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COMPARATIVE GEOMORPHOMETRIC ANALYSIS OF DRAINAGE BASIN USING AW3D30 MODEL IN ARCGIS AND QGIS ENVIRONMENT: CASE STUDY OF THE IBAR RIVER DRAINAGE BASIN, MONTENEGRO

SUMMARY

Geomorphometric analysis provides crucial insights into the hydrological characteristics by delineating the land-surface features of a drainage basin. The study focused on analyzing the geomorphometric parameters of the Montenegrin segment of the Ibar River drainage basin using the ALOS Global Digital Surface Model 30 m (AW3D30). Geomorphometric parameters, covering linear and areal parameters, were computed using standard mathematical formulas in LibreOffice Calc software and hydrology tools in commercial GIS software ArcGIS, as well as open-source software QGIS with SAGA GIS modules. Results reveal a dendritic pattern in the stream network, with an inverse relationship between stream length and order, and an elevated bifurcation ratio indicating heightened vulnerability to flooding, influenced by geological, geomorphological, and climatic factors. Furthermore, examination of diverse areal morphometric parameters, such as drainage density, stream frequency, form factor, circularity ratio, and elongation ratio, unveils the hydrological dynamics of the Ibar basin. This characterization illustrates the region as possessing high permeability and dense vegetation cover, suggesting vulnerability to erosion and consequent effects on water and sediment discharge. Additionally, this study underscores the significance of user-defined parameters in geomorphometric modeling, particularly in selecting algorithms within analysis software, which significantly impact drainage basin parameters.

Keywords: drainage basin, Montenegro, geomorphometry, DEM, AW3D30.

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INTRODUCTION

Geomorphometry is a scientific discipline that deals with the quantitative analysis of the earth's land-surface (Pike *et al.*, 2009). However, drainage basins occupy a large part of the Earth, so the analysis has become dominant in process-oriented implementations of general geomorphometry (Rodríguez-Iturbe & Rinaldo, 1997, Shit *et al.*, 2022).

Analyzing the geomorphometrics of a drainage basin proves valuable in establishing effective systems for land and water management and protection. It plays a crucial role in assessing natural disaster risks such as floods, erosion, wildfires and landslides (Lukić *et al.*, 2018; Spalević *et al.*, 2020; Durlević *et al.*, 2019, 2021, Vujačić *et al.*, 2023, Nikolić *et al.*, 2023). Additionally, it aids in identifying optimal locations for constructing water and other infrastructure facilities (Valjarević *et al.*, 2020, 2023).

Analyses of drainage basin using manual methods from topographic maps in quantitative analyses were initiated by Horton (1932) and Strahler (1952). Traditional approaches have been replaced by computer-graphic methods such as "Surface and distance measuring," "River basins," "Intensity of Erosion and Outflow model," and "Web-based Intensity of Erosion and Outflow model," as indicated in the studies conducted by Spalević *et al.* (1999, 2000, 2011, 2017, 2019).

Over three decades ago, the modern method for analyzing terrain geomorphometric characteristics began to emphasize the use of Digital Elevation Models (DEMs) and the progress of Geographic Information Systems (GIS). Among commercial software options, ArcGIS, developed by Environmental Systems Research Institute (ESRI), is the predominant choice for geomorphometric analysis in GIS environment (Bogale, 2021). Open-source software and free geospatial data are becoming very popular in the field of GIS and remote sensing. Namely, they give users the possibility and rights to use, study, change and distribute them. Quantum GIS (QGIS) is the most popular free open-source software in the world. It belongs to the Open-Source Geospatial Foundation (OSGeo). Among the main advantages of QGIS are the possibility of embedding tools for spatial analysis through plugins, and the user community of developers and users is constantly growing (Graser, 2016, Šiljeg, 2018).

DEM is a digital statistical terrain model with a series of known x, y and z coordinates within an arbitrarily chosen system (Miller & Laflamme, 1958). Data sources for generating DEM have been developing rapidly. From ground surveys and existing topographic maps to passive remote sensing methods and active sensors such as LiDAR and RADAR (Marić *et al.*, 2021; Šiljeg *et al.*, 2023). During the last two decades, several open-access global DEMs models with moderate resolution, including TanDEM-X, SRTM, NASADEM ASTER, AW3D30, MERIT, and EU-DEM for Europe, have been released utilizing RADAR sensors. This has notably enhanced geomorphometric analyses (Uuemaa, *et al.*, 2020; Nikolić *et al., 2024*).

