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MORPHOMETRIC ANALYSIS OF THE WADI AL-NAFT WATERSHED IN EASTERN IRAQ AND ITS HYDROGEOMORPHOLOGICAL SIGNIFICANCE AND THE SUITABILITY FOR A PROPOSED DAM NEAR THE IRANIAN BORDER

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Abstract

An assessment of Al-Naft Valley watershed in eastern Iraq was conducted to study morphometric parameters using Geographic Information Systems (GIS), and a Digital Elevation Model (DEM) was used in hydromorphological analysis to determine the hydromorphological characteristics of the basin identified to evaluate the possibility of constructing a dam on Al-Naft Valley. Thirty morphometric parameters were computed within five main categories. These categories include network properties, drainage properties, areal properties, morphological properties, and relief properties. It was found that the water basin is of the sixth order according to the Strahler method, and the basin covers an area of 1443 square kilometers with a length and width 53.5 – 25.4 kilometer sequentially, and a shape close to circular, with low (drainage density, stream frequency, relative density, and constant of channel maintenance) and high sinuosity coefficient and stream intensity, while the basin has a high relief ratio and low (ruggedness number and relative relief) with moderate (hypsometric integration, basin texture and hypsometric coefficient). Water velocities are high at the headwaters and decrease downstream due to lower gradients and the widening of the valley. Additionally, the tectonic activity of the study basin was identified, it is evident that the area is tectonically active, along with flow velocity and properties, sediment transport ratio, water loss ratio, valley retention capacity, and the maturity stage of the drainage basin, it was revealed that the basin has passed the youthful (inequilibrium) stage and entered the early phase of maturity (equilibrium) stage.

Keywords: Dam feasibility; drainage density; bifurcation; hypsometric; relief; sinuosity.

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1. Introduction

The hydrogeomorphometric studies represent one of the modern trends in the study of river basins. It involves quantitative (numerical) analysis of the earth's surface characteristics and the identification of mathematical relationships that connect topography and water drainage networks (Morisawa, 1985). Studying water basins and identifying their characteristics is crucial in hydrological and geomorphological studies due to their specific hydrological implications, such as drainage properties, channel hydrology, watercourses, and their valleys. However, it can be processed and analyzed through a set of laws that previously relied on descriptive studies to analyze its characteristics. These laws, whose foundations were laid by the scientist Horton in 1945 and further developed by the scientist Strahler in 1957, adopted a mathematical and quantitative approach in studying water basins, their drainage networks, and the relationships between the number of tributaries, their lengths, basin areas, and slopes. The drainage parameters are essential for the evaluation of the morphometry of any basin (Yadav et al., 2014; Choudhari et al., 2018).

Regionally (Saleh et al., 2018), which morphometrically analyzed the reservoir basin of Al-Wand Dam and determined its hydrogeomorphometric characteristics, considering it as an adjacent basin to the basin of Al-Naft Valley intended for study.

This study was conducted to analyze the hydromorphometric characteristics of the Wadi Al-Naft basin to assess the basin's suitability for dam construction from a hydromorphometric perspective. Using the Digital Elevation Model (DEM) and ArcMap tools within ArcGIS 10.8, the study generates various numerical, morphological, areal, and topographic outputs. The outputs and effects of these characteristics, represented by morphometric, topographic, shape, and drainage characteristics, were employed and linked. These data are utilized to interpret the hydrological phenomena of the Wadi Al-Naft basin and to determine the management strategies for the dam based on flow characteristics, including water volume, sediment transport, and associated risks.

1.1. Location

The study area, represented by the basin of the Al-Naft Valley, is located between east of the Diyala Governorate, Iraq, and west of the Kermanshah Governorate, Iran. The area is defined by its geographical coordinates (Figure 1) between the longitude (56°15'45") and (45°20'30") east, and the latitude (34°11'15") and (33°52'30") north. The upper basin sources are located in Iran, covering an area of 1024 Km^2, while the complementary part of the area under study is situated within Iraq, covering an area of 419 Km^2. The study area constitutes the upstream of Al-Naft Valley basin, which eventually flows south towards Mesopotamia to pour into Hor Al-Shibjah between the Governorate of Diyala and Wasit. The valley was named (Al-Naft Valley, which means the oil valley) after this designation due to the oil seepages that flow with the running water in the form of small oil patches.

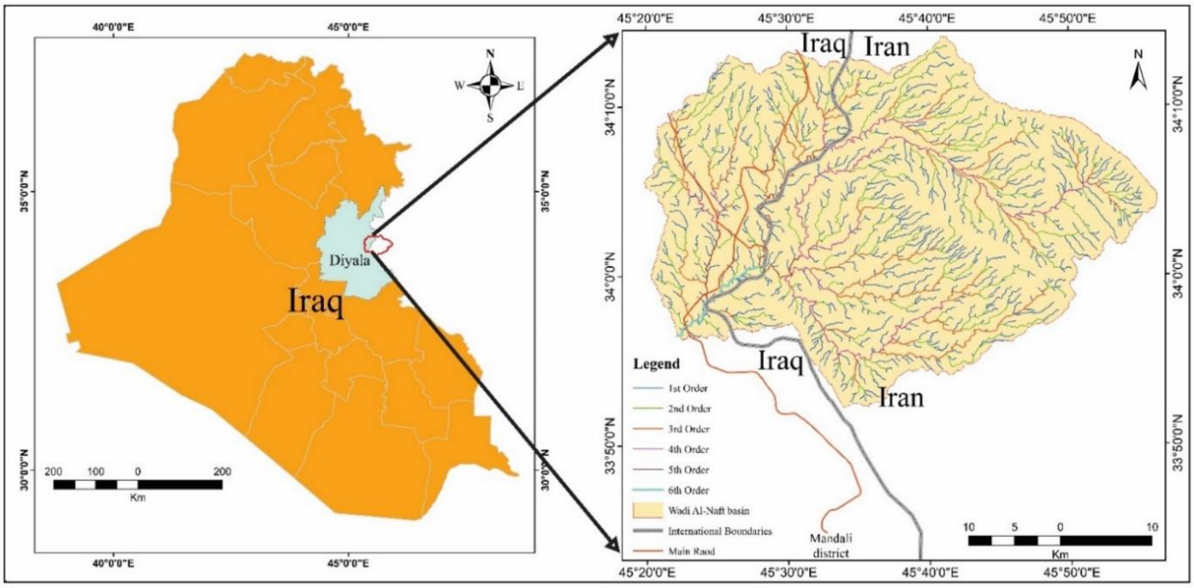

Figure 1. Location map of Al-Naft Valley watershed and its Orders based on radar imagery.

