Drainage Morphometric Analysis of Shope watershed, Rift Valley, Ethiopia: Remote sensing and GIS-based approach

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Abstract

The quantitative drainage morphometric analysis at the watershed level is essential for understanding its geo-hydrological nature. Drainage morphometric evaluation has been conducted to identify the predominant geological divergence, topographical details, structural arrangement, and interrelationship in the Shope watershed Rift Valley, Ethiopia. The Remote Sensing Data and Geographical Information System (GIS) tools have delineated the Shope Watershed and calculated various morphometric attributes. The Shope watershed exhibits a dendritic drainage pattern very clearly. The watershed's drainage pattern also suggested that the region lacked geological structural control over the drainage pattern growth. Shope watershed is categorized as a 5th order drainage watershed. The bifurcation ratio ranges between 1.11 and 2.28 (with an average of 1.72) between various stream orders. Low bifurcation values area is more prone to flooding. Mean drainage length and length ratio values indicating the present study area's undulating topography and steep slope. The Shope watershed's circularity and elongation ratio values are 0.7 and 0.63. Both values indicate that the present watershed is elongated and has steep slopes, and more prone to erosion and flooding. The higher drainage density values 6.75 km/km² indicating low infiltration and high runoff. The Shope watershed's relative relief value is 1757 m, and this high value indicating the study area's proneness to the flooding and soil erosion. The results of the current drainage morphometric analysis of the Shope watershed are essential for assessing and managing soil and water resources and selecting suitable sites for artificial recharge structures and soil conservation structures for future soil and water management in the present study area.

Keywords: Drainage morphometry, Remote sensing, GIS, Shope Watershed, Ethiopia.

1. Introduction

Analysis of morphometry of drainage is an important study in interpreting watershed landscapes, soil properties, hydrological and erosion factors assessment, and priorities for conserving water and managing natural resources [1, 2, 3,4,5]. Morphometry of the watershed explains its surficial features and offers data on the watershed's topography and the associated structures of the geological formations. Further, it helps where access to the area is limited, other data accessibility, and high soil variety [6, 7, 8]. As all geomorphic procedures and hydrological occur within the watershed, the characteristics morphometry of a watershed often reflects its formation and development. A Watershed is a geohydrological unit that drains through a drainage network system at a common point. Basic, areal, linear, and relief aspects of the basin are described in morphometry [9, 10,11]. It is a measure; the form and dimensions of the land shape are determined mathematically by the basin surface configuration.

Emerging developments in computer applications, explicitly mapping, have facilitated the quantitative approach to surface analysis and the framework for analyzing and manipulating quantitative morphometric data sets. Since remote sensing data makes it possible to analyze variations in drainage patterns accurately, land-use trends, and soil conditions, Geographic Information System (GIS) techniques also provide a robust environment for spatial information manipulation and analysis [12, 13, 14,15]. In Pageru River Basin, India [16] has used toposheets and Landsat satellite images to study the drainage characteristics to demarcate potential groundwater zones. In Wadi...
Umm Al Qufta, Jordan [17] has attempted to introduce water harvest techniques at the sub-basins level by analyzing drainage morphometry. The following researchers used drainage morphometric analysis for various purposes in Ethiopia. In the Gumara watershed, [18] made efforts to classify areas vulnerable to erosion using DEM data combined with the (GIS). GIS-assisted morphometric analysis has revealed its effects on the basic hydrological process in the Tikur Wuha river watershed, Ethiopia [19]. Quantitative estimation morphometric parameters of the Agula watershed, Ethiopia, using remote sensing, GIS, and statistical methods [11]. In Gidabo Basin, the Southern Rift Valley of Ethiopia [20] has carried out a morphometric analysis to prioritize and manage the basin. Prioritized sub-watersheds in the sediment erosion study of Welmal watershed, Ethiopia [21]. Flood susceptibility modeling has been carried out in Megech catchment, Northern Ethiopia [22]. Mapped the vulnerable soil erosion zones in the Kullo River basin, Rift valley, Ethiopia [23].

Only mentioned above, limited drainage morphometric research has been carried out in Ethiopia. Hence, the current study intended to examine the morphometry of Shope River watershed, Rift Valley, Ethiopia. The current research has attempted to evaluate the hydrological nature of the Shope watershed, and the same has been studied through morphometric characteristics using GIS tools and Remote Sensing (RS) data. The results of the current study will offer critical data for the management of surface and groundwater resources, and further, this research's results will be helpful in the identification of possible groundwater zones, flood risk analysis; prioritization of soil erosion vulnerable zones; and the selection of appropriate locations for constructing water harvesting structures.