Manufacturers and users of DEMs typically overlook the need to verify their accuracy, disregarding the impact of user-defined parameters and demonstrating inadequate awareness of their significance (Wechsler, 2003, Šiljeg, 2018).

Numerous researchers have conducted geomorphometric analysis of drainage basins, utilizing open-source DEM data and GIS across various geographical regions. This combination has proven to be a valuable instrument with distinct advantages and disadvantages in producing quantitative data for characterizing drainage basins (Ascione *et al*., 2008; Hlaing *et al*., 2008; Javed *et al*., 2009; Rai *et al*., 2018; Asfaw & Workineh, 2019; Różycka & Migoń, 2021; Bogale, 2021; Derakhshani *et al*., 2023)

Thus, the objective of this study is to examine the geomorphometric attributes of the Ibar river basin in Montenegro utilizing the AW3D30 model via SAGA GIS modules within QGIS software, alongside hydrological analysis tools in ArcGIS software.

MATERIAL AND METHODS

Study Area

The Ibar River begins in northeastern Montenegro at Mount Hajla, then travels through southwestern Serbia and the northern part of Kosovo, before finally joining the West Morava River near Kraljevo in central Serbia. The Ibar drainage basin covers 8,059 km², with 413 km² situated within Montenegro's territory (Figure 1).

