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Sub-watershed prioritization for soil and water conservation in the Upper Sebou watershed (Middle Atlas, northern Morocco) using morphometric compound parameter analysis and GIS

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ABSTRACT

Soil erosion and land degradation pose a persistent threat to semi-arid mountain catchments, where steep relief, erodible substrates, and concentrated seasonal runoff drive high sediment loss. This study prioritizes the 53 sub-watersheds of the Upper Sebou watershed (Middle Atlas, northern Morocco; 7368 km²) for soil and water conservation through quantitative morphometric analysis. Basic basin parameters were extracted from a digital elevation model (DEM) in ArcGIS, from which the linear, areal, and relief morphometric parameters were computed using established mathematical formulas. Each parameter was ranked across the sub-watersheds, and the ranks were averaged to obtain a compound parameter (Cp) expressing the relative erosion susceptibility and conservation priority of each unit. Compound parameter values ranged from 19.63 to 38 and were grouped into five priority classes; 12 sub-watersheds (≈23%) were classified as very high and 17 as high priority. The very-high units form a contiguous core along the upper Sebou channel in the center of the basin, together with a detached pocket on the eastern flank, where high drainage density and relief coincide with compact watershed shapes that favor rapid runoff concentration. The drainage network and relief are densest along the central drainage corridor, where the highest-priority sub-watersheds are concentrated; these units also coincide with the more erodible lithologies and the sectors of lowest vegetation cover, which corroborates the ranking with information not used in its calculation. Overall, the approach offers an effective, low-cost means of pinpointing land-degradation hotspots and prioritizing conservation interventions, readily transferable to other data-scarce semi-arid basins.

Keywords: watershed prioritization, morphometric analysis, compound parameter, gully erosion, GIS, Upper Sebou, Middle Atlas, Morocco.

INTRODUCTION

Soil erosion is one of the most widespread forms of land degradation, stripping fertile topsoil, lowering agricultural productivity, and increasing the sediment loads delivered to rivers and reservoirs. The problem is particularly severe in semi-arid Mediterranean mountain environments, where steep slopes, erodible lithologies, sparse vegetation, and intense, short-duration rainfall combine to produce rapid runoff and high sediment yields (Layan et al., 2026; Nairi et al., 2026). Because conservation resources in such regions are limited and cannot be applied uniformly across a basin, identifying the most erosion-prone areas (watershed prioritization) has become a central task of integrated watershed management, especially in the data-poor catchments that are typical of North Africa (Aher et al., 2014; Layan et al., 2025). As the basic unit that integrates the hydrological and geomorphic response of the landscape, the drainage basin is widely accepted as the appropriate framework for this assessment. Quantitative morphometric analysis, formalized by Horton (1945), Miller (1953), Schumm (1956), and Strahler (1964), characterizes the geometry of a basin and its channel network through a set of linear, areal, and relief parameters that jointly express susceptibility to erosion and flooding. The advent of digital elevation models (DEMs) and geographic information systems (GIS) has turned this once labour-intensive procedure into a fast, reproducible workflow in which the basic basin parameters are extracted directly from a DEM and the linear, areal, and relief indices are computed from established mathematical formulas (Eddoum et al., 2025; Mofidi et al., 2025). This makes morphometric prioritization especially well-suited to ungauged and data-poor catchments, where streamflow and sediment records are unavailable, while still capturing the parameters that govern flood and erosion response (Layan et al., 2025).

Among the available techniques, the compound parameter (Cp) method remains one of the most widely applied. Each morphometric parameter is ranked across all sub-watersheds according to its physical relationship with erodibility. Then the ranks are averaged into a single compound value per sub-watershed, the unit with the lowest Cp receiving the highest priority (Aher et al., 2014; Layan et al., 2026). The method is valued for its transparency and minimal data requirements, and it has been applied and benchmarked against alternative multi-criteria schemes such as the fuzzy analytical hierarchy process, which weights parameters rather than ranking them (Maamare et al., 2026). Across these studies, the compound parameter approach consistently provides reliable, low-cost prioritization suitable for rapid conservation planning in resource-limited settings.

In Morocco, where much of the territory faces water erosion under semi-arid conditions, GIS-based morphometric prioritization has recently been applied in several basins, including the Baht watershed (Eddoum et al., 2025) and the Lakhdar and El Abid watersheds upstream of the Oum Er-Rbia (Mofidi et al., 2025; Maamare et al., 2026). Morphometric indicators have likewise served to pinpoint the parameters controlling rare floods in data-poor northeastern catchments (Layan et al., 2025) and, through mathematical erosion models, to monitor the spatial dynamics of water erosion (Nairi et al., 2026). The Sebou basin, which carries close to half of the country's surface-water resources and drains the intensively cultivated plains around Fès and Meknès, is among the most erosion- and sediment-affected systems in northern Morocco. Its mountainous headwater portion (the Upper Sebou watershed in the Middle Atlas) has nonetheless not yet been the subject of a quantitative sub-watershed prioritization, despite its vulnerable landscape.

This study applies the established compound parameter framework rather than proposing a new morphometric method. This framework is valued for its transparency, its low data requirements, and its suitability for ungauged terrain. Its contribution lies in the study area and in the way the ranking is supported. Three points distinguish this contribution. First, the Upper Sebou headwater has not been prioritized at the sub-watershed scale before, although it is the main sediment source of the Sebou and drives siltation of the Allal Al Fassi reservoir. A defined and strategically important gap is therefore filled. Second, the ranking is not left to rest on morphometry alone. It is compared with two datasets that are not used in its calculation: a lithological map and a decadal NDVI change (2014–2024). Third, the analysis covers a comparatively large set of units, 53 sub-watersheds over 7368 km².

On this basis, the present study prioritizes the sub-watersheds of the Upper Sebou basin for soil and water conservation using the compound parameter method (Layan et al., 2026). Specifically, it aims to (i) extract the basic basin parameters from a DEM and compute the linear, areal, and relief morphometric parameters of each sub-watershed within a GIS environment; (ii) integrate these parameters into a compound parameter in order to rank the sub-watersheds by relative erosion susceptibility and group them into priority classes; and (iii) identify the priority hotspots and interpret them against the structure of the drainage network and the lithological and vegetation-cover context, thereby providing a spatially explicit, low-cost basis for targeting conservation interventions in this strategic Middle Atlas headwater basin.

MATERIALS AND METHODS

Generating basics data

Topographic and hydrological processing was based on the Shuttle Radar Topography Mission 1 Arc-Second Global (SRTM 1 Arc-Second Global) dataset, at a spatial resolution of 30 m (1 arc-second), downloaded from the USGS Earth Explorer portal (https://earthexplorer.usgs.gov). All spatial data were projected into the WGS 1984 UTM Zone 30N coordinate reference system to ensure geometric consistency. DEM preprocessing was performed with the Spatial Analyst extension in ArcGIS 10.8.2. Spurious depressions and sinks were removed with the Fill tool to ensure hydrological continuity of the drainage network. Flow direction was derived from the conditioned DEM using the Deterministic Eight-Direction (D8) algorithm (O'Callaghan and Mark, 1984), which assigns to each cell the direction of steepest descent among its eight neighbours, and flow accumulation was then computed. The hydrographic network was extracted with a flow-accumulation threshold of 300 cells (a minimum drainage area of about 0.27 km²; 300 cells × 900 m² per cell). This low threshold captures the smaller drainage channels and was calibrated against the 1:50,000 topographic maps. Outlet points were defined manually at confluences with the main river, and the 53 sub-watersheds were delineated with the ArcGIS Watershed tool and validated against the same topographic maps. Stream ordering followed the Strahler (1957) method. Basin area, perimeter, and length were extracted from the polygon geometry, and stream length and frequency from the vectorized drainage network. Satellite images from 2014 and 2024 were analyzed with the normalized difference vegetation index (NDVI), and lithology was characterized from geology maps. Neither dataset entered the morphometric prioritization. Both were used as independent evidence, to check whether the highest-priority sub-watersheds coincide with the more erodible lithologies and the lowest vegetation cover (Table 1, 2).