1.2. Geological Setting

The geological characteristics of the study area (especially stratigraphy, geomorphology, and structure) fundamentally control the properties of the drainage basin, influencing the patterns and density of drainage. Geological deposits are characterized by a thick and diverse sedimentary cover consisting of sandstone, limestone, claystone, marl, marly limestone, and siltstone layers, in addition to gypsum layers. These geological formations range from the Late Cretaceous to the Quaternary Period (Figure 2). The geomorphology of the area controls the shape and dimensions of the watercourse. The study area is located within the southeastern part of the Himrin Structure, belonging to the unstable shelf within the realm of foothill or mountain front domains (Buday and Jassim 1987). This area is considered part of the outer platform of the Arabian Plate (Fouad, 2012), and its sedimentary cover has been influenced by phases of Alpine tectonic movements resulting from the collision of the Arabian Plate with the Turkish and Iranian plates. Additionally, the area includes various surface and subsurface structures and faults due to the tectonic setting (Buday, 1980).

1.3. Hydrogeological Setting

The groundwater in the study area is shallow to moderately deep with a general direction of flow primarily from northeast to southwest, and the eastern and northeastern areas serve as recharge zones for groundwater with rainfall. The slope of the land and the general dip of bed inclination affect the pattern and direction of groundwater flow within it, and the study features two main aquifers: Pliocene sediments from the Mukdadiyah and Bai Hassan formations in the highlands along the Iraqi-Iranian border, and Quaternary sediments covering most of the region. (Al Jubouri & Al Basrawi, 2013).

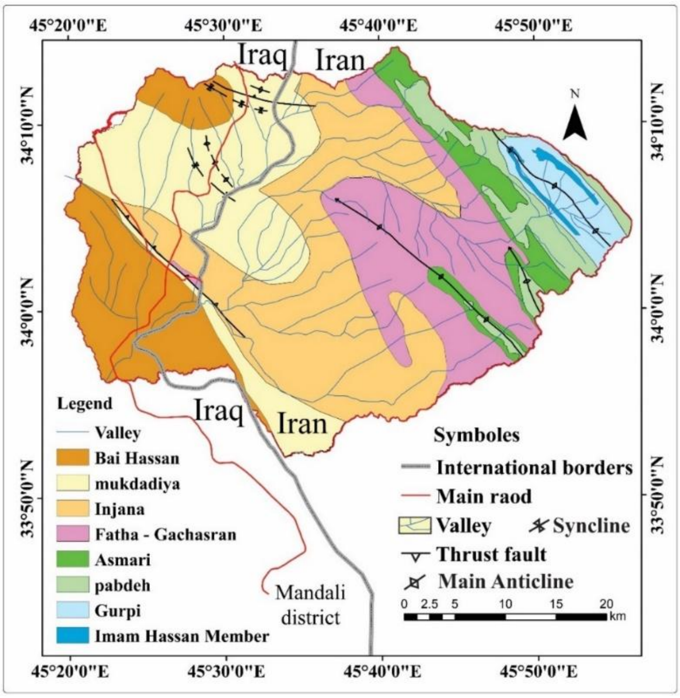

Figure 2. Geological map of Al-Naft Valley Watershed.

1.4. Climate

Climate, geology, and topography dictate surface water flow and groundwater recharge rates, movement speed, and water losses from capillary action and evaporation. Rainfall amount, distribution, and seasonal temperature shifts are key factors affecting groundwater. The area's climate is influenced by location, wind patterns, proximity to large water bodies, and topography (Krasny et al., 2006). The closest weather station, which is the Meteorological and Seismological Observatory in Khanaqin, situated about 42 Km northwest of the study area center and operated by the Iraqi Meteorological Organization (IMO, 2023), was used for this assessment. This station was chosen because it lies on the same precipitation isohyet as the study area center (Al-Sudani, 2020). Recent weather data spanning from 1992 to 2022 was collected from this station, Table 1.

Table 1. Climate members of Al-Naft Valley basin.

Mean\ Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Rainfall	17.9	50.1	38.9	52.9	37.1	39.4	29.7	6.3	0	0	0	0.1
Average Temperature	26.6	18.1	12.7	11.0	12.6	16.6	22.7	29.6	34.3	36.7	36.5	32.2
Average Relative Humidity	39.8	61	72.2	76.2	69.5	59.4	50.2	36.6	26.8	25.5	26.1	30.2
Average Evaporation	520.9	127.1	67.5	55.3	95.4	168.8	237	327.9	461.1	539.4	520.9	390.2
Average Wind Speed	1.2	1.1	0.9	1.2	1.4	1.6	1.6	1.7	1.4	1.4	1.3	1.2

2. Materials and methods

2.1. Datasets Used and Estimation of Morphometric Parameters

The watershed was delineated, and Hydromorphometric parameters were obtained, including its area, boundaries, and the highest and lowest elevation points, from the Digital Elevation Model (DEM) with a resolution of (12.5×12.5) meters (per pixel area) (ALOS PALSAR, JAXA/METI 2007) using ArcMap software in ArcGIS 10.8, Figure 3. Using the 'fill' tool to fill the depressions present in the DEM, and subsequently, the flow direction can be calculated. After filling, the 'flow direction' is then selected, followed by the 'Flow Accumulation' tool according to the flow direction for each pixel. Then, using the 'con' tool with the expression (value > 500). The stream network of the watershed is derived in Figure 1, revealing that the watershed belongs to the sixth order of the Strahler stream order method. According to the Strahler method, small streams without secondary tributaries are considered first-order streams, and second-order streams form when two first-order streams converge. Third-order streams form when two second-order streams converge, and so on until the main stream reaches the highest order (Strahler, 1957).

2.2. Drainage Pattern

Drainage pattern refers to the configuration or system of surface watercourses, including main and secondary tributaries, as observed in rivers and streams. These drainage lines are interrelated in specific forms due to the influence of various factors such as structural and topographic settings, rock exposure nature, and geomorphology of the area (Omar, 1985). Drainage pattern reflects the geological condition of an area, Figure 1. Drainage analysis is an essential tool of geologic interpretation of an air photo or satellite imagery, particularly in areas of low relief. It may provide clues to inactive structural features exposed at the surface, to structural features currently rising, and possibly to buried structural features. Some drainage patterns within the study area appear as follows:

2.2.1. Dendritic pattern

The dendritic pattern has a treelike branching system where tributaries join a gently curving mainstream at acute angles (Parvis, 1950; Howard,1967). This type of drainage predominates in homogeneous rock areas in terms of structure and composition. Tributaries meet each other at acute angles, and they are numerous and short in length, giving the drainage pattern a dendritic or tree-like shape (Al-Dulaimi, 2012). This pattern is widespread in several areas within the Wadi Al-Naft basin, especially in the upper reaches of all valleys.

2.2.2. The trellis pattern

The trellis pattern contains primary tributaries that are long, straight, and parallel to each other, but perpendicular to the main stream. Its secondary tributaries are numerous, short, perpendicular to the primary ones, parallel to the main stream, and essentially the same size (Parvis, 1950; Howard,1967). The trellis pattern is clearly visible at a distance of 2 -4 kilometers north of the Naftkhana region on the Iraq-Iran border.

