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Prioritizing sub-watersheds for soil management and conservation in the Wadi Ouergha watershed, Northern Morocco

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ABSTRACT

The Wadi Ouergha watershed faces significant challenges due to erosion, which directly impacts sedimentation rates and reduces the water storage capacity of the El Wahda dam, a crucial infrastructure for the region. This study aims to prioritize the sub-watersheds most vulnerable to erosion, which pose a direct threat to the dam's efficiency. Through morphometric and hypsometric analysis, the research evaluates the geomorphological evolution, hydrological characteristics, and erosion risks within the sub-watersheds. The results indicate that sub-watersheds SW 6, SW 7, and SW 11 are the most at risk, with high drainage densities and advanced erosion stages, demanding immediate intervention. Sub-watersheds SW 2, SW 3, SW 4, SW 5 and SW 7 are identified as moderately vulnerable but still require erosion control measures to prevent long-term degradation. The findings underscore the need for targeted soil management and conservation efforts in these priority areas. This study introduces a novel integration of spatial analysis with statistical methods, incorporating weighted compound factors (WCF) and quartile analysis to prioritize sub-watersheds according to their vulnerability. This method enables a data-driven classification, establishing a structured framework for conservation priorities. Through combined numerical rankings and spatial mapping, decision-makers gain a clear visualization of high-risk areas, facilitating more targeted watershed management and optimized resource allocation.

Keywords: morphometric parameters, hypsometric analysis, preliminary ranking, erosion, soil loss, GIS, Ouergha sub-watersheds, El Wahda dam.

INTRODUCTION

The Wadi Ouergha watershed holds significant hydrological importance in Morocco, particularly in the northern region, due to its annual water contribution of 2877 million m³, accounting for 57% of the total contribution to the Sebou basin on average, based on data from 1939 to 2002 (according to ABHS). This watershed supplies the El Wahda dam, the largest and most ambitious hydraulic structure in Morocco and the second-largest in Africa, boasting a storage capacity of 3522.3 million m³ (General Directorate of Hydraulics, 2020). The construction of this dam is crucial for managing the region's water resources, optimizing their availability throughout the year.

The dam's infrastructure plays a central role in regulating river flows, storing excess water generated by seasonal floods. Thus, it significantly contributes to mitigating the effects of floods and ensuring a regular water supply, especially during periods of low rainfall. However, the dam faces a major challenge: siltation due to water erosion (Bardouz and Boumeaza, 2016). Estimates indicate an annual siltation rate of 18.5 million m³ (PDAIRE, 2011).

In our previous study (Naoui et al., 2023), we assessed the rate of erosion in the Wadi Ouergha watershed. The results revealed high erosion risks, particularly in mountainous areas with shallow soils and sparse vegetation cover, promoting runoff and erosion. In contrast, the regions downstream of the El Wahda dam and the southwestern part of the Wadi Ouergha have deeper soils and denser vegetation. This reduces erosion risks and enhances water retention. This study is crucial for identifying sub-watersheds most vulnerable to erosion, which directly impacts the operational efficiency of the El Wahda dam, a key water reservoir in the region. By leveraging geographic information systems (GIS) and digital elevation models (DEM), this research examines key morphometric parameters such as drainage density, relief, and slope to understand how these features influence erosion processes. The application of hypsometric analysis further provides insights into the geomorphological maturity of the watershed. This comprehensive approach, combining morphometric and hypsometric analysis, is essential for guiding water management and soil conservation strategies.

The novelty of this approach lies in the integration of spatial analysis with statistical methods, including the use of weighted compound factors (WCF) and quartile analysis, to prioritize sub-watersheds based on their vulnerability. This method ensures a data-driven classification of watersheds, providing a clear framework for prioritizing conservation actions. By using both numerical rankings and spatial mapping, decision-makers can visualize and better address areas that are most at risk, ensuring more effective watershed management and resource allocation (Rahaman et al., 2018; Singh et al., 2021). The findings highlight not only the importance of erosion control but also the value of employing this integrated approach for future environmental studies and resource management strategies.

METHODOLOGY

Study area

The research focuses on the Wadi Ouergha watershed, situated in the Rif region, with geographical coordinates spanning from latitude 35° 9’ N to 34° 20’ N and longitude 5° 49’ W to 3° 54’ W (see Figure 1). This area is noted for its intricate geological structure and high mountain ranges, featuring significant elevations. The watershed includes a sequence of elongated plains within Miocene marl basins, extending from the Upper-Ouergha to the Rharb region. Wadi Ouergha meanders through the lower sections of these plains, forming prominent terraces. It transitions from one plain to another through sharp directional changes in narrow valleys, as described by Maurer (1959).

The terrain within the watershed is rugged, with elevations ranging from 11 meters to 2450 meters. The northern and central parts of the catchment are dominated by mountains with altitudes between 1430 m and 2450 m. In contrast, the southern and southwestern parts consist of a mix of mountains, hills, and plains with altitudes varying from 11 m to 800 m.

From a hydrological perspective, Wadi Ouergha drains an area of approximately 7300 km^2 (ABHS) and spans a length of 1486.5 km with a perimeter of around 600 km (Boukrim et al., 2011). It is the second-largest tributary of Wadi Sebou, following Wadi Baht. The watershed’s main tributaries are primarily located on its right bank. Water contributions from the Wadi Ouergha watershed total approximately 2877 million m^3/year, accounting for 57% of the total inflow to the Sebou basin, based on averages from the period 1939 to 2002 (according to ABHS).

The topographical and hydrological characteristics of the Wadi Ouergha watershed, combined with its significant water contribution, highlight its importance within the broader context of the Sebou basin. These factors make it a critical area for studying soil erosion and water management.

MATERIAL AND METHODS

Morphometric analysis

To perform morphometric analysis of Wadi Ouergha’s sub-watersheds, GIS and DEM tools are employed to extract data on areas, perimeters, and stream networks (Mahala et al., 2020). This data is used to calculate key morphometric parameters such as relief, linear, and shape metrics, which offer insights into the hydrological and physical dynamics of the area. These parameters are critical for water management and identifying

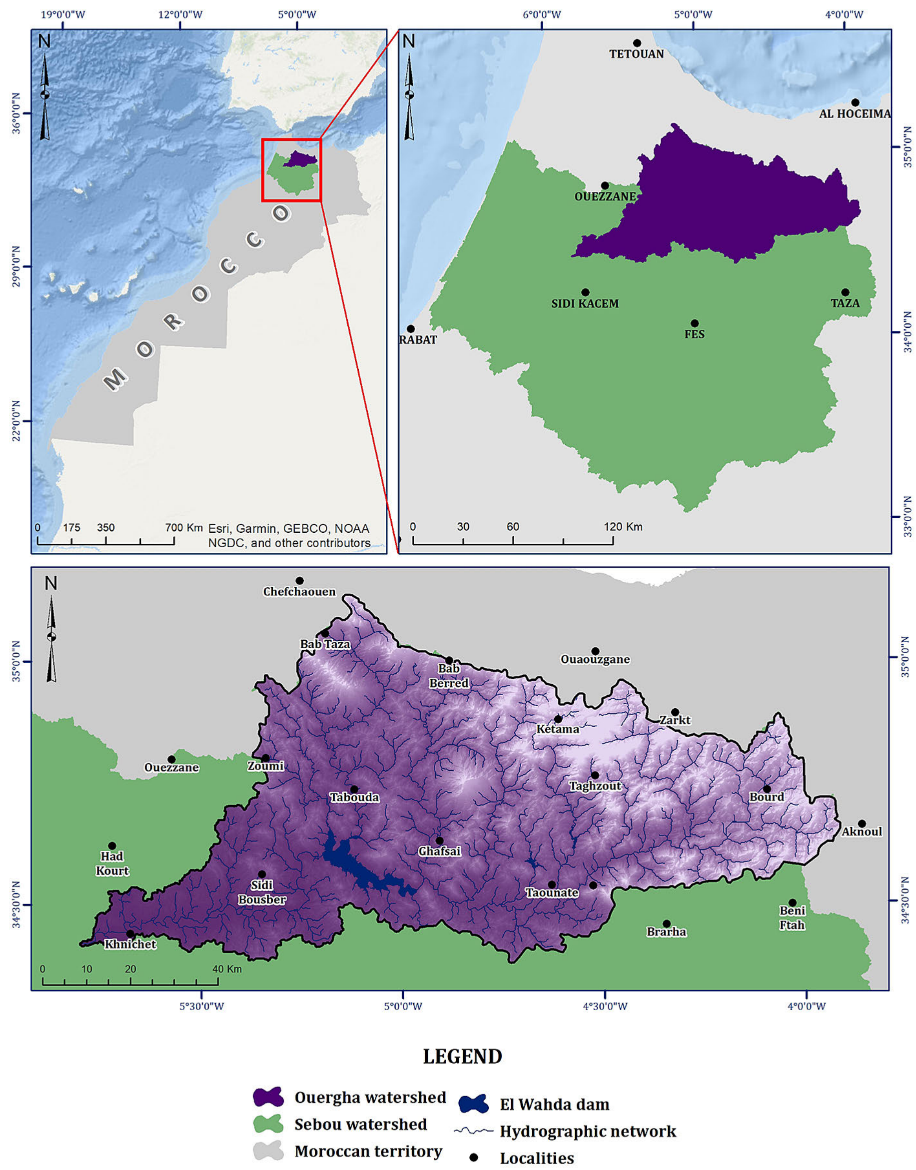

Figure 1. Geographical setting of the Wadi Ouergha watershed

erosion-prone sub-watersheds (Mahala et al., 2020) (Figure 2). The formulas for calculating these parameters are presented in Table 1.

The results of the basic parameters calculated using GIS, such as area, perimeter, stream order, etc., are presented in the following table (Table 2). The results of the calculations for the remaining parameters are presented in Table 3. The spatial distribution of all these parameters is illustrated in Figure 4, Figure 5 et Figure 6.