Case study

The Upper Sebou watershed is in the Middle Atlas Mountains of northern Morocco, specifically between longitudes 5°24′ W and 3°55′ W and latitudes 34°10′ N and 33°09′ N. The watershed covers an area of approximately 7368 km², which

Table 1. Data sources and their uses

Data Source	Type	Resolution / Scale	Source / Reference	Use
SRTM 1 Arc-Second Global	Digital elevation model (DEM)	30 m	USGS Earth Explorer (https://earthexplorer.usgs.gov)	Morphometric analysis and sub-watershed delineation
Sentinel-2 MSI (L2A)	Satellite imagery	10 m	Google Earth Engine (https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2_SR_HARMONIZED)	NDVI to assess vegetation-density change
Geological Maps	Vector data	1:50,000	Mining and Geology Directorate of Morocco	Lithological analysis
Topographic Maps	Vector data	1:50,000	National Agency for Land Conservation, Cadastre and Cartography	Validation of drainage network and sub-watershed boundaries

Table 2. DEM preprocessing and drainage-extraction parameters

Parameter	Setting
DEM source	SRTM 1 Arc-Second Global
Spatial resolution	30 m (1 arc-second)
Coordinate reference system	WGS 1984 UTM Zone 30N
Software	ArcGIS 10.8.2 (Spatial Analyst extension)
Sink removal	Fill — no z-limit (all sinks filled)
Flow-direction algorithm	D8 (O'Callaghan and Mark, 1984)
Flow accumulation	Computed from the D8 flow-direction raster
Stream / channel-initiation threshold	Flow accumulation ≥ 300 cells (≈ 0.27 km²; 300 × 900 m² per cell)
Threshold calibration	Visual match to 1:50,000 topographic maps
Stream ordering	Strahler (1957)
Sub-watershed delineation	ArcGIS Watershed tool; outlets set at confluences; validated against 1:50,000 maps

represents about 15.9% of the Sebou watershed (Figure 1). Within a perimeter of 721,503 km, the main river was formed and flows for approximately 264 km before reaching the city of Fès, which marks the northern outlet of the basin. The watershed is bounded to the south and east by the Moulouya watershed, whose headwaters rise along the High Atlas–Middle Atlas divide, and to the southwest by the Oum Er-Rbia watershed (Figure 1). To the north it opens onto the middle Sebou sub-watersheds and the Saïss plain, while the higher reliefs of the eastern Middle Atlas form its eastern rim, culminating at Jbel Bou Iblane (≈3.088 m, near Imouzzer Marmoucha). Elevations range from about 430 m near Fès to over 3,000 m in the southern and eastern massifs, giving the watershed a marked altitudinal gradient, and its drainage is regulated by several structures, including the Allal Al Fassi, Mahraz, Aggay, and Bled El Gaada dams (Figure 1). The region's climate falls within the semi-arid Mediterranean zone, showcasing remarkable variations throughout the Upper Sebou watershed. The mountainous areas experience considerable humidity, while the lower regions are predominantly dry (HBAS, 2011).

Administratively, the Upper Sebou watershed lies within the Fès-Meknès region and spans parts of the provinces of Fès, Sefrou, and Boulemane, whose urban centers play a vital role in its socioeconomic dynamics. Fès, the regional capital, together with Sefrou, Imouzzer Kandar, El Menzel, Ribate El Kheir, Boulemane, and Imouzzer Marmoucha, stand out as the watershed's principal economic centers, providing essential administrative services as well as healthcare and education for the surrounding population. Beyond these towns, the community maintains a largely traditional, agrarian way of life, with strong ties to family, land, and local Amazigh customs. Households derive income from diverse sources, depending on regional natural resources. These include the sale of agricultural products (cereals, olives, and orchard fruits such as the apples of Imouzzer Kandar and the cherries of Sefrou), alongside livestock farming and seasonal transhumance in the cedar- and oak-forested highlands. The region also sustains vibrant local markets (souks) and a rich artisanal heritage, particularly the leather, ceramic, and metalwork crafts of Fès, reflecting the cultural depth and craftsmanship of the community.

Vegetation cover

Although the vegetation cover is diverse, it tends to be sparse and weak, with extensive cultivated areas. The 2014 NDVI map (Figure 2), shows a substantial area with sparse (yellow) to no vegetation (red), particularly in lower elevations. However, the map also displays a limited area of dense vegetation (green), primarily concentrated in higher elevations and along waterways, indicating a convenient environment in those regions. In

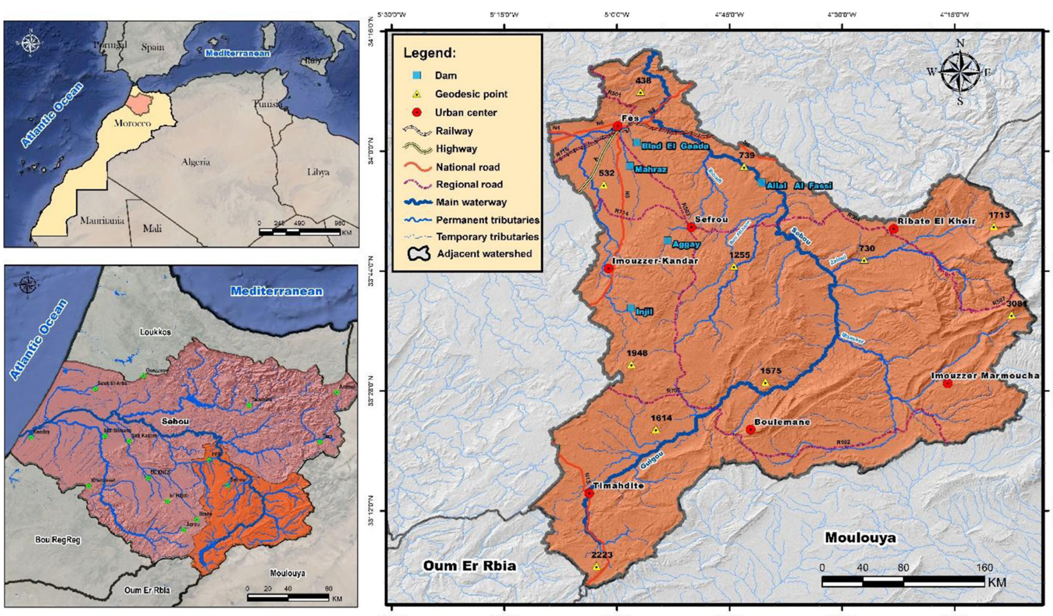

Figure 1. Study area, (a), geographic location of the Sebou watershed within Morocco, (b), geographic location of the Sebou watersed, (c), Upper Sebou watershed

contrast, the 2024 NDVI map exhibits a troubling trend, demonstrating a notable decrease in dense vegetation, with more regions shifting to sparse or no vegetation classifications. This decline may suggest challenges such as increased land degradation or adverse environmental conditions, such as climate change, impacting vegetation growth over the decade. It raises concerns about potential soil erosion and ecological health. Additionally, the current state emphasizes the need to immediately implement targeted conservation efforts and sustainable land management practices in the Upper Sebou watershed.