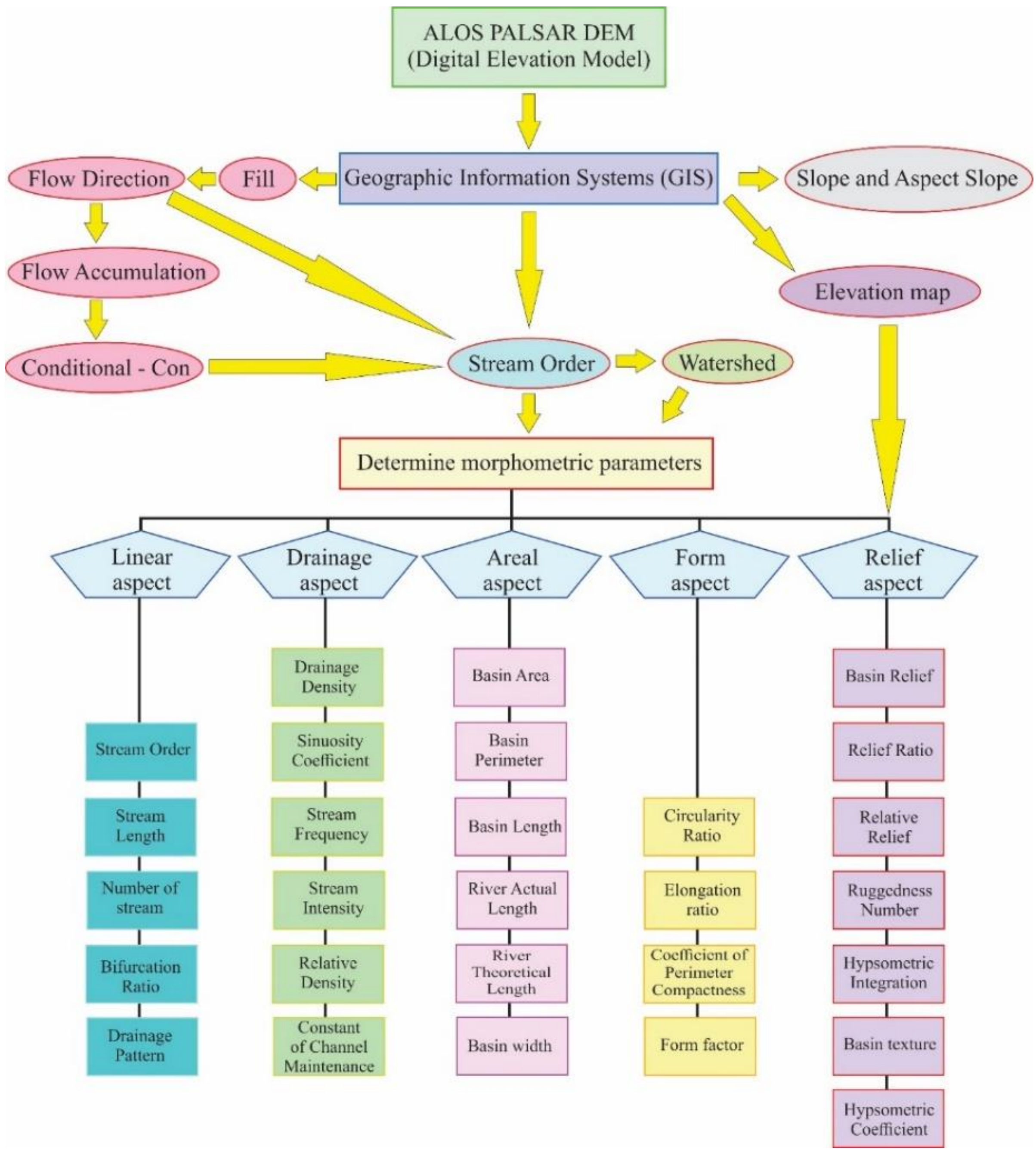

Figure 3. Flowchart of the steps of the methods and data investigation of Al-Naft Valley Watershed.

2.2.3. Rectangular Pattern

This type develops in areas with faults, fractures, and joints that guide the streams and intersect each other at right angles, forming a rectangular shape (Al-Dulaimi, 2012). This pattern arises due to the influence of faults, fractures, and rock fractures on the streams. It is observed in the eastern and northeastern parts of the drainage basin.

2.2.4. Radial Pattern

The radial pattern contains streams radiating from a central area, like the spokes of a wheel (Parvis, 1950; Howard,1967). Watercourses descending from the high mountain peaks tend to take multiple directions, forming a radial pattern. This pattern is evident around Baqcha Hill north of the study area in Iraq, as well as around the northwestern plunge of the Darvana Anticline in Iran.

2.3. Linear Analysis

The evolution of the water drainage network in any region is a reflection of its environmental components, represented by geological, topographical, and climatic factors (Al-Ani, 2010). The water network of the basin was derived, and it became evident that the water basin is of the sixth order of water ranks, based on the Strahler method, which states that small watercourses without secondary tributaries are considered first-order streams. The second order is formed when first-order tributaries converge, while the third order is formed when second-order tributaries converge, and so on, continuing the process until the main stream reaches the highest order (Strahler, 1957). The counts and lengths of the streams for each water rank were extracted from the databases obtained from DEM with a resolution of (12.5×12.5) meters using ArcMap software in ArcGIS 10.8. These data were then included along with the water rank values in Table 2. Bifurcation: The ratio of the number of stream segments **(*Nu*)** of given order to the number of streams in the next higher order **(*Nu*+1).** Horton (1945 The bifurcation ratio (***Rb***) is a unitless measure typically falling between 3.0 and 5.0. Lower Rb values are indicative of watersheds that have experienced minimal structural disruptions. In such cases, the drainage pattern remains unaffected by geological or structural controls. This observation has been noted by various researchers (Schumm, 1956; Chow, 1964; Strahler, 1964) using the following equation:

$$bR = Nu / Nu+1$$

Table 2. River orders and characteristics of the river network are calculated for Al-Naft Valley basin.

Order *Nu*	**No. Streams (*Ns*)**	**Stream Length (*Ls*)**	**Bifurcation Ratio (*Rb*)**
1st	829	913	4.53
2nd	183	482	4.16
3rd	44	246.1	5.5
4th	8	142.2	2.67
5th	3	40.8	3
6th	1	14.9	-
Total	**1068**	**1839**	

2.4. Areal Characteristics

The areal characteristics encompass the geometric dimensions of the watershed, comprising length, width, area, perimeter, and the ratios among these dimensions. They exert a significant influence on the volume of water flow and are intricately related to the development of the lengths and numbers of watercourses (Huggett, 2007). The factors determining the watershed area are diverse, with notable contributions from tectonic movements, rock type, and climatic conditions. Increased erosion activity and the presence of weak rock types typically result in an expansion of the watershed area (Al-Khafaji, 2016). The watershed area is closely intertwined with morphometric characteristics, with larger watersheds exhibiting a lower gradient compared to smaller ones due to their more advanced stage in the erosional cycle. Furthermore, the watershed area serves as a fundamental variable in the measurement of certain morphometric parameters. The areal characteristics of the watershed were computed subsequent to their derivation from the digital elevation model employing (ArcGIS 10.8) software. This process involved extracting the hydrological network, delineating the watershed, and subsequently calculating a range of areal characteristics (Table 5).

