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Sub-Watershed Prioritization for Soil Erosion Risk Assessment in the Wadi Ouahrane Basin (Algeria) Using an Integrated Morphometric Analysis and Entropy-WASPAS Model

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Abstract

Soil erosion is a major environmental challenge affecting watershed sustainability, land productivity, and water resource management. Identifying erosion-prone areas is essential for prioritizing conservation measures and supporting sustainable watershed planning. This study evaluates erosion susceptibility and prioritizes sub-basins within the Wadi Ouahrane watershed (Algeria) using an integrated morphometric analysis and Entropy-WASPAS multi-criteria decision-making framework. Fourteen sub-basins were delineated and analyzed using morphometric parameters related to basin shape, drainage characteristics, relief, and hypsometry derived from digital elevation and drainage network data. The Entropy method was applied to determine objective weights for the selected criteria, while the WASPAS model was used to rank sub-basins according to erosion susceptibility. Results indicate that the watershed is predominantly characterized by elongated basin geometries, reflected by low values of form factor (0.36–0.42), elongation ratio (0.38–0.41), and circularity ratio (0.23–0.50). Drainage density ranged from 1.60 to 1.95 km/km², while drainage texture values below 2 classified all sub-basins as very coarse-textured, suggesting relatively favorable infiltration conditions. The watershed was identified as a fifth-order drainage basin comprising 428 stream segments, with first-order streams accounting for 45.56% of the network. Entropy weighting revealed that the bifurcation ratio (0.283) and stream length ratio (0.252) were the most influential factors controlling erosion susceptibility. WASPAS ranking identified SW-3, SW-4, SW-5, SW-7, SW-12, and SW-13 as very high-risk sub-basins, with SW-4 exhibiting the highest susceptibility (VSPM = 0.857). This integrated approach proved effective for erosion risk assessment and watershed prioritization, providing a robust basis for soil conservation and sustainable watershed management.

Introduction

Soil is one of the most fundamental natural resources that ensures the continuity of terrestrial life. The structural condition and spatial distribution of land cover, which directly determine soil fertility and ecosystem health, play a critical role in the environmental and economic sustainability of countries (Dursun, 2025a).

The arid and semi-arid ecosystems of the Mediterranean Basin show a high level of vulnerability to erosion under the simultaneous influence of natural dynamics and anthropogenic pressures. Natural constraints such as heavy rainfall, steep topography, and sparse vegetation, combined with inappropriate land use, grazing pressure, and forest fires, increase the threat of water erosion to serious levels (Peñuela et al., 2026).

Soil erosion is one of the most important forms of soil degradation in the world, with approximately 75 billion tons of soil eroded globally every year (Mokhtari et al., 2018). Algeria, located in North Africa, is highly susceptible to soil erosion due to its topographical structure, steep slopes, and sparse vegetation, and ranks among the countries with the highest erosion severity worldwide (Tachi et al., 2020; Limane et al., 2026). It is reported that over 50 million hectares of land in the country are at risk of erosion and

exhibit a vulnerable structure (Kessaissia & Mazour, 2019). Moreover, this situation leads to the accumulation of sediment (siltation) in large dams, resulting in an annual loss of 20 million m^3 of storage space (Limane et al., 2026). To effectively combat erosion and related siltation problems, it is necessary to identify priority areas and develop urgent management and planning strategies. In these management and planning processes, basins stand out as the most ideal spatial and hydrological base units for the examination and planning of natural resources. Findings obtained through the analysis of the morphometric structures of basins function as a critical decision support mechanism in many areas, from the efficient management of water reserves to the prevention of erosion and the creation of landslide risk maps, by calculating various risks and ranking sub-basins according to risk (Singh et al., 2021).

One of the most critical steps in basin management strategies is identifying and prioritizing at-risk areas that are under threat of degradation and require urgent protection and rehabilitation measures (Bharath & Maddamsetty, 2026). In this process, morphometric analyses are frequently used to measure the susceptibility of areas to erosion. Morphometry quantifies geomorphological parameters such as slope, relief, drainage density, and stream length, revealing their relationships with erosion processes, and it also forms the fundamental measurement mechanism for hydrological modeling and basin prioritization studies (Dursun & Babalık, 2025). Since applying morphometric analyses alone cannot provide comprehensive decision support in watershed planning, the inclusion of Multi-Criteria Decision Making (MCDM) approaches, which combine numerous parameters, is of great importance. This integrated structure offered by MCDM methods allows decision-makers to produce unbiased solutions and obtain highly comprehensive and accurate results by integrating different topographic and geographical variables into a single framework (Guria et al., 2024; Dwivedi & Sharma, 2024; Keramati & Shapouri, 2016).

In the literature, various MCDM methods are used to prioritize sub-watersheds according to their erosion susceptibility. These applications generally evaluate different morphometric and environmental criteria together to identify areas with high erosion risk and to implement conservation measures. In erosion susceptibility analyses, the WASPAS (Weighted Aggregated Sum Product Assessment) method has emerged as a powerful tool in recent years for its high accuracy and stability in decision-making (Sarkar & Gayen, 2024; Dursun & Babalık, 2025). In multi-criteria decision-making models, the reliability of the findings largely depends on how the criteria are weighted. The entropy method is an ideal solution at this stage because it prevents the subjectivity that personal expert assessments may introduce and provides an objective measurement based entirely on data variance. In the present study, objective criterion weights, determined using entropy, were integrated into the WASPAS algorithm, yielding a transparent, verifiable model for prioritizing sub-basins based on their erosion risk levels. The developed hybrid (Entropy-WASPAS) model structure increases the effectiveness of conservation strategies by enabling the identification of areas requiring urgent intervention in basin management planning on scientific grounds (Akay et al., 2023; Sampath & Radhakrishnan, 2024; Dursun, 2025b).

This study presents an integrated assessment based on morphometric analyses in the Wadi Ouahrani Basin, Algeria. The main objective of the study is to objectively determine the erosion potential of the sub-basins that make up the Wadi Ouahrani Basin and to rank these sub-basins in terms of management priority. For this purpose, the linear, areal, and relief morphometric parameters of the basin were first calculated; then these parameters were weighted using the Entropy method. The obtained weights were evaluated within the framework of multi-criteria decision analysis using the WASPAS method, and the sub-basins were prioritized in terms of erosion risk.

The combination of Entropy and WASPAS methods with GIS-based morphometric analyses provides a scientifically sound, transparent, and repeatable decision support mechanism in basin management. The results obtained apply not only to the Wadi Ouahrani Basin but also to other basins with similar morphological structures and climatic challenges. In this respect, the study provides concrete data and strategic analyses for the development of sustainable land and water resource management policies.

Materials and methods

Study Area

The Wadi Ouahrane basin of north Algeria, which is located between 36°00' and 36°24' N and between 01°00' and 01°3' E, has been chosen for this study. It is a tributary of one of the most important basins of the region, the Wadi Cheliff basin, and it borders the Wadi Fodda basin to the east, with the Wadi Ras basin to the west, the Wadi Allala basin to the north, and the Wadi Sly basin to the south. As a result, the basin extends over an area of 270 km^2 with a maximum altitude of 991 m and a minimum altitude of 165 m (Fig. 1).