Lithology

Understanding the lithology types contributes to assessing the landscape's sensitivity to degradation. The lithological characteristics influence soil stability, drainage patterns, and erosion rates. In our study (Figure 3), the geology map reveals a diverse type of formations, with Cambrian Lower rocks indicative of ancient marine environments. These older formations may exhibit greater resistance to erosion due to their compaction and cementation over time. The Cretaceous formations, including both Senonian and Lower epochs,

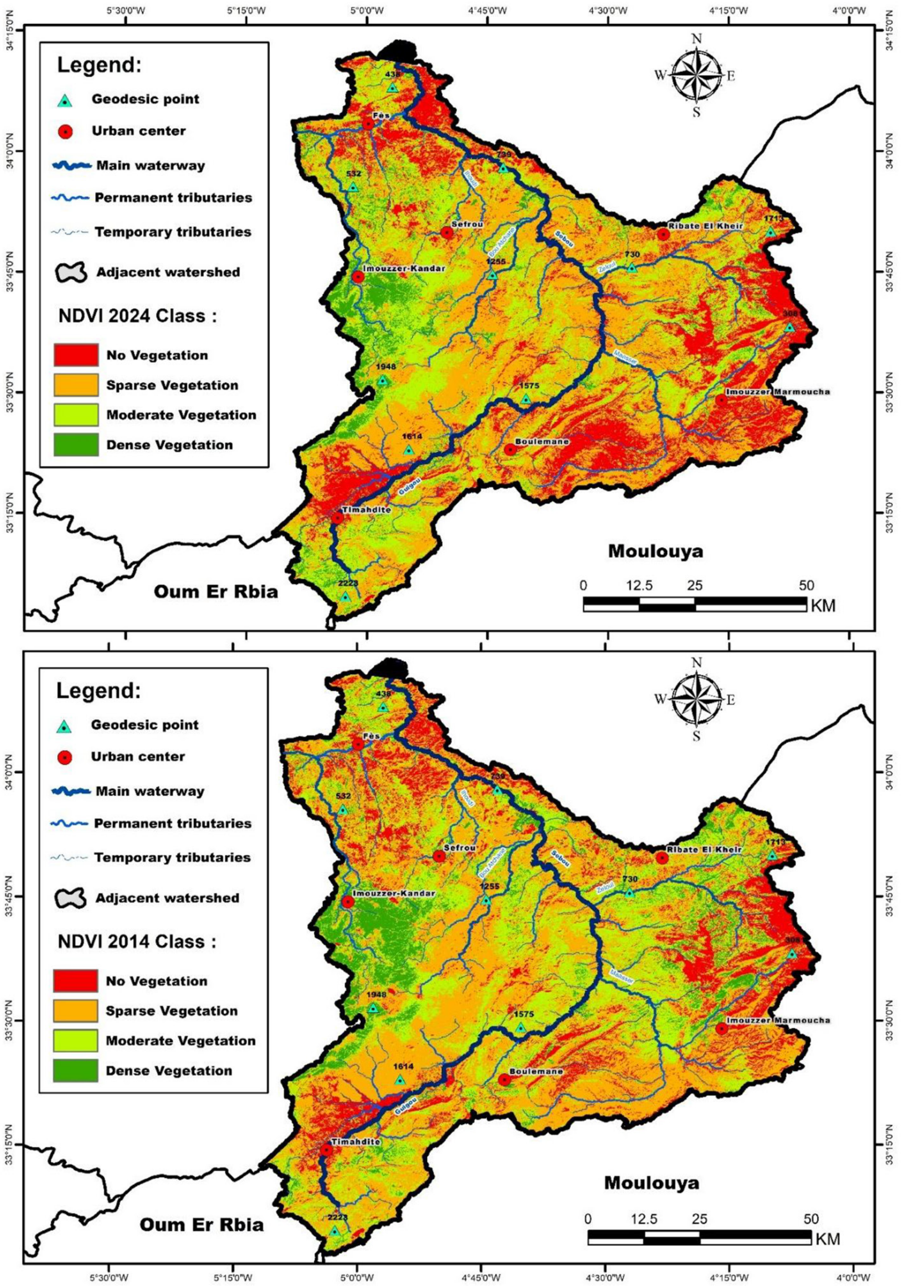

Figure 2. NDVI map in the Upper Sebou watershed

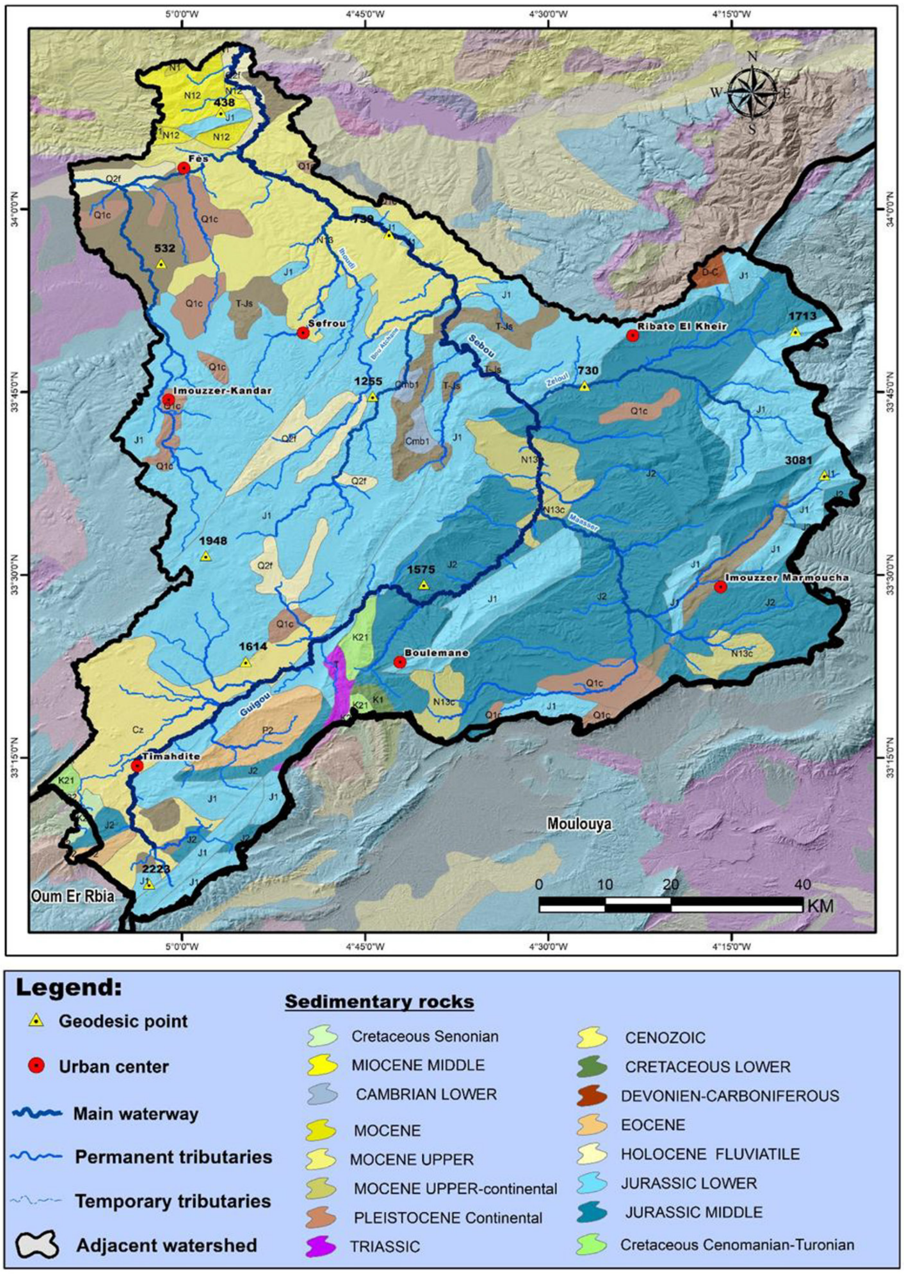

Figure 3. Geology of the Upper Sebou watershed

reflect a period of significant sediment deposition and tectonic activity during the late Mesozoic era, which may also contribute to their durability against erosive forces. Additionally, the presence of Miocene Middle and Miocene Upper rocks signifies active sedimentation influenced by fluctuating sea levels and climatic conditions. These formations can vary in their resistance to erosion, depending on their composition and structure. The Pleistocene Continental deposits, indicative of glacial influences, may be more vulnerable to erosion due to their loose, unconsolidated nature. In contrast, the Holocene Fluviatile deposits, which are shaped by contemporary hydrological dynamics, can be particularly susceptible to erosion during periods of high-water flow.

