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INVESTIGATION OF THE BASIN CHARACTERISTICS THROUGH MORPHOMETRIC ANALYSIS OF HADEJIA RIVER SUB-BASIN: IMPLICATIONS FOR GROUNDWATER RECHARGE

Mudassir Hassan[1*] and Murtala Mohammed Ruma[2]

[1&2]Department of Geography, Umaru Musa Yar'adua University, P.M.B 2218 Katsina, Nigeria.

[*]Corresponding Author's Email: mudassir.hassan@umyu.edu.ng; Tel.: +2348065047825

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ABSTRACT: *Understanding the geohydrological properties of a drainage basin in relation to the topographical feature and its flow patterns depends heavily on morphometric analysis. Estimating a watershed's frequency of infiltration and runoff as well as its other hydrological characteristics is also helpful. The study was conducted using Geographical Information System (GIS) techniques with the aim of establishing relationship between surface morphometry, underlying geology and groundwater recharge. For detailed measurement and analysis, Digital Elevation Model (DEM) and high resolution imageries were employed for basin delineation, slope characterization, channel network extraction and stream ordering in order to derive the linear, areal, and relief aspects of morphometric parameters. The findings showed that a total number of 116 streams joined the 4th order stream in which 83 streams were 1st order, 25 streams were 2nd order, 7 streams were 3rd order and the major trunk was 4th order stream, occupied an area of 1486.86km^2. The stream network's drainage system exhibits dendritic design. The results further indicate that the values for stream frequency, infiltration number, drainage density, drainage texture, length of overland flow, elongation ratio and basin relief are 0.08, 0.032, 0.41km/km^2, 0.023, 1.22km, 0.54 and 28.59m respectively. The observed values of both linear, areal and relief parameters were generally low. Low values for the areal and relief criteria indicates that the sub-basin is at its youthful stage of development and possesses very good permeable subsurface formation and prospect with the possibility of high potential groundwater resources. The result help us understand the connections between hydrological variables and geomorphological parameters as guidance and/or decision-making instruments for the authorities to develop decisions for the environmentally friendly growth of the basin, water supply planning, water budgeting, and disaster mitigation within the Hadejia river sub-basin.*

KEYWORDS: Morphometric Analysis, Groundwater resource, Hadejia River Sub-Basin, Geospatial Approach

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INTRODUCTION

The proper correlation between the properties of drainage basins' river networks, their density and length, and the surface area of the basins is revealed by the morphometric analysis of rivers. (Mishra, *et al.,* 2023). Drainage basin morphometric parameters provide evidence for describing a basin's topographical, geological, and hydrological behavior (Asfaw and Workineh, 2019). Morphometric parameters have an impact on basin processes (Singh, *et al.,* 2014); characterize the characteristics of geomorphology and hydrogeology (Soni, 2016) and provide useful information on the assessment and management of water resource potential (Kabite and Gessesse, 2018; Misha *et al.,* 2023). The estimation of various topographical and hydro-morphometric characteristics of drainage basins has recently been simplified due to advances in remote sensing and spatial technologies (Gizachew and Berhan, 2018; Khan, *et al.,* 2023). A number of scholars who used geospatial approaches to undertake morphometric analyses revealed that detailed and up-to-date information about drainage basins may be created in a systematic manner (Ayele, *et al.,* 2017; Gizachew and Berhan, 2018; Hassan and Kabir, 2019; Saha, *et al.,* 2022; Tassew, *et al.,* 2023). Their findings demonstrated that morphometric analysis gives basic information regarding hydro-geologic and watershed characteristics in terms of both surface and groundwater potential.

