**Sub-basin II**	**Sub-basin III**	**Sub-basin IV**	**Khumal Basin**
Stream order U	4	5	4	5	5
Basin area in km^2 (A)	233.7	248.2	175.95	234.75	892.6
Total drainage length (km)	132.9	139.13	100.13	125.14	497.3
Drainage density (m/km^2) (D_d)	527.82	561.30	568.34	569.96	556.33
Average over Land Flow (m)	1036.3	968.5	1048.6	1050.4	995.6
Basin Length (km)	23.9	29.5	30.2	28.6	63.3
Perimeter (km)	106.6	117.4	123.7	123.1	244.6
Circularity (E_c)	0.26	0.23	0.14	0.19	0.19
Elongation (E)	0.72	0.60	0.50	0.60	0.53
Basin slope (S) (m/m)	0.14	0.10	0.15	0.06	0.11
Form Factor	0.41	0.29	0.19	0.28	0.22
Sinuosity Factor	1.16	1.13	1.15	1.38	1.22
Relief m (H_b)	1057	1018	1692	196	1761
Relief ratio (R)	0.044	0.035	0.056	0.007	0.028
Bifurcation ratio (Rb)	4.06	1.87	3.54	2.65	2.89
Stream-length ratio (Rl)	3.48	2,08	2.04	1.45	2.18
Stream-area ratio (Ra)	5.23	2.24	3.85	2.79	3.24

is (556.33 M/km^2), while of the four sub-basins are shown in **Table 1.** D_d gives an idea about the physical properties of the relief and the underlying rocks in the study area. Low D_d (527.82 M/km^2) occurs in the regions of highly resistant of types of rocks and height relief of the topographical feature in the Wadi Khumal Basin; whereas high D_d (569.96 M/km^2) is prevalent in the region of weak impermeable sub surface materials which are sparsely vegetated and show Low relief in the whole of study area.

4- Form Factor (Ff)

Form Factor *(Ff)* is defined as the ratio of the basin area to the square of the basin length as an equation 2:

$$R_f = A / L^2 \qquad (2)$$

Horton (1945) proposed this parameter to predict the flow intensity of a basin of a defined area. The *(Ff)* of the whole basin is 0.22, while the form factor *(Ff)* of four sub-basins is shown in **Table 1**. *(Ff)* gives an idea about the physical properties of the relief and the underlying rocks in the study area. High *(Ff)* (0.41 km) occurs in the sub-basin **I**, region of highly faults, joints and height relief of the topographical feature in the Wadi Khumal Basin.

5- Relief and Relief Ratio

Relief *(Hb)* is the maximum vertical distance between the lowest and the highest points of a basin. Basin relief is an important factor in understanding the denudation characteristics of the basin. The maximum height of the whole basin in the study area is 1763 m and the lowest is two meter above sea level. Therefore, the relief of the basin is 1761 m. While the Relief Ratio *(R)* was found by dividing the relief *(H_b)* by the basin length *(L_b)* as an equation 3:

$$R = H_b / L_b \quad (3)$$

The relief ratio *(R)* of the Khumal Basin is 0.028, while those reliefs of the four sub-basins are shown in **Table 1**. While high relief values (0.056) are characteristic of hill regions in sub-basin **III**, and the low values (0.007) are characteristic of bed plains and valleys. In field it has been observed that there is a high degree of correlation between high relief and high drainage frequency, high stream frequency and high stream channel slopes which bring out high discharges in short duration (Gopalakrishna et al., 2004). These are characteristic of watersheds three (0.056) and one (0.044) in the study area (**Table 1**), and are indicating that the discharge capability expected of these watersheds in the Khumal Basin are moderately high and the groundwater potential is meager.

6- ***Circularity Ratio (Rc)***

Miller (1953) define circularity ratio *(Rc)* as the ratio of the basin area to the area of a circle having the same circumference perimeter as the basin. Circularity ratio *(Rc)* is dimensionless and expresses the degree of circularity of the basin. While equation 4 is shown the Circularity of the basin *(Rc)*; as:

$$E_b = A / (P^2 / 4\pi) \quad (4)$$

If the Circularity *(Rc)* is near to one, the basin is of circular shape and as a result, it gets scope for uniform infiltration and takes long time to reach excess water at basin outlet, which further depends on the prevalent geology, slope and land cover. The ratio is more influenced by length, frequency, and gradient of various orders rather than slope conditions and drainage pattern of the basin (Sreedevi et al., 2009). The ***Rc*** of the whole basin in the study area is 0.19, while those of the four sub-basins are shown in **Table 1**. It is a significant ratio, which indicates the dendritic stage of a basin.