Sub-watersheds prioritization

Several steps are employed to prioritize sub-watersheds that are most vulnerable to erosion through morphometric analysis (Shekar et al., 2023; Kamaraj et al., 2024; Singh et al., 2022), below:

- Step 1: Preliminary priority – a total of 21 parameters are considered key indicators for assessing erosion risk (Biswas et al., 1999). These parameters were used in this study to prioritize sub-watersheds (Shekar et al., 2023) in order to identify those most vulnerable to soil erosion, thus requiring conservation measures. Since soil erosion is directly influenced by relief parameters and linear parameters, the highest values were given higher priority (Biswas et al., 1999). Conversely, since soil erosion is indirectly related to shape/area parameters, the lowest values were given higher priority (Ratnam et al., 2005). Thus, relief and linear parameters with the highest values were ranked first, and so on. Similarly, shape parameters with the

Table 1. Morphometric parameters

Parameters	Symbols	Formulae	References
Linear parameters			
Stream order	U	Derived using GIS tools	Strahler, 1964
Stream number	N_U	Derived using GIS tools	Horton, 1945
Stream length	L_U	Derived using GIS tools	Horton, 1945
Mean stream length	L_{Um}	Mean of $L_{U\,N}$	Strahler, 1964
Stream length ratio	R_l	$R_l = \frac{L_U}{L_{U-1}}$	Horton, 1945
Mean stream length ratio	R_{lm}		Strahler, 1964
Bifurcation ratio	R_b	$R_b = \frac{N_U}{N_{U+1}}$	Strahler, 1964
Mean Bifurcation ratio	R_{bm}	$R_{bm} = \frac{\sum R_b}{n}$	Strahler, 1964
Aire	A	Derived using GIS tools	-
Perimeter	P	Derived using GIS tools	-
Drainage density	D_d	$D_d = \frac{\sum L_U}{A}$	Schumm, 1956
Stream frequency	F_s	$F_s = \frac{\sum N_U}{A}$	Schumm, 1956
Drainage intensity	D_i	$D_i = \frac{F_s}{D_d}$	Faniran, 1968
Length of overland flow	L_o	$L_o = \frac{1}{2D_d}$	Horton, 1945
Constant of channel maintenance	C_{cm}	$C = \frac{1}{D_d}$	Schumm, 1956
Drainage texture	D_t	$D_t = \frac{\sum N_U}{P}$	Schumm, 1956
Infiltration number	I_f	$I_f = F_s \times D_d$	Faniran,1968
Rho coefficient	ρ	$\rho = \frac{R_{lm}}{R_{bm}}$	Horton, 1945
Relief parameters			
Min. elevation	h	Derived using GIS tools	-
Max. elevation	H	Derived using GIS tools	-
Mean elevation	H_m	Derived using GIS tools	-
Basin relief	B_h	$B_h = H - h$	Strahler, 1952
Relief ratio	R_h	$R_h = \frac{H}{B_h}$	Schumm (1956)
Relative relief	R_{hp}	$R_{hp} = \frac{B_h}{P}$	Melton, 1957
Ruggedness number	R_n	$R_n = B_h \times D_d$	Strahler, 1945
Shape/ areal parameters			
Basin length	L_b	$L_b = 1.312 \times A^{0.568}$	Nooka Ratnam et al., 2005
Form factor	F_f	$F_f = \frac{A}{{L_b}^2}$	Horton, 1932
Ciculatory ratio	R_c	$R_c = \frac{4\pi A}{P^2}$	Miller (1953)
Compactness coefficient	C_c	$C_c = \frac{P}{2(\pi A)^{0.5}}$	Horton (1945)
Elongation ratio	R_e	$R_e = \frac{(2 \times (\frac{A}{\pi})^{0.5})}{L_b}$	Schumm (1956)
Lemniscate ratio	K	$K = \frac{{L_b}^2}{4A}$	Chorely (1957)

Table 2. Stream analysis

SBW	A	P	U	N_u	L_u	L_{um}	R_l	R_{lm}	R_b
SW 1	422.13	122.37	1	70	120063.65	1715.20		0.65	2.33
			2	30	45832.47	1527.75	0.38		1.11
			3	27	52031.18	1927.08	1.14		2.70
			4	10	22254.63	2225.46	0.43		
				137	240181.93	1753.15			
SW 2	1037.94	180.41	1	198	304085.70	1535.79		0.69	2.00
			2	99	142558.52	1439.99	0.47		2.75
			3	36	47454.34	1318.18	0.33		1.06
			4	34	54308.89	1597.32	1.14		1.36
			5	25	44227.94	1769.12	0.81		
				392	592635.39	1511.82			
SW 3	848.31	168.14	1	149	233511.27	1567.19		1.86	2.10
			2	71	127464.86	1795.28	0.55		2.45
			3	29	39782.30	1371.80	0.31		5.80
			4	5	10913.17	2182.63	0.27		0.12
			5	42	68827.27	1638.74	6.31		
				296	480498.88	1623.31			
SW 4	561.50	156.65	1	90	151143.57	1679.37		0.84	2.50
			2	36	65826.44	1828.51	0.44		1.71
			3	21	33087.59	1575.60	0.50		0.66
			4	32	52424.99	1638.28	1.58		
				179	302482.59	1689.85			
SW 5	555.23	139.42	1	98	132703.77	1354.12		0.64	2.51
			2	39	70823.31	1815.98	0.53		1.26
			3	31	52260.90	1685.84	0.74		1.35
			4	23	33321.25	1448.75	0.64		
				191	289109.23	1513.66			
SW 6	138.66	65.62	1	22	35870.55	1630.48		1.12	2.44
			2	9	12467.83	1385.31	0.35		0.75
			3	12	23644.92	1970.41	1.90		
				43	71983.30	1674.03			
SW 7	535.48	130.10	1	96	122017.18	1271.01		0.57	2.09
			2	46	70555.15	1533.81	0.58		1.31
			3	35	54739.10	1563.97	0.78		2.69
			4	13	19816.20	1524.32	0.36		
				190	267127.62	1405.93			
SW 8	321.26	96.72	1	53	69173.02	1305.15		0.65	2.12
			2	25	47668.72	1906.75	0.69		1.92
			3	13	27518.82	2116.83	0.58		1.00
			4	13	18929.07	1456.08	0.69		
				104	163289.63	1570.09			
SW 9	204.11	73.42	1	36	49829.46	1384.15		0.79	2.40
			2	15	26521.64	1768.11	0.53		0.75
			3	20	28038.23	1401.91	1.06		
				71	104389.32	1470.27			

Table 2. Cont.

SW 10	253.89	89.86	1	45	60797.55	1351.06		0.60	1.88
			2	24	35646.56	1485.27	0.59		1.60
			3	15	19152.76	1276.85	0.54		3.00
			4	5	13138.93	2627.79	0.69		
				89	128735.79	1446.47			
SW 11	235.51	67.77	1	43	61310.48	1425.83		0.50	1.72
			2	25	39597.22	1583.89	0.65		2.78
			3	9	16390.99	1821.22	0.41		1.50
			4	6	7269.00	1211.50	0.44		
				83	124567.68	1500.82			
SW 12	128.06	60.84	1	23	41124.70	1788.03		0.81	2.88
			2	8	16966.60	2120.82	0.41		0.57
			3	14	20336.33	1452.60	1.20		
				45	78427.63	1742.84			
SW 13	247.30	99.39	1	48	87102.18	1814.63		0.48	1.71
			2	28	37893.66	1353.35	0.44		2.15
			3	13	19048.52	1465.27	0.50		3.25
			4	4	9767.04	2441.76	0.51		
				93	153811.40	1653.89			
SW 14	179.02	75.12	1	31	52734.41	1701.11		0.70	1.72
			2	18	27185.59	1510.31	0.52		1.64
			3	11	23903.84	2173.08	0.88		
				60	103823.84	1730.40			
SW 15	146.45	69.87	1	29	47251.80	1629.37		0.38	1.53
			2	19	27300.71	1436.88	0.58		3.80
			3	5	7593.01	1518.60	0.28		5.00
			4	1	2054.02	2054.02	0.27		
				54	84199.54	1559.25			
SW 16	325.53	103.12	1	55	118155.44	2148.28		0.45	2.50
			2	22	46431.65	2110.53	0.39		1.57
			3	14	23693.97	1692.43	0.51		1.17
			4	12	10910.34	909.20	0.46		
				103	199191.41	1933.90			
SW 17	1167.96	221.81	1	198	410328.34	2072.37		0.66	2.15
			2	92	171442.40	1863.50	0.42		1.80
			3	51	80909.59	1586.46	0.47		1.00
			4	51	88169.09	1728.81	1.09		
				392	750849.42	1915.43			

lowest values were ranked first, and so on. After assigning scores based on each individual parameter, the rating values for each sub-watershed were averaged to obtain a composite factor. This composite factor reflects the overall vulnerability of each sub-watershed to soil erosion. The individual parameters might include factors such as slope gradient, vegetation cover, soil type, land use, rainfall intensity, and erosion rates.

- Step 2: Correlation matrix – to assign individual weights to the selected variables, a correlation matrix was constructed. It includes the correlation coefficients between each pair of variables, which measure the strength and direction of the linear relationship between two variables (Rahaman et al., 2018; Jothimani et al., 2020). This matrix serves as the foundation for determining the influence of each