Elevations

The altitude map of the Upper Sebou watershed reveals a varied topography ranging from low-lying areas to significant elevations (Figure 4). It indicates altitudes varying from approximately 119 meters to over 2200 meters, highlighting pronounced elevation gradients across the region. Such topographical variation reinforces hydro-geomorphological processes, which can lead to increased soil erosion. Areas with higher

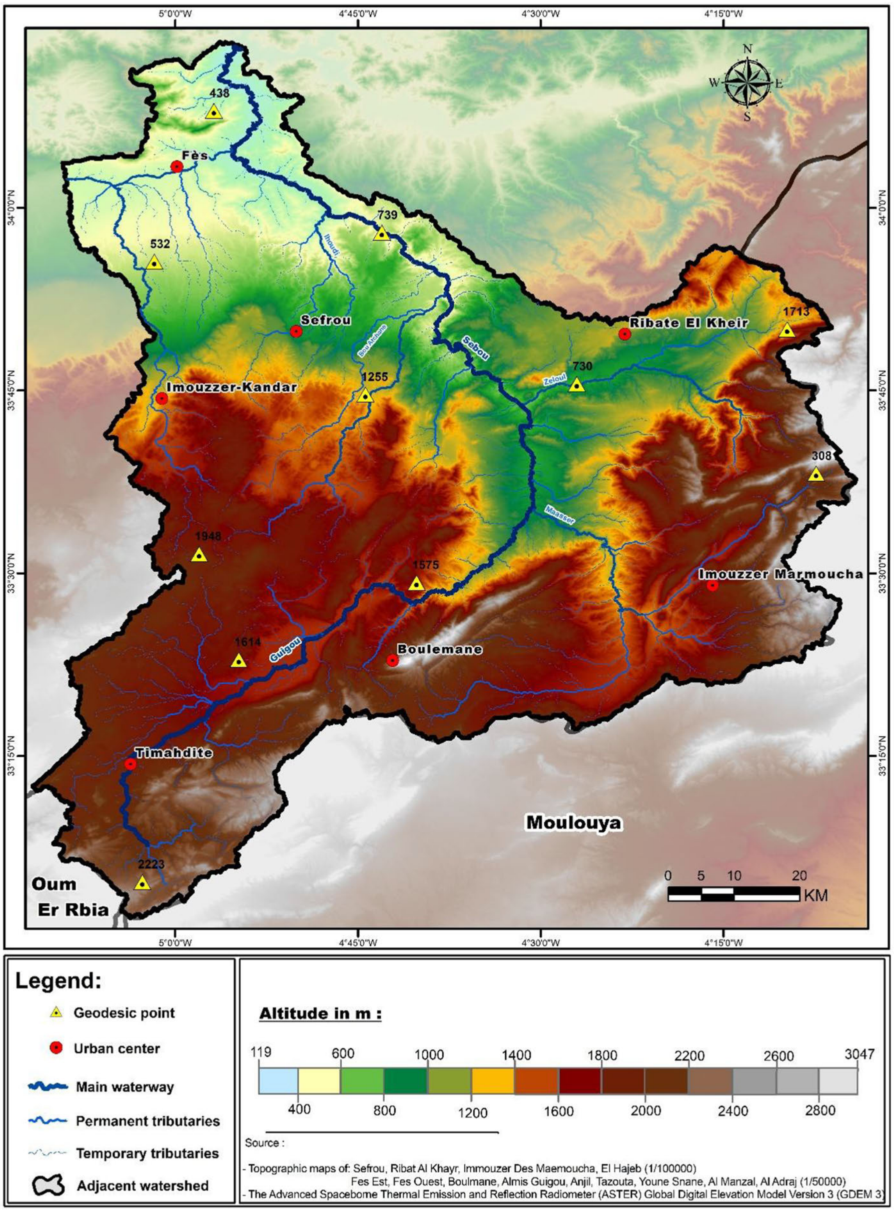

Figure 4. Elevations within Upper Sebou watershed

elevations, like the peaks around Timahdite and Imouzzer Kandar, are likely to experience increased erosion rates. This phenomenon is due to gravitational forces acting on surface water, which gains velocity as it flows downhill. Conversely, lower elevations may show reduced erosion rates due to enhanced water retention, which promotes greater soil stability.

Slopes

Slopes akin to elevations provide critical insights into the terrain's steepness and its implications for soil erosion and hydrological behavior. Figure 5 categorizes slopes into various classes, ranging from horizontal to extreme, highlighting the heterogeneity of the landscape. Areas characterized by very low to sub-horizontal slopes are likely to experience minimal erosion, as water runoff is reduced, allowing for greater infiltration and soil retention. Conversely, moderate to steep slopes present a heightened risk for erosion due to increased water runoff velocity. In these areas, the gravitational forces acting on water can lead to significant soil displacement, particularly during intense rainfall events. Regions classified as very steep or extreme slopes are particularly vulnerable to erosion. The risk of landslides and surface runoff is elevated in these areas, making them critical zones for conservation efforts. The interplay between slope gradient and vegetation cover

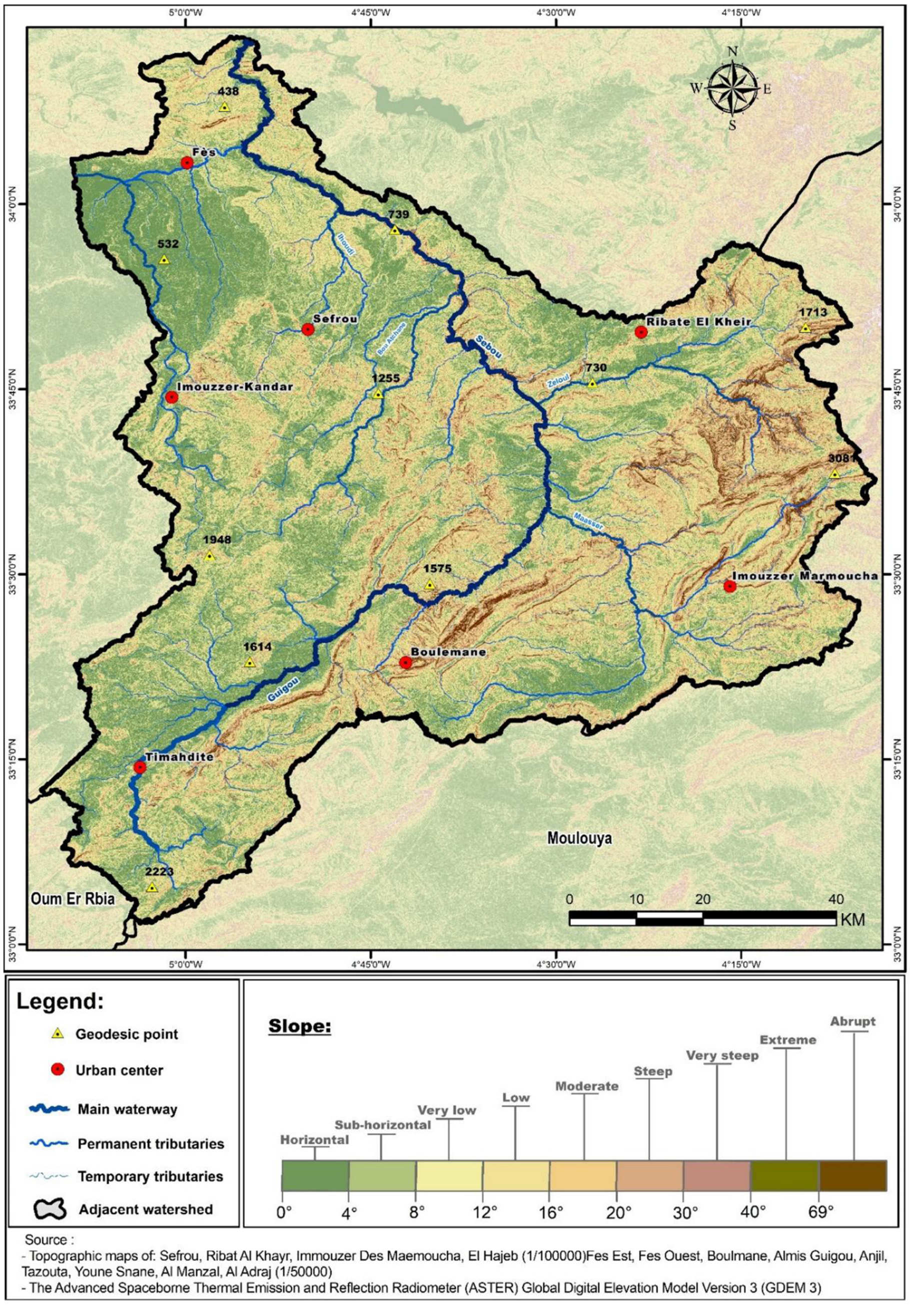

Figure 5. Slopes of the Upper Sebou watershed

becomes vital; densely vegetated steep slopes can mitigate erosion by stabilizing the soil, whereas bare or sparsely vegetated slopes are more susceptible to degradation.

