GIS-Based Morphometric terrain analysis for watershed characterization: case study of Ain Leuh watershed, Morocco

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Abstract

The Ain Leuh watershed occupies a strategic hydrogeographic position that favors surface water circulation and accumulation. Considering the persistent water stress affecting Morocco, a detailed characterization of this watershed is essential to support sustainable water resource management and to mitigate geohazards such as flooding and soil erosion. This study aims to characterize the Ain Leuh watershed using morphometric analysis based on the FABDEM (Forest and Buildings removed Copernicus DEM). Covering an area of 143.58 km², the watershed is geomorphologically young, well-drained, and characterized by significant surface runoff. Surface and linear morphometric include drainage density (2.96 km/km²), stream frequency (7.41 km^{-2}), drainage texture (13.45 km^{-1}), elongation ratio (0.40), circularity ratio (0.29), and form factor (0.10). The values reflect a long, narrow basin with high runoff potential and limited infiltration capacity. Hypsometric contour mapping at 200-meter intervals highlighted a dominant NE–SW alignment, indicative of the region's terraced geomorphology. Elevation data pointed to higher altitudes in the southeastern part of the basin and lower elevations in the northwest, while slope analysis indicated that low to moderate gradients are more dominant. These results were complemented by the relief parameters: the relief ratio (Rh), dissection index (Dis), and roughness number (Rn). The relief ratio (0.03) underscores the predominance of broad, low-relief areas such as floodplains and wide valleys. The dissection index (0.58) confirms considerable valley incision, implying a heightened risk of both fluvial and slope-driven erosion, while the roughness number (3.43) combines indicators of steep terrain and dense drainage to describe a rugged watershed with a significant susceptibility to surface water dynamics and erosion. The morphometric analysis identifies the Ain Leuh watershed as a young, elongated basin with efficient drainage, high surface runoff, and moderate to steep slopes. While its flood potential appears limited due to its geomorphological structure, the basin exhibits significant vulnerability to erosion. These findings provide valuable insights for regional water management strategies and underscore the need for erosion control measures to enhance the watershed's resilience.

1. Introduction

The surface that is drained by a water course and its affluents at the end of the segment is known as the watershed (Laborde, 2009). It is completely defined by its outflow, which allows us to determine the beginning and ending points of the line of sharing of the waters that delineate it. The functioning of the watershed is influenced by both climatic circumstances and physical characteristics that affect the volume and temporal distribution of eddies (Roche, 1963). Therefore, the morphology (shape, relief, drainage network), soil type, and vegetation cover can all be used to describe the watershed.

The landscape and physiography descriptions were largely qualitative before Horton's (1945) work. The hydrographic networks and corresponding watersheds were described as young, old, well- or poorly drained, without addressing the issues of their sources, mechanisms, or numbers. It was not until 1945, based on morphometric parameters, that Horton quantified hydrographic networks. The interpretation of geology and hydrology suggests that geological structures, bedrock topography, thickness of unconsolidated deposits, lithology, and basin slope are the main geomorphological and geological factors that can influence the evolution of the hydrographic network (Cheng et al., 2001).

Currently, the use of Digital Elevation Models (DEM) makes it easy to characterize watersheds. Indeed, the morphometric characterization of a watershed and its hydrographic network can be carried out according to three aspects: a linear aspect, a relief aspect and a surface aspect.

The objective of the present research is to use Geographic Information System (GIS) techniques to extract the morphometric parameters from the FABDEM DEM in order to characterize Ain Leuh.

2. Study Site

The Ain Leuh watershed, the subject of the study, is situated at the convergence of central Morocco and the Middle Atlas Mountains, about 40 km SW of Azrou, at the level of the municipalities of Aïn Leuh and Had Oued Ifrane (Figure 1). It is bounded by the Lambert coordinates 487470 < X < 510934 m and 294000 < Y <309462 m. Oued Aïn Leuh crosses this watershed going from east to west. The range of altitudes is 840 m to 1991 m.

The study area straddles two different structural units: the eastern part of Hercynian Central Morocco; consisting of metamorphosed and deformed Paleozoic terrains (Termier 1936; Bouabdelli 1989. Habibi 1989). The western part of the Middle Atlas Causse which is an intra-continental mountain chain-oriented NE-SO (Michard, 1976; Fedan, 1988); consists of limestone-dolomite from the Lower Jurassic (Colo 1961; Martin 1981; El Arabi et al. 1986; Charrière 1990).