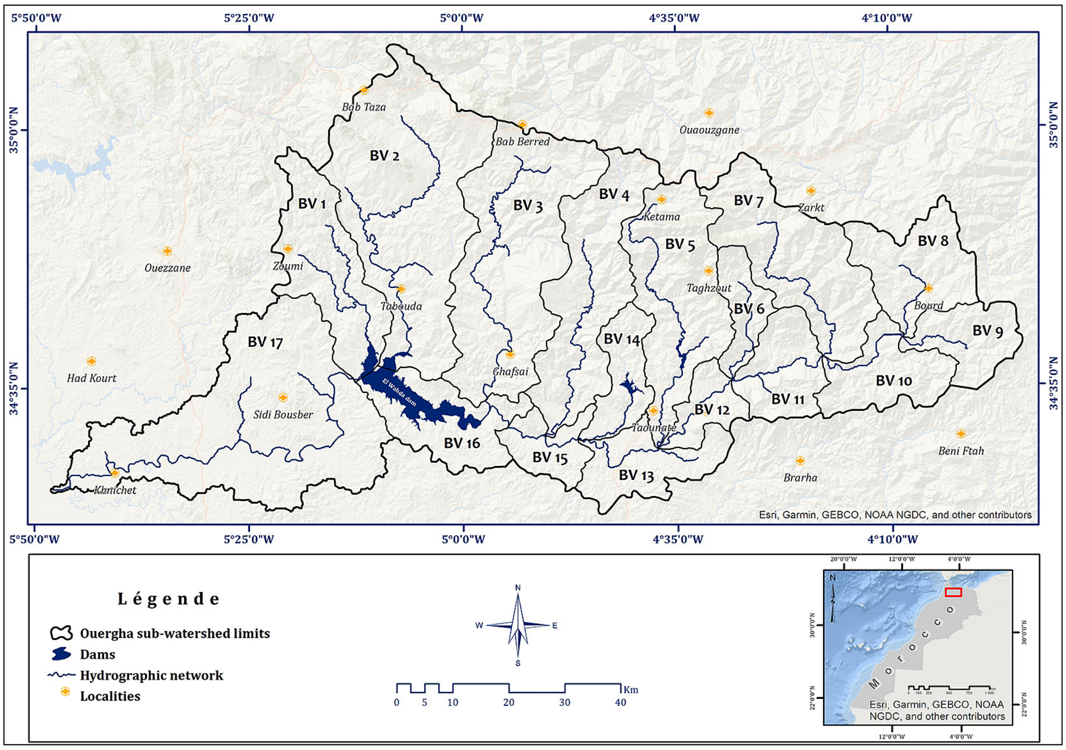

Figure 2. Wadi Ouergha sub-watershed

Table 3. Calculation result of all morphometric parameters

Param-eters	Linear parameters										Relief parameters				Shape/ areal parameters						
SW	L_{Um}	R_{bm}	D_d	F_s	D_i	L_o	C_{cm}	D_t	I_f	ρ	B_h	R_h	R_{hp}	R_n	L_b	F_f	R_c	C_c	R_e	K	S_b
BV 1	0.65	2.05	0.57	0.32	0.57	0.88	1.76	1.12	0.18	0.32	0.82	0.02	0.90	0.47	40.66	0.26	0.35	1.68	0.57	0.98	3.92
BV 2	0.69	1.79	0.57	0.38	0.66	0.88	1.75	2.17	0.22	0.39	1.96	0.03	0.93	1.12	67.78	0.23	0.40	1.58	0.54	1.11	4.43
BV 3	1.86	2.62	0.57	0.35	0.62	0.88	1.77	1.76	0.20	0.71	1.93	0.03	0.92	1.09	60.44	0.23	0.38	1.63	0.54	1.08	4.31
BV 4	0.84	2.18	0.54	0.32	0.59	0.93	1.86	1.14	0.17	0.39	1.93	0.04	0.92	1.04	47.82	0.25	0.29	1.87	0.56	1.02	4.07
BV 5	0.64	1.71	0.52	0.34	0.66	0.96	1.92	1.37	0.18	0.37	2.19	0.05	0.89	1.14	47.51	0.25	0.36	1.67	0.56	1.02	4.07
BV 6	1.12	1.60	0.52	0.31	0.60	0.96	1.93	0.66	0.16	0.70	1.97	0.09	0.85	1.02	21.61	0.30	0.40	1.57	0.62	0.84	3.37
BV 7	0.57	2.03	0.50	0.35	0.71	1.00	2.00	1.46	0.18	0.28	1.96	0.04	0.80	0.98	46.54	0.25	0.40	1.59	0.56	1.01	4.05
BV 8	0.65	1.68	0.51	0.32	0.64	0.98	1.97	1.08	0.16	0.39	1.14	0.03	0.60	0.58	34.82	0.26	0.43	1.52	0.58	0.94	3.77
BV 9	0.79	1.58	0.51	0.35	0.68	0.98	1.96	0.97	0.18	0.50	1.12	0.04	0.60	0.57	26.91	0.28	0.48	1.45	0.60	0.89	3.55
BV 10	0.60	2.16	0.51	0.35	0.69	0.99	1.97	0.99	0.18	0.28	1.33	0.04	0.73	0.67	30.46	0.27	0.39	1.59	0.59	0.91	3.66
BV 11	0.50	2.00	0.53	0.35	0.67	0.95	1.89	1.22	0.19	0.25	1.45	0.05	0.81	0.77	29.19	0.28	0.64	1.25	0.59	0.90	3.62
BV 12	0.81	1.72	0.61	0.35	0.57	0.82	1.63	0.74	0.22	0.47	1.36	0.07	0.84	0.83	20.65	0.30	0.43	1.52	0.62	0.83	3.33
BV 13	0.48	2.37	0.62	0.38	0.60	0.80	1.61	0.94	0.23	0.20	1.35	0.05	0.88	0.84	30.01	0.27	0.31	1.78	0.59	0.91	3.64
BV 14	0.70	1.68	0.58	0.34	0.58	0.86	1.72	0.80	0.19	0.42	0.94	0.04	0.83	0.55	24.98	0.29	0.40	1.58	0.60	0.87	3.49
BV 15	0.38	3.44	0.57	0.37	0.64	0.87	1.74	0.77	0.21	0.11	0.57	0.03	0.78	0.33	22.29	0.29	0.38	1.63	0.61	0.85	3.39
BV 16	0.45	1.75	0.61	0.32	0.52	0.82	1.63	1.00	0.19	0.26	0.73	0.02	0.89	0.45	35.08	0.26	0.38	1.61	0.58	0.95	3.78
BV 17	0.66	1.65	0.64	0.34	0.52	0.78	1.56	1.77	0.22	0.40	0.82	0.01	0.98	0.53	72.48	0.22	0.30	1.83	0.53	1.12	4.50

variable relative to others (Taib et al., 2023). For each parameter, the correlation total (CT) was computed by summing up all the correlation coefficients related to that parameter from the matrix. The correlation total reflects how strongly each parameter correlates with all other variables (Jothimani et al., 2020; Taib et al., 2023). After computing the correlation totals for all parameters, the grand total (GT) was calculated by summing all the individual correlation totals, representing the overall sum of correlation values in the matrix.

- Step 3: Determining the individual weights (Wi) – the individual weight for each parameter (Wi) was calculated by dividing the parameter's CT by the GT. The formula is as follows (Kamaraj et al., 2024).

$$Wi = \frac{CT}{GT} \quad (1)$$

This step ensures that each parameter's weight reflects its relative importance within the dataset, based on its correlation with other variables. The calculated individual weights (*Wi*) for each parameter are presented in Table 5, providing a clear view of how much influence each variable has relative to others (Jothimani et al., 2020; Rahaman et al., 2018). This method allows for a systematic and statistically grounded approach to assign weights to parameters based on their interrelationships, ensuring that more influential variables are given higher importance in further analysis.

- Step 4: Weighted compound factor (WCF) – The weighted compound factor (WCF) represents the combined and weighted effect of all parameters for the final priority. The WCF is calculated using the following formula:

$$WCF = (PP_1 \times W_1) + (PP_2 \times W_2) + + \cdots + (PP_n \times W_n) \quad (2)$$

where: *PP* is the preliminary priority of each parameter, and *W* is the corresponding individual weight (Taib et al., 2023).

- Step 5: Quartile method and final classification – in statistical analysis, quartiles are used to divide a dataset into four equal segments, offering an effective method for ranking or classifying data based on its distribution (Kamaraj et al., 2023). The quartile method enables differentiation between various data ranges, which is particularly useful in environmental management tasks such as watershed prioritization (Rahaman et al., 2018; Kamaraj et al., 2023).
  - The lower quartile (Q1): Represents the 25th percentile, where 25% of the data falls below this value.
  - The median (Q2): Corresponds to the 50th percentile, meaning half of the data points are below this value.
  - The upper quartile (Q3): Represents the 75th percentile, indicating that 75% of the data falls below this point.
  - The upper boundary (Q4): Encompasses the maximum data values above Q3.

The quartile method was applied to the WCF values for the classification of watersheds into four priority levels. This quartile-based approach provides a statistically balanced framework to rank watersheds, ensuring a clear distinction between higher and lower priority areas, facilitating targeted environmental management and resource allocation (Kamaraj et al., 2023).

The final result is a clear categorization of watersheds into four distinct groups: very high, high, medium, and low, facilitating more focused management and conservation strategies based on the quartile-based statistical distribution and spatial characteristics (Rahaman et al., 2018; Kamaraj et al., 2023).

Hypsometric analysis

Hypsometric analysis is a method employed to examine the topographic relief of a landscape by analyzing the distribution of elevation in a given region. This method uses a hypsometric curve, which plots the cumulative area of the landscape at different elevations, helping to show how much of the area lies within specific elevation ranges. This approach is particularly important in understanding landscape evolution, erosion processes, and watershed characteristics (Kabite and Gesesse, 2018; Walia et al., 2021).

To perform hypsometric analysis using a DEM, the following steps are typically involved; The first step is to extract the elevation data from the DEM (Figure 3). Once the elevation data is extracted, it is divided into different elevation intervals, which represent sections of the landscape. For each elevation interval, the area is calculated. This provides insight into how much land lies within certain elevation ranges. The cumulative area for each elevation range is calculated and plotted against the elevation values. This plot is known as the hypsometric curve, which helps visualize the distribution of land across elevations. The hypsometric index (HI) is calculated using the elevation-relief ratio method (eq xx), which represents the relative distribution of elevations in the watershed. The HI values offer a numerical summary of the curve and provide insights into the stage of landscape evolution (Walia et al., 2021). Higher HI values typically suggest a younger, more eroded landscape, whereas lower

HI values indicate an older, more stable region (Ghasemlounia and Utlu, 2021). The HI values are then classified into three intervals. Based on these intervals (Walia et al., 2021; Kabite and Gesesse, 2018):

- high priority: is assigned to the watersheds with the highest HI values.
- medium priority: is given to those in the middle interval.
- low priority: is for watersheds with the lowest HI values.

To calculate the HI value, we use the following formula (Meshram et al., 2015):

$$E = \frac{H_{moy} - H_{min}}{H_{max} - H_{min}} \quad (3)$$

RESULT AND DISCUSSION

Morphometric analysis

The morphometric analysis of the Ouergha Wadi Watershed provides a comprehensive assessment of its geometric structure, enabling a better understanding of its geomorphological features and hydrological behavior. This quantitative approach facilitates the examination of how the watershed's physical characteristics influence its responses to various hydrological processes. For detailed analysis, the morphometric parameters of the Ouergha Wadi Watershed are generally categorized into three main groups: linear, areal, and relief aspects (Farhan et al., 2015). This classification is critical in evaluating factors such as stream order, drainage density, and slope, all of which contribute to a clearer interpretation of the watershed's dynamics and potential erosion risks (El Brahimi et al., 2024).