It is influenced by the Mediterranean climate with an interannual average rainfall of 333 mm over the period (1972–2018). The mean annual temperature is 18°C (Achite et al., 2022a). The monthly series of the meteorological parameters for the period 1972–2018 were obtained from the National Agency for Hydraulic Resources (ANRH) and the National Meteorological Office (ONM) of Algeria. The runoff data from 1972 to 2018 were also collected from ANRH. By analyzing the data on runoff, we can uncover various hydrological features pertaining to the catchment area. In particular, the monthly runoff within the Wadi Ouahrane basin exhibits a strong correlation with the rainy season. This correlation becomes apparent as the highest monthly runoff values are observed during the winter months, specifically in December and June. Conversely, during the summer season, when rainfall amounts are typically lower, the runoff values reach their lowest point, and in some years with minimal precipitation, they may even dwindle to zero (Achite et al., 2023).

Methodological Approach for Erosion Risk and Watershed Prioritization

A stream network was extracted from the DEM data via the ArcHydro module, utilizing Strahler's (1964) hierarchical ordering system (Dursun & Babalık, 2025). Following this, stream numbers and lengths were determined through ArcGIS attribute analysis (Fig. 2). The Wadi Ouahrani Basin was delineated into 14

sub-basins through hydrological analyses conducted using the ArcHydro extension integrated into ArcGIS. The spatial data used to calculate the morphometric parameters of these sub-basins, which constitute the research area, were generated using ArcGIS 10.2 software.

Morphometric analyses

Morphometric analyses play a critical role in the effective management and planning of natural resources within a basin. In this context, a detailed examination of the drainage networks and hydrological structures of the main basin and its sub-basins facilitates the prediction of natural hazards such as floods, droughts, and erosion. This provides vital guidance for decision-makers in developing future-oriented strategies (Dursun, 2025a; Colín-García et al., 2026). Within the scope of this research, the areal, linear, and relief morphometric parameters of the Wadi Ouahrani Basin were analyzed, and the corresponding formulas are presented in Table 1.

Table 1
Calculation Criteria for Morphometric Parameters

Basic Morphometry	Formula	Unit	References
Basin area (A)	GIS operation	km^2	-
Perimeter of the basin (P)	GIS operation	km	-
Basin length (Lb)	$Lb = 1.312*A^{0.568}$	km	Schumm (1956)
Linear			
Stream number (Nu)	$N_u = N_1 + N_2 + \ldots N_n$	Dimensionless	Horton (1945)
Bifurcation ratio (Rb)	$Rb = N/N_{u+1}$	Dimensionless	Horton (1945)
Stream length (Lu)	Linear measurement of each stream/GIS	km	Horton (1932)
Mean stream length (Lsm)	$L_{um} = Lu/Nu$	km	Horton (1945)
Stream length ratio (Rl)	$Rl = lu/lu + 1$	Dimensionless	Horton (1945)
Length of overland flow (Lo)	$Lo = 1/2Dd$	km	Horton (1932)
Areal			
Form factor ratio (Ff)	$Ff = A/Lb^2$	Dimensionless	Horton (1945)
Elongation ratio (Re)	$Re = 2/Lb \times A^{0.5}/\Pi$	Dimensionless	Schumm (1956)
Circularity ratio (Rc)	$Rc = 12.57 \times (A/P^2)$	Dimensionless	Strahler (1964)
Stream frequency (Fs)	$Fs = Nu/A$	km^{-2}	Schumm (1956)
Drainage density (Dd)	$Dd = Lu/A$	km^{-1}	Schumm (1956)
Drainage texture (Dt)	$Dt = Nu_1/P$	km^{-1}	Schumm (1956)
Compactness coefficient (Cc)	$Cc = P/2(\Pi A)^{0.5}$	Dimensionless	Gravelius (1914)
Relief			
Basin relief (R)	$R = H–h$	km	Strahler (1952)
Relief ratio (Rr)	$Rr = R/Lb$	Dimensionless	Schumm (1956)

Basic Morphometry	Formula	Unit	References
Relative relief (Rhp)	Rhp=(H*100/P)	Dimensionless	Melton (1958)
Ruggedness number (Rn)	Rn = Dd × R	Dimensionless	Strahler (1964)
Hypsometric integral (Hi)	Hi = $(H_{mean} - H_{min})/(H_{max} - H_{min})$	Dimensionless	Mayer (1990)

Entropy Criteria Weighting

The concept of entropy was first introduced in 1865 by the German scientist Rudolf J. E. Clausius to quantitatively measure the uncertainty and disorder within systems (Tsallis, 2022). The Entropy method was employed in this study to determine the relative criterion weights. As the method comprises five successive and interdependent steps, each phase must be fully completed before advancing to the next. Commencing with the construction of the decision matrix within the Multi-Criteria Decision Making (MCDM) framework, the procedural steps of this method are outlined in Table 2 (White, 1982; Dursun & Babalık, 2025).

Table 2
Steps and mathematical equations of the Entropy weighting method

Step	Description	Equation
1	**Standardization of the Decision Matrix**: Standardizing the data based on whether they are benefit or cost criteria.	Benefit Criteria:$r_{ij} = \frac{x_{ij}}{max_i(x_{ij})}$ Cost Criteria: $r_{ij} = \frac{min_i(x_{ij})}{x_{ij}}$
2	**Normalization**: Converting the data into the 0–1 range by dividing them by their respective column totals.	$P_{ij} = \frac{a_{ij}}{\sum_{j=1}^{m} a_{ij}}$
3	**Calculation of Entropy Values**: Calculating the entropy value (E_j) for each criterion	$\mathrm{E_j} = -\mathrm{k}^{*}\sum_{\mathrm{j}=1}^{\mathrm{m}} \mathrm{P_{ij}}^{*}\ln\left(\mathrm{P_{ij}}\right)$
4	**Degree of Divergence**: Calculating the degree of divergence (d_j) for each criterion	$\mathrm{d_j} = 1 - \mathrm{E_j}$
5	**Calculation of Criterion Weights**: Proportionally determining the final criterion weight coefficients (w_j).	$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$
Abbreviations and Symbols: i: Alternative, j: Criterion, m: Number of alternatives, n: Number of criteria, x_{ij}/a_{ij}: Initial performance values in the decision matrix, r_{ij}: Standardized values, P_{ij}: Normalized values, k: Entropy coefficient -, E_j: Entropy value, d_j: Degree of divergence, w_j: Criterion weight coefficient		

Sub-basin Prioritization via a Hybrid Entropy-WASPAS Approach

Introduced by Zavadskas et al. (2012), the WASPAS approach functions as a hybrid framework that synthesizes the strengths of both WSM and WPM models. This methodology yields results that minimize error margins in multidimensional decision-making processes, such as the sustainability of forest assets, analysis of ecosystem functions, and strategic resource management. Widely utilized today in fields ranging from environmental strategies to engineering solutions, the procedural steps of this methodology are detailed in Table 3.