2.4.1. Basin Area (A)

This property is crucial in hydrological and geomorphological studies for identifying other hydro-morphometric characteristics such as drainage density, numerical density, hypsometric coefficient, and others. Additionally, it facilitates the establishment of quantitative relationships through which watershed hydrology can be assessed. Moreover, it holds significant importance as it governs the magnitude of water flow (Strahler, 1958). The watershed area serves as a comprehensive water supply zone (Catchment Area), influencing the determination of the quantity of water entering the existing water network within it (Al-Tamimi, 2016).

2.4.2. Basin Length (Lb)

One of the important morphometric variables associated with other features of the watershed is known as the "stream length." It is defined as the measured distance along the axis of the watershed, extending from the water outlet point to the furthest point above the watershed divide at the highest perimeter of the watershed (Schumm, 1956). There is typically a positive correlation between the length and area of the watershed, meaning that an increase in the length of the watershed leads to an increase in its area (Horton, 1945).

2.4.3. River lengths (L)

River lengths can be classified into two types: actual length and theoretical length. The actual length refers to the distance traveled by the river or watercourse from its source to its outlet on land. On the other hand, the theoretical length represents the shortest distance that the watercourse can traverse between the source and the outlet (Morisawa, 1985).

2.4.4. Basin Width (W)

The watershed width refers to the average length of the set of lines perpendicular to the straight line representing the length of the watershed. The geomorphological significance of the variation between the source and the outlet area is due to differences in climatic and slope characteristics (Zuraiqat and Al-Hasban, 2015). Similar to length, the width of the watershed plays a significant role in determining its shape. The width of the watershed affects the amount of rainfall received, as well as runoff, evaporation, and infiltration. An increase in the width of the watershed leads to an increase in the amount of rainfall received, thereby increasing surface runoff, and vice versa (Mahsub, 1997).

2.4.5. Basin Perimeter (P)

The perimeter of the watershed is defined as the dividing line between the watershed under study and adjacent watersheds (Al-Ariani, 2000). It is influenced by various factors, including the evolution of watercourses and streams, especially first-order streams, whose channels expand and deepen during the rainy season due to vertical and lateral erosion processes. Additionally, the extension of faults, fractures, and linear structures contributes to the increase in first-order streams (Al-Oqail, 2001).

2.5. Characteristics of the Drainage Network

2.5.1. Drainage Density (Dd)

It is a measure of the valley's capacity to transport rainfall runoff towards the outlet. As the density is higher, the greater the surface runoff. It is typically observed to increase in regions noted for heavy rainfall and where the surface soil or rocks have low permeability (Al-Jubouri, 2009). Drainage density calculated by dividing the total length of the watercourse network of all orders (Table 3) by the area of the watershed according to Horton (1945), using the following equation:

$$Dd = \sum L_{/A}$$

Where: **Dd** is drainage density (Km/Km²), $\sum L$ is the total stream length of all orders (Km), and A is watershed area (Km²).

The drainage density value might indicate the degree of deformation occurring within the region. Nonetheless, in this context, it's also essential to consider the lithology of the area. This parameter can elucidate both the material characteristics and the permeability conditions of the region, Sukiyah (2018).

Table 3. Geomorphological texture classification based on drainage density (Sukiyah, 2009).

Texture	Drainage density (*Dd*)
very rough	less than 1.38
rough	1.38 until 2.75
intermediate	2.76 until 4.13
rather smooth	4.14 until 5.51
smooth	5.52 until 6.89
very smooth	more than 6.89

2.5.2. Sinuosity Coefficient (S)

Sinuosity is considered one of the patterns of watercourses in the watershed. It refers to the relationship between ***La,*** the actual length of the meandering river, and ***Lh,*** the straight-line distance extending from the source to the mouth (Schumm, 1963). The degree of curvature is influenced by the slope of the basin, geological structure, and rock type, and its value ranges between 1 and 4 or more. Rivers with a curvature coefficient of less than 1.5 are called "sinuous," while those with a value greater than 1.5 are called "meandering" (Wolman et al., 1964). It can be calculated according to the following equation:

$$S = La \text{ (Km)} / Lh \text{ (Km)}$$

The sinuosity coefficient is used to infer tectonic activity in the study area (Table 4). It indicates that the watershed is situated within a region characterized by active tectonics (Doornkamp, 1986).

Table 4. Classification of tectonic activity degree, Doornkamp (1986).

Class	Sinuosity *S*	Tectonic Activity	Characteristics of Smf
1	1.2 - 1.6	Active	Associated with alluvial fan landform, the drainage basin is elongated, the valley floor is narrowed, and the slope is steep.
2	1.8 - 3.4	Intermediate weak	Associated with alluvial fan landform, drainage basin widened, steep slope, the valley floor is wider than the floodplain.
3	2.0 - 7.0	Not active	Associated with pediment mountain front landform and embayment, a steep slope only on resistant rock layers, the valley is slightly more comprehensive and integrated.

2.5.3. Stream Frequency (Sf)

Stream frequency index is a relative relationship between the total number of streams at all orders and the area of the basin (Almomani, 1997). Therefore, an increase in the number of streams or tributaries increases the numerical discharge density (river repetition) and the amount of water flow, thereby increasing the activity of erosion processes. It can be calculated according to Horton (1945) using the following equation:

$$Sf = \sum Ns / A$$

2.5.4. Stream Intensity (Si)

Stream intensity refers to the numerical ratio between the longitudinal density (discharge density) and the numerical density (stream frequency). It is a significant property because it reflects the speed of transfer of discharge waves from different parts of the watershed to the main water channel to convey them to the discharge peak (Al-Ananze, 2005). It can be calculated using the following equation:

$$Si = Dd / Sf$$

2.5.5. Relative Density (Rd)

Relative density represents the ratio of the numerical density (river repetition) to the square of the longitudinal density (discharge density), as shown in the following equation:

$$Rd = Sf\ (\text{stream/Km}^2) \,/\, Dd^{2}\ (\text{Km / Km}^2)$$

2.5.6. Constant of Channel Maintenance (C)

The inverse of discharge density, known as the constant of channel maintenance, represents the area of watersheds required to maintain one kilometer length of channel. It doesn't solely depend on permeable rock types, climatic regime, vegetation cover, and topography, but also on erosion and climatic history (Srivastava et al., 2014). It can be calculated according to Horton (1945) using the following equation:

$$C = A / \sum L$$

2.6. Morphological Characteristics

2.6.1. Circularity Ratio (Rc)

The circularity ratio is defined as the ratio of basin area to the extent of the circle having the same perimeter as the basin (Miller, 1953; Ali and Khan, 2013). It is also referred to as the Area Compactness Ratio. Watersheds can exhibit geometric shapes resembling rectangles, squares, circles, or triangles. The Circularity Ratio ranges from (0 – 1), where a high value approaching one (1) signifies the watershed's proximity to a circular shape, as one represents complete circularity. This indicates the watershed's advancement in its erosional cycle, with increased stream efficiency in deepening its channel at the expense of widening it. Conversely, a low value deviating from one suggests the watershed's deviation from a circular shape, indicating that the erosional cycle is still active (Reddy et al., 2004). The circularity ratio is measured by dividing the watershed area (Km^2) by the area of a circle whose perimeter is equal to the perimeter of the watershed itself (Km^2), so that the Circularity Ratio is a dimensionless parameter.