Linear aspects

Stream order (U): Indicates the hierarchy of streams within a watershed (Strahler, 1964). Stream classification is performed using GIS. A 5th-order stream, as observed in SBV 2 and SBV 3, indicates a well-developed hydrographic network and considerable drainage capacity. This suggests that these sub-watersheds feature a complex hydrological structure with multiple confluences.

Number of streams (N_u): Represents the total number of streams of order n. Note that the number of streams decreases as the stream order increases. The values recorded for SBV 2 (392 streams), SBV 3 (296 streams), and SBV 17 (392 streams) indicate a high drainage density. This means that these sub-watersheds benefit from good drainage, with numerous tributaries contributing to a dense hydrographic network. A high number of streams is often characteristic of areas with rugged topography and a rainy climate.

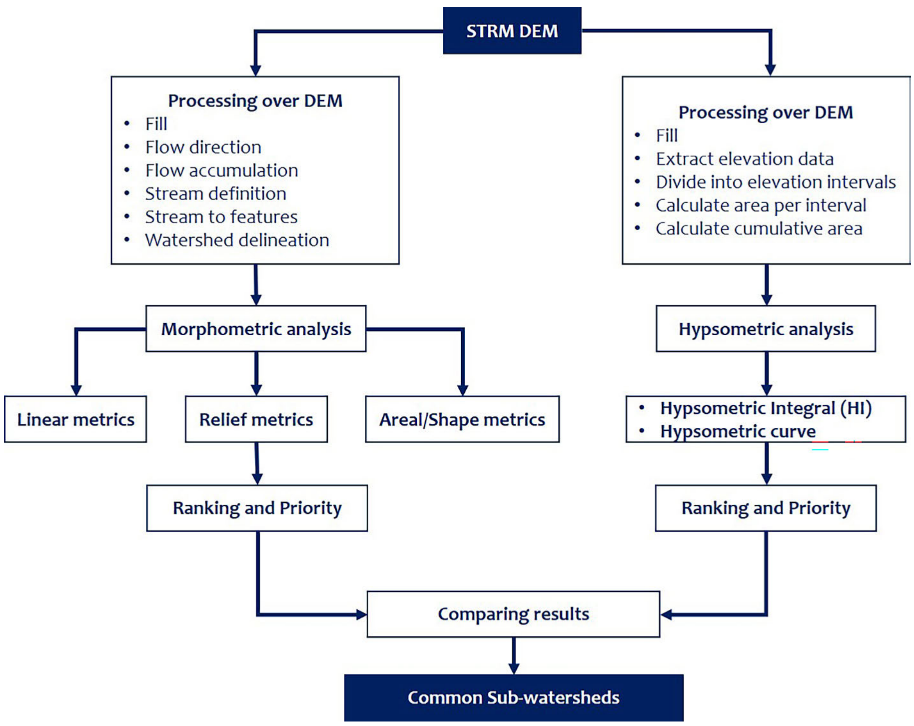

Figure 3. Methodology of present study

Stream length (L_u): Measures the sum of the lengths of all streams within a sub-watershed (Horton, 1945). The observed values for SBV 2 (593 km), SBV 3 (480 km), and SBV 17 (751 km) indicate the presence of an extensive drainage network. This is attributed to the large size of the sub-watersheds compared to the other sub-watersheds and the geology that supports the development of long streams, primarily composed of marl (Naoui et al., 2023).

Bifurcation ratio (R_b): This parameter quantifies the branching of a watershed's drainage network and illustrates the complexity and dissection of the watershed, serving as an indicator of the underlying geological structure (Bharadwaj et al., 2014). The values in SBV 15 (3.44), SBV 3 (2.62), and SBV 13 (2.37) have the highest R_{bm} among the sub- watersheds of Wadi Ouergha.

Drainage density (D_d): Defined as the ratio of the total length of streams within a watershed to the area of that watershed. Watersheds with a D_d less than 1 have a developed hydrographic network and are well-drained, while those with a D_d greater than 1 have a less developed network and are poorly drained (Horton, 1932). The highest values were observed in SBV 17 (0.64), SBV 13 (0.62), and also in SBV 12 and SBV 16 (0.61). These values, being less than 1, indicate a well-developed hydrographic network and well-drained sub-watersheds. This is attributed to complex topography and limited soil permeability, leading to significant surface runoff.

Stream frequency (F_s): This indicator is used to evaluate the density of hydrographic networks and provides insights into the hydrological and geological characteristics of a region. It is defined as the number of streams per unit area (Schumm, 1956). A high F_s suggests a rough surface and low basin permeability, contributing to increased soil erosion (Arabameri et al., 2020). The highest values were observed in SBV 2 and SBV 13 (0.38), followed by SBV 15 (0.37) and SBV 9, 3, 10, 12, 11, and 7 with a value of 0.35. This indicates that these sub-watersheds are most vulnerable to soil erosion, associated with permeability, slope, precipitation, relief, and groundwater retention capacity.

Drainage texture (D_t): Defined as the total number of stream segments per unit area of the watershed (Schumm, 1956). The D_t is influenced by factors such as soil permeability, vegetation, terrain slope, and precipitation. Generally, a lower D_t indicates less vulnerable geological conditions with fine texture, reducing erosion risk (Kadam et al., 2019). High D_t values observed in SBV 2 (0.69), SBV 17 (0.66), SBV 3 (1.86), SBV 7 (0.57), and SBV 5 (0.64) suggest that these sub-watersheds are more susceptible to erosion.

Surface flow length (L_o): It is a hydrological measure describing the average distance rainwater travels from its point of fall to a stream (Horton, 1945). It is essential for understanding concentration time and runoff processes in a watershed. The highest L_o values observed in SBV 7 (1.00), SBV 10 (0.99), SBV 8 and SBV 9 (0.98), SBV 6 and SBV 5 (0.96), and SBV 11 (0.95) are considered low. This implies that these sub-watersheds have faster runoff, which promotes soil erosion.

Drainage intensity (D_i): A geomorphological indicator describing the development degree of a drainage network in a region. Defined as the ratio of D_d to F_s (Faniran, 1968). This indicator helps understand the efficiency and capacity of a watershed to drain precipitation. High drainage intensity was observed in SBV 7 (0.71), SBV 10 (0.69), SBV 9 (0.68), SBV 11 (0.67), and SBV 2 (0.66).

Rho coefficient (ρ): A geomorphological parameter used to quantify the interaction between watersheds and the hydrographic network (Horton, 1945). It is particularly useful for assessing erosion potential and drainage capacity, incorporating various hydrological and morphological factors for a comprehensive measure of surface water dynamics. High values of ρ in SBV 3 (0.71), SBV 6 (0.70), SBV 9 (0.50), SBV 12 (0.47), and SBV 14 (0.42) indicate relatively stable soils with some susceptibility to erosion.

Infiltration index (I_f): A hydrological measure quantifying a soil's capacity to absorb rainfall (Faniran, 1968). This index is crucial for understanding surface and groundwater dynamics, and for assessing runoff and flood risks. Factors influencing infiltration include soil texture, vegetation cover, terrain slope, and climatic conditions. Higher infiltration indices indicate greater runoff and lower infiltration rates (Akhtar et al., 2021). SBV 13 (0.23), SBV 17, SBV 2, and SBV 12 with a value of (0.22), along with SBV 15 (0.21), show the highest infiltration indices, indicating limited infiltration capacity due to impermeable soils (Akhtar et al., 2021). This results in increased runoff and, consequently, greater soil erosion.

Channel maintenance constant (C_{cm}): A geomorphological parameter used to measure the ratio of the total stream length in a watershed to the watershed's area (Schumm, 1956). This indicator is essential for understanding the development and efficiency of a region's hydrographic network. Generally, higher C_{cm} values indicate greater rock permeability within the watershed (Dar et al., 2012). SBV 7 (2.00), SBV 10 (1.97), SBV 9 (1.96), and SBV 6 (1.93) exhibit the highest C_{cm} values among the sub-watersheds. Although these values are low, they indicate reduced infiltration capacity and higher potential runoff, which may lead to increased soil erosion (Dar et al., 2012).

Relief aspects

Watershed Relief (B_h): A geomorphological indicator that describes the difference in elevation between the highest and lowest points within a watershed (Strahler, 1952). This indicator is crucial for understanding hydrological dynamics and erosion processes within a watershed. Relief influences runoff, infiltration, and water speed in the drainage network (Babu et al., 2014). High B_h values observed in SBV 5 (2.19), SBV 6 (1.97), SBV 2 and SBV 7 (1.96), as well as in SBV 4 and SBV 3 (1.93), indicate significant topographic variations, rapid runoff, and increased erosion due to steep slopes. These conditions can impact hydrological processes such as surface flow and erosion.

Relief ratio (R_h): A geomorphological indicator used to assess the average slope and degree of topographic dissection of a watershed. It is defined as the ratio between the elevation of a watershed and the L_b of its main course. This ratio helps understand erosion processes, runoff, and landscape formation. The highest R_h values observed in SBV 6 (0.09), SBV 12 (0.07), SBV 11, SBV 5, SBV 13 (0.05), and SBV 10 (0.04) suggest that these basins have gentler and less abrupt slopes, which may promote greater infiltration and slower runoff.

Relative relief (R_{hp}): A geomorphological indicator measuring altitude variation in a watershed relative to a reference point (Melton, 1957). This indicator is used to evaluate local topography, including slopes, ridges, and valleys, and is crucial for understanding erosion, runoff, and soil formation processes (Hadley and Schumm, 1961). The highest R_{hp} values are observed in SBV 17 (0.98), SBV 2 (0.93), SBV 3 and SBV 4 (0.92), SBV 1 (0.90), and SBV 5 (0.89), reflecting marked topographic conditions and high potential energy for erosion.

Roughness ratio (R_n): A geomorphological parameter measuring topographic variation over a given surface (Strahler, 1945). This indicator is crucial for understanding the complexity and heterogeneity of a landscape, influencing aspects such as runoff, erosion, and natural habitats. The highest R_n values observed in SBV 5 (1.14), SBV 2 (1.12), SBV 3 (1.09), SBV 4 (1.04), and SBV 6 (1.02) indicate a rugged topographic surface (Kabite and Gessesse, 2018). High rugosity can result in more turbulent flow and affect water velocity, thereby increasing the potential for erosion and sediment deposition.

Surface aspects

Area (A) and perimeter (P): Calculated directly using GIS. The amount of runoff generated by a watershed is directly influenced by the watershed's area.