Table 3
Steps and mathematical equations of the WASPAS method

Step	Description	Equation
1	**Formation of the Decision Matrix**: Structuring the performance values of alternatives against the evaluation criteria.	$X = \left[x_{ij}\right]_{m*n}$
2	**Normalization**: Linear normalization of the decision matrix based on whether the criteria are benefit or cost-oriented.	Benefit : $\overline{x} = \frac{x_{ij}}{max_i * x_{ij}}$ Cost : $\overline{x} = \frac{min_i * x_{ij}}{x_{ij}}$
3	**Weighted Sum Model (WSM)**: Calculating the total relative importance of the alternative ($Q_i^{(1)}$) by summing the weighted normalized values.	$Q_i^{(1)} = \sum_{j=1}^{n} \overline{x_{ij}} * w_j$
4	**Weighted Product Model (WPM)**: Calculating the total relative importance of the alternative ($Q_i^{(2)}$)by multiplying the exponentiated weighted values.	$Q_i^{(2)} = \prod_{j=1}^{n} \left(\overline{x_{ij}}\right)^{w_j}$
5	**Aggregated Joint Score**: Calculating the final WASPAS score (Q_i) by linearly combining the WSM and WPM models.	$Q_i = \lambda * Q_i^{(1)} + (1-\lambda) * Q_i^{(2)}$
Abbreviations and Symbols: i: Alternative(i = 1, 2, …..m), j: Criterion (j = 1, 2, …..n), x_{ij}: Initial performance value of the i-th alternative for the j-th criterion, w_j: Weight of the j-th criterion $Q_i^{(1)}$: Relative importance based on $Q_i^{(2)}$: Relative importance based on WPM, Q_i: Final aggregated score of the alternative, λ: Joint generalized criteria parameter (typically set to 0.5)		

Results and Discussions

Morphometric Analysis and Areal Morphometric Parameters

An examination of Table 4 reveals that the Ff values in the study basin range between 0.36 (SW-6) and 0.42 (SW-10). As noted by Dursun & Babalık (2023), as the form factor approaches 0, it indicates an

elongated basin morphology, suggesting that water reaches the basin outlet slowly, which is associated with lower surface runoff velocities and weaker drainage channels.

Re values range from 0.38 to 0.41, with the lowest value recorded in SW-6 and the highest in the SW-10 sub-basin. These data confirm that the study area possesses an elongated structure in terms of morphology. Elongated basins tend to trigger erosion processes by allowing surface runoff to persist for longer durations on low-slope surfaces. Similarly, in a study by Petiangma et al. (2026), Re values were determined to be in the range of 0.43–0.57; it was stated that these values serve as critical determinants for hydrological responses, flow accumulation models, and erosion risk. The findings of the current research show results consistent with this literature.

Rc is one of the primary morphometric indicators reflecting the influence of basin shape on hydrological response, providing significant information regarding the general character of the basin. A low value for this parameter indicates that the basin exhibits an elongated morphology, characterized by relatively higher infiltration capacity and slower surface runoff. This morphological structure can partially limit the erosion risk across the basin. Examinations conducted specifically for the sub-basins in the study area show that Rc values vary between 0.23 and 0.50, with the lowest ratio recorded in SW-9 and the highest in the SW-6 sub-basin. These results demonstrate that the basins in the study area possess a distinctively elongated character rather than a circular structure. Similar findings have been reported by Das et al. (2026), who highlighted that basins within the 0.24–0.42 range exhibit an elongated structure. The data obtained from the current research support these assessments in the literature.

Fs values calculated in the study area exhibit a distribution ranging from 2.67 to 4.54 (Table 4). Notably, the lowest Fs value was recorded in the SW-13 sub-basin, while the highest was found in the SW-11 sub-basin. In the literature, Shekar & Mathew (2024) emphasize that high Fs values indicate that the basin surface is densely fragmented and surface runoff is intensified; this condition naturally entails an increased risk of erosion. In contrast, lower values point to more stable surface characteristics and conditions where water infiltration into the soil is higher, which in turn limits erosion formation. Based on an evaluation of the findings, it has been determined that the SW-11 sub-basin has a more sensitive structure toward surface runoff and associated erosion processes, whereas the SW-13 sub-basin exhibits a relatively lower risk of erosion.

Dd, used as a fundamental indicator in the analysis of basin morphometry and erosion susceptibility, ranges from 1.60 to 1.95 km/km² across the study area (Table 4). When the data are evaluated, it is observed that the lowest Dd value occurs in SW-3, while the highest value is found in the SW-7 sub-basin. As emphasized by Basavareddy et al. (2025), drainage density provides critical information regarding the hydrological response and erosion risk of a basin. In this context, the high Dd in the SW-7 sub-basin signifies a developed drainage network, rapid surface runoff, and consequently, increased flood and erosion potential. Conversely, the low Dd observed in SW-3 indicates that this region is relatively more stable in terms of flood and erosion risk. The obtained findings support the control of basin morphometry over hydrological processes in a manner consistent with the literature.

Dt values for the sub-basins range from 0.89 (SW-14) to 1.86 (SW-6). According to the classification system proposed by Smith (1950), values less than 2 are defined as very coarse, 2–4 as coarse, 4–6 as moderate, 6–8 as fine, and values greater than 8 as very fine-textured. Based on this scale, it is observed that all sub-basins in the study area cluster within the 'very coarse' texture class. As is known, Dtis are shaped by the complex interaction of numerous natural factors, such as climatic conditions, lithological structure, infiltration capacity, vegetation cover, and topographic relief (Benzougagh et al., 2022). Regarding erosion susceptibility, the 'very coarse' texture class corresponds to high infiltration and lower surface runoff, indicating a low erosion potential. When comparing the sub-basins, it is predicted that SW-14, which has the lowest Dt value, is the most resistant sub-basin to erosion, whereas SW-6, which has a relatively higher Dt value, exhibits a more sensitive structure in terms of surface runoff and erosion risk.

The fact that the Cc approaches 1 indicates that the basin has a circular form, and this morphology increases erosion risk by causing concentrated surface runoff (Dursun & Babalık, 2023). Conversely, an increase in this coefficient suggests that the basin acquires a longitudinal character, and erosion susceptibility decreases relatively. Analyses conducted specifically for the sub-basins determined that Cc values vary between 1.42 and 2.08; the lowest value was recorded in SW-6, and the highest in the SW-9 sub-basin. Similar findings were reported in a study conducted in northern Algeria by Dali et al. (2023), where Cc values greater than 1 were observed in all sub-basins, and it was noted that this situation indicates a structure resistant to flooding and soil erosion. Therefore, the fact that all sub-basins in the study area satisfy the condition Cc > 1 confirms that these basins have a longitudinal character due to their morphological structures and exhibit lower susceptibility to flash floods and severe erosion processes.

Table 4
Areal morphometric parameters

SW	Ff	Re	Rc	Sf	Dd	Dt	Cc
SW-1	0,39	0,40	0,38	3,17	1,78	1,31	1,63
SW-2	0,38	0,39	0,34	3,09	1,75	1,19	1,70
SW-3	0,38	0,39	0,35	3,36	1,60	1,35	1,68
SW-4	0,38	0,39	0,37	3,72	1,84	1,35	1,65
SW-5	0,39	0,40	0,47	3,22	1,60	1,33	1,46
SW-6	0,36	0,38	0,50	3,24	1,76	1,86	1,42
SW-7	0,39	0,40	0,39	3,05	1,95	1,10	1,59
SW-8	0,39	0,40	0,40	2,74	1,64	1,11	1,58
SW-9	0,41	0,41	0,23	3,90	1,71	0,98	2,08
SW-10	0,42	0,42	0,38	3,31	1,67	0,93	1,63
SW-11	0,40	0,40	0,38	4,54	1,80	1,48	1,62
SW-12	0,38	0,39	0,31	3,20	1,77	1,14	1,80
SW-13	0,41	0,41	0,40	2,67	1,69	0,90	1,58
SW-14	0,40	0,40	0,27	3,10	1,94	0,89	1,92

Linear Morphometric Parameters

According to Strahler (1964), the Wadi Ouahrane basin is classified as a fifth-order basin. Analysis of the basin reveals a notably high number of first-order streams, particularly in the steeper sections. Based on the ordering and stream count estimates at the sub-basin level, a total of 428 streams were identified across the fourteen sub-basins. Of these, 195 are first-order streams, accounting for 45.56% of the total stream count. These findings indicate that first-order streams constitute the most frequent class in the study area, providing significant insights into the structural characteristics of the drainage network.