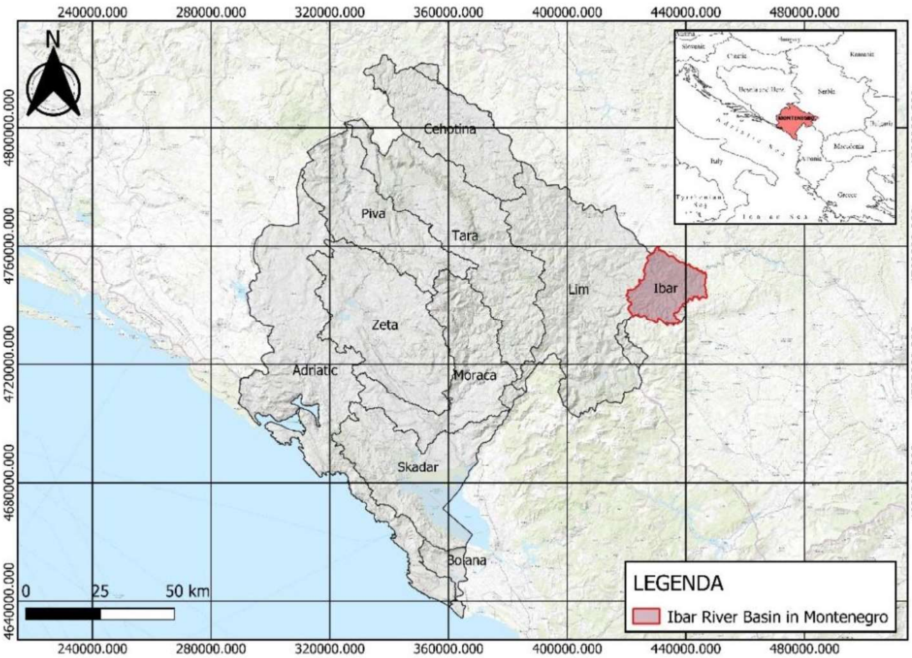

Figure 1: Location map of the Ibar River Basin in Montenegro

The area in Montenegro encompasses hilly-mountainous terrains and upper valleys along the Ibar River, with elevations ranging from 784 m asl in the Draga region to 2,382 m asl at the summit of Rusolija Mountain (Figure 2a). The upper reaches of the Ibra River are located in Montenegro, specifically in the municipality of Rožaje. This region is situated in the Inner Dinarides and falls under the "Durmitor" tectonic zone (Bešić, 1983). Interpreter of the Geological Map of Montenegro (1:200,000 scale) indicate a prevalence of Mesozoic limestones and dolomites (T, K) in terms of geological composition. Additionally, the area features diabase-hornblende formations (J2+3), Neogene deposits comprising clay, marl, sand, and coal, as well as glacial and glacial-fluvial deposits (Mirković *et al*., 1985). The landscape is characterized by numerous surface and subsurface karst landforms. The Ibar River, along with its tributaries, serves as the primary hydrological network in this region, representing the upper course of the river Ibar. Forests represent the pivotal form of plant communities and vegetation cover in the area (Figure 2b).

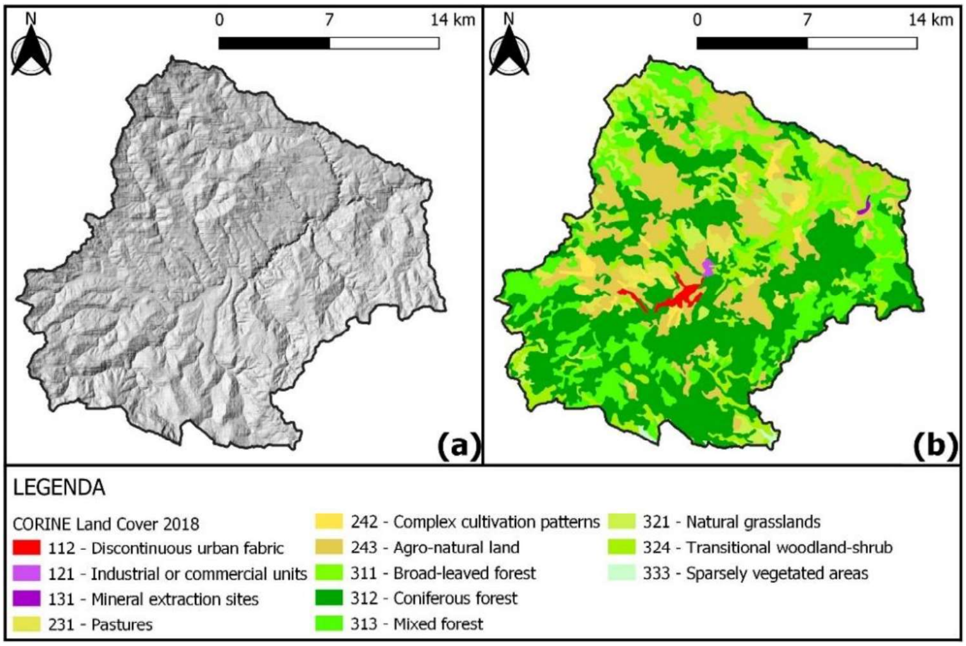

Figure 2: (a) Hillshade of the Ibar River Basin in Montenegro using the EU-DEM model (https://www.copernicus.eu/en/use-cases/eu-dem); (b) Land cover of the Ibar River Basin in Montenegro using the Corine Land Cover 2018 (https://land.copernicus.eu/en/products/corine-land-cover)

According to the Köppen classification, the area is classified as cold temperate D climate (Burić *et al*., 2012). This climate is characterized by cold winters and mild summers, with an average annual air temperature of 6.3˚C and an annual precipitation of 920 mm. It falls under the pluvio-nival regime, specifically the moderate-Mediterranean subtype as identified by Dukić & Gavrilović (2006).

The perennial flow of HS Rožaje is documented at 2.51 m^3/s for the period 1968-2003 (https://www.meteo.co.me/page.php?keyword=reports). Unfortunately, reliable data for HS Bać is lacking due to interruptions in the station's operation.