$$Rc = 4\pi A / P^2$$

Where **Rc** is the circularity ratio, **A** is the basin area, and **P** is the perimeter of the basin.

2.6.2. Elongation ratio (Re)

This coefficient indicates the degree to which the shape of the basin approaches elongation or not. Its value ranges from 0 to 1. If the result approaches one, it means the shape is not rectangular, indicating the basin is approaching a circular shape. If it approaches zero, it indicates the basin shape is more elongated. The elongation coefficient, proposed by Schumm (1956), is a measure of how closely the shape of a water basin resembles a rectangle or deviates from it. It is calculated using the following equation:

$$Re = 2 / Lb * (A / \pi)^{0.5}$$

2.6.3. Coefficient of Perimeter Compactness (Cp)

The coefficient of perimeter compactness is another indicator to confirm whether the basin's shape is approaching or deviating from a circular shape. As the ratio exceeds one, the basin shape becomes more elongated, moving away from circularity. It's worth noting that the result of the perimeter compactness ratio is always greater than one (Sherif, 2000). The perimeter compactness ratio is derived from the following equation:

$$Cp = \sqrt[2]{1 / (\textbf{Circularity Ratio})}$$

2.6.4. Form factor (Ff)

The form factor of the basin illustrates the extent of overall shape consistency of the basin, indicating how regular the width of the water basin is along its length from the source area to the mouth. It is determined by the relationship between the area of the water basin and its length. A low value deviating from the ideal value of 1 indicates that the water basin shape is approaching a triangular shape. Conversely, a high value approaching 1 indicates a deviation from the triangular shape (Al-Sahaf and Moussa, 1998). Form factor (Ff), as proposed by Horton (1945), is used to determine the shapes of river basins according to the following equation:

$$Ff = A\ (Km^2) / (Lb)^2\ (Km^2)$$

2.7. Relief Characteristics

Relief characteristics are considered important for researchers in geomorphological and hydrological studies due to their significance in determining the stages of water and air weathering processes, as well as their role in shaping the Earth's surface. They also reflect the geological nature and structural characteristics of rocks, and understanding the development of the water basin, its hydrological cycle, and prevailing weathering processes relies on these characteristics. Therefore, researchers have varied in the measures of topographic characteristics, which include the following:

2.7.1. Basin Relief (RB)

Basin relief refers to the variation in elevation within the watershed, specifically the difference between the maximum and minimum altitudes (Rawat et al., 2017). Elevation data is typically acquired from Digital Elevation Models (DEMs) with a resolution of 12.5 meters. The basin relief is calculated using the equation provided below:

$$Rb = H \text{ (m)} - h \text{ (m)}$$

Where Rb is the base basin relief, H is the maximum elevation in the basin, and h is the minimum elevation in the basin.

2.7.2. Relief ratio (Rr)

Relief ratio is one of the significant topographic characteristics due to its importance in understanding the terrain nature and the degree of relief in the water basin, concerning variations in elevation between the source and the mouth. This reflects on the watercourse's ability to carry out geomorphological processes, such as erosion in the upper basin and deposition in the estuarine area. It indicates the impact of topographic elevations in the river basin on its flow. The effect of relief depends on several factors, such as slope, basin shape, and discharge density. There is a direct relationship between relief and the effectiveness of erosion factors; it increases with their increase and decreases with their decrease. Relief ratio is also a good indicator for estimating transported sediments, as their proportion increases with relief ratio. The relief ratio is measured according to (Strahler, 1957) using the following method:

$$Rr = Rb \text{ (m)} / Lb \text{ (Km)}$$

Where ***Rr*** is the relief ratio, and ***Lb*** is Basin Length.

2.7.3. Relative Relief (RR)

The relief ratio serves as an important indicator in measuring the intensity of relief in drainage basins, as it indirectly reflects the slope gradient of the basin's surface. The values of the relief ratio are directly proportional to the degree of relief. Relief plays a significant role in shaping terrestrial features and is another important measure of relief intensity for water basins. It represents the relationship between the relief of the basin (the difference between its highest and lowest points) and the basin's perimeter (Strahler, 1957). This relationship demonstrates the extent of correlation between the basin's area and the resistance of rocks to weathering processes. There exists a negative correlation between relative relief and the resistance of rocks to weathering processes under similar climatic conditions. It is measured according to the following formula:

$$\boldsymbol{RR} = \boldsymbol{Rb}\ (\mathrm{m}) / \boldsymbol{P}\ (\mathrm{Km}) \ldots$$

Where ***RR*** is Relative Relief.

2.7.4. Ruggedness Number (Rn)

The value of roughness is an important characteristic used to assess the relief of a basin, indicating the degree of surface incision resulting from the erosion of water channels, and the slope of the watercourse based on the longitudinal discharge density of the basin (Al-Kara'i et al., 2016). It is measured according to the following method:

$$\boldsymbol{Rn} = [\boldsymbol{Rb}\ (\mathrm{m}) \times \boldsymbol{Dd}\ (\mathrm{Km/Km^2})] / 1000$$

Where ***Rn*** is Ruggedness Number.

The roughness value increases with an increase in basin relief, in addition to increasing the lengths of the channels at the expense of the area. The roughness value varies during the stages of the hydrological cycle, decreasing at the beginning of the cycle, then gradually increasing until reaching its maximum at the beginning of the maturity stage. Then, it decreases again as it reaches the stage of old age and the end of the hydrological cycle (Ashour, 1986).

2.7.5. Hypsometric Integration (HI)

Hypsometric integration is a characteristic used to determine the time span of the geomorphic cycle in river basins and to understand the age of river basins. It represents the level of erosion and the weathering cycle in the river basin. The geomorphic cycle is the total time required to reduce the land area to the base level or the base level of the river basin. This method is represented by the following equation (Mehar & Tripathi, 2018):

$$HI = (Hmean - \mathrm{h}) / (H - \mathrm{h}) \ldots$$

Where HI is Hypsometric Integration.