According to Table 5, the Lu values of the sub-basins range between 16.67 and 56.30 km. It is noteworthy that stream length is a significant feature of the basin, as it reflects surface runoff characteristics in the region. As presented in Table 6, the stream lengths for orders 1, 2, 3, 4, and 5 were measured as 16.78, 6.41, 3.44, 1.41, and 3.87 km, respectively. The total stream length is 453.33 km. The maximum first-order stream length was calculated as 221.79 km, and the average fifth-order stream length was determined to be 15.44 km.

Table 5
Numbers of Stream Orders

SW	1. Nu	2. Nu	3. Nu	4. Nu	5. Nu
SW-1	32	13	7	4	1
SW-2	33	16	9	7	
SW-3	38	11	18	8	
SW-4	36	12	9		21
SW-5	29	17	11		
SW-6	53	33	12	6	
SW-7	26	9	4	14	
SW-8	27	14	11		
SW-9	27	8	6	14	
SW-10	17	7	7	2	
SW-11	34	19	9	11	
SW-12	34	14	7	3	12
SW-13	18	10	6		
SW-14	24	13	7	4	1
Total Number	428	195	120	78	34

Table 6
Lengths of Stream Orders

SW	1. Lu	2. Lu	3. Lu	4. Lu	5. Lu	SW Lu
SW-1	**16,78**	**6,41**	**3,44**	**1,41**	**3,87**	**31,91**
SW-2	**21,29**	**8,35**	**4,56**	**2,55**		**36,75**
SW-3	**16,73**	**9,54**	**6,59**	**2,90**		**35,77**
SW-4	**20,30**	**7,62**	**3,20**		**7,50**	**38,62**
SW-5	15,19	8,32	4,78			**28,29**
SW-6	27,35	21,75	5,00	2,21		**56,30**
SW-7	16,32	7,67	3,41	6,50		**33,90**
SW-8	15,56	9,14	6,45			**31,15**
SW-9	12,92	3,41	3,69	4,15		**24,16**
SW-10	8,42	2,74	3,11	2,40		**16,67**
SW-11	11,36	9,69	3,81	4,12		**28,98**
SW-12	**16,84**	**11,06**	**5,36**	**1,38**	**4,07**	**38,71**
SW-13	**10,50**	**7,63**	**3,36**			**21,49**
SW-14	**12,23**	**10,75**	**4,42**	**3,22**		**30,63**
Total Length	221.79	124.08	61.18	30.84	15.44	**31,91**

RI values calculated for the sub-basins in the study area range from 1.55 to 2.80 (Table 5). Basin-specific examinations reveal that the lowest RI value is concentrated in SW-11, while the highest is found in the SW-6 sub-basin. Morphometric analyses conducted by Dursun (2025b) emphasize that in basins with high RI values, surface flows tend to converge simultaneously, which significantly increases flood potential. The findings obtained from the current study demonstrate a strong parallel with this theoretical framework in the literature. Therefore, it is evaluated that the increase in RI values within the study area is directly related to the flood and erosion risks across the basin.

The Lo values exhibit a distribution ranging between 0.80 and 0.97. Studies in the literature (Jothimani et al., 2021; Denekewu et al., 2025) suggest that high Lo values indicate lower slopes across the basin, increase the distance water travels before concentrating in a channel, and consequently limit erosion potential. According to these findings, SW-7, which possesses the highest Lo value, exhibits a character where erosion risk is at a minimal level. Conversely, SW-5, where the lowest Lo value was recorded, stands out as an area where surface runoff occurs more violently and the topsoil layer remains more

vulnerable to erosion. The results obtained once again confirm the decisive and strong impact of the Lo parameter on erosion susceptibility in basin-scale risk analyses.

The Rb values calculated for the sub-basins constituting the study area vary between 1.57 and 2.52. When the data are examined (Table 7), it is observed that the lowest Rb value is clustered in SW-11, and the highest value in the SW-1 sub-basin. While the low Rb ratio in SW-11 indicates a more regular and balanced drainage system and, consequently, a lower flood potential, the high Rb value possessed by SW-1 highlights complex flow dynamics and the accompanying flood-erosion risk. In light of these morphological data, it is evaluated that the SW-1 sub-basin is an area requiring priority intervention in risk management processes. Analyses conducted in a different study area by Singh et al. (2014) are consistent with these findings. In that study, it was revealed how Rb values ranging from 1.08 to 3.37 trigger erosion processes through steep slopes and accelerated surface runoff, while it was emphasized that lower values correspond to a more stable hydrological structure. The results obtained from the current research support these observations in the literature, once again demonstrating the critical role of this differentiation in the drainage system in basin-scale risk analyses.

Table 7
Linear morphometric parameters

SW	Rb	Rl	Lo
SW-1	2,52	1,82	0,89
SW-2	1,71	2,06	0,87
SW-3	2,11	1,82	0,80
SW-4	1,59	1,82	0,92
SW-5	1,63	1,78	0,80
SW-6	2,12	2,80	0,88
SW-7	1,81	1,63	0,97
SW-8	1,60	1,56	0,82
SW-9	1,71	1,87	0,86
SW-10	2,31	1,75	0,84
SW-11	1,57	1,55	0,90
SW-12	1,75	1,95	0,89
SW-13	1,73	1,82	0,84
SW-14	1,81	1,65	0,97

Relief Morphometric Parameters

It has been emphasized by Dursun (2025a) that an increase in R triggers erosion potential in direct proportion to slope values. In this study, the R parameter has been adopted as a key variable in classifying the erosion susceptibility of the sub-basins. In this context, it has been determined that SW-14, which stands out with its high R values, ranks first among the areas requiring priority intervention and erosion risk management.

Rr is a critical indicator in erosion analyses as it reflects the relationship between the vertical and horizontal components of basin morphology; high values are considered to be directly related to steep topography and accelerated surface runoff (Mahala, 2020). When the sub-basins are examined, it is observed that Rr values exhibit a distribution between 0.05 and 0.15 (Fig. 3). In light of the data in Table 8, sub-basin SW-14 stands out with an Rr value of 0.15, representing the steepest topography in the basin and, consequently, the highest erosion susceptibility. Conversely, the value of 0.05 in sub-basin SW-6 indicates a gentler terrain, surface runoff with dissipated energy, and a more stable morphology where the erosion risk remains limited.

Rhp parameter provides direct data regarding the resistance of basin morphology and topographic slope characteristics; in the literature, low values are associated with gentler topographic conditions and the presence of sediment with low erosion resistance (Erdoğan Yüksel et al., 2024). According to the analysis results, Rhp values show a distribution between 0.01 and 0.04. While the SW-4 sub-basin represents a flatter and low-slope terrain structure with the lowest value, SW-14, reaching the highest value of 0.04, stands out with its distinct topographic variations and steep slope structure. This morphological characteristic reveals that SW-14 exhibits a more sensitive character with higher risk regarding erosion processes.

Rn is accepted as an indicator of topographic irregularities and slope characteristics on the basin surface; high Rn values represent erosion-sensitive areas characterized by steep, long slopes, while low values represent more stable and resistant structures (Basavareddy et al., 2025). The Rn values, ranging from 0.61 to 1.89 in the study area, reveal a significant morphological diversity among the sub-basins. SW-6, possessing the lowest Rn value, displays a resistant profile against erosion with low slope and high permeability parameters. In contrast, the maximum value of 1.89 recorded in the SW-14 sub-basin signifies steeper slope gradients, ground conditions with lower permeability, and the resulting increased potential for surface runoff. In light of these data, it is evident that the SW-14 sub-basin is one of the most sensitive units in the field regarding surface runoff processes and flood/erosion risk.