The hydrological processes in a river basin greatly influence the spatiotemporal distribution of water resources (surface and groundwater) and, as a result, prospective water resource-related activities in the basin (Kabite and Gessesse, 2018; Ma, *et al.,* 2023). Morphometric analysis can provide significant information regarding hydrologic properties (Soni, 2016) and physiographic and geologic information of basins. Studying morphometry is crucial for identifying groundwater prospects when there is insufficient hydrological data available (Arefin and Alam, 2020). Despite the relevance of morphometric study for planning and management of ungauged basins, the Hadejia river sub-basin has received very little attention. So far, the implications of several morphometric factors on groundwater recharge have not been addressed. However, for their daily water needs, the residents in the study area rely solely on groundwater. As a result, our study attempted to fill this gap by quantifying valuable drainage morphometric factors using a remote sensing and GIS technique for water resource management. The study's goal is to measure the effect of morphometric characteristics on groundwater recharge. The study would enable us to understand the geological and geomorphological history of the drainage basin and its development with the aid of the morphometric analysis of the Hadejia river sub-basin.

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MATERIALS AND METHOD

Study Area Description

Hadejia River sub-basin is located between latitude 12º10' and 12º50' North of the equator, and longitude 09º40 and 10º40' East of the Greenwich meridian (Figure 1). The river sub-basin covers an area of about 1486.86km^2. This river catchment falls largely in the northeastern part of Nigeria. The hydrology of the basin is dendritic in nature (Figure 1). The area has a mean annual flow of about 1,396 mm^3/s to 43 mm^3/s, and a peak flow of about 597 mm^3/s to 38 mm^3/s (Umar, *et al.*, 2018). The area experienced a very wet and dry climatic type. The annual rainfall is comparatively low, and annual evaporation is also very high, reaching up to 1500mm. Annual mean rainfall is about 600 mm to 700 mm in the entire basin. Generally, wet season last between five months. The area has a maximum day temperature of about 36ºC usually in May and a minimum day temperature of about 22ºC mostly in the months of December and January. Relative humidity ranges from 80% in the peak period of wet season to 23% duting the extreme dry period between the month of January and March. (Garba, *et al.,* 2023). The overall relief is nearly flat (Sombroek and Zonneveld, 1971). Precambrian basement complex rock, predominantly granite, gneiss, quartzite, and several types of intermediate metamorphic rocks, underpins the study area (Obaje, 2009). Furthermore, the study river is located in an area covered by Fadama soils, which are flood plain soils. The entire basin is located in the Sahel savannah ecological zone, which is distinguished by very short grasses and shrubs with thick bark (Chukwujekwu, 2010).