2.7.6. Basin texture (Bt)

Basin texture is an important characteristic in morphometric analysis, referring to the relative spacing of drainage network lines (Reshma et al., 2012). It helps determine the degree of terrain ruggedness, surface incision, and drainage density. When drainage network lines become congested, the number of valleys increases, indicating the intensity of incision and the volume of sediment transport within them. It is influenced by natural factors such as climate, precipitation, rock and soil type, infiltration capacity, and vegetation cover (Schumm, 1977). The value of basin texture is calculated according to (Ritter et al., 1995) using the following equation

$$Bt = \sum(Ns)/P \text{ (Km)} \ldots$$

Where ***Bt*** is Basin texture.

2.7.7. Hypsometric Coefficient (Hc)

The hypsometric coefficient is a temporal scale indicating the developmental stage of aquatic basins or their different parts, with reference to the quantity of materials still awaiting their turn in hypsometric and denudation processes (Al-Moumeni, 1997). It is calculated according to the following formula:

$$Hc = \text{Relative elevation} / \text{Relative area} \ldots$$

Where ***Hc*** is the hypsometric coefficient.

3. Results and Discussions

The morphometric parameters of the Wadi Al-Naft watershed were inferred using theoretical frameworks and morphometric equations using ArcGIS 10.8 software. The results obtained are summarized in Table 5.

For the areal characteristic, it can be observed that the watershed area amounted to 1442.98 square kilometers; to facilitate computational operations, the value has been rounded to 1443 square kilometers. The length of the watershed in the study area amounted to 53.5 kilometers. The difference between the length and width of the watershed is distinct and noticeable (Figure 1), which means the discharge at the outlet remains high for a long time (wide hydrograph). The actual length of the watershed area is greater than the theoretical length. The actual length of the river was 87 kilometers, while its theoretical length was 52.91 kilometers. These lengths are important for determining the sinuosity coefficient, which is one of the key characteristics of the drainage network. The width of the study area watershed amounted to 25.4 kilometers, and the value of the watershed perimeter amounted to 193.97 kilometers, Table 5. In the drainage Network Characteristic, the drainage density of Al-Naft Valley watershed was found to be 1.27 kilometers per square kilometer, indicating a low density of streams within the basin and consequently a low discharge of water from these streams. Drainage density increases with the length of streams in the basin. This low drainage density corresponds to a low discharge density according to the classification by Strahler (1957). Therefore, this value reflects its impact on the proposed reservoir for dam construction to slow down the process of rainfall runoff until water accumulates in the outlet of the main valley, reducing the opportunity for developing watercourses in the upper basin and increasing their area. Consequently, this situation is considered negative for the proposed reservoirs.

Table 5. Linear, areal, drainage network, relief, and morphological characteristic value of the Wadi Al-Naft basin.

Aspect	Criteria	Formula	Value	Units	Reference
Linear	Bifurcation Ratio	$bR=Nu/Nu+1$	order / bR value 1st 4.53 2nd 4.16 3rd 5.5 4th 2.67 5th 3	-	Strahler (1964)
Areal	Basin Area		1443	Km^2	Strahler (1958)
	Basin Length	Lb	53.5	Km	Morisawa (1985)
	River Actual Length	La	87	Km	Morisawa (1985)
	River Theoretical Length	Lh	52.91	Km	Morisawa (1985)
	Basin Width	W	25.4	Km	Mahsub (1997)
	Perimeter Basin	P	193.97	Km	Al-Ariani (2000)
Drainage Network	Drainage density	$Dd = \sum L / A$	1.27	Km/ Km^2	Horton (1945)
	Coefficient sinuosity	$S = La / Lh$	1.64	-	(Wolman et al., 1964)
	Stream frequency	$Sf= \sum Ns / A$	0.74	$stream/ Km^2$	Horton (1945)
	Stream intensity	$Si = Dd / Sf$	1.72	Stream/ Km	(Al-Ananze, 2005)
	Relative density	$Rd = Sf / Dd^2$	0.25	stream/ Km	Horton (1945)
	Constant of Channel Maintenance	$C = A / \sum L$	0.79	Km^2/ Km	Horton (1945)
Morphological	Circularity ratio	$Rc = 4\pi A / P^2$	0.48	-	(Reddy, et al., 2004)
	Elongation ratio	$Re=2/Lb*(A/\pi)^{0.5}$	0.8	-	Schumm (1956)
	Coefficient of perimeter Compactness	$Cp= \sqrt{1 / (Rc)}$	1.44	-	Sherif (2000)
	Form factor	$Ff=A / (Lb)^2$	0.5	-	Horton (1945)
Relief	Basin relief	$RB= H - h$	1125	m	(Rawat et al., 2017)
	Relief ratio	$Rr= Rb /Lb$	12.9	m/ Km	Strahler (1957)
	Relative relief	$RR= Rb / P$	5.8	m/ Km	Strahler (1957)
	Ruggedness number	$Rn= (Rb*Dd)/ 1000$	1.43	Km/ Km^2	(Al-Kara'i et al., 2016)
	Hypsometric integration	$HI=(Hmean-h) (H-h)$	41 %	-	(Mehar et al., 2018)
	Basin texture	$Bt = \sum(Ns) / P$	8.53	$Stream/ Km/ Km^2$	(Ritter et al., 1995)
	Hypsometric coefficient	*Hc = Relative elevation/ Relative area*	46.64 %	-	(Al-Moumeni, 1997)

The basin exhibits a rough texture (Sukiyah, 2009), suggesting the presence of either detrital rocks, rocks with low hardness, or rocks with fractures. This is consistent with the geological composition of the basin. Whereas the sinuosity coefficient of the watershed is 1.64, this value signifies a low level of straightness, implying a high degree of meandering, slow flow velocity, and a prolonged travel time for water to reach the estuary area. The relatively high sinuosity value reflects the presence of tectonic activity within the study area (Table 4), Doornkamp (1986). The stream frequency watershed is 0.74 streams per square kilometer, indicating an extremely low discharge density according to the classification by Strahler (1958). This suggests a scarcity of streams and tributaries, resulting in diminished water flow and, consequently, reduced erosion activity. While the stream intensity for the watershed reached a relatively high value of 1.72 (Km/stream), according to Al-Zuhairi (2020). This signifies that surface runoff will occur rapidly, indicating a high velocity of the movement of runoff waves from different parts of the watershed towards the main water channel. This scenario increases the likelihood of flooding events and intensifies erosion. The relative density of Al-Naft watershed is (0.25 stream/Km), which is a very low value, indicating a scarcity of distributed streams and consequently reducing the speed of water wave transmission from various parts of the watershed to the main water channel. This leads to a decrease in erosion processes and activity. Finally, the lower value of the constant of channel maintenance suggests convergence of channels and narrowness of the basin at the expense of long channel lengths (Al-Adhari, 2006). This was observed in Al-Naft Valley watershed, where the channel maintenance constant was 0.79 square kilometer per kilometer.