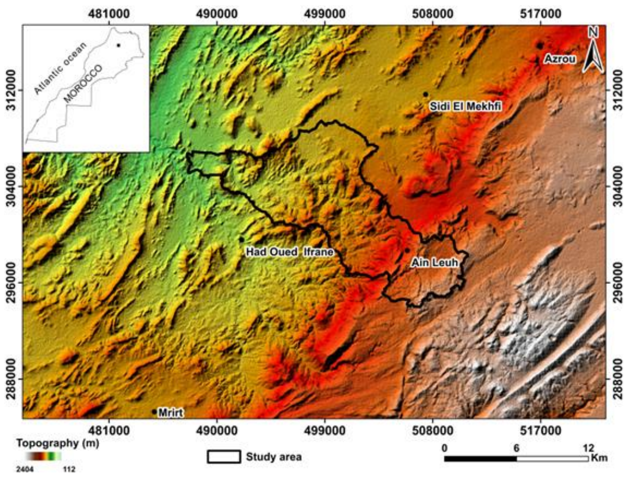

Figure 1. Location and topographic overview of the study area as illustrated by SRTM DEM.

This area is marked by a major tectonic accident called Tizi N'Tretten accident (Colo, 1961) whose average direction is NE-SO, marks the central part of the Causse. The latter also shows NO-SE transverse faults which have influenced the Tectono-Sedimentary evolution from the Triassic to the Quaternary (Hinaje, 2004).

3. Materials and Methods

The research was based on FABDEM (Forest And Buildings removed Copernicus DEM) which is the result of the use of a random forest machine learning technique to eliminate vegetation and urban buildings from the Copernicus GLO 30 DEM (GLO-30 DEM) between 60° S and 80° N at 1 arc-second (30 m) grid spacing (Hawker et al. 2022).

In comparison to the Copernicus GLO 30 DEM, the mean absolute vertical error was therefore decreased from 5.15 to 2.88 meters in forested areas and from 1.61 to 1.12 meters in built-up areas. Compared to the current global DEMs, FABDEM performs noticeably better. Compared to the current global DEMs, FABDEM performs noticeably better (El Mhamdi et al., 2024). Thus, using FABDEM will be beneficial for applications such as hydrology, glaciology, and geomorphology when it is required to depict the bare-earth landscape.

In 2021, the FABDEM's first iteration (FABDEM V1.0) was made available to the public for non-commercial use. In 2023, a second version (FABDEM V1.2) was made available with additional adjustments to the grid spacing and artifact correction.

From the second version, the watershed's boundaries are established, and its hydrographic network is extracted. Next, the morphometric variables are calculated to characterize the watershed morphometrically. Figure 2 below provides illustrations of the methodology's steps.

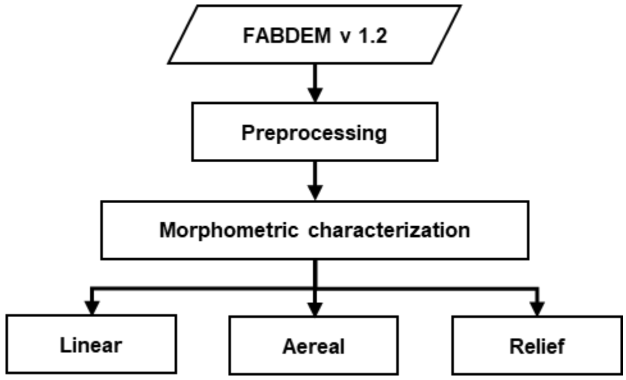

Figure 2. Schematic diagram of research methodology.

Aspect	Morphometric parameters	Formulas	References
Linear aspect	Stream order (N_u)	N_u	(Strahler, 1964)
	Stream Length (L_u)	L_u	(Horton, 1945)
	Stream Length ratio (R_L)	$R_L = \frac{L_u}{L_{u-1}}$	(Horton, 1945)
	Bifurcation ratio (R_b)	$R_b = \frac{N_u}{N_{u+1}}$	(Strahler, 1964)
Areal aspect	Drainage density (D_d)	$D_d = \frac{Lu}{A}$	(Horton, 1945)
	Drainage texture (T)	$T = \frac{Nu}{P}$	(Smith, 1950)
	Stream frequency (F_s)	$F_s = \frac{\sum N_u}{A}$	(Horton, 1945)
	Elongation ratio (R_e)	$R_e = \frac{D}{L} = 1.28\frac{\sqrt{A}}{L_b}$	(Schumm, 1956)
	Circularity ratio (R_c)	$R_c = {4\pi A}/{P^2}$	(Strahler, 1964)
	Form factor (F_f)	$F_f = {A}/{L_b{}^2}$	(Horton, 1945)
Relief aspect	Relief (R)	$R = H - h$	(Hadley & Schumm, 1961)
	Relief ratio (R_r)	$R_r = \frac{R}{L}$	(Schumm, 1963)
	Dissection index (Dis)	$Dis = \frac{R}{H}$	(Singh & Dubey, 1994)
	Roughness number (R_n)	$R_n = D_d * (R/1000)$	(Melton, 1957)

Table 1. Linear, areal and relief morphometric parameters formulas.