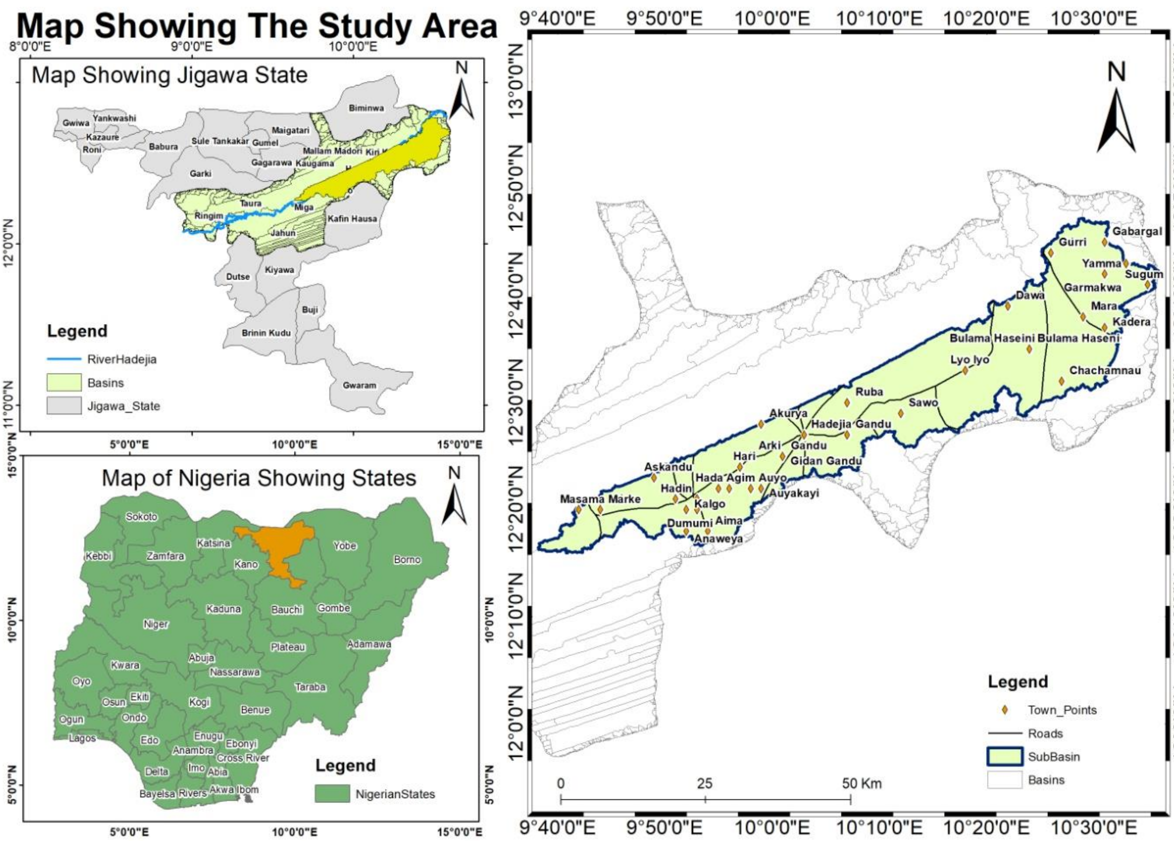

Figure 1: Map of the Study Area

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METHODOLOGY

The morphometric analysis entails the extraction of all existing streams for hydrologic inferences. In the present study, the Digital Elevation Model generated from Landsat imageries of the study area downloaded from www.earthexplorer.usgs.gov (30-m spatial resolution) data have been used to extract the sub-basin and its stream network in ArcGIS Environment using the hydrology toolset (Figure 2). All the morphometric parameters are calculated by measuring the length, width, area, and perimeters of the basin with the help of specific algorithms in the ArcGIS environment. Various basin morphometric characteristics of linear, aerial, and relief aspects were derived for comprehensive measurement and analysis using the following formula:

Table 1: Formulae used for the calculation of morphometric parameters of Hadejia river sub-basin

S/N	Parameters	Formula	Reference
1	Stream order	Hierarchical rank	Strahler 1952
2	Stream number (Nu)	Nu=N1+N2+…….Nn	Horton 1945
3	Stream length (Lu)(Km)	Length of the stream	Strahler 1964
4	Stream length ratio (Lur)	Lur=Lu/(Lu-1)	Strahler 1964
5	Mean stream length (Lsm) (Km)	Lsm=Lu/Nu	Strahler 1964
6	Bifurcation ratio (Rb)	Rb=Nu/Nu+1	Strahler 1964
7	Basin area (A) (Km^2)	GIS Software Analysis	Schumm 1956
8	Stream frequency (Fs)	Fs=Nu/A	Horton 1932
9	Drainage density (Dd)	Dd=Lu/A	Horton 1932
10	Drainage texture (Dt)	Dt=Nu/P	Horton 1945
11	Form factor (Ff)	$Ff=A/Lb^2$	Horton 1932
12	Circularity ratio (Rc)	$Rc=12.57x(A/P^2)$	Miller 1953
13	Elongation ratio (Re)	Re=1.128√A/Lb	Schumm 1956
14	Length of overland flow (Lg)	Lg=A/2*Lu	Horton 1945
15	Infiltration number (If)	If= Dd*Fs	Zavoianu, 1985
16	Texture ratio (Rt)	Rt=N1/P	Schumm 1956
17	Max. basin height in (m)	GIS Software Analysis	
18	Min. basin height in (m)	GIS Software Analysis	
19	Basin relief (R) (m)	R=Max H-Min H	Strahler, 1952
20	Ruggedness number (Rn)	Rn=Dd*(H/1000)	Patton & Baker 1976

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RESULT AND DISCUSSIONS

Linear Aspect

Using the formula presented in Table 1, the linear characteristics of the Hadejia River sub-basin were quantitatively analyzed and the result obtained are presented in Table 2.