For the morphological characteristic, the Circularity Ratio of Wadi Al-Naft basin (0.48) indicates a slight preference towards a more rectangular shape over a circular one. This suggests a relative increase in the basin's width compared to its length, likely influenced by structural factors. This stands in contrast to basins in their youthful stage, which tend to exhibit shapes closer to rectangular than circular. Taken together, these observations indicate that the basin has transitioned into a maturity stage. On the other hand, since the length of the diameter of the basin area is 42.87 Km, the Elongation Ratio of the basin is 0.8, which indicates that the basin is approaching a circular shape and deviating from a more elongated shape. This finding aligns with the value obtained for the Elongation Ratio and supports what has been observed regarding the Circularity Ratio. Strahler (1964) argued that basins with elongation coefficients ranging from 0.6 to 1 exhibit geological formations variation, which applies to Al-Naft Valley basin, and climatic condition differences. The perimeter compactness ratio for the Al-Naft Valley basin was found to be 1.44; this value, approaching 1, indicates the basin's rotation and its proximity to a circular shape, moving away from a rectangular one. This suggests a low degree of watercourse curvature or basin perimeter curvature, indicating that the basin is in a stage of maturity in terms of geomorphological development. The drainage pattern for this basin is likely to be good due to the wider streams compared to their length, resulting in less water loss during flow. This corresponds well with the findings from the Circularity Ratio and Elongation coefficient. Finally, the Form Factor for the Al-Naft Valley basin was found to be 0.5, which, being lower than the ideal value of 1, suggests that the basin's shape is relatively distant from a triangular shape. It also indicates that the area of the water basin is relatively small compared to its length. This implies a relative similarity in different parts of the basin in terms of climate and rock type, with minor variations in rock structure, such as the presence of some joints, faults, and fractures (Abdulla, 2010). The decrease in the form factor value and its approximation to a triangular shape affect the water drainage system. When the source area forms the apex of the triangle and the outlet area represents its base, the water drainage increases immediately after rainfall, leading to a rapid rise in water levels due to the proximity of ponds and streams to the main outlet, and vice versa (Gregory & Walling, 1973).

About the relief characteristic, the topographic situation varies from one place to another (Figure 4), where the Slope on the eastern and northeastern side of the Al-Naft Valley basin is higher and steeper than the western and southwestern side, which is shown by slope and slope aspect (Jiang et al., 2014). Hence, water velocities are notably elevated in the eastern and northeastern sectors, progressively diminishing as they flow southwestward towards the basin's outlet, while the valley cross-section undergoes a transition to a broad U-shape. The highest point in the basin was recorded at 1243 meters above sea level, while the lowest point was at 100 meters above sea level. Thus, the total relief equals 1143 m. Where the relief Ratio in small watersheds significantly influences the increased velocity of water waves, leading to a greater sediment transport (Schumm, 1956). This applies to the studied basin, as its relief ratio amounted to 20 meters per kilometer. This has little effect when constructing a dam downstream due to the decrease of areas' slope near the outlet; however, the areas with gentle to flat slopes constitute approximately 89% of the total drainage basin area, Table 6. As a result, the process of water wave transmission becomes moderate to slow, which is reassuring when constructing a hydraulic structure on the stream channel.

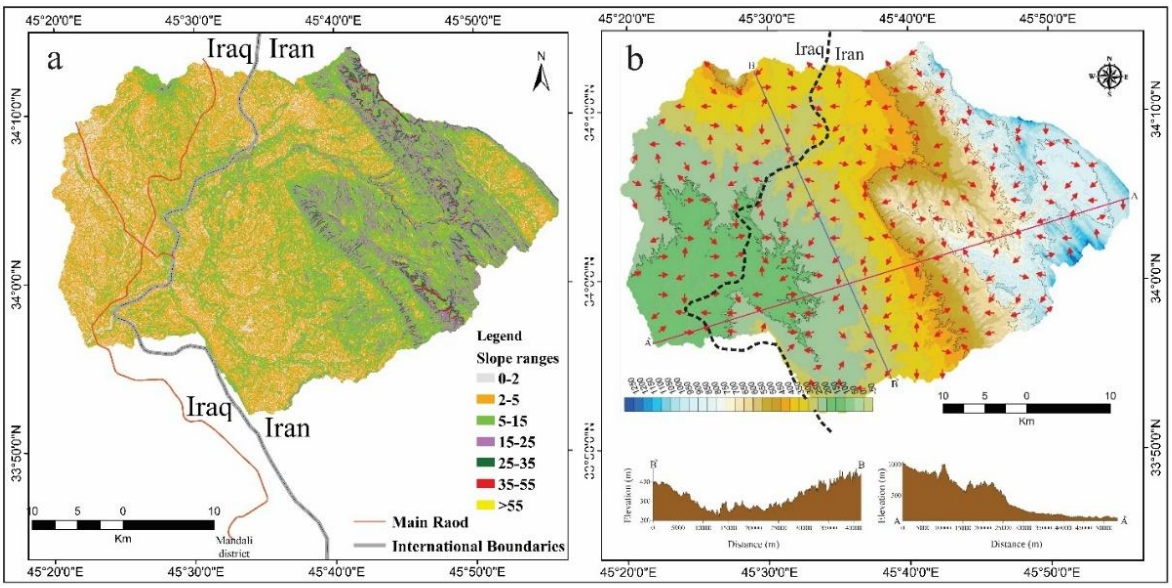

Figure 4. a) illustrates the slope and b) the aspect slope in the Al-Naft Valley basin derived from the Digital Elevation Model (DEM) with a resolution of (12.5×12.5 meters) per pixel.

Table 6. Slope values and their associated areas are obtained from the overall area of the Al-Naft Valley watershed (Jiang et al., 2020).

Slope range°	Description	Area (Km^2)	Area %
0 – 2	Flat	199.03	13.79
2 – 5	Very gentle	552.69	38.30
5 – 15	Gentle	528.52	36.63
15 – 25	Moderate	126.58	8.77
25 – 35	Moderately steep	26.39	1.83
35 – 55	Steep	4.06	0.28
>55	Very steep	0.05	0.003