4. Results and Discussion

Using the FABDEM DEM preprocessed, the watershed has been delineated, the hydrographic network extracted (Fig.3), and the various morphometric parameters quantified through several treatments.

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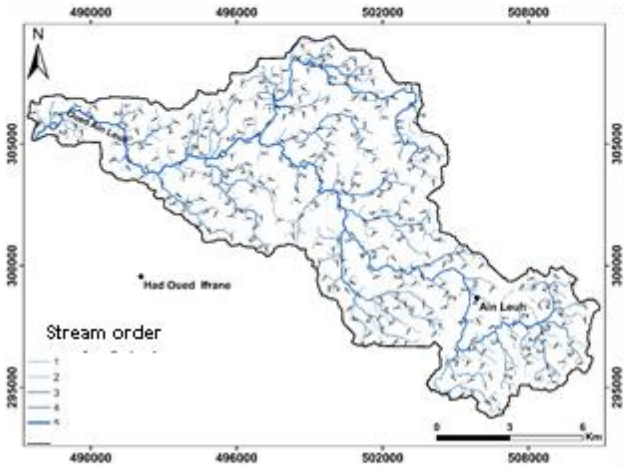

Figure 3. Ain Leuh watershed's hydrographic network (Strahler Order) map

The Ain Leuh watershed delimited from the FABDEM DEM, has an area A = 143.58 km^2, a perimeter P = 79.10 Km and a length Lb = 38.55 Km.

The results of the classification of the hydrographic network according to Strahler (1964) are presented in Figure 3 and Table 2. This network consists of 1064 linked stream segments, with five orders spread over an area of 143.58 km^2.

Parameters	**Stream order**					
	1	***2***	***3***	***4***	***5***	***Total***
Stream number	535	256	99	110	64	1064
Stream length (Km)	176.23	161.64	32.68	33.68	20.97	425.20
Bifurcation ratio	2.09	2.59	0.90	1.72	-	7.29

Table 2. Linear morphometric parameters of the Ain Leuh watershed.

According to Howard's classification (1976 in Deffontaines, 1990), the hydrographic network is of the dendritic type. This type corresponds either to uniformly resistant sediments, horizontal or bevelled by a horizontal surface, or to crystalline rocks; a low regional slope must have existed at the time of the installation of the drainage.

Stream length (Lu) of different orders is measured using GIS techniques. The length of first order streams is 176.23 km; second order streams is 161.64 km, third order streams is 32.68 km, fourth order is 33.68 km and fifth order streams are 20.97 km long. This variation in stream length may indicate flow from high altitude, lithological variation and steep slopes (Singh, 1986).

Bifurcation ratio (Rb) of the Ain Leuh watershed varies from 0.9 to 2.59. These values are very low, which indicates, according to Strahler (1957), a weak geological control in this watershed.

The drainage density (Dd) value of the study area is 2.96 km/km^2. This value is higher than 1.5 Km/Km2 (Horton, 1945; Pakhmode et al., 2003; Reddy et al., 2004), which means that the Ain Leuh watershed is well drained. This indicates the presence of impermeable soil, low vegetation and a significant slope.

The Streams frequency (Fs) of in this watershed is equal to 7.41. According to (Pakhmode et al., 2003), this value greater than 5 reveals a strong surface runoff and a significant slope, this agrees with the results provided by the drainage density.

The drainage texture (T) value for the study area is 13.45, which allows for a very fine texture (Smith, 1950). This texture indicates a resistant terrain, moderate to high runoff and sparse vegetation that characterize the sub-arid climate prevailing in the study area.

The elongation ratio (Re) of 0.4 (< 0.5), indicates an elongated watershed, with low infiltration capacity and high runoff (Reddy et al., 2004; Mesa, 2006).

The circularity ratio (Rc) is 0.29 < 0.55 shows the low circularity of the Ain Leuh watershed, which indicates the young stage of the life cycle of this watershed (Sreedevi et al., 2005).

The value of the form factor (Ff) is 0.10. This value is less than 0.5 indicates an elongated watershed with a low peak flow of long duration (Reddy et al., 2004), therefore absence of flood risk.

The hypsometric map (Figure 4) shows equidistant altitude slices of 200 m. These slices, generally oriented NE-SW, reflect the structure of the study region in stepped plateaus. The high-altitude zones are located in the SE of the basin, while the low altitude zones are in the NW part of the watershed.