Stream Order	No. of streams (Nu)	Stream length (Km)	Mean stream length	Stream length ratio	Values	Bifurcation ratio	Mean bifurcation ratio
1st	83	263.37	3.17	2nd/1st	0.59		
2nd	25	155.72	6.23	3rd/2nd	0.65	3.48	
3rd	7	101.27	14.47	4th/3rd	0.90	3.57	4.68
4th	1	91.10	91.1			7	
4 orders	116	616.46			-	14.05	-

Table 2: Linear parameters of the study river

Source: *Authors' computation (2024)*

The term bifurcation ratio (Rb) is used to express the ratio of the number of streams of any given order (Nu) to the number of streams in next higher order (Nu+1). Bifurcation ratio is dimensionless which indicates the degree of integration between streams segments of different orders in drainage basin (Gutema, *et al.,* 2017). It has fundamental importance in drainage basin analysis as it is the principal parameter to associate the hydrological character of a basin with the geological structure and climatic conditions (Singh, *et al.,* 2014; Gizachew and Berhan, 2018). If bifurcation ratio ranges between 3.0 and 5.0, the geological structures of the watershed do not affect drainage pattern of streams (Strahler 1964). Similarly, if the bifurcation ratio is less the 3.0, the geological structure of the basin is flat and homogenous. In this respect, the bifurcation values observed in this study basin range from 3.48 to 7.0) with the mean bifurcation ratio value of 4.68. This indicates that some part of the stream network was influenced by the lithology and geological structure of the drainage basin.

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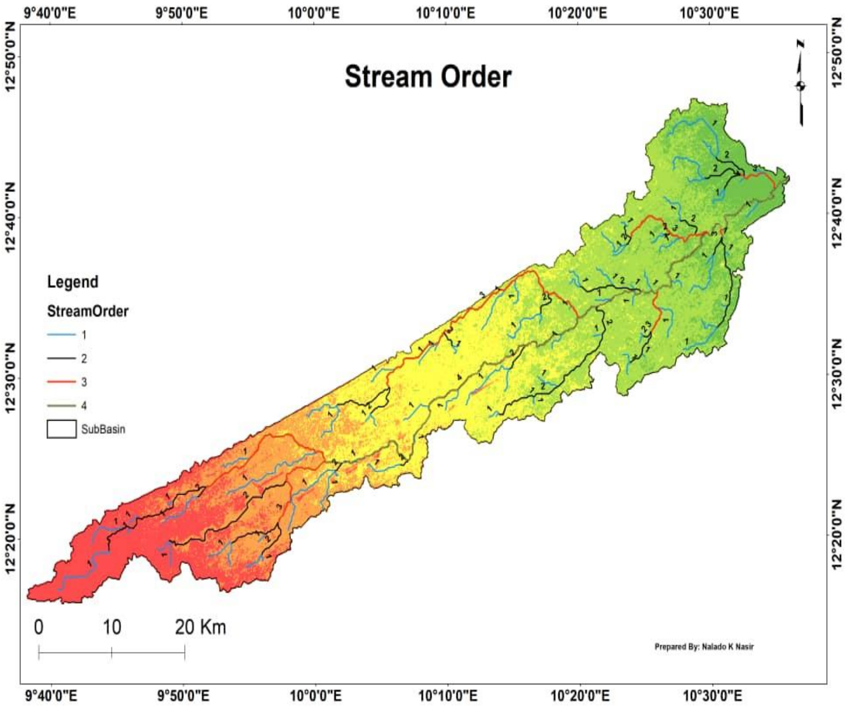