1.1. Study area

The study Shope watershed is the current study area, and it is situated in the Ethiopian Rift Valley. It is located 400km from the south of Addis Ababa, Ethiopia's capital city. The current study area covers 127 km². It comes under the South National, Nationalities, People's Region (SNNPR). It locates between the latitudes 6° 15′ 00″ to 6° 25′ 00″ N and longitudes 37° 35′ 00″ to 37° 50′ 00″ E (Fig. 1). 1239 m and 2996 m are the minima and maximum altitudes, and slope ranges from 0° to 69°. The high altitude and steep slopes have been noticed in the north and northwestern part of the study area (Fig. 2). The average annual precipitation and temperature are 1250 mm and 23°C, respectively. The current study area is one of Ethiopia's bimodal areas. The primary rainy season is July-December, while the area's minor rainy season is March-May. The Shope river is one of Lake Abaya's major tributaries, and it is the second-largest lake in Ethiopia, situated in Rift Valley. The present study area mainly comprises the following rock types pyroclastic and amygdaloidal basaltic deposits, unwelded to welded rhyolitic ignimbrites, and minor pyroclastic deposits age of Eocene to Lower Oligocene and lower Oligocene massive basalt lava flows. And there are alluvial deposits around lake Abaya. The major land-use / land cover categories of the present study area are forests, shrubland, bushland, plantation, water bodies, and barren rock.

2. Materials and Methods

Demarcation of the watershed boundary is the primary step in the morphometric analysis. Ethiopia Mapping Agency (EMA) toposheet (scale 1:50,000) and number 0637 D1 have been used for the Shope watershed boundary. Satellite-borne ASTER (Advanced Spaceborne Thermal Emission and Reflection, with 30 m spatial resolution, January 2013, Sheet no. ASTGTMV003_N06E037) DEM (digital elevation model) has downloaded from https://search.earthdata.nasa.gov/. Using ArcMap 10.6.1 software and ArcHydro tools with ASTER DEM, the extraction of drainage networks has been done. The following standard DEM processing techniques such as fill sinks, flow direction, flow accumulation, stream order definition, stream segmentation, stream order calculation, and stream to line conversion) were adopted to extract the drainage network.

Further, Landsat -8 OLI (spatial resolution: 30 m, 27- December- 2020, Path 169, Row 056) has also been downloaded https://earthexplorer.usgs.gov/, and the same data have been employed to update the network of the drainage. The study of morphometric parameters has been classified into three groups: aerial, linear, and relief aspects, based on their spatial orientation. Table 1 shows the standard morphometric formula and their definitions, and the same has been adopted in the present research.
Fig. 1. Study area map

Fig. 2. Elevation and slope map
### Table 1. Morphometric parameters and their formula

| S.No | Morphometric parameters | Formula | References |
|------|-------------------------|---------|------------|
| 1    | Order of drainage (u)   | Hierarchical rank | [24] |
| 2    | Drainage number (N_i)   | Total number of drainage in a particular order | [25] |
| 3    | Length of the watershed L_w | L_w = 1.312 * Watershed area ^ 0.568 | [26] |
| 4    | Drainage length (L_u)   | GIS tool, length in Kms | [25] |
| 5    | Mean drainage length (L_m) | L_m = Overall drainage length of the particular order u / Overall drainage number of particular order u | [24] |
| 6    | Drainage length ratio (R_L) | R_L = Average drainage length of order u / average drainage length of its next lower order | [25] |
| 7    | Bifurcation ratio (R_b) | R_b = Overall number of drainage segments of the particular order u / amount of drainage segments of the following higher-order | [27] |
| 8    | Mean bifurcation ratio (R_bm) | R_bm = average of bifurcation ratios of all orders | [24] |
| 1    | Area of the watershed (A) | GIS tool | [27] |
| 2    | Perimeter of the watershed (P) | GIS tool | [27] |
| 3    | Form factor (R_f) | R_f = watershed area / square of the watershed length | [25] |
| 4    | Circulatory ratio R_c | R_c = 4 * 3.14 * watershed area / square of watershed perimeter | [28] |
| 5    | Elongation ratio R_e | R_e = 2 * (watershed area) / 3.14 / watershed length (km) | [27] |
| 6    | Drainage density D_d | D_d = Overall drainage length / watershed area | [29] |
| 7    | Drainage texture D_t | D_t = Overall drainage amount / watershed perimeter | [25] |
| 8    | Drainage frequency F_s | F_s = Overall drainage amount / watershed area | [29] |
| 1    | Maximum relief (Z)      | Watershed's maximum height | [24] |
| 2    | Minimum relief (z)      | Watershed's minimum height | [24] |
| 3    | Watershed relief (W_r)  | W_r = (Watershed's maximum height - Watershed's minimum height) | [24] |
| 4    | Relief ratio (R_r)      | R_r = Watershed relief / watershed length | [27] |

### 3. Results and Discussions

#### 3.1. Linear morphometric parameters

The linear morphometric features are primarily linked to its drainage network's characteristics and controlled by the watershed topography. The following linear morphometric attributes measured in this study contain the length of the drainages, average drainage length, length ratio, bifurcation ratio, and average bifurcation ratio. The following section discusses details about the mentioned-above morphometric parameters.