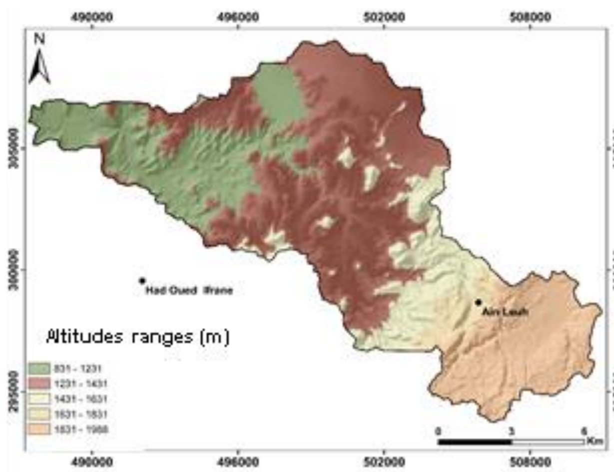

Figure 4. Hypsometric map of the Ain Leuh watershed.

The slope map of the Ain Leuh watershed (Figure 5) shows the dominance of low and medium slopes throughout the watershed, while steep to very steep slopes occupy a reduced area.

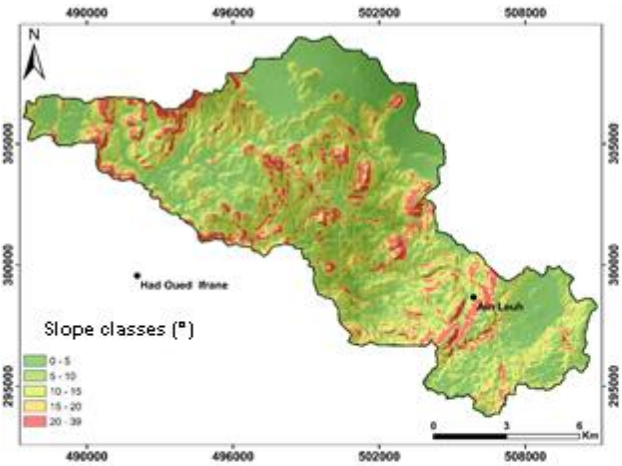

Figure 5. Slope map of the watershed of Ain Leuh

The linear and surface characteristics were considered as two-dimensional aspect. The third dimension is introduced by the relief through the analysis of three important parameters; the relief ratio (Rh), the dissection index (Dis) and the roughness number (Rn).

The total relief (R) of the Ain Leuh watershed is 1157 m. The high relief value indicates conditions of relatively high flow, low permeability and high runoff.

The relief ratio (Rr) value of this watershed is 0.03. This low value indicates a terrain dominated by wide plains and valleys.

The dissection (Dis) value of the Ain Leuh watershed is 0.58. This value, greater than zero, indicates that this basin is dissected and therefore susceptible to erosion.

The roughness number (Rn) is 3.43. This value reflects the high drainage density as well as the significant relief, which means an area of significant roughness and therefore the possibility of flooding.

The analysis of the hydrographic network of the Ain Leuh watershed shows an orientation in accordance with that of the faults of the region, thus suggesting a structural control of this network. According to the descriptive classification of Howard (1976), this hydrographic network is of a dendritic type, indicating that this watershed is made up of resistant sediments or crystalline rocks and relatively low regional slopes had to exist at the time of the installation of this network. On the other hand, the number and order of streams are proportionally inverse (Table 2), provides information on a lithological variation and steep slopes. These results can also be supported by the lithology of the region which shows a change of lithology by going from the tabular Middle Atlas to central Morocco, so the map of slopes (Figure 5) shows areas of the watershed with very high values exceeding 20 °. This analysis is consolidated by surface data which shows a waterproof soil, low infiltration and a reduced plant cover favoring a strong runoff. All this data and information on this watershed, make it possible to formulate the hypothesis that the downstream part is threatened by floods. However, this hypothesis can be neglected if we consider the elongated form of this watershe which implies slow runoff, making it possible to avoid cutting -edge flows. Without also neglecting the important role of the Moulay Hmad dam located towards the most downstream part of this basin is contributed to minimizing the probability of flooding. If the flood hypothesis is neglected, that of erosion is favored thanks to the association of strong runoff with the relief as important and the dissected nature of this watershed. This raises the question on the measures to protect this problem which first threaten the productivity of the earth, pollutes the rivers and causes the siltation of the region's only dam, that of Moulay Hmad.

5. Conclusion

The morphometric characterization is carried out from the FABDEM DEM after its preprocessing. The delineated watershed has an area of 143.58 km² compared to 138 km² raised on the topographic map. The analysis of the morphometric variables (linear and surface) shows that it is a young watershed, elongated, well-drained with significant runoff. This watershed is characterized by a significant relief and a dominance of medium to high slopes on the one hand. On the other hand, it has low flood potential and susceptibility to erosion.

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