Figure 2: Drainage network of Hadejia river sub-basin

Areal Aspect

Table 3 presents an analysis of the areal parameters of the Hadejia river sub-basin. According to the results, the basin has an area of 1,486,86 km^2 with the length of about 83.13km The sub-basin has a larger area with a very high length. The basin's stream frequency, drainage density, and infiltration number, on the other hand, are 0.078, 0.41, and 0.032, respectively. The low stream frequency suggests that the surface runoff is slow with high possibilities of recharging permeable sub-surface. The low drainage density means that the basin has low relief, permeable subsurface material (very coarse), and improved ground water potential, as well as a shorter length of stream channel to carry runoff (Ali, *et al.*, 2018; Strahler, 1964). Furthermore, a lower drainage density results in a coarser catchment texture; drainage density indicates the land's infiltration capacity (Yunus *et al.*, 2014). In this study, a low infiltration number suggests a high rate of infiltration and low runoff. However, the calculated length of overland flow (Lg) in this sub-basin is low (1.22) as seen from Table 3, explaining the longer path for flow concentration. The form factor is a function of the basin shape and indicates the rate at which water enters the stream. Stream flow intensity is directly related to form factor (Gregory and Walling, 1973). Low groundwater recharge is associated with high river flow intensity (Konwea and Ajayi, 2022). The form factor result in this investigation was 0.22, which indicates a low peak flow with a prolonged duration of time. Furthermore, the low form factor observed suggests that the basin is elongated and has a very significant area of low relief. Under normal climatic and lithologic circumstances, elongation ratios range between 0.1 to 1.0. The elongation ratio of the study area is 0.52, indicating that it has an elongated basin. A drainage basin with an elongation ratio close to 1.0 indicates low relief, which translates to lower runoff intensity and higher groundwater recharge, whereas lower values indicate high relief and steep topography, which translates to higher runoff intensity and lower groundwater recharge (Strahler, 1964). Circularity ratio is affected by elements

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such as stream length and frequency, geological formations, land use/land cover, climate, and basin slope (Rai *et al.*, 2018). The calculated circulatory ratio for the study region is 0.16, indicating that the basin is in the dentritic stage and almost an elongated shape with high permeability and homogeneous geological materials. Texture ratio, as established by Schumm (1956), is an important component in drainage morphometric analysis that is dependent on the underlying lithology, infiltration capacity, and relief aspect of the terrain. The texture ratio is defined as the ratio of the total number of first-order streams to the basin's perimeter. The texture ratio of the Hadejia river sub-basin is 0.33, indicating low nature.

Table 3. Areal Aspect of Hadejia River Sub-basin

(A) in km^2	(Fs) in km^2	(Dd) in km/km^2	(Dt)	If	Lg	Re	Rc	Ff	Rt
1486.86	0.078	0.41	0.032	0.032	1.22	0.52	0.16	0.22	0.33

Area (A), Stream frequency (Fs), Drainage density (Dd), Drainage texture (Dt), Infiltration number (If), Length of overland flow (Lg), Elongation ratio (Re), Circularity ratio (Rc), Form factor (Ff), Texture ratio (Rt)

Relief Aspect

Table 4 illustrates the relief aspect. The overall relief of the sub-basin is found to be 28.59m above mean sea level. The result also revealed that the relief ratio of the studied basin is 0.34. The mild nature of the sub-basin slope accounts for the low value of relief ratio in this study sub-basin. This is consistent with the findings of Pareta and Pareta (2010), who discovered that places with low to moderate relief and slope have moderate relief ratios, owing to the basin's resistant basement complex rocks and low degree of slope.

Table 4. Relief Aspect of Hadejia River Sub-Basin

R (m)	Rr (m)	Sb	Sf	Rn
28.59	0.34	0.34	4.65	11.72

Basin relief (R), Relief ratio (Rr), Basin slope (Sb), Shape factor (Sf), Ruggedness number (Rn).

The basin slope value of the study river was discovered to be 0.34, indicating that the sub-basin has low degree in slope. The ruggedness number denotes the level of smoothness and roughness of the basin terrain or surface irregularity (Asfaw and Workineh, 2019). The basin's Rn value obtained in this study is 11.72, indicating that the basin has a sharp ruggedness since it is greater than 1.0.