High values in the study area were found to range between 0.16 and 0.47 (Table 8). When examined at the sub-basin level, the lowest Hi value was calculated in SW-2 (0.16), while the highest was recorded in SW-6 (0.47). As emphasized in the literature by Colín-García et al. (2026), an Hi value below the 0.3 threshold indicates that the basin has stabilized and reached the late stage of erosion, whereas values between 0.3 and 0.6 signify a state of morphological maturity and equilibrium. In light of these findings, the fact that the majority of the basins fall within the 0.3–0.6 range reflects that erosion and sedimentation processes have largely reached equilibrium, and the topography has attained relative

stability. Nevertheless, basins such as SW-6, where the Hi value approaches the 0.5 threshold, serve as an indicator that erosional processes and morphological dynamics remain more active and vigorous compared to other regions.

Table 8
Relief morphometric parameters

SW	R	Rr	Rhp	Rn	Hi
SW-1	515	0,08	0,02	0,92	0,20
SW-2	900	0,12	0,03	1,57	0,16
SW-3	420	0,05	0,01	0,67	0,40
SW-4	359	0,05	0,01	0,66	0,32
SW-5	382	0,06	0,02	0,61	0,44
SW-6	456	0,05	0,02	0,80	0,47
SW-7	366	0,06	0,02	0,71	0,41
SW-8	473	0,07	0,02	0,78	0,45
SW-9	434	0,07	0,02	0,74	0,30
SW-10	432	0,09	0,02	0,72	0,46
SW-11	424	0,07	0,02	0,76	0,25
SW-12	448	0,06	0,01	0,79	0,33
SW-13	374	0,07	0,02	0,63	0,35
SW-14	975	0,15	0,04	1,89	0,18

The morphometric analysis of the Wadi Ouahrane Basin indicates a structurally controlled and geomorphologically heterogeneous landscape. Linear parameters (Dd, Rb, Dt) show strong spatial variability, reflecting lithological contrasts and tectonic influence on drainage organization. High drainage density and elevated bifurcation ratios point to low infiltration capacity and structural disturbance, suggesting that channel development is strongly guided by fracture systems and geological boundaries. Areal indices (Rc, Cc, Re) describe a predominantly elongated basin geometry. This configuration generally delays peak discharge and reduces flash-flood immediacy, although localized sub-basins may still concentrate runoff due to irregular basin boundaries and varying geomorphic maturity. Relief parameters (R, Rr, Hi) reveal marked vertical dissection and strong spatial contrasts in landscape evolution. High-relief sectors indicate active erosion and steep slopes, while lower hypsometric values reflect more mature, stabilized surfaces (Fig. 3).

Prioritizing Basins Using a Hybrid Entropy-WASPAS Approach

The results clearly demonstrate the relative importance of each criterion in driving the erosion potential within the area. According to Fig. 3, the Rb (0.283) and Rl (0.252) parameters account for the majority of the total weight, whereas the impact of factors such as Re (0.001) and Ff (0.002) is practically negligible. Additionally, Dt (0.090), Rr (0.073), and Rlp (0.071) serve as other significant variables providing moderate contributions to the overall process (Fig. 4). This established hierarchy confirms that the Entropy method offers a highly consistent and unbiased evaluation by leveraging the inherent data variations, thereby eliminating any subjective bias from the assessment.

To evaluate the erosion susceptibility of the sub-basins from a holistic perspective, this study integrates the Entropy and WASPAS methods into a hybrid model. In the initial stage of the process, criteria weights were determined based entirely on objective data using the Entropy algorithm; subsequently, the risk degrees of the sub-basins were hierarchically ranked utilizing the WASPAS method. The selection of the λ parameter as 0.5 within the model balanced the fundamental characteristics of the Weighted Sum Model (WSM) and the Weighted Product Model (WPM) equally, ensuring that morphological differences between the basins were reflected in the analysis completely and impartially. The findings indicate a heterogeneous and distinct distribution of risk across the study area in terms of erosion. Specifically, the basins ranking highest have been identified as 'critical areas' where erosion is most severe, necessitating immediate prioritization in basin management and rehabilitation projects. Ultimately, the results demonstrate that the implemented methodological framework serves as a robust decision-support tool for spatially mapping erosion risk and accurately identifying strategic intervention areas (Dursun & Babalık, 2025)

The Entropy-based WASPAS model, which minimizes subjectivity and provides an objective perspective in decision-making mechanisms, has been frequently preferred by researchers in recent morphometric analyses (Akay et al., 2023; Sarkar & Gayen, 2024; Dursun & Babalık, 2025). In the implementation of this model, fixing the λ parameter at 0.5 establishes an optimal balance between the characteristics of the Weighted Sum Model (WSM) and the Weighted Product Model (WPM) algorithms. This optimization ensures that both computational logics are reflected in the final performance values in a balanced and proportional manner.

Table 9
Entropy-WASPAS-Based Basin Prioritization

SW	WSM	WPM	WSPM	Final rank
SW-1	0,693	0,690	0,691	11
SW-2	0,561	0,520	0,541	13
SW-3	0,791	0,767	0,779	5
SW-4	0,869	0,846	0,857	1
SW-5	0,797	0,762	0,780	4
SW-6	0,732	0,695	0,713	9
SW-7	0,810	0,783	0,797	2
SW-8	0,712	0,688	0,700	10
SW-9	0,773	0,763	0,768	6
SW-10	0,681	0,652	0,666	12
SW-11	0,753	0,746	0,750	8
SW-12	0,771	0,761	0,766	7
SW-13	0,801	0,778	0,790	3
SW-14	0,534	0,476	0,505	14

The Entropy-supported WASPAS algorithm provides an analytical methodological foundation for watershed management studies, owing to the precision of its mathematical processing and the objectivity of its weighting process. This model extends beyond the descriptive analysis of field data, enabling the formulation of regional-scale conservation strategies through a rational and data-driven perspective. The hybrid structure constituting the methodology of this study possesses a dynamic capacity for expansion, allowing for the future integration of temporal change analyses and socio-economic parameters. This approach not only identifies current erosion risks but also represents a scalable and robust theoretical framework for future watershed rehabilitation planning.

The WASPAS model employed in this study provides a hierarchical prioritization for the sub-basins based on the calculated VSPM values. According to the analysis results, SW-4 emerges as the region with the highest risk burden for watershed management, with a score of 0.857. When erosion parameters – such as soil loss, morphological degradation, and slope factors – are evaluated collectively, it becomes evident that SW-4 is under severe destructive pressure, necessitating the immediate implementation of soil and water conservation interventions. The VSPM scores clearly demonstrate the spatial heterogeneity across the basin within a spectrum ranging from 0.505 to 0.857, categorized into five distinct risk classes (Table 10). In accordance with this classification, sub-basins SW-3, SW-4, SW-5, SW-

7, SW-12, and SW-13 have been identified as critical areas requiring urgent rehabilitation, falling within the 'very high risk' group with scores between 0.756 and 0.857 (Fig. 4). Conversely, sub-basins SW-9 and SW-1 are classified under the 'high risk' category, while SW-10 is characterized as 'low risk', and sub-basins SW-2 and SW-14 are categorized within the 'very low risk' group.

This distribution demonstrates that risk levels are not homogeneous across the watershed, proving that soil and water conservation priorities must be differentiated at the sub-basin scale. The Entropy-based weighting method employed in this study determined the importance levels of the criteria in an objective manner, based on the variance within the dataset, while eliminating subjective judgments. This methodological approach reinforces the scientific reliability of the analysis results and provides decision-makers with a concrete, measurable, and rational decision-support tool for developing sustainable watershed management policies at a regional scale.