Data Acquisition

The ALOSWorld3D 30 m Digital Elevation Model (AW3D30; version 3.1) was created utilizing a vast collection of images captured by the panchromatic optical sensor (PRISM) aboard the Advanced Land Observing Satellite (ALOS), operated by the Japan Aerospace Exploration Agency (JAXA). These stereoscopic images were obtained in nadir, backward, and forward views with a spatial resolution of 2.5 m. Initially introduced in 2016, AW3D30 has undergone subsequent updates to enhance absolute/relative height accuracies through additional calibrations and void filling. The most recent version, utilized in this study, was released in April 2020 (Takaku, *et al.*, 2020). This aligns with previous findings indicating that the vertical Root Mean Square Error (RMSE) remained below 5 m in flat areas, while it increased to 12 or 14 m in regions with more complex terrain. The AW3D30 model exhibited the highest accuracy and the least uncertainty compared to other global DEM models such as ASTER, SRTM and NASADEM (Uuemaa, *et al.*, 2020). The data was obtained by downloading from the JAXA Geoportal, which provides geospatial data collected through satellites and other space missions (https://www.eorc.jaxa.jp/ALOS/en/index_e.htm).

Methodology in QGIS

The data were acquired at a resolution of 30 meters in the WGS 84 Geographic Coordinate System and then transformed into the Mercator Universal Transverse Projection (UTM 34N) Projected Coordinate System, utilizing the WGS 84 rotating ellipsoid (EPSG: 32634). For the purposes of geomorphometric analysis, the border of Ibar River drainage basin is defined in the administrative borders of Montenegro. Geomorphometric analysis is based on complex algorithms and other features that can be done with SAGA GIS modules for Terrain Analysis in QGIS 3.6.3. software (https://www.qgis.org/en/site/forusers/download.html). In the beginning, Clip tool was used to define AW3D30 model within the borders of Montenegro. Fill Sink tool was used to fill sink on DEM. Basin boundary, stream orders, number of stream segments, and lengths were obtained using Channel Network and Drainage Basins tool (Threshold: 5). Area, perimeter and length were calculated using formulas in Field Calculator. While the other linear and areal parameters were obtained based on formulas (Table 1) in software LibreOffice Calc 7.3 (https://www.libreoffice.org/download/download-libreoffice/).

Methodology in ArcGIS

The same border of the Ibar river basin in Montenegro and reprojected DEM data as in QGIS were used. The complete GIS methodology was carried out using ArcGIS 10.4.1 (https://desktop.arcgis.com/en/quick-start-guides/10.4/arcgis-desktop-quick-start-guide.htm) software, making use of the Hydrology toolset found within the Spatial Analyst toolbox module in ArcMap. The Fill tool is employed to fill sink areas. Subsequently, the Flow Direction and Flow Accumulation tools come into play. Following this, a threshold value of 350 is set for the flow accumulation model. Once the Flow Direction model is obtained, a drainage basin is delineated and selected using tool Basin. The Strahler classification is then conducted using the Stream Order tool based on Flow direction model with threshold value. Following classification, the resultant raster models are converted into vector formats for final analysis and estimation of geomorphometric parameters. Area, perimeter, and length are determined using the Calculate Geometry tool. While the other linear and areal parameters were obtained based on formulas (Table 1) in software LibreOffice Calc 7.3 (https://www.libreoffice.org/download/download-libreoffice/).

Table 1: Analyzed geomorphometric parameters in GIS and formulas

S. no	Parameter	GIS Analaysis/Formula	Unit	Reference
1.	Stream order (So)	GIS analysis	km	Strahler (1952)
2.	Stream number (Nu)	GIS analysis		Strahler (1952)
3.	Stream length (Lu)	GIS analysis	km	Horton (1945)
4.	Basin perimeter (P)	GIS analysis	km	Horton (1945)
5.	Basin length (Lb)	GIS analysis	km	Horton (1945)
6.	Basin area (A)	GIS analysis	km^2	Horton (1945)
7.	Mean stream length (Msl)	$L_{sm} = \frac{L_u}{N_u}$	km	Horton (1945)
8.	Bifurcation ratio (Rb)	$R_b = \frac{N_u}{N_{u+1}}$		Schumm (1956)
9.	Mean bifurcation ratio (Mrb*)*	$R_{bm} = \frac{\sum R_b}{n \times u}$		Schumm (1956)
10.	Drainage density (Dd)	$D_D = \frac{\sum L_u}{A}$	km/km^2	Horton (1945)
11.	Stream frequency (Fs)	$F_s = \frac{\sum Nu}{A}$	km/km^2	Horton (1945)
13.	Form factor (Rf)	$R_f = \frac{A}{Lb^2}$		Horton (1945)
14.	Circulatory ratio (Rc)	$R_c = \frac{4\pi A}{P^2}$		Miller (1953)
15.	Elongation ratio (Re)	$R_e = \frac{2\sqrt{\frac{A}{\pi}}}{Lb}$		Schumn (1956)