The primary phase in the morphometry drainage study is to determine the order of drainage (u). This research adopted the approach suggested by [24] because of its directness. The [24] technique designates the minor drainage parts as a 1st order; a 2nd drainage segment is produced if two 1st order drainages join; two 2nd drainage join, 3rd order category drainage is constructed; and so forth. The present study area, Shope watershed, is categorized as a 5th order drainage watershed. Fig. 2 shows the Shope watershed's drainage network and its order category. In the 1st order, the maximum amount of drainages has been found, and the drainage amount is decreasing when the drainage order is increasing. The number of drainages from 1st order to 5th order is 339, 149, 81, 49, and 44, respectively, and the total number of drainages is 662. And the length of drainages from 1st order to 5th order is 153, 65, 28, 14, and 12, respectively, and the total length of drainages is 272 (Table 2). The Shope watershed exhibits a dendritic drainage pattern very clearly. The watershed's drainage pattern also suggested that the region lacked geological structural control over the drainage pattern growth—further, the drainage pattern indicated homogenous hard rock in the current research area.

The bifurcation ratio is the primary parameter connecting the watershed's hydrological processes [30]. The bifurcation ratio value less than 3.0 suggests a lack of structural control and that more than 5.0 demonstrates structural control over the distribution of a drainage pattern [31]. In the current research area, the bifurcation ratio
ranges between 1.11 and 2.28 (with an average of 1.72) between various stream orders (Table 2). According to [32], the low bifurcation ratio result will be greater chances of flooding. It can also be inferred that, for drainage orders 3 and 4, which have a low bifurcation ratio of 1.65 and 1.11, water appears to concentrate rather than spreading. In comparison, the probability of flooding is poor for drainage orders 1 and 2, with higher bifurcation ratios of 2.28 and 1.84.

Mean drainage length directly relates to the watershed's topography [33]. And its values vary from 0.27 to 0.45 in the present study area (table 2). 0.42 and 0.86 are the least and highest drainage length ratio standards of the present study area (table 2). Undulating topography and lithological variations of the Shope watershed are the leading causes for the drainage length ratio and mean drainage length ratio variations. Essential observation reveals an increased tendency of the length ratio of drainages in the present research area from the lower to the higher-order; this suggests a mature topographical state.

| Drainage order | Number of drainages | Drainage length (L) (km) | Bifurcation ratio (Rb), N_b/(N_b+1) | Mean drainage length, (km), L = L/N_b | Length ratio of the drainages |
|----------------|---------------------|--------------------------|-------------------------------------|--------------------------------------|-----------------------------|
| 1st            | 339                 | 153                      | 2.28                                | 0.45                                 |                             |
| 2nd            | 149                 | 65                       | 1.84                                | 0.44                                 | 0.42                        |
| 3rd            | 81                  | 28                       | 1.65                                | 0.35                                 | 0.43                        |
| 4th            | 49                  | 14                       | 1.11                                | 0.29                                 | 0.50                        |
| 5th            | 44                  | 12                       |                                     | 0.27                                 | 0.86                        |
| Total          | 662                 | 272                      | Mean= 1.72                          | Mean=0.55                            |                             |

3.2. Areal morphometric parameters

The Shope watershed area, perimeter, and length are 127 km², 48 km, and 20 km, respectively. According to [34], for the precisely circular watershed, the form factor values always will be more than 0.78, and the less form factor, the elongated the watershed. Smaller form factor values suggest a longer length, more elongated basin with lower peak flow. If the form factor value high, the basin shape is more circular with the flash flood potential due to a shorter period of higher peak flow. The present study area's form factor value is 0.32. The Shope watershed's circularity and elongation ratio values are 0.7 and 0.63, respectively. Watershed with an elongation ratio greater than 0.9 is circular, and watershed with an elongation ratio of less than 0.7 are elongated [35]. Typically elongation ratio values ranging from 0.6 to 1.0. The 0.7 is the circularity, and 0.63 is the elongation ratio values for the Shope river watershed, and both values indicate that the present watershed is elongated and has steep slopes. Lower circulatory values reflect the youngest stage in watershed growth, where the flow of surface water takes relatively more little time to reach the outlet. The present study area shows a moderate circulatory value of 0.7, and it suggests a mature topography.