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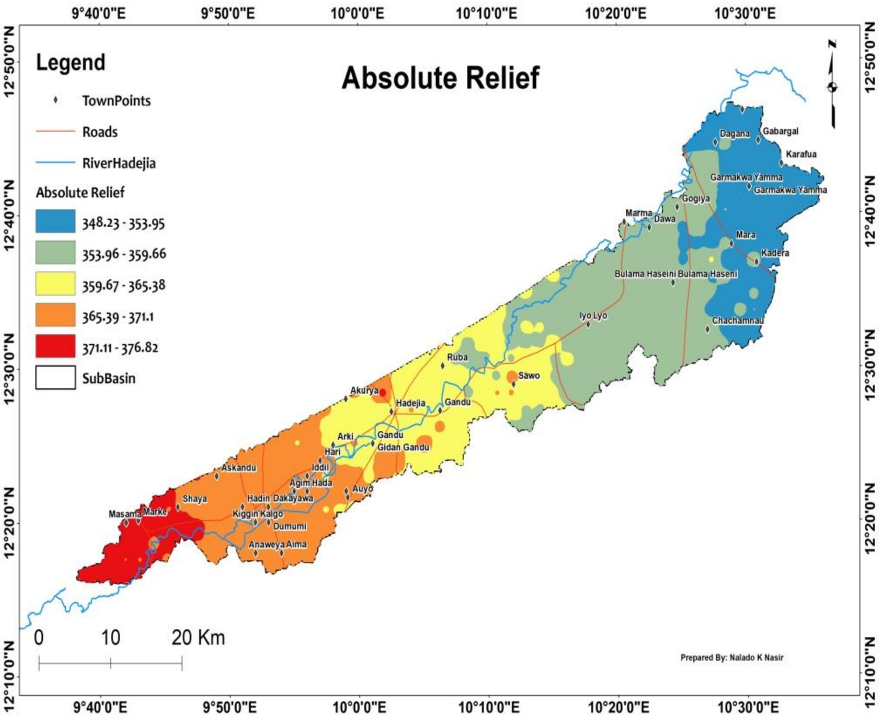

Figure 3: Map of the Absolute Relief of the Study Sub-basin

Land use land cover pattern

The most crucial elements in determining the groundwater water conditions of any given location are changes in land use and land cover patterns. Climate change and land use patterns are placing tremendous strain on water resources. Changes in land use patterns and their assessment provide insight into how land resources are used by human activities, especially urbanization and agriculture (Nian, *et al.,* 2014; Singh, *et al.,* 2014). In addition to being utilized to understand the infiltration, recharge, and runoff rates of the watershed, hydrological inferences from land use patterns can aid in understanding the changing picture of water demand from various activities such as agricultural requirements, household needs, and industrialization. Changes in land use patterns play a significant role in managing natural resources and hydrological surveillance (Rawat, *et al.,* 2013).

Future research will primarily require analyzing changes in land use for hydrologic systems (Liu, *et al.,* 2024), which comprises: adjustments to water supply brought about by modified hydrological processes of infiltration, groundwater recharge, and runoff; adjustments to water demands brought about by changing land use patterns, such as irrigation and urbanization. Various scholars have emphasized the significance of land use maps in comprehending the hydrological dynamics of watersheds and how to manage them. (Ayalew, *et al.,* 2024; Belay, and Mengistu, 2024; Pande, *et al.,* 2024).

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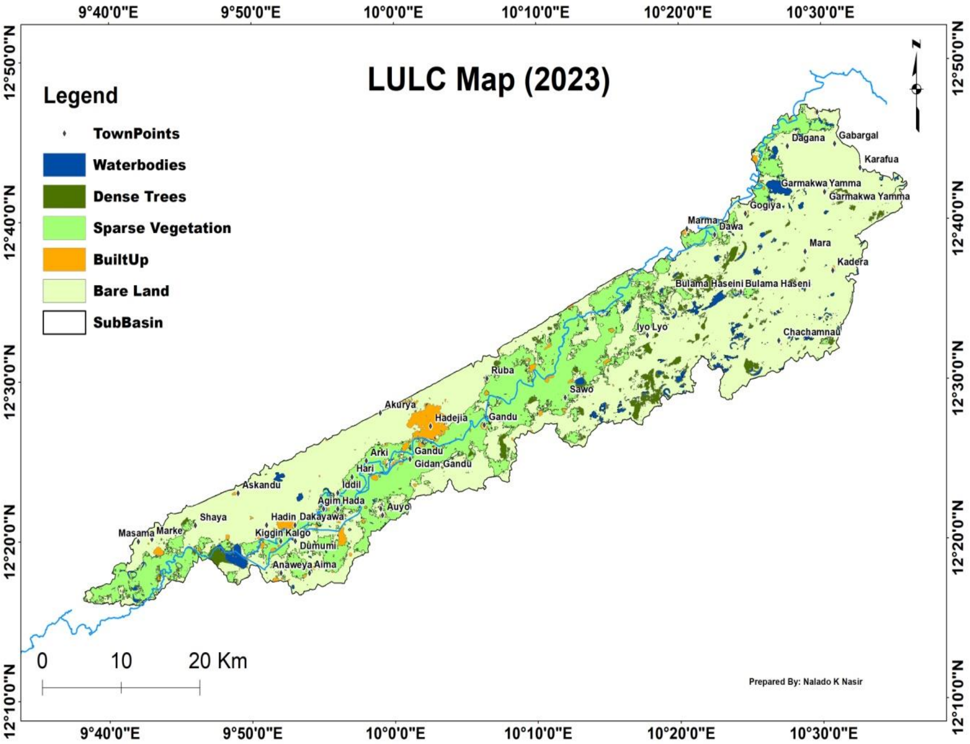