Relative relief for the Al-Naft Valley basin was 5.8 meters per kilometer (Table 5). This is a low ratio resulting from low values of rock resistance and the intensity of weathering factors, as well as an increase in the basin area. It indicates that the basin is in a mature stage of the riverine weathering cycle. This result confirms the values of the relief ratio. The roughness value for the Al-Naft Valley basin was 1.43 Km/Km^2, which is considered a low value indicating low discharge density. The decrease in the Roughness value is attributed to the scarcity of channels and their small basin area. Additionally, the diversity in rock types contributes to this decrease. This value indicates that the basin is in the maturity stage. The hypsometric integration value for Al-Naft Valley basin was 0.41. This indicates that approximately 59% of the rock mass in this basin has been eroded. It also suggests that these basins are in an advanced stage of equilibrium (Strahler, 1952). This value indicates that the basin has a moderate hypsometric integration and has reached the maturity stage from a geomorphological perspective. This aligns perfectly with the conclusions drawn from the other morphometric and spatial parameters. The basin texture for Al-Naft Valley watershed was determined to be 8.53; this categorizes it as having a medium texture, indicating its moderate ability to retain water. According to Schumm (1977), the hypsometric coefficient value for Wadi Al-Naft is 46.64% (Table 5), suggesting that the basin has completed 53.36% of its hypsometric cycle. This means that 53.36% of the rock materials susceptible to denudation have been lost from the basin, while 46.64% of the rock materials susceptible to denudation are still awaiting their turn in the hypsometric cycle. According to the classification by Horton (1945), the Al-Naft Valley basin is in the mature stage. Where the relative elevation is the ratio between the elevation of any contour line and the maximum elevation in the basin, while the relative area represents the ratio between the area enclosed by any contour line and the perimeter of the basin to the total area of the basin (Ritter, et. al., 1995), The hypsometric curve of the basin also indicates that the basin is in the mature stage, Figure 5. Areas with steep slopes indicate regions that are still in the youthful stage or early maturity, whereas areas with gentle slopes indicate an advanced stage of the hypsometric cycle and the transition to the senescent stage (Al-Kara'i et al., 2016).

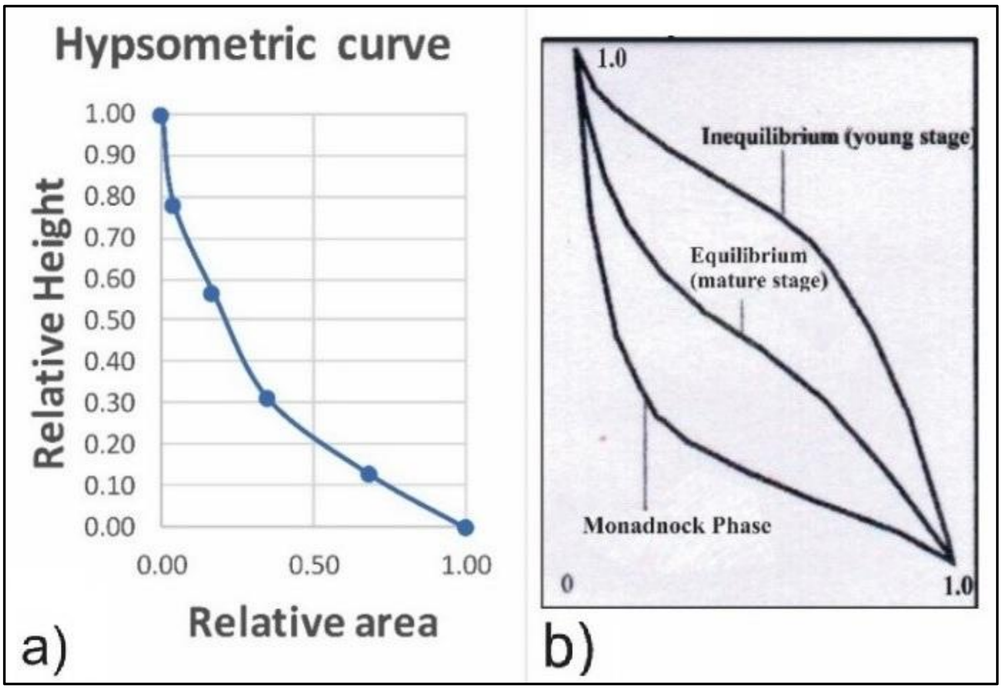

Figure 5. a) The hypsometric curve of the Wadi Al-Naft basin. b) Standard curves (Ritter et al., 2002).

4. Conclusions

Remote sensing, integrated with GIS techniques, was utilized to analyze the drainage basin of the study area. It was found that dendritic and parallel patterns are predominant, while radial and trellis patterns are rare. The basin was determined to be of the sixth order, and the number of channels was found to be inversely proportional to the stream orders. The values of drainage density indicate a very coarse texture of the basin, and the sinuosity coefficient values reflect some tectonic activity. Numerous numerical, drainage-related, morphological, spatial, and topographical characteristics reduce the discharge of water from valleys and decrease the speed of surface runoff, as well as causing a decrease in erosion activity, such as low drainage density, lack of valley straightness, low number of valleys, low relative density, and an increase in basin length at the expense of its width. Water velocities are initially high in the headwaters and decrease due to reduced gradient as they move towards the outlet. Additionally, the widening of the valley cross-section towards the south and southwest also contributes to the decrease in flow velocity. While some factors increase the flow velocity, thus enhancing erosion activity and sediment transport, such as high discharge intensity, high relief ratio, and high Relative relief. The basin is characterized by a low loss of significant water quantities during flow due to the close proximity of channel lengths to their widths, as well as the coefficient of perimeter Compactness close to 1, indicating an increase in channel width at the expense of their length. At the same time, the basin's moderate texture enables it to retain water. The western part of the watershed is in a stage of maturity, evidenced by a relatively high sinuosity ratio, a cohesion ratio close to 1, low ruggedness, moderate hypsometric integration, and the hypsometric coefficient; all signs point to the basin having completed its youthful stage and entered the early maturity phase. Whereas the eastern part of the watershed is still in a youthful stage, evidenced by the high hypsometric coefficient.

The hydromorphometric characteristics reveal that Wadi Al-Naft can supply large volumes of water. In the upper reaches, the flow is fast and carries significant amounts of sediment, whereas near the mouth within Iraq, the water velocity and sediment transport decrease. The basin has a moderate water retention capacity. Flood waves reach the gorge early, necessitating caution from dam operators. Additionally, the area is tectonically active, as evidenced by recent earthquakes, which requires decision-makers to consider more earthquake-resistant dams, such as earthen and rockfill dams near the Iranian border.

5. Recommendations

1- The size of the drainage basin provides considerable water resources, and harnessing these quantities could lead to the development of the water situation in the study area.
2- The inability to develop water facilities in the source areas within Iranian territories due to the topographic, morphological, and drainage characteristics of the basin encourages the harvesting of unused water quantities from the upstream region to Iraq.
3- Water discharge of the basin increases immediately after rainfall, leading to a rapid rise in water levels due to the proximity of ponds and streams to the main valley. This necessitates that operators of any water facility along the valley take appropriate actions early on, and the discharge remains high for a long time (wide hydrograph) due to the length of the basin relative to its width and low drainage density.
4- Constructing a dam or several dams on the main valley of Wadi Al-Naft or on the secondary valley, which is located (even its watershed) entirely within Iraqi territory, depending on the capacity of the reservoirs built on it.
5- To overcome sedimentation issues in the dams of eastern Diyala Governorate, constructing reservoirs with storage capacities matching or more than the projected water yield into Al-Naft Valley basin is advisable.

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