Methodology

We used the mathematical formulas in Table 3 to find the fundamental morphometric parameters. Figure 6 shows how the process included several phases that had all been linked together. The method used a compound parameter to rank and prioritize sensitive sub-watersheds. The main part of this method is figuring out the weighted average of the various parameter ranks for each sub-watershed. This lets you rank them based on the final compound parameter value (Layan et al., 2026).

There are three basic morphometric characteristics that characterize the geometry of the watershed: relief, linear, and areal (shape) features. Linear parameters look at things like drainage density, length of overland flow, and stream frequency that have to do with rivers. The relief and areal parameters, on the other hand, look at watershed characteristics including the relief ratio,

Table 3. Formulas used for morphometric analysis

Morphometric aspect	Morphometric parameter	Formula	Reference
Areal aspects	Form factor (Rf)	$Rf = A / Lb^2$	Horton, 1932
	Circularity ratio (Rc)	$Rc = 4\pi A / P^2$	Strahler, 1964
	Elongation ratio (Re)	$Re = 1.128 \times \sqrt{(A / Lb)}$	Schumm, 1956
	Compactness coefficient (Cc)	$Cc = 0.28 \times P / \sqrt{A}$	Strahler, 1964
	Shape factor (Bs)	$Bs = Lb^2 / A$	Horton, 1932
Linear aspects	Stream length ratio (Rl)	$Rl = Lu / L(u-1)$	Horton, 1945
	Bifurcation ratio (Rb)	$Rb = Nu / N(u+1)$	Schumm, 1956
	Rho coefficient (ρ)	$\rho = Rl / Rb$	Strahler, 1952
	Texture ratio (Rt)	$Rt = N_1 / P$	Schumm, 1956
	Drainage texture (Dt)	$Dt = Ns / P$	Horton, 1945
	Stream frequency (Fs)	$Fs = Ns / A$	Horton, 1932
	Drainage density (Dd)	$Dd = Ls / A$	Horton, 1932
	Drainage intensity (Di)	$Di = Fs / Dd$	Faniran, 1968
	Infiltration number (It)	$It = Fs \times Dd$	Faniran, 1968
	Length of overland flow (Lo)	$Lo = 1 / (2 \times Dd)$	Horton, 1945
Relief aspects	Relief ratio (Rh)	$Rh = H / Lb$	Schumm, 1963
	Ruggedness number (Rn)	$Rn = H \times Dd$	Schumm, 1963
	Dissection index (Dis)	$Dis = H / Hmax$	Singh, 1994
	Relative relief (Rre)	$Rre = H / P$	Schumm, 1963

Note: A – basin area (km^2); P – basin perimeter (km); Lb – basin length (km); u – stream order; Nu – number of streams of order u; N(u+1) – number of streams of the next higher order; Lu – mean length of streams of order u (km); L(u−1) – mean length of streams of the next lower order (km); N_1 – number of first-order streams; Ns – total number of streams of all orders; Ls – total length of streams of all orders (km); H – basin relief – Hmax − Hmin (m); Hmax – maximum elevation (m); Hmin – minimum elevation (m).

dissection index, circularity ratios, and compactness coefficients (Eddoum et al., 2025).

In our case study, we concentrated on three critical morphometric parameters to assess and rank the sub-watersheds. These factors are directly related to the risks of peak flow, runoff, and soil erosion (Osman, 2014). A well-developed drainage network, steep slopes, and rough terrain are suggested by higher values in linear and relief parameters. Higher values also mean that runoff processes and water erosion are more likely to happen, which can make muddy floods more likely (Abdeta et al, 2020). We sorted the linear and relief parameter values in order from highest to lowest so that we could systematically look at how these factors affected each other. This method put the parameters with the highest values in the top row, the ones with somewhat lower values in the next row, and the ones with the lowest values in the last row.

The form factor (Rf), circularity ratio (Rc), and elongation ratio (Re) directly influence hydro-geomorphological behaviors, while the shape factor (Bs) and compactness coefficient (Cc) exert indirect effects. In the first group, higher values indicate a more circular watershed, whereas lower values signify a more elongated shape. Conversely, in the second category, larger values correspond to elongated watersheds, while smaller values reflect a more compact or circular form, which typically increases the likelihood of erosion. Consequently, we ranked the first category from highest to lowest values and the second category from lowest to highest values.

After establishing the ranks for individual parameters, we proceeded to calculate the compound parameter value for each sub-watershed. This calculation involved summing the ranks assigned to each parameter and dividing the total by the number of variables. We applied this method systematically across all Upper sebou-watersheds. From the calculated compound parameter values, we classified the sub-watersheds into five distinct categories: very low, low, moderate, high, and very high priority. Sub-watersheds with lower compound parameter values were categorized

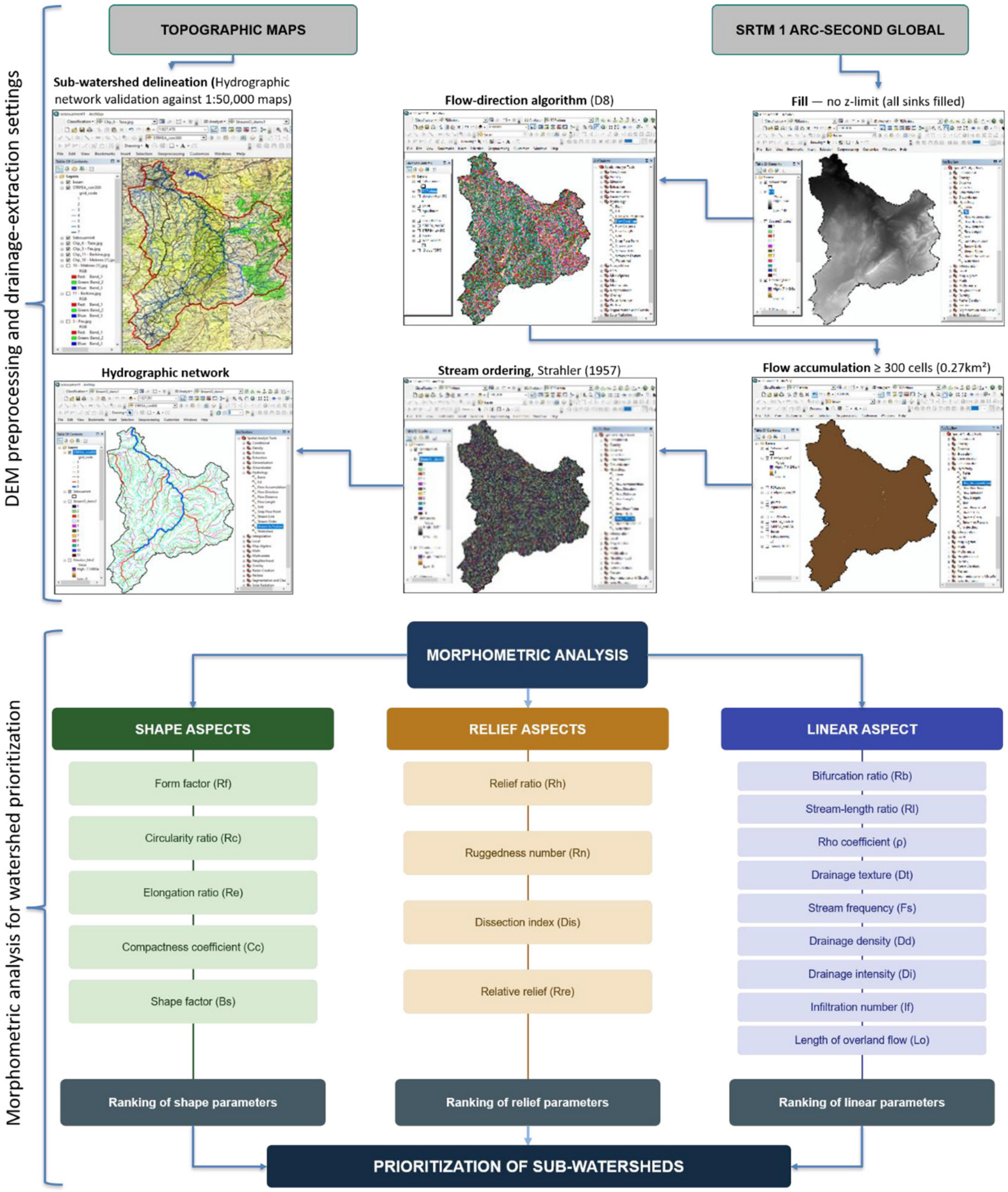

Figure 6. Methodology flowchart for the compound parameters approach

as high priority, indicating a heightened risk of runoff, peak flow, and soil erosion. Conversely, those with higher values were classified as low priority, suggesting reduced vulnerability. Thus, a high-priority classification signifies significant risk, while a very low priority classification indicates greater stability (Layan et al., 2025; Mofidi et al., 2025).