RESULTS AND DISCUSSION

Linear parameters

Table 2 contains the analysis outcomes for linear parameters processed using QGIS software, while Table 3 presents the analysis results processed through ArcGIS software. Figure 3 illustrates the cartographic depiction of linear parameters based on Strahler's classification.

Table 2: Results of analysis of linear parameters in QGIS environment

Stream order	**No. of segments**	**Stream length**	**Mean Stream length**
QGIS			
1st order	377	272.57	0.72
2nd order	72	134.70	1.87
3rd order	17	69.22	4.07
4th order	6	34.54	5.76
5th order	1	23.34	23.34
Total	473	534.37	
Bifurcation ratio			
1st/2nd	2nd/3rd	3rd/4th	4th/5th
5.24	4.24	2.83	6.00
Mean	4.58		

Table 3: Results of analysis of linear parameters in ArcGIS environment

Stream order	**No. of segments**	**Stream length**	**Mean Stream length**
ArcGIS			
1st order	509	309.60	0.61
2nd order	98	144.65	1.48
3rd order	23	79.26	3.45
4th order	6	43.71	7.29
5th order	1	23.25	23.25
Total	704	600.47	
Bifurcation ratio			
1st/2nd	2nd/3rd	3rd/4th	4th/5th
5.19	4.26	3.83	6.00
Mean	4.82		

Stream order, a fundamental parameter in hydrological analysis, refers to the hierarchical classification of stream segments. Originally pioneered by Horton (1945), stream sorting techniques were later refined by Strahler (1952). The arrangement of the stream network in the Montenegrin section of the Ibar River indicates a dendritic pattern typical of terrain where channels align with the slope. Analysis reveals a reduction in the number of segments with increasing stream order, influenced significantly by geological factors and other physical-geographical conditions (Dukić & Gavrilović, 2006).

Stream length is also one of the most potential parameters used to understand hydrological characteristics. The mean length of the stream is a parameter from the group of derived linear parameters and shows the characteristic size of the component basin. In this study, stream length shows an inverse relationship with stream order. The higher stream order, the lower is stream length. Streams of lower order and shorter stream lengths are located on terrains with a steep slope and a fine texture of the basin. This indicates the geological consistency of the basin, as well as the strong control of drainage network characteristics in the moving water.

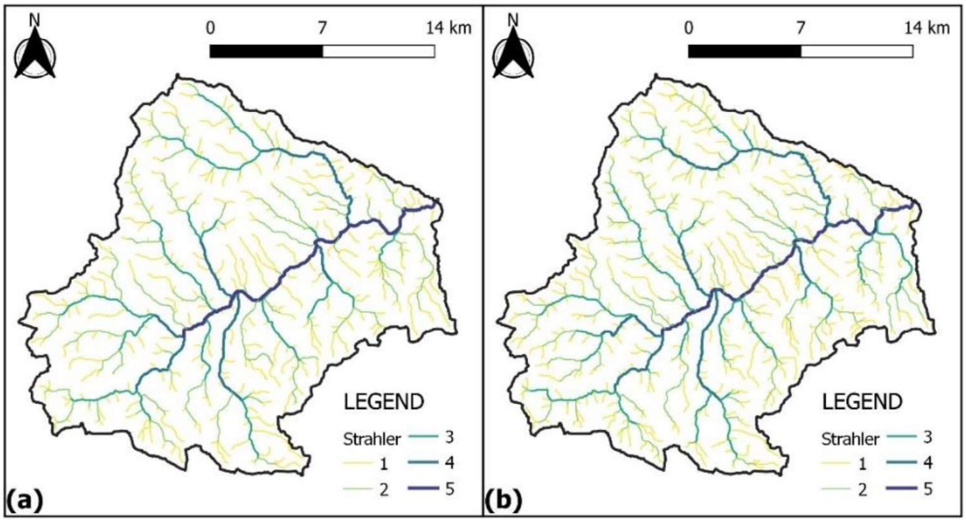

Figure 5: (a) Map of linear parameters in QGIS (b) Map of linear parameters in ArcGIS