Watershed length (L_b): A geomorphological measure representing the maximum linear distance from the farthest point of the watershed to the outlet (Ratnam et al., 2005). This measure is essential for understanding hydrological flow dynamics and erosion processes within a watershed. The lowest values among the sub-watersheds in the Wadi Ouergha watershed are observed in SBV 12 (20.65 km), SBV 6 (21.61 km), SBV 15 (22.29 km), SBV 14 (24.98 km), and SBV 9 (26.91 km).

Form factor (F_f): A geomorphological indicator used to evaluate the shape of a watershed. It is defined as the ratio between A and the square of its L_b (Horton, 1932). This indicator helps understand a watershed's tendency to generate either rapid or slow surface runoff, influencing runoff potential and flood risk (Horton, 1932). The sub-watersheds SBV 17 (0.22), SBV 2 and SBV 3 (0.23), as well as SBV 4, SBV 5, and SBV 7 (0.25) exhibit the lowest F_f values. This suggests that these sub-watersheds generate less intense but longer-lasting flood flows, increasing their susceptibility to flooding.

Circularity ratio (R_c): An essential indicator for evaluating the shape of a watershed by comparing its area to that of a circle with the same perimeter (Miller, 1953). This parameter provides information on the watershed's topographic maturity. A high R_c value indicates a mature watershed, while a lower value suggests that the watershed is still in development and is therefore considered young (Rai et al., 2017). SBV 4 (0.29), SBV 17 (0.30), SBV 13 (0.30), SBV 1 (0.35), and SBV 5 (0.36) have the lowest R_c values, indicating that these sub-watersheds are still in the development phase and are considered young (Rai et al., 2017).

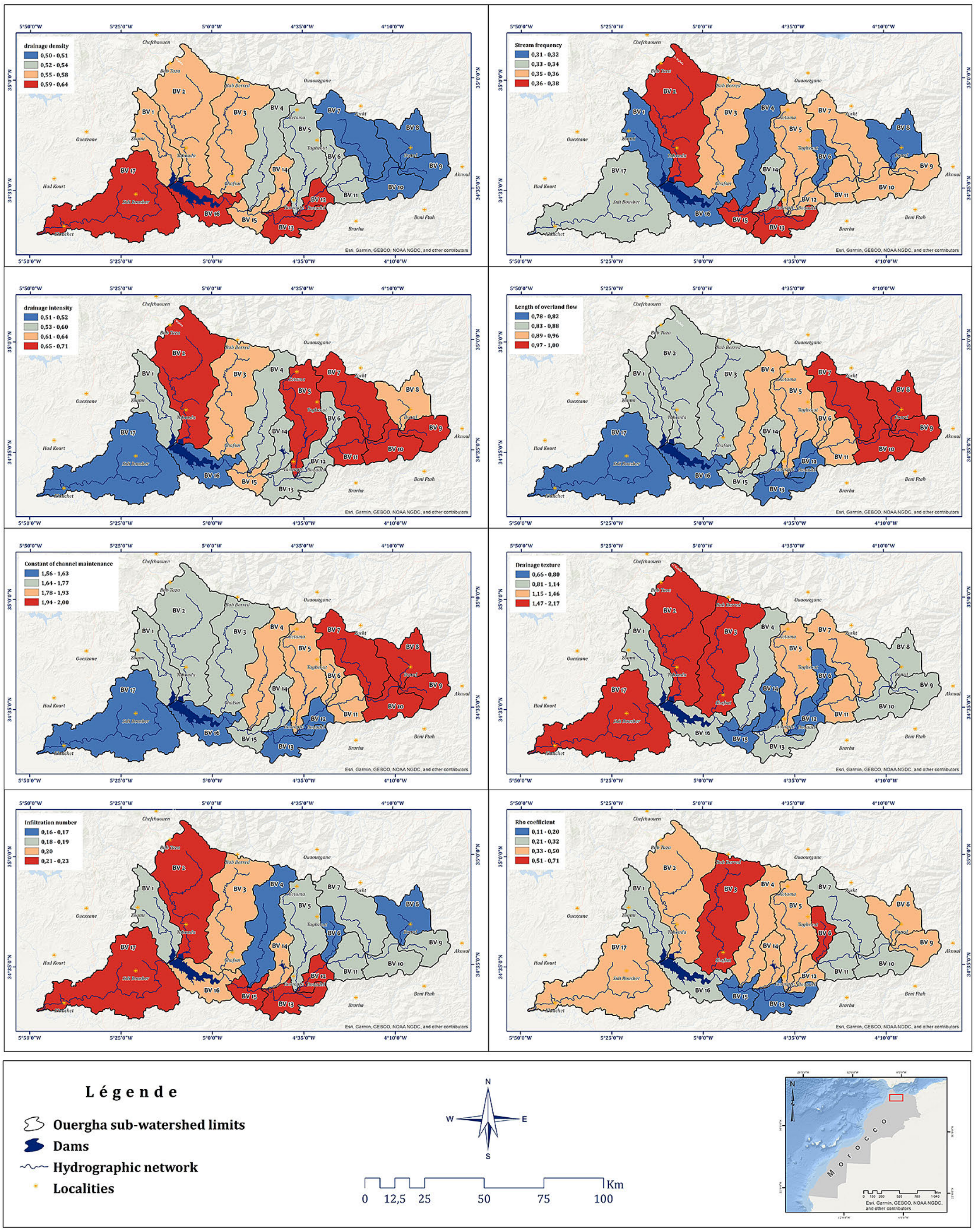

Figure 4. Linear parameters

Compactness coefficient (C_c): Also known as Gravelius' coefficient (K_G), it is defined as the ratio of the watershed perimeter to the perimeter of a circle with the same area (Horton, 1932). This index determines the watershed shape, influencing overall river flow. SBV 11 (1.25), SBV 9 (1.45), SBV 12 and SBV 8 (1.52), SBV 6 (1.57), and SBV 2 (1.58) show the lowest values, all above 1, indicating that these sub-watersheds have an elongated or irregular shape. This characteristic can lead to significant variations in hydraulic regime, affecting flows and concentration times.

Elongation ratio (R_e): A geomorphological indicator used to evaluate the shape of a watershed. It is defined as the ratio between the diameter of a circle with the same area as the watershed and the L_b (Schumm, 1956). This indicator helps understand a watershed's tendency to generate either rapid or slow surface runoff, influencing runoff potential and flood risk. The sub-watersheds SBV 17

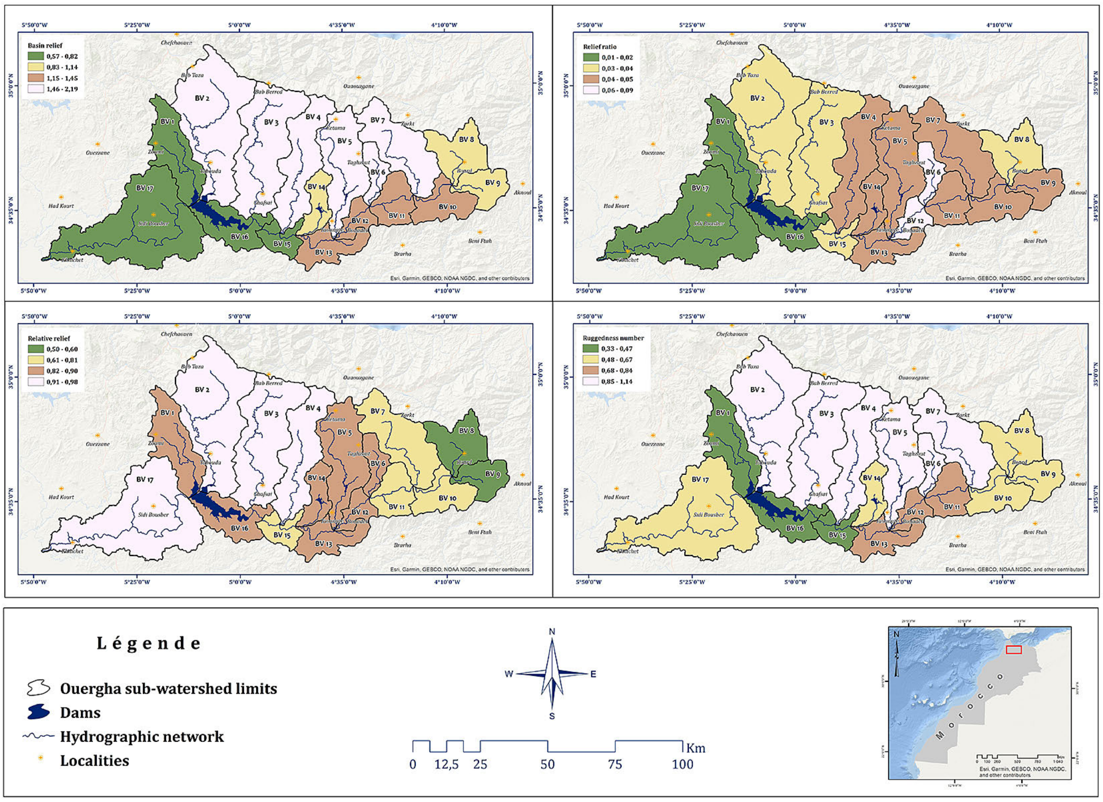

Figure 5. Relief parameters

(0.53), SBV 2 and SBV 3 (0.54), SBV 4, SBV 5, and SBV 7 (0.56), SBV 1 (0.57), as well as SBV 16 and SBV 8 (0.58), exhibit relatively low elongation ratios, suggesting an elongated shape that makes them susceptible to erosion (Patel et al., 2023).

Lemniscate ratio (K): A geomorphological indicator used to describe the shape and efficiency of a watershed in terms of water flow. It is defined as the ratio of the square of the L_b to its A (Chorely, 1957). This ratio evaluates the extent of elongation and complexity of the watershed's shape, influencing flow dynamics and erosion processes. Low K values, as observed in SBV 12 (0.83), SBV 6 (0.84), SBV 15 (0.85), SBV 14 (0.87), and SBV 9 (0.89), indicate less elongated basins, promoting more efficient flow and reducing water concentration time.

Shape index (S_b): A geomorphological parameter used to describe the form of a watershed (Horton, 1932). This indicator helps understand the compactness of a watershed, influencing surface flow and runoff processes. SBV 12 (3.33), SBV 6 (3.37), SBV 15 (3.39), SBV 14 (3.49), and SBV 9 (3.55) have low K values, indicating a less elongated shape. This can influence the speed and volume of water flow, affecting water resource management and flood risks.