Figure 4: Land use land cover map of the study area

In the current work, a supervised classification system was used to evaluate the land use pattern and its regional variation using recently released, publicly available Lasndsat-8 satellite data from December 2023, which has a spatial resolution of 30 m. Using the Erdas Imagine 9.1 software, a typical procedure was used to classify the satellite image. This involved first setting the training locations, then extracting signatures from the image, and then doing classification. Ultimately, the classification techniques of Maximum Likelihood Classification (MLC) were used. To complete the watershed's land use/cover map, a field survey was conducted using a GPS receiver to confirm any classes that were dubious. According to their water requirements, common land use types were determined, i.e., waterbodies, dense trees, sparse trees, settlement and bare land. (Fig. 4). Assessment of land use pattern of the sub-basin reveals that most part of the area comes under bare land (66.59%) followed by sparse vegetation (25.40%) which indirectly supports the future for watershed management (Table 5).

Table 5. Land use percent of Hadejia River Sub-Basin

Land use Category	Area (Km^2)	Percentage (%)
Water bodies	38.22	2.57
Dense trees	46.16	3.10
Sparse vegetation	377.72	25.40
Build up	34.72	2.33
Bare Land	990.12	66.59
Total	**1486.94**	**100.00**

Source: *Authors' computation (2024)*

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Slope Analysis

Slope is an important parameter in geomorphic studies. An understanding of slope distribution is essential as it plays a significant role in determining infiltration vs. runoff relation. Infiltration is inversely related to slope *i.e.* gentler is the slope, higher is infiltration and less is runoff and vice-versa (Parveen, *et al.*, 2012). Slope analysis showed that slope in the study area varies from 0 to 6.8 with mean slope of 2.115 as illustrated in Figure 5. High slope is witnessed in the north western part of the sub-basin. Slope data may thus be used in planning and many other resource conservation strategies.