Bifurcation ratio, as defined by Schumm (1956), represents the relationship between the quantity of channels within a specific order and the quantity of channels in the subsequent higher order. In the context of the study, the drainage basin exhibits heightened susceptibility to flooding, attributed to its elevated bifurcation ratio. This suggests that the basin is impacted by both geology and geomorphology, and when coupled with climatic conditions, it results in the occurrence of floods.

Areal parameters

Table 4 presents areal parameters that have been analyzed using both QGIS and ArcGIS software. Drainage density is the ratio of total stream length of all the orders per unit basin area (Horton 1945). The density of drainage is influenced by geology, geomorphology, climate, vegetation and soil characteristics. Moreover, this parameter serves as an indicator of soil infiltration capacity (Radulović, 2000) and contributes to the discharge of water and sediment from the drainage basin, as well as indicating susceptibility to erosion (Spalević *et al*, 2020; Vujačić *et al*., 2023). The drainage density indicates that the basin is highly permeable and has a fairly well-developed vegetation cover. The stream frequency of a basin is characterized as the quantity of streams per unit area (Horton, 1945). Previous studies show that current frequency is positively related to drainage density.

Table 4: Areal parameters of the Ibar River Basin in Montenegro

Areal Parameters	QGIS	ArcGIS
Basin perimeter (P)	117.60 km	116.35 km
Basin length (Lb)	28.29 km	27.99 km
Basin area (A)	404.77 km^2	403.90 km^2
Drainage density (Dd)	1.32 km/km^2	1.40 km/km^2
Stream frequency (Fs)	0.93 km/km^2	1.74 km/km^2
Form factor (Rf)	0.51	0.52
Circulatory ratio (Rc)	0.37	0.37
Elongation ratio (Re)	0.80	0.81

Form factor is a dimensionless ratio of the area of a drainage basin to the square of its maximum length (Horton, 1945). The form factor serves as an indicator for the formation and movement of floods, the extent of erosion, and the transport capacities of sediment loads within a river basin. The form factor ratio in this area indicates a lower form factor value. Consequently, the basin is characterized by a lower peak flow and an extended duration, attributed to its elongated shape.

As per Miller (1953), the circularity ratio is defined as the ratio of the basin area to the area of a circle with an equivalent perimeter to that of the basin. For the Ibar basin, this parameter indicates similar characteristics to other areal parameters (Table 2).

Elongation ratio is described as the proportion of the diameter of a circle with an equivalent area to that of the basin, relative to the maximum length of the basin (Schumm 1956). According to the results in Table 4, the study area is classified as an oval type characterized by a steep slope and high altitudes in combination with other physical-geographical factors.

ArcGIS vs. QGIS: A Comparison

Table 5 shows the percentage deviation between the linear parameters generated in QGIS and ArcGIS, while Table 6 shows the percentage differences for the areal parameters. Tools in the open-source software QGIS, incorporating SAGA GIS modules, and the commercial software ArcGIS utilize different algorithms for deriving geomorphometric parameters of drainage basins. QGIS offers users a choice among multiple algorithms for Fill Sinks, such as Wang & Liu, QM of ESP, and Planchon/Darboux, 2001, whereas ArcGIS provides only one method. Once the Fill Sinks algorithm is applied in QGIS, the entire process of deriving the modelling of streams and basins is automated through the Channel Network and Drainage Basins algorithm, whereas in ArcGIS, each step needs to be executed separately. Although both software utilize the 8D (Eight Direction) method within the Flow Direction algorithms, crucial modeling algorithms such as

Fill Sink, Flow Accumulation and Basin exhibit slight variations. Furthermore, in QGIS, algorithm Channel Network and Drainage Basins automatically sets the threshold for the flow accumulation algorithm, offering the option to define the threshold as needed. In contrast, in ArcGIS, this step must be done manually. The research results confirmed the significance of this user-defined parameter, regulating stream order, number of segments, and length, emphasizing notable differences between the linear parameters obtained in QGIS and ArcGIS. Regarding the areal parameters, the disparities between these two software environments are relatively minor.