Each of the 19 parameters was ranked across 53 sub-watersheds, based on how it relates to erosion and runoff. Each sub-watershed then received a compound parameter value, calculated as the average of its 19 ranks. All parameters were given equal weight, which is the basis of the compound-parameter approach (Javed et al., 2009; Malik et al., 2019); no weighting or normalization was used. When two sub-watersheds had the same parameter value, they received the same rank. The sub-watersheds were then grouped into five priority classes using the equal-interval method, which splits the range of compound values into categories of equal width (Patel et al., 2012). A low compound value means a high priority. Low values come from features such as an elongated shape, a dense drainage network, and steep slopes, which speed up runoff, reduce infiltration, and increase erosion. High values come from more

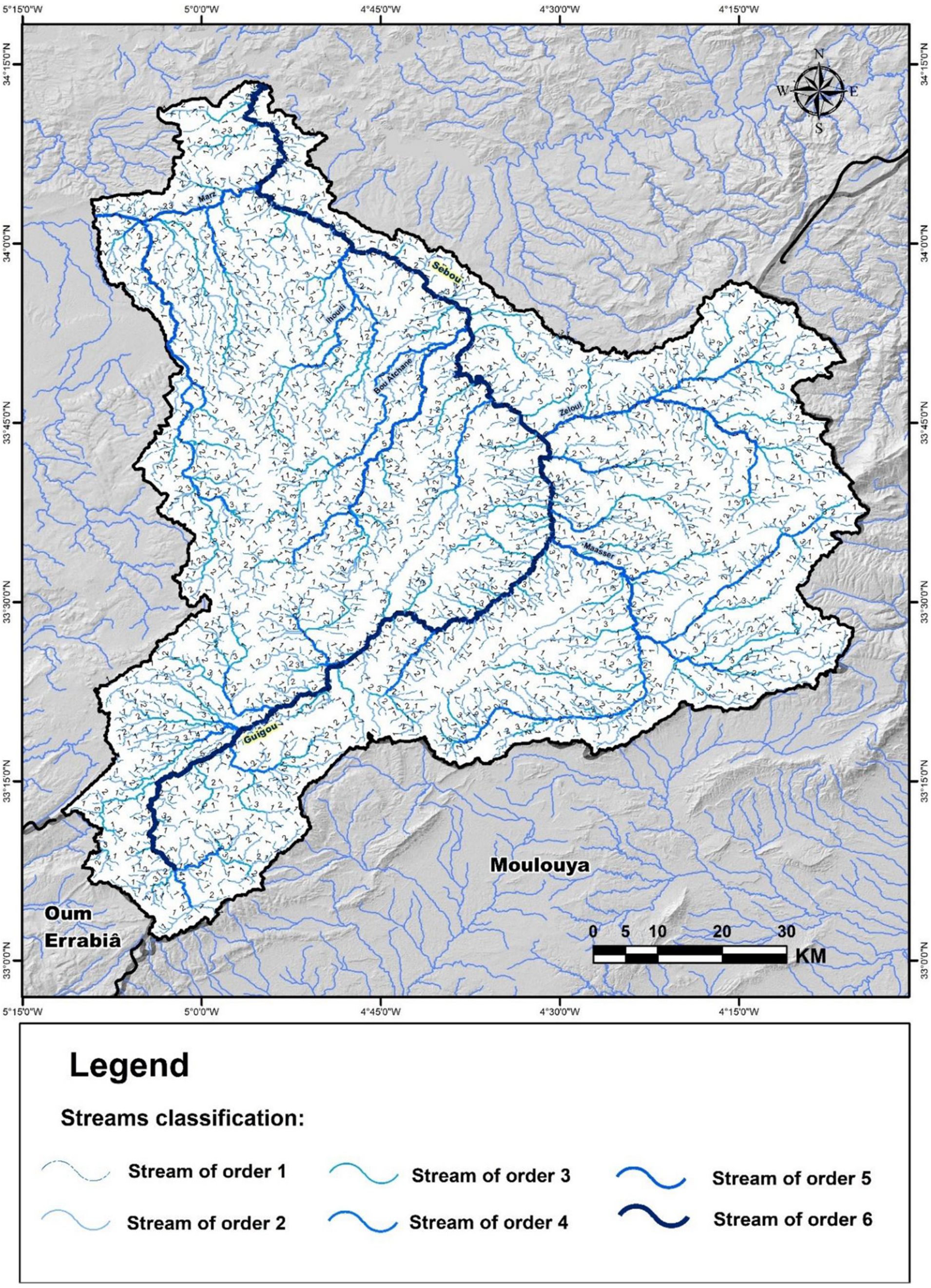

Figure 7. Drainage system of the Upper Sebou watershed

rounded, gently sloping basins, where water is retained more easily (Farhan et al., 2017; Malik et al., 2019).

- Compound parameters method in Equation 1
- Equal interval class in Equation 2

RESULTS

The network is a fully integrated sixth-order system, which tells that the basin is geomorphologically mature and well-drained (Figure 7).

$$Cp = \frac{Rf_n+Rc_n+Re_n+Cc_n+Bs_n+Rl_n+Rb_n+Rho_n+Dt_n+Fs_n+Dd_n+Di_n+It_n+Lo_n+Rh_n+Rn_n+Dis_n+Rre_n}{19} \quad (1)$$

$$Equal\ interval = \frac{Cp_{max}-Cp_{min}}{5} \quad (2)$$

The order-6 trunk is the Sebou itself, assembled from the Guigou headwaters in the south and flowing north to the outlet at Fès, gathering the lower orders along its axis. The pattern is overwhelmingly dendritic, branching like a tree with no preferred channel direction, which points to a relatively homogeneous, gently structured lithology and little structural control across most of the basin. The main exception lies on the eastern side, toward the folded Causse and the Bou Iblane massif, where relief begins to organize the channels. The texture is fine and the network dense, especially through the central and southern uplands, and that density is the diagnostic point: a high drainage density and stream frequency are consistent with low infiltration (impermeable or readily saturated substrate), steep slopes, and thin vegetation, which tend to favour flashy runoff and active surface erosion. In other words, the channel map already explains the prioritization result, the very-high core sits exactly where the network is densest and most incised along the central trunk.

The sub-watersheds vary greatly in size: the mean area is 120 km² but the median is only 35 km², indicating that a few large basins occur among many smaller ones (Figure 8). The largest sub-watersheds are the peripheral, eastern and western catchments. Maasser (SW-11) is by far the biggest at 1.321 km² (about 21% of the basin on its own), followed by Marz (SW-6, 911 km²), Zeloul (SW-8, 771 km²), Bou Atchane (SW-37, 546 km²), and Ihoudi (SW-53, 412 km²). These five units together cover roughly 62% of the watershed (Figure 7). The smallest are tiny headwater and rim units: Khouabi (SW-49, 3.1 km²), El Ahrar (SW-45, 5.9 km²), El Aderrha (SW-46, 8.7 km²), Aït Said (SW-17, 10.4 km²), and Imazili (SW-52, 10.9 km²).