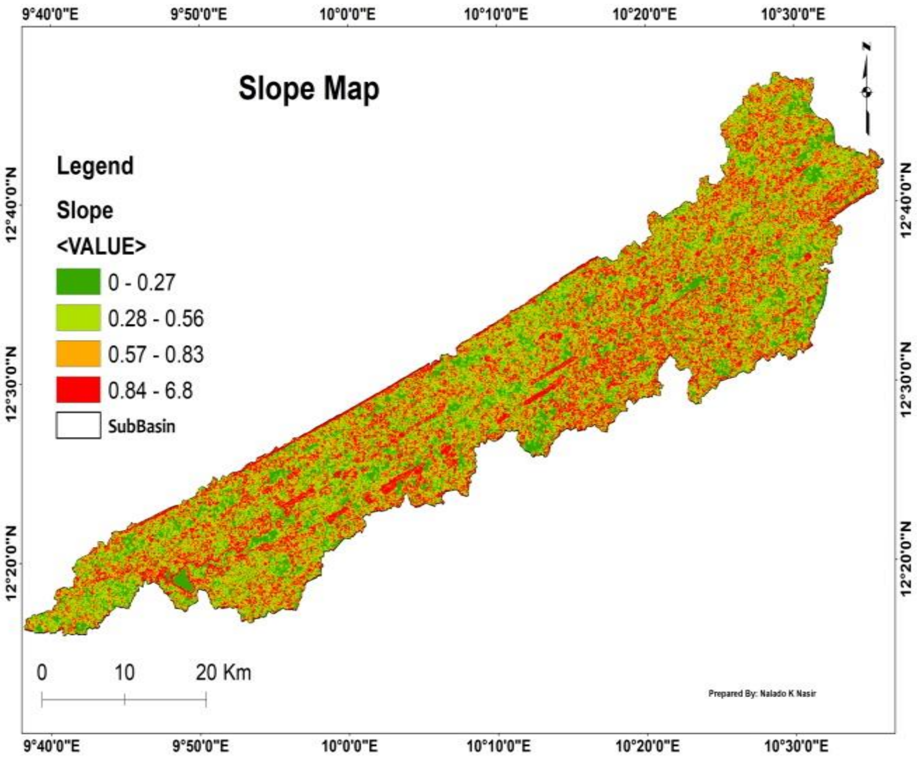

Figure 5: Slope map of the study area

Drainage Morphometry for Groundwater Recharge Potentials

Morphometric analysis based on GIS and satellite generated Digital Elevation Model (DEM) are the most crucial data for hydrological investigation of any terrain, which indirectly supports the watershed's hydrogeological status. Planning of water resource conservation and management for future sustainability is quite crucial. The morphometric analysis of the Hadejia sub-basin shows that the watershed has a elongated shape and very gentle slope. In addition, if the morphometric information is integrated with other hydrological parameters of the river basin, the strategy for water harvesting and recharging measures gives a better plan for groundwater management and development for the future.

The drainage pattern of the sub-basin is dendritic in nature. The pattern was affected by less heterogeneous structural and lithological characteristics. In addition, very low drainage density was observed in the sub-basin along with very low relief and permeable sub-soils. Nevertheless, it has been observed that in most semi-arid environment with low drainage

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density have very coarse texture which is favorable for high water infiltration and potential groundwater zones. However, slope plays a significant role in determining the relationship between infiltration rate and runoff velocity, where infiltration rate is inversely controlled by regional slope. Therefore, all evaluated parameters are more important for the analysis of future water availability in the study region.

Furthermore, the morphometric analysis shows that runoff generation and conveyance in the sub-basin is slow. During such slow movement, runoff has more opportunity to infiltrate. This could be owing to the presence of permeable underlying materials, as shown by the basin's drainage characteristics and geological map.

CONCLUSION

In this study, a Geospatial based technique was used to assess the morphometric parameters of basin hydrology. It aids in understanding the basin hydrology and the possibility for groundwater resource potentials. The morphometric analysis was conducted out in the Hadejia river sub-basin in Jigawa state. The results revealed that the basin's areal and relief parameters were low. The near surface lithology is characterized by good permeable capacity with very low drainage density and low relief which indicates a strong possibility for groundwater recharge. Since runoff water flow peaks are flatter and last longer, the majority of the elongated basin area's gentle slope allows for prolonged infiltration. The evaluation morphometric analysis of the basin using Geospatial approach assisted us in understanding topographical factors such as infiltration capacity, runoff, lithology, and relief that affect the hydrological process of the basin. Therefore, the examined morphometric parameters show that groundwater recharge can be used to manage the Hadejia river sub-basin's water resources. It aids in a better knowledge of the management and planning of drainage and river basins and will be helpful to planners and decision-makers in managing and developing the natural resources in a way that is environmentally sound.

The hydrological, hydrogeological, and geophysical data will then be combined with the morphometric parameters to help determine the best locations for water conservation structures (such as check dams, percolation tanks, artificial groundwater recharge using MAR technique, etc.) for groundwater development and management programs. In order to improve the management strategy based on morphometric analysis of the watershed utilizing remote sensing and GIS techniques, this study will offer recommendations to the water resource managers in Jigawa state.

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