Table 5: Comparison of linear parameters in ArcGIS and QGIS

Stream order	**No. of segments**	**Stream length**	**Mean Stream length**
QGIS vs ArcGIS			
1st order	-25.93%	-11.96%	18.03%
2nd order	-26.53%	-6.88%	26.35%
3rd order	-26.09%	-12.67%	17.97%
4th order	0.00%	-20.98%	-20.99%
5th order	0.00%	0.39%	0.39%
Total	-32.81%	-11.01%	
Bifurcation ratio			
1st/2nd	2nd/3rd	3rd/4th	4th/5th
0.96%	-0.47%	-26.11%	0.00%
Mean	-4.98%		

Table 6: Comparison of areal parameters in ArcGIS and QGIS

Areal Parameters	**Difference**
Basin perimeter (P)	1.07%
Basin length (Lb)	1.07%
Basin area (A)	0.22%
Drainage density (Dd)	-5.71%
Stream frequency (Fs)	-46.55%
Form factor (Rf)	-1.92%
Circulatory ratio (Rc)	0.00%
Elongation ratio (Re)	-1.23%

Constraints in Establishing User-Defined Parameters

Throughout the process of computing geomorphometric parameters for the drainage basin, the user identifies several factors that impact the output result variably. This collection of numerous parameters, crucial for the accuracy of the output result, which the user can adjust, is referred to as user-defined parameters (Barada, 2017).

One of the primary and crucial user-defined parameters is selecting the appropriate DEM. Selecting the appropriate DEM can improve the reliability and accuracy of morphometric analyzes for the drainage basin. The accuracy of both horizontal and vertical data of the DEM holds significant importance in geomorphometric analyses of drainage basins. Generally, according to previous studies, it can be inferred that higher-resolution DEMs offer enhanced accuracy (Shekar & Mathew, 2023). Even with similar resolutions, DEMs datasets like SRTM, NASADEM, ASTER, AW3D30, MERIT, and EU-DEM might yield varied results when generating geomorphometric parameters for drainage basins. The AW3D30 model showed the highest accuracy and lowest uncertainty compared to other global DEM models in previous studies (Uuemaa, *et al*., 2020; Shekar & Mathew, 2023).

Another significant user-defined parameter in geomorphometric modeling of drainage basins involves selecting algorithms within geomorphometric analysis software. As outlined in the implementation study, various tools within both QGIS and ArcGIS software yield disparate outcomes for drainage basin parameters. Areal parameters exhibit significantly lower deviations compared to linear parameters, which are contingent on user-defined factors like the threshold for flow accumulation.

In future studies on this subject, it would be beneficial to conduct a geomorphometric analysis of the drainage basin comparing global DEMs data with supplementary relevant sources such as topographic maps, orthophoto maps, or LIDAR technology. Exploring the impact of user-defined parameters when utilizing DEMs of varying resolution and quality, and their effects on the output results, would be a valuable endeavor.

CONCLUSIONS

Examining stream order, stream length, and bifurcation ratio offers valuable insights into the hydrological and geomorphological features of the investigated drainage basin. These parameters illustrate the intricate relationship among physical-geographical variables, which collectively shape the behavior of the drainage network and its vulnerability to flooding. The analysis of drainage density, stream frequency, form factor, circularity ratio, and elongation ratio provides valuable insights into the hydrological and geomorphological characteristics of the studied basin, reflecting its permeability, vegetation cover, flood potential, and erosion susceptibility. This approach contributes to gaining insights into river basin hydrology, facilitating the prioritization of river basin, executing efficient soil and water conservation initiatives, overseeing natural resource management, and conducting analyses for hydrology disasters. The accuracy and reliability of geomorphometric analyses for drainage basins are notably impacted by the selection of suitable user-defined parameters, especially concerning the choice of DEM and algorithms within geomorphometric analysis software.

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