7- **Elongation Ratio *(Re)***

Schumm (1956) defined elongation ratio ***(Re)*** as the ratio of diameter of a circle of the same area as the drainage basin and the maximum length of the basin, while equation 5 is shown the elongation ratio of the basin ***(Re)***; as:

$$Re = A^{0.5} / L_b \quad (5)$$

A circular basin appears more efficient in the discharge of run-off than that of an elongated basin (Singh and Singh 1997).

Elongation ratio ***(Re)*** for the whole basin in the study area was estimated at 0.53, and the four sub-basins are shown in **Table 1**. The ***Re*** values generally ranges between 0.50 and 0.72 over a wide variety of climatic and geological types. The sub-basins I are characterized by high ***Re***, while sub-basins III have low ***Re***. The sub-basins having high ***Re*** values are the most affected by faults and joints, while the sub-basins having low ***Re*** values are susceptible to high erosion and sedimentation load(Sreedevi et al.,2009).

8- Average Overland Flow (AOLF)

Horton (1945) was defined the length of overland flow **(AOLF)** as the length of flow path, projected to the horizontal of non channel flow from point on the drainage divide to a point on the adjacent stream channel. He further noted that **(AOLF)** is one of the most important independent variable affecting both hydrologic and physiographic development of drainage basins. The length of overland flow is approximately equal to the half of the reciprocal of drainage density. This factor basically relates inversely to the average slope of the channel and is quiet synonymous with the length of sheet flow to a large degree. **Table 1** reveals that **(AOLF)** always is high to drainage density. The computed value of all four watersheds varies from 968.5 m to 1050.4 m.

9- Sinuosity Factor (*P*)

Sinuosity Factor (*P*) is commonly defined as the ratio of straight valley length to actual length of the stream and there is a strong relationship between sinuosity of a stream and its slope (Shekhar et al., 2011). Generally, if the slope gentle there was greater values in the sinuosity. Sinuosity has also been used in classifying the streams into perennial, intermittent or ephemeral. Sinuosity (*P*) is calculated as the ratio of the channel length (l_c) to the distance of the valley(l_v) as an equation 6:

$$P = l_c / l_v \qquad (6)$$

A stream is straight when the sinuosity value is one. It is considered a sinuous stream if sinuosity ranges from one to 1.5, and finally a stream is considered meandering if sinuosity is greater than 1.5 (Kunze, 2004). Sinuosity factor *(P)* for the Khumal Basin was estimated at 1.22, while the other four sub-basins are shown in **Table 1**. The Sinuosity factor *(P)* values in the study area generally range between 1.13 for sub-basin **II** and 1.38 for sub-basin **IV**, according to (Kunze 2004, after Mesa, L. M. (2006) it tends to be more sinuosity.

10- Basin Slope (S)

Basin Slope (S) has a pronounced effect of the velocity of over land flow, watershed erosion potential, and local wind system. The average basin slope is defined as in equation 7 (Shekhar et al., 2011):

$$S = h / L \qquad (7)$$

Where the **S** is average basin slope (m/m), **h** is the fall (m), **L** is the horizontal distance (m) over which the fall occurs. Average Basin Slope (S) for the Khumal Basin is estimated at 0.11 m/m, while those of the four sub-basins as shown in **Table 1**, varies from low slope (0.06) in sub-basin **I** to moderate slope in sub-basin **IV**.

11- Determination of Horton's Ratio

Three Horton's ratio namely bifurcation **(Rb)**, stream-length ratio **(Rl)**, and stream-area ratio **(Ra)** are unique representative parameters for a give watershed and are fixed values for a given watershed system. These parameters play an important role in deriving the geomorphologic instantaneous unit hydrograph and thus the flood unit hydrograph for catchments (Shekhar et al., 2011). Determination of Horton's Ratio depends on the Horton statistics operation calculates for each (Strahler) stream order number and for each merged catchment **(Table 2)**.