In a comprehensive analysis conducted by Saouita et al. (2024) in the Tigrigra Basin, Algeria, 26 sub-basins were evaluated across five distinct erosion risk classes using the WASPAS model. The performance scores obtained in this study, ranging from 0.118 to 0.319, indicated that the basin consists primarily of low- and moderate-risk areas. These findings demonstrate that although erosion is a widespread phenomenon at the regional level, its intensity remains relatively limited. The high sensitivity of the WASPAS model applied in our study to differentiate varying levels of erosion risk is consistent with the literature findings presented by Saouita et al. (2024), thereby reinforcing the methodological validity of this approach in erosion assessment studies.

Table 10
Erosion risk classes according to the WASPAS method

Erosion Risk Levels	**Qi (1)**	**SW**
Very Low	0.505–0.604	2–14
Low	0.604– 0.668	10
Moderate	0.668–0.731	1–6–8
High	0.695–0.795	9-11-
Very High	0.756– 0.857	3-4-5-7-12-13

The morphometric characteristics of the Wadi Ouahrane watershed demonstrate a significant alignment with findings reported for semi-arid and Mediterranean environments in contemporary research. Specifically, the predominance of elongated basin geometries, reflected in low form factor (Ff), elongation ratio (Re), and circularity ratio (Rc) values, is consistent with observations from watersheds throughout North Africa and Asia. These elongated basin shapes are associated with longer runoff concentration times, reduced peak flows, and specific erosion responses (Khanchoul & Saaidia, 2017; Sarkar & Gayen, 2024). The drainage density values observed in this study, ranging from 1.60 to 1.95 km/km^2, indicate a moderately developed drainage network that aligns with those documented in semi-

arid catchments, where there is a balance between infiltration and surface runoff processes (Mani et al., 2024). Furthermore, the substantial proportion of first-order streams (45.56% of the total stream network) reflects a drainage configuration typical of actively evolving watersheds, corroborating findings from analogous morphometric investigations. These results contribute to the growing body of evidence suggesting that the organization of drainage networks and relief-related parameters exert a more pronounced influence on erosion susceptibility than basin shape metrics alone. In particular, the notable emphasis placed on the bifurcation ratio (Rb) and stream length ratio (Rl) in the Entropy analysis aligns with the conclusions drawn by Sarkar & Gayen (2024), who underscored the importance of drainage network characteristics in prioritizing sub-watersheds for erosion management. At a broader regional scale, the pronounced spatial heterogeneity of erosion susceptibility observed within the Wadi Ouahrane watershed is reminiscent of patterns reported in northeastern Algeria, where erosion risk is concentrated in specific sub-watersheds rather than uniformly distributed across the basin (Hadji et al., 2025).

These similarities indicate that the morphometric controls governing erosion processes in the study area follow patterns widely reported across Mediterranean and semi-arid environments, thereby confirming the applicability of morphometric-based prioritization frameworks for sustainable watershed management and soil-conservation planning. Despite the robustness of the adopted approach, certain limitations should be acknowledged. The present assessment relies primarily on morphometric parameters derived from topographic and drainage network characteristics and therefore does not explicitly incorporate other important erosion-driving factors, such as land-use and land-cover changes, soil properties, rainfall erosivity, vegetation dynamics, and anthropogenic pressures. In addition, the analysis represents a static assessment of current conditions and does not account for temporal environmental changes or future climate-related impacts.

Future studies should integrate morphometric indicators with environmental, climatic, and socio-economic variables within a comprehensive geospatial framework to improve erosion-risk prediction and watershed prioritization. The inclusion of high-resolution soil and land-cover datasets, remotely sensed vegetation indices, rainfall erosivity parameters, and field-based erosion observations would provide a more holistic understanding of watershed processes. Furthermore, incorporating climate change scenarios, long-term monitoring data, and alternative multi-criteria decision-making or machine-learning approaches could enhance the predictive capability and reliability of future assessments. Such developments would strengthen the applicability of the proposed framework for long-term watershed conservation, restoration, and sustainable resource management.

Conclusions

This study demonstrated the effectiveness of integrating morphometric analysis with the Entropy – WASPAS multi-criteria decision-making framework to assess erosion susceptibility and prioritize watershed management interventions in the Wadi Ouahrane basin. The morphometric evaluation revealed that most sub-basins exhibit elongated basin geometries, as indicated by low form factor, elongation ratio, and circularity-related values. These characteristics generally favor longer runoff

concentration times, enhanced infiltration capacity, and relatively lower susceptibility to flash flooding. Nevertheless, substantial spatial variability was identified among the sub-basins, indicating that erosion risk is controlled by the combined influence of drainage network characteristics, relief properties, and basin morphology.

The drainage network analysis highlighted the dominance of first-order streams, reflecting the active role of surface runoff processes in shaping the watershed. Parameters associated with drainage development and topographic relief, including drainage density, stream frequency, bifurcation ratio, stream length ratio, relief ratio, ruggedness number, and relative relief, proved particularly effective in differentiating areas with elevated erosion susceptibility. Sub-basins characterized by steeper slopes, greater topographic irregularity, and more developed drainage systems exhibited higher erosion and flood potential.

The Entropy weighting procedure objectively identified the bifurcation ratio (Rb) and stream length ratio (Rl) as the most influential criteria in determining erosion susceptibility, whereas the contributions of elongation ratio (Re) and form factor (Ff) were minimal. By eliminating subjective bias in the weighting process, the Entropy method enhanced the reliability of the assessment. The subsequent WASPAS analysis revealed a heterogeneous distribution of erosion risk throughout the watershed. Sub-basins SW-3, SW-4, SW-5, SW-7, SW-12, and SW-13 were classified as very high-risk areas requiring urgent soil and water conservation measures, while SW-2 and SW-14 were identified as very low-risk zones. Among all evaluated units, SW-4 emerged as the highest-priority sub-basin for watershed rehabilitation and erosion-control interventions. The results confirm that the integrated Entropy- WASPAS framework constitutes a robust and reliable decision-support tool for watershed prioritization and erosion susceptibility assessment. The methodology offers a scientifically based decision-support framework for sustainable watershed management. Furthermore, it contributes to informed land-use planning, improved environmental governance, and the promotion of long-term watershed resilience under increasing anthropogenic and climatic pressures.

Declarations

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Authors' contribution: M. A., İ. D. and N. M. M. conceptualized the study, designed the methodology, and wrote the draft of the manuscript. M. A., İ. D. and M. Ali Ç. prepared all figures and conducted the mapping. M. A., İ. D. and M. Ali Ç. collected and processed the datasets, and performed the statistical analysis. All authors reviewed the manuscript.