Sub-watersheds prioritization

Preliminary priority and compound factor calculation

After thoroughly analyzing the morphometric parameters of the Wadi Ouergha watershed, we now proceed to identify the sub-watersheds most vulnerable to soil loss. For this prioritization step, we used the preliminary ranking method detailed previously, which assigns a priority rank to each studied parameter and ranks the sub-watersheds accordingly.

To determine the priority ranking, the average composite factor for each sub-watershed was calculated. The sub-watershed with the lowest average composite factor, indicating the highest vulnerability to soil erosion, was assigned the highest priority number of 1. This means that this sub-watershed requires the most immediate attention for erosion control measures. The sub-watershed with the next lowest average composite factor was assigned priority number 2, indicating it is the second most vulnerable, and so on.

Conversely, the sub-watershed with the highest average composite factor, indicating the least vulnerability to soil erosion, was given the last priority number. This ranking system helps in

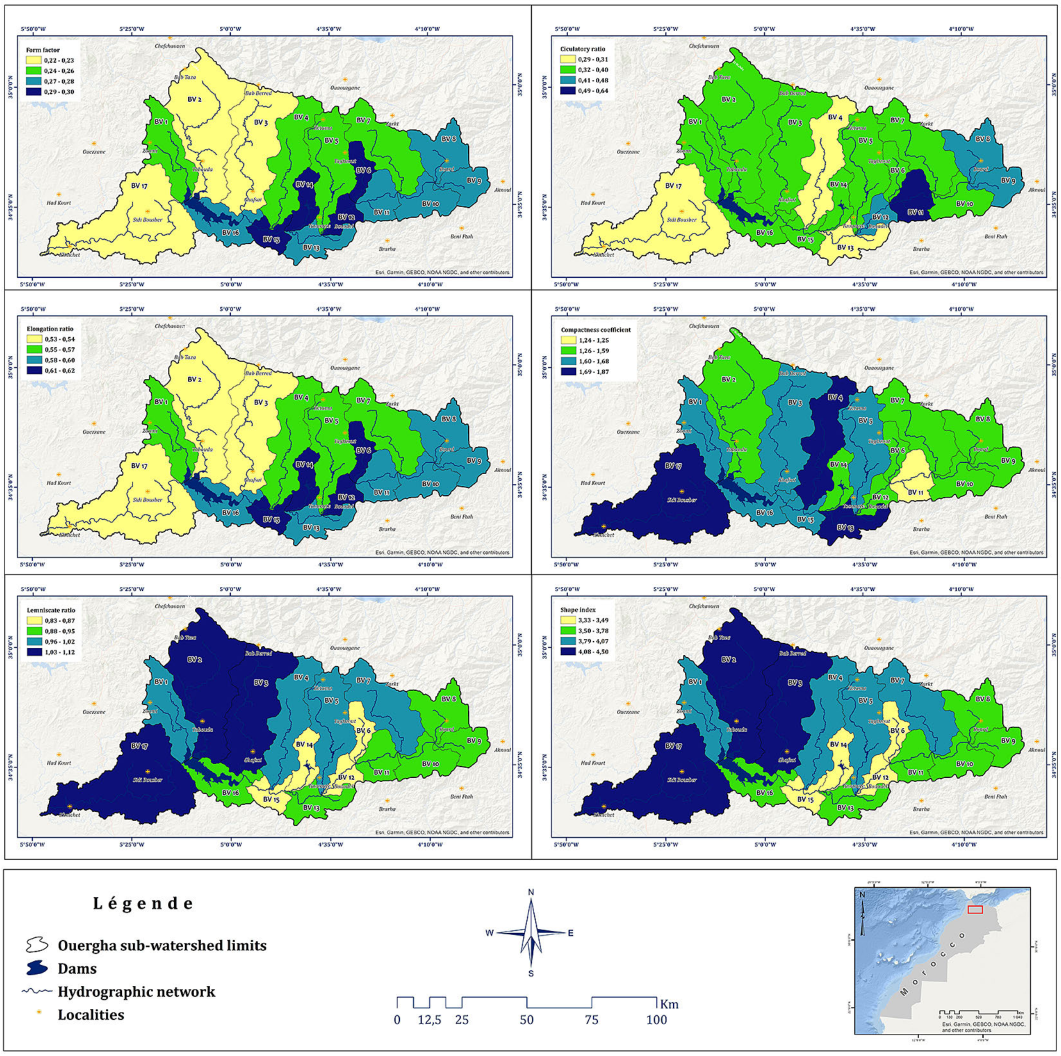

Figure 6. Shape parameters

identifying which sub-watersheds are most in need of intervention and allows for a targeted approach to soil conservation efforts (Figure 7).

Table 4 presents the results of the preliminary ranking. From this analysis, it is evident that sub-watersheds BV 3, BV 2, and BV 5 exhibit high values for several key parameters, making them particularly vulnerable to erosion. These sub-watersheds receive the highest priority ranks. Additionally, sub-watersheds BV 7 and BV 4 also show notable vulnerability, though not as pronounced as that observed in BV 3, BV 2, and BV 5. Therefore, these sub-watersheds are identified as priorities for the implementation of erosion control measures.

Correlation matrix and weight calculation

The correlation matrix shows the relationships between various morphometric parameters, with values ranging from -1 to 1. A positive value indicates a direct relationship between two parameters, while a negative value signifies an inverse relationship. For instance, R_{lm} and ρ have a strong positive correlation (0.88), indicating they increase together, whereas D_d and L_o have a strong negative correlation (-1.00), meaning when one increases, the other decreases. These correlations help in understanding how different parameters influence each other in erosion risk and landscape analysis. The individual weights are derived from these correlations, emphasizing parameters that exhibit stronger relationships with erosion and hydrological behavior (Walia et al., 2021; Ghasemlounia and Utlu, 2021).

The WCF gives a comprehensive priority score by integrating both the preliminary priority (PP) of each parameter and its Wi, thus providing a balanced approach to determining the final priority

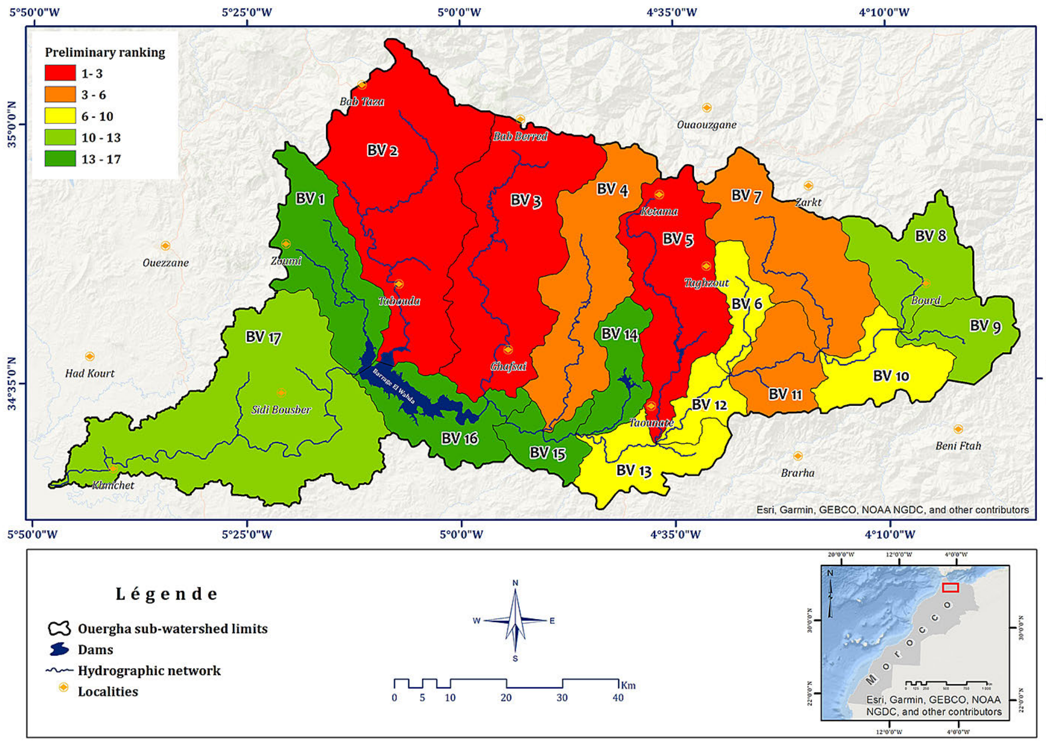

Figure 7. Map highlighting preliminary priority sub-watersheds susceptible to soil erosion

Table 4. Preliminary ranking of morphometric parameters

Sub watershed	Linear parameters										Relief parameters				Shape/ areal parameters						Compound factor	Preliminary rank
SW	L_{Um}	R_{bm}	D_d	F_s	D_i	L_o	C_{cm}	D_t	I_f	ρ	B_h	R_h	R_{hp}	R_n	F_f	R_c	C_c	R_e	K	S_b	CF	PR
BV 3	1	2	9	8	9	9	9	3	6	1	6	12	3	3	3	7	11	3	15	15	6.75	1
BV 2	7	9	7	1	5	11	11	1	3	9	3	13	2	2	2	12	6	2	16	16	6.9	2
BV 5	11	12	12	10	6	6	6	5	11	10	1	4	6	1	5	5	13	5	13	13	7.75	3
BV 7	13	7	17	4	1	1	1	4	14	12	4	7	13	6	6	10	8	6	12	12	7.9	4
BV 4	3	4	10	15	12	8	8	7	15	8	5	9	4	4	4	1	17	4	14	14	8.3	5
BV 11	14	8	11	5	4	7	7	6	9	15	7	3	12	9	12	17	1	12	6	6	8.55	6
BV 12	4	11	3	6	14	15	15	16	4	4	8	2	10	8	17	15	3	17	1	1	8.7	7
BV 6	2	16	13	17	11	5	5	17	17	2	2	1	9	5	16	13	5	16	2	2	8.8	8
BV 13	15	3	2	2	10	16	16	13	1	16	9	5	8	7	11	3	15	11	7	7	8.85	9
BV 10	12	5	16	7	2	2	2	11	13	13	10	6	15	10	10	9	9	10	8	8	8.9	10
BV 9	5	17	14	9	3	4	4	12	12	3	12	8	17	12	13	16	2	13	5	5	9.3	11
BV 17	8	15	1	11	16	17	17	2	2	6	15	17	1	14	1	2	16	1	17	17	9.8	12
BV 8	9	13	15	14	8	3	3	9	16	7	11	11	16	11	9	14	4	9	9	9	10	13
BV 14	6	14	5	12	13	13	13	14	7	5	13	10	11	13	14	11	7	14	4	4	10.15	14
BV 1	10	6	8	13	15	10	10	8	10	11	14	16	5	15	7	4	14	7	11	11	10.25	15
BV 15	17	1	6	3	7	12	12	15	5	17	17	14	14	17	15	6	12	15	3	3	10.55	16
BV 16	16	10	4	16	17	14	14	10	8	14	16	15	7	16	8	8	10	8	10	10	11.55	17

ranking. Parameters with higher individual weights and higher preliminary priority values will contribute more significantly to the final weighted compound factor, ensuring a weighted consideration of both inherent priority and statistical influence.