Morphometric analysis

Tables 4 and 5 regroup the results of morphometric analysis, which encompass shape, linearity, and relief. They allowed defining drainage systems, as they provided information about sub-watersheds' quantitative features. To present and discuss these outputs, we classified each parameter's values into three primary categories: high, moderate, and low. This classification allows for

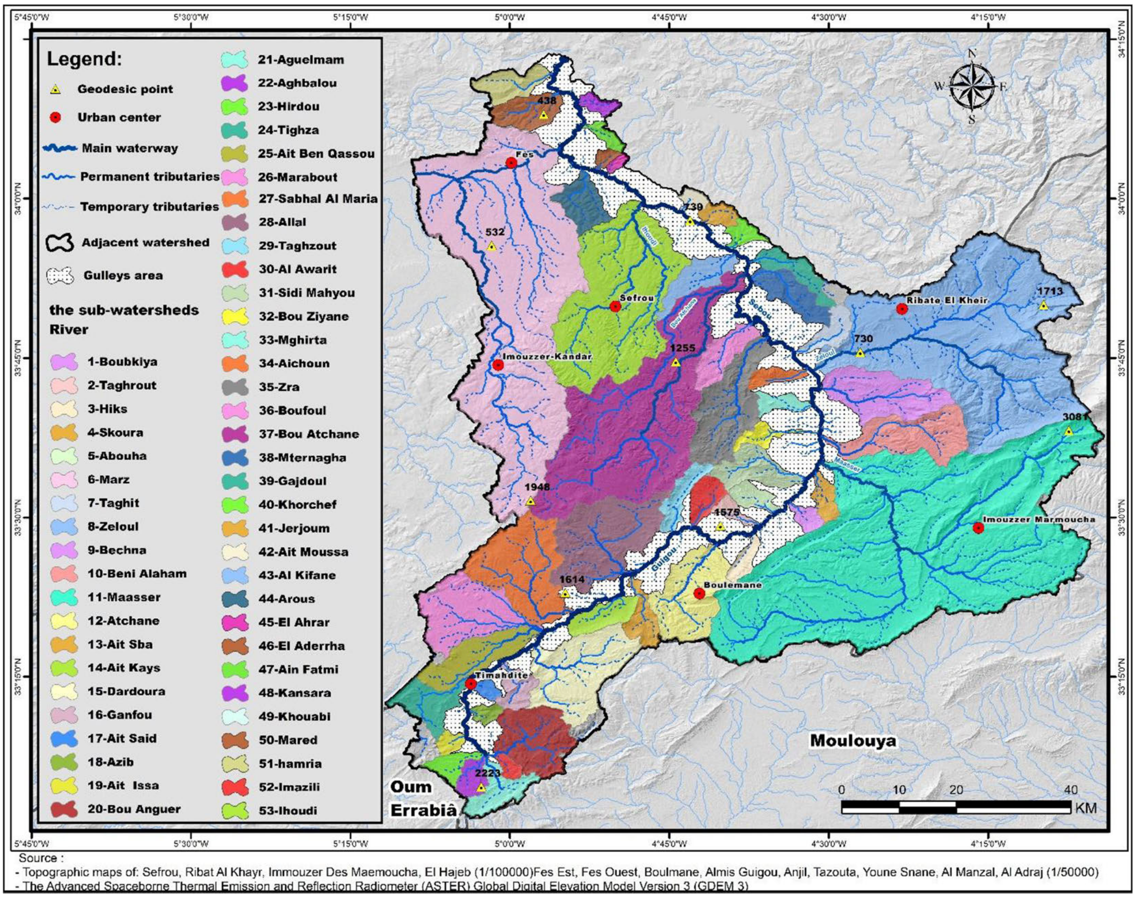

Figure 8. Sub-watersheds map

a clearer understanding of the variations in morphometric characteristics and their implications for watershed management. It enables us to more effectively identify areas that may require urgent attention, facilitating the implementation of management strategies.

Shape parameters

Rf is a hydrological parameter used to characterize the shape of a river's hydrograph. It is defined as the ratio of A to the square of the Lb. generally, a high form factor indicates a sharp and steep hydrograph, suggesting a rapid response of the watershed to precipitation events, while a low form factor reflects a flatter hydrograph, demonstrating a more gradual response (Horton 1932). In the current study, sub-watersheds such as SW17, SW18 SW45, SW42, SW46, and SW49 are characterized by high form factor values. These values exhibit a more elongated shape, which typically facilitates efficient drainage and may influence runoff patterns. The moderate form factor group encompasses a variety of sub-watersheds such as SW1, SW2, SW3, SW4, SW20 and SW35, emphasizing a more balanced shape, which may lead to moderate runoff characteristics. The grouping illustrates a transitional phase where watershed shapes begin to vary but still maintain a certain level of efficiency in drainage. Furthermore, the final group consists of sub-watersheds with low form factor values, such as in SW6, and SW37. These sub-watersheds display a more compact shape, which may lead to slower drainage and increased water retention.

The circularity ratio (Rc) quantifies the shape of a watershed by comparing its area to the area of a circle with the same perimeter. It is defined as the ratio of the area of the watershed to the area of a circle whose circumference is equal to the perimeter of the watershed. A high circularity ratio, and a low circularity ratio indicates a more elongated or irregular shape (Strahler 1964). In the current study, the group characterized by high circularity ratios includes sub-watersheds SW1, and SW17, which exhibit shapes that are closer to circular. Such high Rc values suggest that these sub-watersheds are well-structured for water management and runoff efficiency. Moreover, the moderate circularity ratio group comprises sub-watersheds like SW5, SW19, and SW45. These sub-watersheds display moderately elongated shape, leading to ordinary runoff dynamics. Additionally, sub-watersheds of SW6 and SW21 emphasize lower circularity ratios. These sub-watersheds exhibit more irregular shapes, which can hinder drainage efficiency and increase the risk of water retention and flooding. The current state of sub-watersheds may require additional management strategies to mitigate potential flooding and improve overall drainage.

Elongation ratio (Re) is defined as the ratio of the length of the watershed to its maximum width. Generally, low elongation ratio suggests a more circular shape, and a high elongation ratio indicates an elongated watershed shape (Schumm 1956). In this study, a notable trend emerges in the high elongation ratio group, highlighted by sub-watersheds such as SW49 and SW45. These sub-watersheds show a pronounced elongated shape, demonstrating an efficient drainage system. The higher values indicate a favorable configuration for water management, making these watersheds particularly effective in channeling water. Moreover, sub-watersheds with moderate values, such as SW1, SW2, and SW19, demonstrate a modest shape, which still allows for reasonable drainage efficiency. This group represents a transitional state where the watersheds are not as elongated as those in the high group yet still maintain runoff processes. Conversely, the sub-watersheds with lower elongation ratio, like SW6, and SW11, exhibit more compact shapes. These lower Re values suggest a higher risk of flooding and slower runoff, necessitating careful management strategies to mitigate potential issues.

The compactness coe (Cc) is defined as the ratio of the perimeter of the watershed to the square root of its area, typically expressed in the following form: $Cc = (P / \sqrt{A})$. A lower compactness coefficient indicates a more compact shape, and a higher compactness coefficient reflects an irregular or elongated shape (Strahler 1964). Our results indicate that the sub-watersheds such as SW6 and SW32 are high in compactness coefficient, which display a high level of compactness. The elevated Cc values imply a configuration that potentially contributes to flooding risks, necessitating careful management strategies to mitigate adverse impacts. Furthermore, sub-watersheds like SW1, SW3, and SW20, characterizing by moderate Cc values, exhibit a relatively elongated shape that may allow handling runoff dynamics. Finally, sub-watersheds such as SW30 and SW45 show low Cc values, displaying more elongated shapes, which may enhance their drainage capabilities and reduce flood susceptibility. Such lower Cc values signify a favorable disposition for water movement, which demonstrate that these sub-watersheds are suited for effective drainage system.

The shape factor (Bs) is a hydrological parameter that characterizes the geometry of a watershed by relating its area to the square of its length. A lower shape factor indicates a more compact and circular watershed shape, while a higher shape factor suggests a more elongated or irregular shape, (Horton 1932). The examination of the shape factor (Bs) for the various watersheds delivers valuable insights of how this parameter influences the hydrological behaviors. In our study, the results that watersheds like SW6 and SW11 are found in the high shape factor group. This group exhibit irregular shapes that can retard hydrological responses. Moreover, the moderate shape factor group comprises sub-watersheds such as SW1, SW3, and SW20. These sub-watersheds display more balanced shapes that generally allow for water to normally flow. On the other hand, sub-watersheds with lower values, are significantly presented at SW49 and SW45. These sub-watersheds emphasize more compact shapes, which can promote structured drainage systems.