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Figures

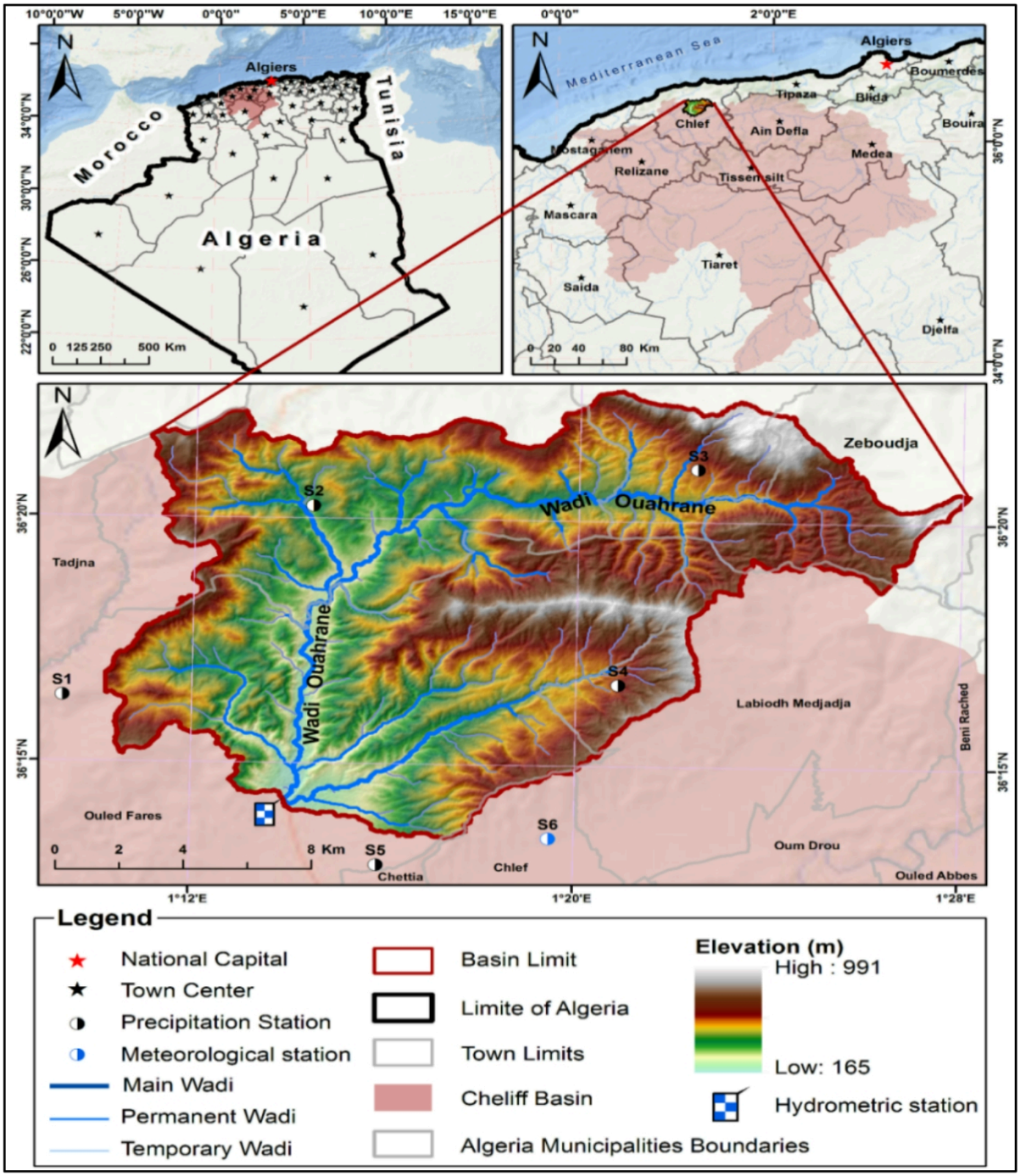


Figure 1

Location Map and Digital Elevation Model (DEM) of the Wadi Ouahrane Basin, Algeria