Final weighted compound factor (WCF) calculation

The final WCF value is calculated by summing the products of each parameter's weight

Table 5. Correlation matrix and weight calculation

Para-meter	Linear parameters										Relief parameters					Shape/ areal parameters					
	R_{lm}	R_{bm}	D_d	F_s	D_i	L_o	C_{cm}	D_t	I_f	ρ	B_h	R_h	R_{hp}	R_n	L_b	F_f	R_c	C_c	R_e	K	S_b
R_{lm}	1.00	0.02	-0.09	-0.19	-0.07	0.07	0.07	0.24	-0.16	0.88	0.46	0.23	0.19	0.49	0.27	-0.23	-0.09	0.05	-0.23	0.25	0.25
R_{bm}	0.02	1.00	0.10	0.45	0.17	-0.12	-0.12	-0.06	0.33	-0.39	-0.17	-0.24	0.07	-0.15	-0.08	0.08	-0.17	0.19	0.08	-0.08	-0.08
D_d	-0.09	0.10	1.00	0.15	-0.78	-1.00	-1.00	0.08	0.83	-0.15	-0.47	-0.37	0.59	-0.29	0.19	-0.09	-0.38	0.42	-0.10	0.13	0.13
F_s	-0.19	0.45	0.15	1.00	0.50	-0.15	-0.15	0.31	0.67	-0.38	0.09	-0.12	-0.01	0.15	0.10	-0.05	0.13	-0.13	-0.05	0.07	0.07
D_i	-0.07	0.17	-0.78	0.50	1.00	0.78	0.78	0.15	-0.31	-0.13	0.45	0.23	-0.53	0.33	-0.09	0.03	0.42	-0.45	0.04	-0.05	-0.05
L_o	0.07	-0.12	-1.00	-0.15	0.78	1.00	1.00	-0.08	-0.83	0.14	0.46	0.37	-0.60	0.28	-0.19	0.09	0.38	-0.41	0.10	-0.13	-0.13
C_{cm}	0.07	-0.12	-1.00	-0.15	0.78	1.00	1.00	-0.08	-0.83	0.14	0.46	0.37	-0.60	0.28	-0.19	0.09	0.38	-0.41	0.10	-0.13	-0.13
D_t	0.24	-0.06	0.08	0.31	0.15	-0.08	-0.08	1.00	0.22	0.12	0.38	-0.48	0.44	0.42	0.94	-0.91	-0.12	0.16	-0.92	0.93	0.93
I_f	-0.16	0.33	0.83	0.67	-0.31	-0.83	-0.83	0.22	1.00	-0.31	-0.29	-0.32	0.44	-0.12	0.19	-0.09	-0.23	0.25	-0.10	0.13	0.13
ρ	0.88	-0.39	-0.15	-0.38	-0.13	0.14	0.14	0.12	-0.31	1.00	0.45	0.43	0.08	0.46	0.16	-0.08	0.00	-0.05	-0.09	0.12	0.12
B_h	0.46	-0.17	-0.47	0.09	0.45	0.46	0.46	0.38	-0.29	0.45	1.00	0.51	0.23	0.98	0.31	-0.33	0.00	0.01	-0.33	0.32	0.32
R_h	0.23	-0.24	-0.37	-0.12	0.23	0.37	0.37	-0.48	-0.32	0.43	0.51	1.00	-0.17	0.48	-0.54	0.58	0.31	-0.33	0.58	-0.57	-0.57
R_{hp}	0.19	0.07	0.59	-0.01	-0.53	-0.60	-0.60	0.44	0.44	0.08	0.23	-0.17	1.00	0.35	0.57	-0.51	-0.47	0.55	-0.52	0.54	0.54
R_n	0.49	-0.15	-0.29	0.15	0.33	0.28	0.28	0.42	-0.12	0.46	0.98	0.48	0.35	1.00	0.36	-0.36	-0.07	0.08	-0.36	0.37	0.37
L_b	0.27	-0.08	0.19	0.10	-0.09	-0.19	-0.19	0.94	0.19	0.16	0.31	-0.54	0.57	0.36	1.00	-0.98	-0.40	0.44	-0.98	0.99	0.99
F_f	-0.23	0.08	-0.09	-0.05	0.03	0.09	0.09	-0.91	-0.09	-0.08	-0.33	0.58	-0.51	-0.36	-0.98	1.00	0.39	-0.44	1.00	-1.00	-1.00
R_c	-0.09	-0.17	-0.38	0.13	0.42	0.38	0.38	-0.12	-0.23	0.00	0.00	0.31	-0.47	-0.07	-0.40	0.39	1.00	-0.97	0.39	-0.40	-0.40
C_c	0.05	0.19	0.42	-0.13	-0.45	-0.41	-0.41	0.16	0.25	-0.05	0.01	-0.33	0.55	0.08	0.44	-0.44	-0.97	1.00	-0.44	0.45	0.45
R_e	-0.23	0.08	-0.10	-0.05	0.04	0.10	0.10	-0.92	-0.10	-0.09	-0.33	0.58	-0.52	-0.36	-0.98	1.00	0.39	-0.44	1.00	-1.00	-1.00
K	0.25	-0.08	0.13	0.07	-0.05	-0.13	-0.13	0.93	0.13	0.12	0.32	-0.57	0.54	0.37	0.99	-1.00	-0.40	0.45	-1.00	1.00	1.00
S_b	0.25	-0.08	0.13	0.07	-0.05	-0.13	-0.13	0.93	0.13	0.12	0.32	-0.57	0.54	0.37	0.99	-1.00	-0.40	0.45	-1.00	1.00	1.00
CT	3.42	0.81	-1.08	2.45	2.41	1.02	1.02	3.67	0.58	2.49	4.85	1.38	2.17	5.06	3.07	-2.80	-0.32	0.40	-2.84	2.94	2.94
GT	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62	33.62
Weight	0.10	0.02	-0.03	0.07	0.07	0.03	0.03	0.11	0.02	0.07	0.14	0.04	0.06	0.15	0.09	-0.08	-0.01	0.01	-0.08	0.09	0.09

(Wi) and its corresponding compound factor. In this study, WCF values range from 5.13 (SW6) to 16.99 (SW16). The watershed with the lowest WCF value (SW6) is assigned the highest priority ranking, while SW16 with the highest WCF receives the lowest priority. These rankings (Table 6) help determine which watersheds are most vulnerable to erosion and require immediate attention for soil conservation measures.

Quartile method and final classification

This classification allows for targeted conservation efforts, particularly in watersheds deemed most vulnerable to erosion. Such prioritization is critical for effective watershed management, especially in regions where erosion control and sustainable water management are key concerns (El Brahimi et al., 2024). To classify the sub-watersheds based on their WCF values using the quartile method, the data is divided into four groups: very high, high, medium, and low vulnerability. This classification helps prioritize SWs based on

Table 6. Priority ranking

SWs	WCF	Rank
SW 6	5,1345603	1
SW 5	6,97720634	2
SW 2	7,23433823	3
SW 7	7,2737392	4
SW 12	7,49484463	5
SW 11	7,69971357	6
SW 3	7,83407398	7
SW 9	8,78604301	8
SW 10	9,47057106	9
SW 4	9,63003258	10
SW 13	10,6012517	11
SW 8	11,154744	12
SW 14	11,4845828	13
SW 15	13,5211739	14
SW 1	14,6157578	15
SW 17	16,1345873	16
SW 16	16,9930714	17

Table 7. Final classification of sub-watershed based on morphometric parameters

Quartiles	Vulnerability	Classification	Value
Q4	Very High	SW 6	5,1345603
		SW 5	6,97720634
		SW 2	7,23433823
		SW 7	7,2737392
Q3	High	SW 12	7,49484463
		SW 11	7,69971357
		SW 3	7,83407398
		SW 9	8,78604301
Q2	Medium	SW 10	9,47057106
		SW 4	9,63003258
		SW 13	10,6012517
		SW 8	11,154744
Q1	Low	SW 14	11,4845828
		SW 15	13,5211739
		SW 1	14,6157578
		SW 17	16,1345873
		SW 16	16,9930714

erosion risk, with Q4 requiring the most urgent attention (Table 7).

The analysis of the morphometric parameters of the Wadi Ouergha sub-watersheds reveals distinct characteristics influencing their hydrological dynamics and erosion vulnerabilities. These sub-watersheds (BV 3, BV 2, BV 5, BV 7, and BV 4) are characterized by a high number of streams, long stream lengths, and high drainage texture, creating conditions conducive to rapid runoff, concentrated flow, and consequently, increased erosion potential.

High watershed relief, high relative relief, and high roughness ratio indicate that these

Table 8. Hypsometric integral (HI) values of the Oued Ouergha Sub-Watersheds

SWs	H_{min}	H_{max}	H_{mean}	*HI*	Geological maturity
SW 1	92	912	430	0.41	Mature
SW 2	146	2104	617	0.24	Old
SW 3	161	2086	658	0.26	Old
SW 4	177	2107	835	0.34	Mature
SW 5	257	2443	999	0.34	Old
SW 6	350	2320	1132	0.40	Mature
SW 7	484	2440	1266	0.40	Mature
SW 8	753	1892	1200	0.39	Mature
SW 9	753	1873	1277	0.47	Mature
SW 10	484	1810	1076	0.45	Mature
SW 11	340	1791	811	0.32	Mature
SW 12	255	1614	585	0.24	Old
SW 13	193	1544	387	0.14	Old
SW 14	193	1137	527	0.35	Mature
SW 15	164	738	298	0.23	Old
SW 16	92	822	253	0.22	Old
SW 17	16	833	168	0.19	Old
Ouergha SW	16	2447	676	0.27	Old

sub-watersheds have marked topographical variations and turbulent flow, affecting water runoff speed and increasing erosion potential. A low form factor and low elongation ratios signal elongated sub-watersheds with less intense but prolonged flood flow, thus increasing their susceptibility to flooding and consequently, a higher erosion potential.