The high drainage density value suggests that the watershed is highly dissected with a relatively quick hydrological reaction for precipitation. In contrast, the low drainage density represents a poorly drained watershed [36]. There will be less infiltration, increased runoff, and the presence of erodable surface materials in areas of high drainage density [37]. The greater the drainage density, the larger the runoff volume and the greater the channel's degree of erosion for specified precipitation [38]. According to [39] drainage density classification, the current research area comes under the coarse drainage density. 6.75 km/km² is the drainage density value of the present study area (Figure. 3).

Drainage density and drainage frequency have a direct association; the lower the drainage frequency values, the lower the drainage density, the lower the runoff value, and the less likely the flood will occur [40]. 5.21 km−² is the drainage frequency value of the present study (Table 2). Drainage frequency indicates that the rise in the number of drainage frequencies is related to drainage density. It has generally regulated by the watershed lithology. The precipitation amount, vegetation density, soil types, infiltration potential, landscapes, and topography of the area influence drainage texture [25, 39]. According to (Smith 1950), drainage texture is very coarse if the value is < 2, 2 to 4 is coarse drainage texture, 4 to 6 is medium texture, 6 to 8 is fine, and the value > 8 is then the texture is called very fine. The current research watershed's drainage texture is 14 km−¹ (Table 2), and the present study area comes under the very fine drainage texture category. And the same is indicating low water infiltration capacity and more chances for flooding and soil erosion.
### Table 3. Morphometric analysis results

| S.No | Morphometric parameter      | Results        |
|------|-----------------------------|----------------|
| 1    | Watershed area (A)          | 127 km²        |
| 2    | Watershed perimeter (P)     | 48 km          |
| 3    | Watershed length (L)        | 20 km          |
| 4    | Form factor Rf              | 0.32           |
| 5    | Circulatory ratio Rc        | 0.70           |
| 6    | Elongation ratio Re         | 0.63           |
| 7    | Drainage density Dd         | 6.75 km/km²    |
| 8    | Drainage frequency Fs       | 5.21 km⁻¹      |
| 9    | Drainage texture Dd         | 14 km⁻¹        |
| 10   | Maximum relief (Z)          | 2996 m         |
| 11   | Minimum relief (z)          | 1239 m         |
| 12   | Watershed (relative) relief (H) | 1757 m   |
| 13   | Relief ratio (Rr)           | 0.08           |

#### 3.3. Relief morphometric parameters

The minimum and maximum heights of the present study area are 1239 m and 2996 m, respectively. The erosion phase of a river system is indicated by basin relief and varies according to the lithology, structures, landforms, and characteristics of the particular area’s drainage. The Shope watershed’s relative relief value is 1757 m, and this high value indicating the study area’s proneness to the flooding and soil erosion. As per [41], higher relief ratio values suggested a high flow rate and increased susceptibility to soil erosion due to increased sediment loss. 0.08 is the present study area’s relief ratio value, and this higher value indicating the high erosion proneness of the Shope watershed.
4. Conclusions

The advancement of remote sensing data and GIS tools made watershed studies more straightforward than ever before. Using DEM, it is easy to perform drainage morphometric studies with high accuracy for a watershed covering a large area. These modern technologies have replaced the traditional methods of morphometric analysis. Hydrological perspectives of the Shope watershed's morphometric parameters, Rift Valley, Ethiopia, have been evaluated in this current study. The result showed spatial variability and association between various morphometric attributes. The number of drainages from 1st order to 5th order is 339, 149, 81, 49, and 44, respectively, and the total number of drainages is 662. And the length of drainages from 1st order to 5th order is 153, 65, 28, 14, and 12, respectively, and the total length of drainages is 272. The dendric drainage pattern of the current study area indicating the presence of hard rock. The form factor value is 0.32, indicating that the watershed is less prone to flood and soil erosion. The drainage orders 3 and 4, which have a low bifurcation ratio of 1.65 and 1.11, water appears to concentrate rather than spreading.

In comparison, the probability of flooding is poor for drainage orders 1 and 2, with higher bifurcation ratios of 2.28 and 1.84. Drainage length ratio indicating the presence of undulating topography and steep slopes in the Shope watershed. The current study area shows coarse drainage density, and the value is 2.14 km/km2. The Shope watershed's relative relief value is 1757 m, and this high value indicating the study area's proneness to flooding and soil erosion. The present study's overall analysis indicates that the Shope watershed is highly prone to flooding and soil erosion. The results of the current study will offer critical data for the management of surface and groundwater resources, and further, this research's results will be helpful in the identification of possible groundwater zones, flood risk analysis; prioritization of soil erosion vulnerable zones; and the selection of appropriate locations for constructing water harvesting structures. Further, this research provides critical data to the researchers in the same field, policy-makers, and administrators to carry out integrated design and execution of water and soil management programs in the current study area, Shope watershed, Ethiopia. It also benefits researchers in other fields who deal with similar research topics.

5. References

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