Table 2: The Horton statistics operation calculates for each (Strahler) stream order number and for each merged catchment.

order	C1_N	C1_L	C1_A	C2_N	C2_L	C2_A	C3_N	C3_L	C3_A	C4_N	C4_L	C4_A
1	33	1.82	4.14	29	2.42	5.21	25	2.23	4.93	30	1.95	4.69
2	6	8.74	31.53	7	5.15	24.51	5	4.16	26.77	7	5.40	25.35
3	2	22.02	113.04	3	19.07	77.76	2	9.25	73.03	2	10.95	96.21
4	1	26.90	233.80	2	22.23	123.20	1	33.74	178.32	1	11.40	197.48
5	?	?	?	1	24.05	251.92	?	?	?	1	42.31	241.23

N: The number of streams,
L: The average stream length, and
A: The average area of catchments

1- Bifurcation Ratio (Rb)

The term of bifurcation ratio (**Rb**) was introduced by Horton (1932) to express the ratio of the number of streams of any given order to the number in the next lower order. According to Strahler (1964), the ratio of number of streams of a given order (**N**) to the number of segments of the higher order (**N+1**) is termed as the **Rb**. It is expressed in term of the following equation 8:

$$Rb = N/ N+1 \qquad (8)$$

Where; N = number of streams of a given order.

N+1= number of streams of next higher order.

Chow (1964) stated that an **Rb** ranged from three to five for watersheds of a geologic structure does not exercise a dominant influence on the drainage pattern. The Bifurcation Ratio (**Rb**) of four sub-basins of

Khumal Basins are given in Table 3. During this study the Bifurcation Ratio (**Rb**) of Khumal sub-basins are found to be ranging from 1.87 for sub-basin **II** to **4.06** for sub-basin **I**. The Bifurcation Ratio (**Rb**) of streams of these four sub-basins indicating that there is apparently minimal structural control in drainage development.

2- Stream Length Ratio (Rl)

The Stream Length Ratio (**Rl**) can be defined as the ratio of the mean stream length of a given order to the mean stream length of next lower order (Horton, 1945) and having important relationship with surface flow and discharge (Sreedevi et al., 2009). Horton proposed a law of Stream Lengths in which the average lengths of the streams of successive orders are related by a length ratio R_L as an equation 9:

$$R_L = L_{i+1}/L_i \qquad (9)$$

$$L_i = L_1 r_L^{i-1}$$

Where; L_i is the average length channel of order i

The stream length ratios (**Rl**) are changing haphazardly at the basin and sub-basin levels. It is noticed that the **Rl** between successive stream orders of the basin vary due to differences in slope and topographic conditions (Kumar et al., 2001; Sreedevi et al., 2005). The values of the **Rl** vary from 1.45 for sub-basin **IV** that have low slope surface to 3.48 for sub-basin **I** that have high slope surface. It is noticed that the **Rl** has an important relationship with the surface flow discharge as shown in Figure 7.

3- Stream Area Ratio (Ra)

The Horton (1945) law of stream areas states that there exists a geometric relationship between the average area drained by streams of a given order and the corresponding order. Schumm (1956) proposed a *Law of Stream Areas* to relate the average areas (**A_i**) drained by streams of successive order, as an equation 10:

$$R_A = A_{i+1}/A_i \qquad (10)$$

Where; **Ra** is the average area of order i

Stream area ratio (**Ra**) for the Khumal Basin was estimated at 4.58, while the other four sub-basins vary from 2.24 for sub-basin **IV** to 5.23 for sub-basin **I** as shown in **Table 1**.

12- Flood Discharge Measurements

The occasional heavy rains in the present time have take place in winter season along the highland in the study area remain a short period as a flash floods. The maximum-recorded precipitation in the study area during a rainstorm could reach up to 25 mm. Unexpected torrential floods in the study area causes a serious problem and cause excessive life and property losses. One of the most important factors in groundwater recharge studies is to define the hydraulic response of the wadi basin. This includes peak discharge, lag time, and time of concentration. The following procedure can be used to estimate peak discharges for small storm events. It relies on the volume of runoff computed using the Small Storm Hydrology Method (Pitt, 1994) and utilizes the TR-55 Graphical Peak Discharge Method (USDA, 1986).

Curve Number (CN) was computed utilizing the following equation, 11:

$$CN = \frac{1000}{\left[10+5p+10Qa-10\sqrt{Q_a^2+1.25QaP}\right]} \quad (11)$$

where: P = rainfall, in inches (use 1.0" or 0.9" for the Water Quality Storm)

Qa = runoff volume, in inches

Once a CN is computed, the time of concentration (*tc*) is computed based on the methods identified in TR-55 (Ref.).

13- Time of Concentration (T_c)

Time of concentration (**Tc**) is the time required for water to flow from the most remote (in time of flow) point of the area to the outlet once the soil has become saturated and minor depressions filled (Claytor and Schueler, 1996). It is assumed that when the duration of the storm equals the time of concentration, all parts of the watershed are contributing simultaneously to the discharge at the outlet. There are several methods for computing time of concentration. Two of the most popular methods are the Kirpich equation and the SCS lag formula.