All these parameters indicate that these sub-watersheds have conditions favorable to erosion processes, making them vulnerable to soil degradation, which significantly impacts the El Wahda dam by causing sedimentation and reducing its storage capacity.

Hypsometric analysis

Using the methodology described above, the various HI values observed in the sub-watersheds of the Oued Ouergha are presented in Table 8.

According to the classification by Singh et al. (2008) and Xiang et al. (2015), the hypsometric analysis of the sub-watersheds of the Oued Ouergha reveals three stages of geomorphological evolution. Sub-watersheds with an HI ≤ 0.35 are in an old stage, characterized by advanced erosion and gentle slopes, such as SW 2, SW 3, and SW 16. Those with an HI between 0.35 and 0.6 are considered to be in a mature stage, with moderate relief, such as SW 1, SW 4, and SW 10. Sub-watersheds with an HI > 0.6 represent a young stage with pronounced relief, but no sub-watershed in the Oued Ouergha falls into this stage.

The hypsometric curve is calculated using relative surface area (a/A) and relative altitude (h/H), which normalize the topographical features of a watershed, allowing for the comparison of basins with varying scales and sizes. The relative surface area (a/A) represents the fraction of the total basin area below a specific elevation, while relative altitude (h/H) indicates the elevation as a fraction of the basin's maximum altitude. This normalization is crucial for analyzing altitude distribution within watersheds regardless of their absolute size, aiding in identifying stages of erosional evolution (Strahler, 1952). The hypsometric curve helps assess landscape maturity by showing how the relief is distributed, offering insights into geomorphological processes and tectonic history (Pike and Wilson, 1971). This standardized approach is widely used for comparing watershed morphology across different regions and scales. The results of the hypsometric curves are presented in the following Figure 8.

The interpretation of results for the sub-watersheds (SW) of the Oued Ouergha evaluates their geological maturity and stages of erosion. The minimum altitude (H_{min}), maximum altitude (H_{max}), average altitude (H_{mean}), and HI provide essential insights into the geomorphological evolution of each sub-basin.

- Sub-watersheds with old maturity (HI ≤ 0.35): SWs such as SW 2, SW 3, SW 5, SW 12, SW 13, SW 15, SW 16, SW 17, and Ouergha display HI values ≤ 0.35, indicating advanced geological maturity. These areas are heavily eroded,

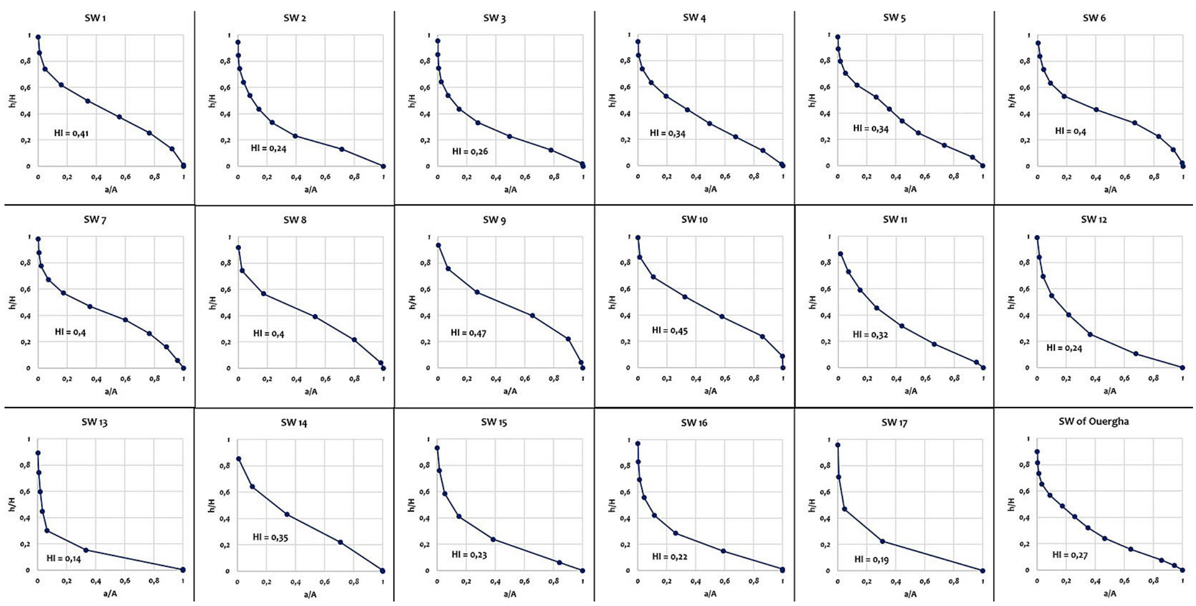

Figure 8. Hypsometric curve of sub-watersheds

with gentle relief and minimal altitude differences. For example, SW 13 has a particularly low HI value (0.14), suggesting an advanced stage of erosion. SW 2 and SW 3, despite high H_{max} values (2104 m and 2086 m), indicate that they have experienced past tectonic activity but are now dominated by erosion.
- Sub-watersheds with intermediate maturity (0.35 < HI ≤ 0.6): SWs like SW 1, SW 4, SW 6, SW 7, SW 8, SW 9, SW 10, SW 11, and SW 14 are at a mid-maturity stage, with HI values between 0.35 and 0.6. These basins still have significant relief, but erosion is reducing the altitudes. For instance, SW 9, with an HI of 0.47, reflects a balance between erosion and tectonic forces, suggesting ongoing geomorphological processes such as river incision or landslides. SW 6, SW 7, and SW 8, with maximum altitudes above 1800 m, indicate areas where erosion is active but significant relief remains.

Here is the final classification of all the sub-watersheds (SWs) based on the Hypsometric Integral (HI) values (Table 9). This classification helps in identifying which sub-watersheds require more immediate attention for management and conservation based on their erosion vulnerability.

Common sub-watersheds

The comparison between the Morphometric Analysis and Hypsometric Analysis of the sub-watersheds (SWs) reveals important differences in the priority rankings for watershed management (Table 10). Results show that:

- SW 1: Rated as low in morphometric analysis but very high in hypsometric analysis, suggesting that despite low morphometric vulnerability, the area has significant relief features indicating potential erosion.
- SW 2 and SW 3: Both have very high and high morphometric priorities but rank medium in hypsometric analysis, showing that erosion processes may be less advanced despite their morphometric characteristics.
- SW 4 and SW 5: These watersheds have consistent results with medium to high ratings in both analyses, aligning morphometric and hypsometric evaluations regarding vulnerability.
- SW 6 and SW 7: Both analyses rate these watersheds as very high, indicating a strong agreement between the two methods about their high erosion potential.
- SW 8: Rated as medium in morphometric analysis but high in hypsometric analysis, indicating the area may have more pronounced topographical features than originally suggested by the morphometric analysis.

Table 10. Common sub-watersheds

SWs	Morphometric analysis	Hypsometric analysis
SW 1	Low	Very High
SW 2	Very high	Medium
SW 3	High	Medium
SW 4	Medium	High
SW 5	Very high	High
SW 6	Very high	Very high
SW 7	Very high	Very high
SW 8	Medium	High
SW 9	High	Very High
SW 10	Medium	Very High
SW 11	High	High
SW 12	High	Medium
SW 13	Medium	Low
SW 14	Low	High
SW 15	Low	Medium
SW 16	Low	Medium
SW 17	Low	Low

Table 9. Hypsometric priority classification

SWs	HI	Priority
SW 13	0,14	Low
SW 17	0,19	Low
SW 16	0,22	Medium
SW 15	0,23	Medium
SW 2	0,24	Medium
SW 12	0,24	Medium
SW 3	0,26	Medium
SW 11	0,32	High
SW 4	0,34	High
SW 5	0,34	High
SW 14	0,35	High
SW 8	0,39	High
SW 6	0,4	Very High
SW 7	0,4	Very High
SW 1	0,41	Very High
SW 10	0,45	Very High
SW 9	0,47	Very High

- SW 9 and SW 10: These watersheds show high to very high vulnerability in both methods, indicating consistent recognition of significant erosion risks.
- SW 11 and SW 12: Display differences, where morphometric analysis ranks them higher than hypsometric analysis, suggesting the need for further fieldwork to confirm their erosion vulnerability.
- SW 13 and SW 14: These watersheds show opposing results—medium to low for SW 13 and low to high for SW 14 highlighting the importance of a combined approach to assess their true vulnerability.
- SW 15, SW 16, and SW 17: These watersheds are rated low to medium in both analyses, consistently indicating lower vulnerability.

To develop effective management strategies for these sub-watersheds, it is essential to consider the distinct morphometric and hydrological characteristics identified. Sub-watersheds SW 6, SW 7, and SW 11 show high erosion risk due to their specific topographical features and flow patterns. Although the two analytical methods generally align, certain discrepancies underscore the need for further investigation, particularly through field validation, to accurately assess erosion risk and establish management priorities for each sub-watershed (Rahaman et al., 2018; Singh et al., 2021). The combined results of morphometric and hypsometric analyses provide a robust scientific basis for identifying initial erosion vulnerability across sub-watersheds. This foundation supports the development of targeted management measures, guiding effective, data-informed strategies for mitigating erosion risks.

CONCLUSIONS

The analysis of the Wadi Ouergha watershed using both morphometric and hypsometric methods highlights the varied geomorphological and hydrological characteristics across its sub-watersheds. The integration of these approaches provides a comprehensive understanding of erosion risk, with several sub-watersheds identified as vulnerable due to their high stream frequency and drainage density. The study confirms that areas with high HI values are younger and less eroded, while older sub-watersheds exhibit advanced erosion. However, the results are initial and should be validated through fieldwork to ensure accurate prioritization of conservation efforts. This combined methodology serves as a valuable tool for watershed management and highlights the need for continued research, particularly in regions affected by erosion and sedimentation.

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