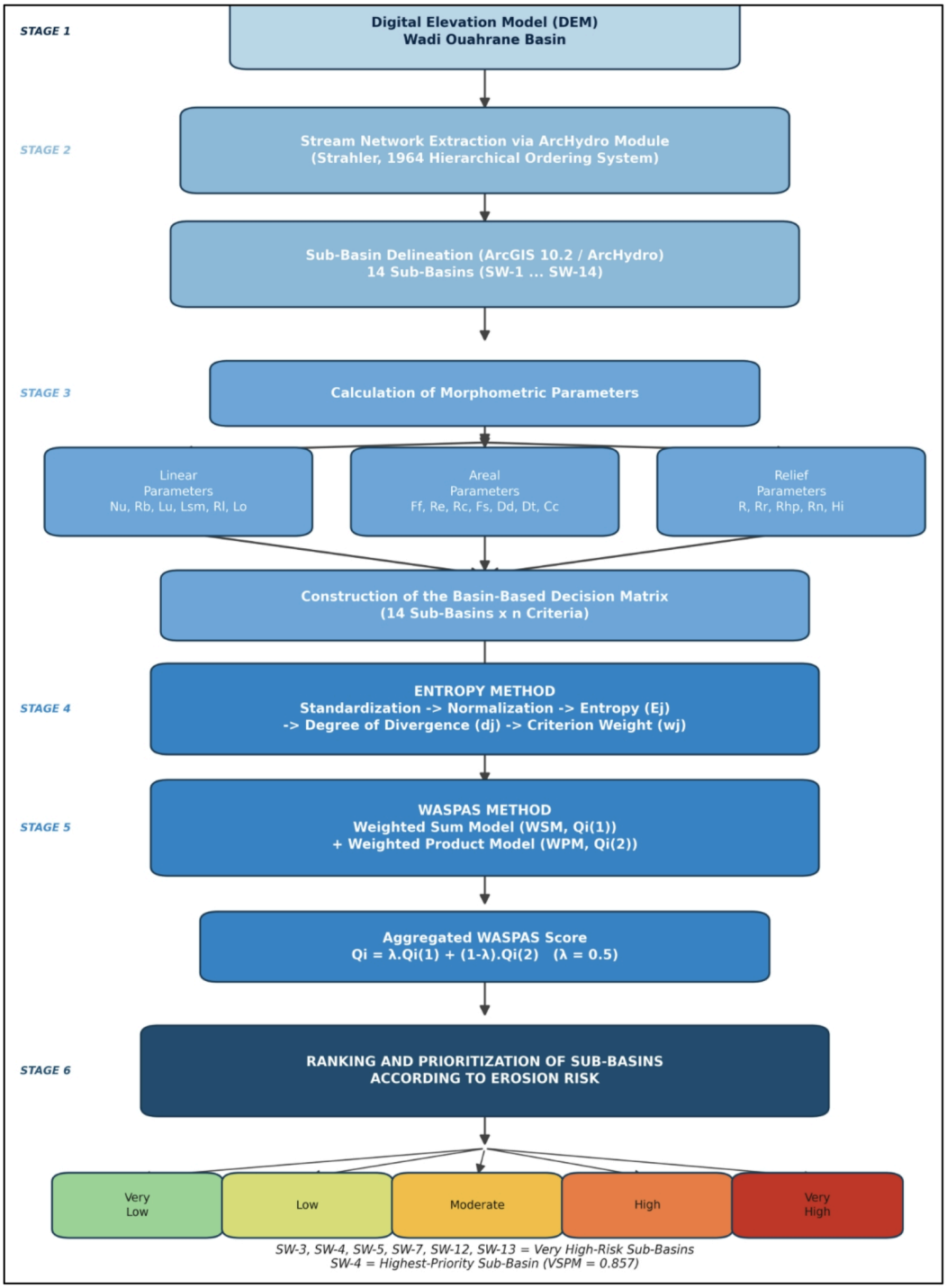


Figure 2

Flowchart of the methodology for sub-basin prioritization

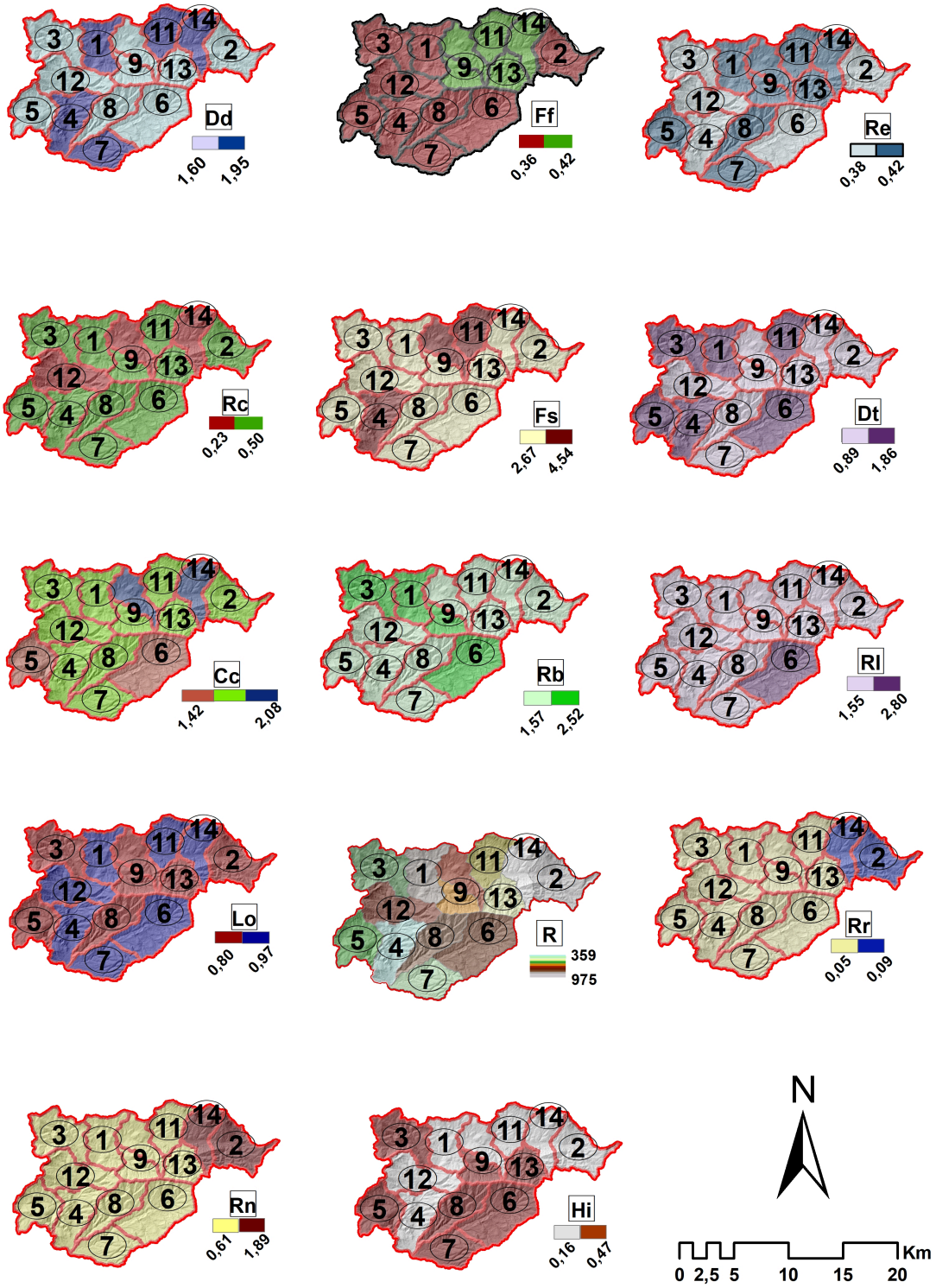


Figure 3

Classification of morphometric parameters into linear, areal, and relief categories over the defined study area

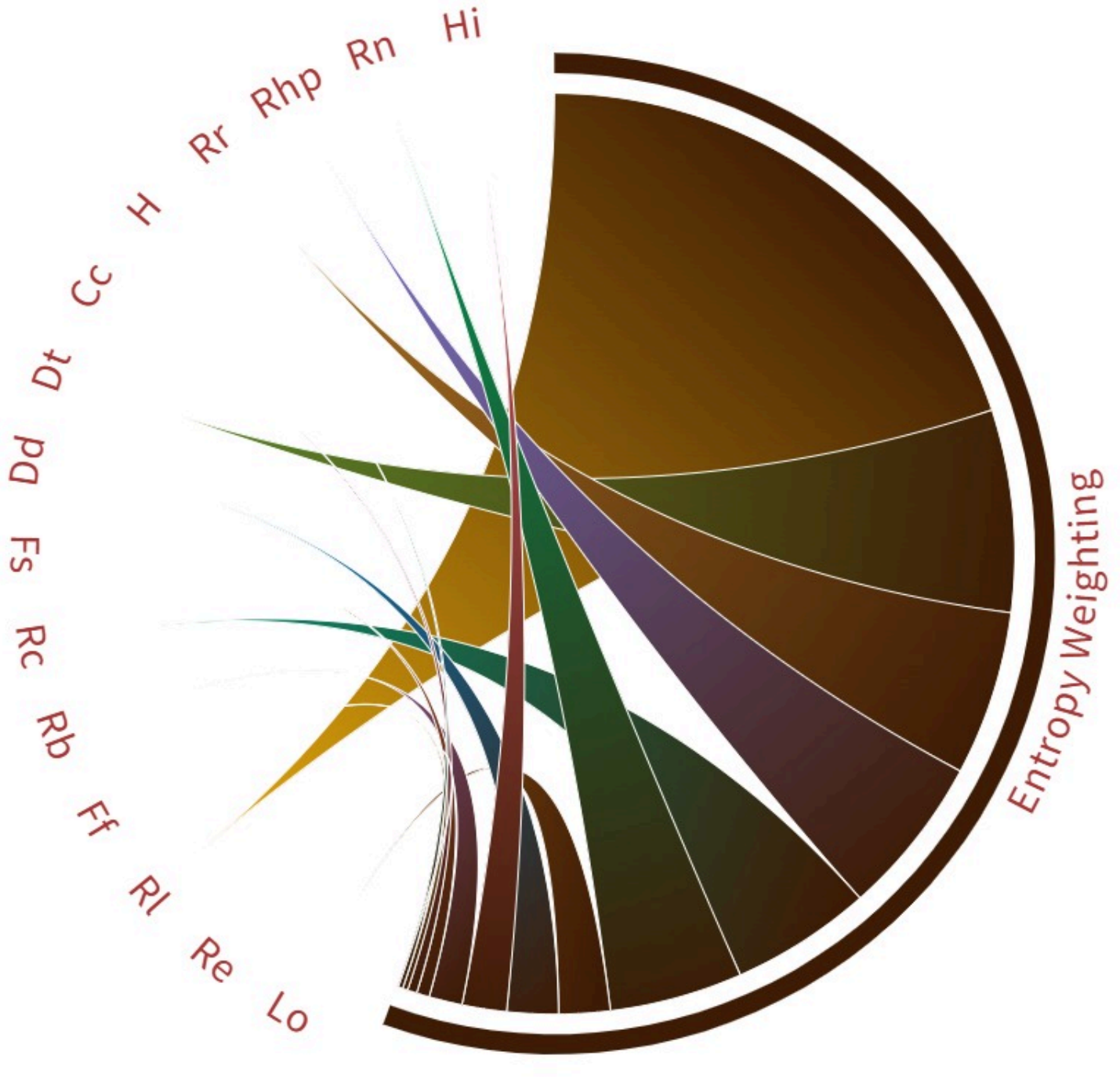


Figure 4

Entropy weights of morphometric parameters