1- Kirpich Equation (Tc)

$$T_c = 0.0078\ L^{0.77} S^{-0.385} \quad (12)$$

Where; T_c = time of concentration in minutes.

L = maximum length of flow (ft)

S = the watershed gradient (ft/ft) or the difference in elevation between the outlet and the most remote point divided by the length L.

2- Peak Discharge (Qp)

Peak Discharge (*Qp*) is the maximum volume flow rate passing a particular location during a storm event. Peak discharge (*Qp*) has units of volume / time (e.g. ft^3/sec, m^3/sec, acre-feet/hour).

Using the computed **CN, Tc**, and drainage area (*A*), in acres; the peak discharge (*Qp*) for the Water Quality Storm is computed based on the procedures identified in TR-55.

Using the runoff volume (*Qa*), compute the peak discharge (*Qp*) as in equation 13.

$$Qp = qu \times A \times Qa \qquad (13)$$

where; Qp = the peak discharge, in cfs

qu = the unit peak discharge, in cfs/mi²/inch

A = drainage area, in square miles

Qa = runoff volume, in watershed inches.

Based on the above-mentioned methods, it is necessary to build this model hydrological data provides the rainy storm, and determine the proportion of loose sediments, as well as land use in the drainage basin area. The results obtained are shown in **Table 3**, while the hydrographs are illustrated in **Figure 7.**

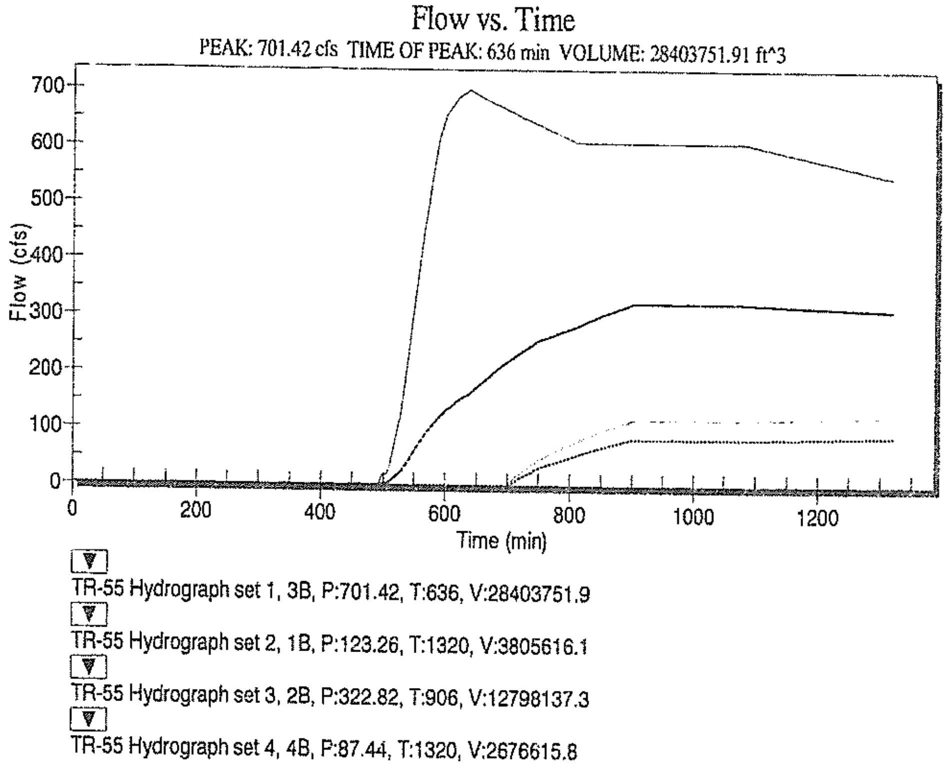


Figure 7: Tr-55 hydrographs for Khumal sub-basins (SCS method)

Table 3: Wadi Khumal Hydrologic Parameters

Basins	Area (km²)	Time of Concentration (H)	Peek flow (Cfs)	Peek flow (Ms)	Peek discharge (Cfs)	Peek discharge (Ms³)	Time of Peak (M)	Volume (ft³)	Volume (M³)
Basin-1	233.7	3.37	123.3	3.5	101.4	2.87	1320	3805616	107763
Basin-2	246.2	2.57	322.8	9.14	428.5	12.13	906	12798137	362402.8
Basin-3	1٧5.٩٥	2.46	701.4	19.7	1279.4	36.2	636	28403751	804304.7
Basin-4	234.7	9.2	81.5	2.3	87.4	2.47	1320	2676615	75793.7
Wadi Khumal	**890.6**	**6.6**	**456.7**	**12.93**	**452.4**	**12.8**	**1320**	**15277019**	**432579**

Table 3 reflects the variability in hydrological parameters within Wadi Khumal, increasing of volume of runoff, peek flow, peek discharge in sub-basin **III** due to its small size compared to other sub-basins as well it have high slope degree. On the contrary, the run-down of the volume of runoff, peek flow, peek discharge in sub-basin I due to the low slope, and sedimentary surface, which helps to water leakage while the volume of runoff of wadi Khumail is low **Figure 8**. This corresponds with the results of the morphometric study, in the study area high drainage density is observed over the hilly terrain with impermeable hard rock substratum, and low drainage density over the highly permeable sub-soils and low relief areas. Low drainage density areas are favourable for identification of groundwater potential zones.

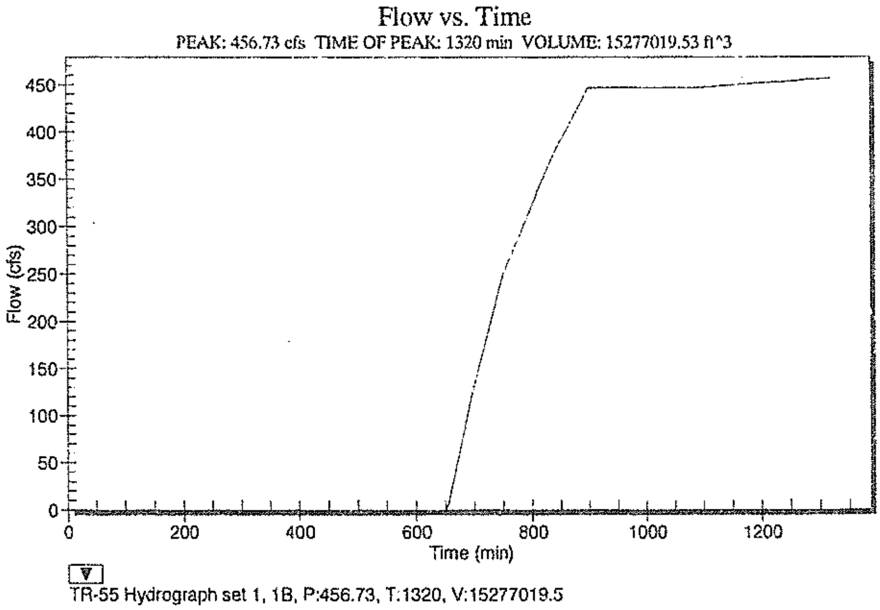


Figure 8: Tr-55 hydrograph for Khumal Basin (SCS method).

CONCLUSION

Wadi Khumal is one of the largest undeveloped wadis in Yanbu area. It drains a wide catchment area of about 890.6 km^2, start from Radwa Mountains in the east to the Red Sea Coast in the west. The geological and geographical setting of Wadi Khumal Basin can be divided into three main zones: the Red Sea coastal plain, the hills, and the Radwa Mountains. These zones reflect the features of topographic, morphometric, and hydrology situations and actually reflect the human population and different activities in the study area.

PCRaster GIS was used for determined the type of network and the watershed surface of the Wadi Khumal Basin, and which was classified in different orders using SRTM data. The Khumal Basin has been classified as fourth order basin. The Drainage Density (Dd) of Khumal watershed, as well as those of the four sub-basins reveals that the subsurface strata are permeable. This is a characteristic feature of coarse drainage system as the density value is less than 5.0. The study reveals that the drainage areas of the basin are passing through an early mature stage of the fluvial geomorphic cycle. Lower order streams mostly dominate the basin. The development of stream segments in the basin area is more or less affected by rainfall. The triangular shape of the Wadi Khumal Basin is mainly due to the guiding effect of Scarp-Radwa Mountains and for many structural effects of the thrusts, faults, and dykes. The erosional processes of fluvial origin deposits are predominantly influenced by surface and subsurface lithology of the basin. Relief ratio indicates that the discharge capability of these watersheds is very high and the groundwater potential is meager. This study and others are very useful for rainwater harvesting and watershed management plans in the dry areas in the world.

Hydrologic parameters peak discharge, peak flow, and volumes of runoff were calculated for four sub-basins using Tr-55 model, based on (CN) method, for the study area the results are shown in Fig. (7&8) and Table3.

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