Relief parameters

Relief ratio (Rh) is a measure of the elevation difference relative to the horizontal distance. It indicates the steepness or ruggedness of the terrain, with higher values suggesting steeper slopes and lower values indicating gentler gradients (Schumm 1963). In the study area, SW3 is the higher sub-watersheds in relief ratio. This higher value suggests a very steep terrain, which can increase runoff dynamics and ultimately water erosion during rainfall events. Such steep slopes water running, posing as result soil stability at serious risk. Other sub-watersheds like SW5 (119.38) and SW4 (176.88), representing moderate relief ratios, indicate a balance between elevation and horizontal distance. These sub-watersheds allow efficient runoff and a stable environment for soil and vegetation. Conversely, watersheds like SW6 and SW26 emphasize very low relief ratios. These values indicate flatter terrain, which typically allows for better water retention and lower runoff rates.

Ruggedness number (Rn) quantifies the complexity or ruggedness of a landscape by comparing the total relief of a region. A higher Ruggedness Number indicates a more rugged terrain with significant elevation changes over a relatively small area, while a lower Ruggedness Number suggests a flatter terrain with less variation in elevation (Schumm 1963). In the study area, SW8 is the higher ruggedness number. This subwatershed represents a highly complex terrain with significant elevation changes, increasing runoff and erosion processes specifically during heavy rainfall events. Such rugged landscapes create challenges for vegetation and soil stability, as steep slopes are more susceptible to erosion. Moderate ruggedness numbers found in sub-watersheds, such as SW1 and SW4 indicate a more stable terrain that can handle water flow. These sub-watersheds offer appropriate soil conditions, contributing positively to the local ecosystem. In contrast, sub-watersheds like SW19 and SW20 exhibit low ruggedness numbers, which suggests flatter terrains, consequently reducing water erosion dynamics and allowing smooth flowing.

Dissection index (Dis) quantifies the degree to which a landscape has been dissected or broken up by erosion or other geological processes. It assesses how much the terrain has been shaped by valleys, by ridges, or by other topographical elements. A higher Dissection Index indicates a more dissected landscape, characterized by steep slopes and a greater number of valleys and ridges. Conversely, a lower Dissection Index suggests a less dissected landscape, which may be flatter and more uniform (Singh 1994). In our case study, the high dissection index is observed in SW6. This indicates a highly dissected sub-watershed suggests significant elevation changes and a complex topography. Such conditions can increase water runoff and soil erosion, particularly during intense rainfall events. Furthermore, sub-watersheds like those found in SW4, and SW10 are typically characterized by Moderate dissection indices reflecting a balanced landscape that can manage water flow effectively. These sub-watersheds create a proper terrain to achieve a good balance between runoff and water retention. In contrast, watersheds like SW19 and SW20 exhibit low dissection indices, suggesting less fragmented land and promoting greater water retention and reduced erosion rates.

Relative relief (Rre) is calculated by taking the difference between the maximum and minimum elevations in a region and comparing that to the average elevation of the area. A higher Relative Relief indicates significant elevation changes within a relatively small area, emphasizing a

Table 4. Shape and relief parameters

ID	Shape parameters					Relief parameters			
	Rf	Rc	Re	Cc	Bs	Rh	Rn	Dis	Rre
1	0.40	0.55	0.71	1.35	2.50	208.61	2.24	0.58	68.88
2	0.40	0.37	0.72	1.65	2.48	144.53	1.35	0.45	38.90
3	0.39	0.45	0.70	1.48	2.57	221.97	1.84	0.58	67.69
4	0.38	0.42	0.70	1.54	2.63	176.88	2.27	0.62	52.52
5	0.38	0.54	0.69	1.36	2.65	119.38	1.50	0.48	40.33
6	0.23	0.22	0.54	2.12	4.35	29.63	2.94	0.91	8.22
7	0.36	0.32	0.68	1.75	2.74	76.99	0.96	0.52	20.49
8	0.24	0.33	0.55	1.74	4.25	41.55	3.42	0.78	13.91
9	0.30	0.46	0.62	1.48	3.31	76.19	2.23	0.69	26.39
10	0.30	0.33	0.62	1.75	3.30	81.02	2.28	0.68	23.77
11	0.22	0.33	0.53	1.74	4.57	28.09	3.14	0.73	9.72
12	0.30	0.46	0.62	1.47	3.34	71.23	2.15	0.53	24.92
13	0.36	0.28	0.68	1.90	2.79	90.88	1.24	0.38	22.51
14	0.33	0.50	0.67	1.42	2.84	78.76	1.41	0.36	26.44
15	0.29	0.38	0.61	1.62	3.45	35.74	1.22	0.35	11.54
16	0.37	0.36	0.68	1.67	2.74	78.57	0.91	0.30	21.90
17	0.42	0.62	0.73	1.27	2.37	95.01	0.67	0.21	32.41
18	0.41	0.48	0.73	1.44	2.42	87.18	0.57	0.20	26.51
19	0.41	0.53	0.72	1.37	2.44	53.44	0.40	0.14	17.18
20	0.31	0.43	0.63	1.53	3.25	22.04	0.58	0.18	7.32
21	0.34	0.24	0.66	2.02	2.90	39.81	0.67	0.19	9.45
22	0.38	0.44	0.69	1.51	2.65	54.09	0.76	0.18	16.41
23	0.38	0.30	0.69	1.84	2.64	61.43	0.64	0.20	15.31
24	0.34	0.28	0.65	1.89	2.98	27.60	0.51	0.17	7.12
25	0.32	0.34	0.64	1.71	3.14	28.93	0.85	0.23	8.47
26	0.30	0.35	0.62	1.69	3.35	25.27	0.88	0.25	7.75
27	0.29	0.34	0.61	1.72	3.48	23.50	0.85	0.28	7.20
28	0.29	0.30	0.60	1.82	3.50	21.47	0.84	0.27	6.21
29	0.36	0.29	0.68	1.87	2.79	61.91	0.86	0.30	15.65
30	0.37	0.55	0.68	1.35	2.73	59.09	0.95	0.27	20.36
31	0.33	0.40	0.65	1.59	3.00	83.08	1.72	0.57	25.52
32	0.39	0.19	0.70	2.28	2.60	128.50	1.53	0.55	25.58
33	0.38	0.34	0.70	1.72	2.60	84.03	1.16	0.46	22.16
34	0.39	0.39	0.70	1.59	2.59	102.70	1.17	0.52	29.26
35	0.30	0.31	0.61	1.78	3.37	57.64	1.85	0.68	16.75
36	0.34	0.38	0.66	1.62	2.92	100.78	1.81	0.70	29.99
37	0.25	0.23	0.56	2.07	4.06	34.80	2.50	0.80	9.53
38	0.34	0.34	0.66	1.71	2.97	52.42	0.94	0.61	14.87
39	0.35	0.22	0.67	2.12	2.83	64.19	0.92	0.62	14.38
40	0.40	0.36	0.71	1.67	2.53	48.46	0.44	0.44	13.02
41	0.39	0.49	0.71	1.43	2.56	61.62	0.53	0.57	19.46
42	0.42	0.52	0.73	1.39	2.40	63.18	0.44	0.53	19.85
43	0.34	0.26	0.66	1.98	2.93	38.75	0.69	0.53	9.45
44	0.34	0.41	0.66	1.57	2.94	34.48	0.52	0.67	10.64
45	0.46	0.53	0.76	1.37	2.19	89.67	0.43	0.60	27.30
46	0.43	0.51	0.74	1.40	2.31	81.25	0.44	0.64	24.92
47	0.41	0.35	0.72	1.69	2.44	65.90	0.42	0.68	17.15
48	0.41	0.44	0.72	1.51	2.46	65.44	0.51	0.71	19.17
49	0.50	0.53	0.80	1.37	2.01	124.04	0.34	0.67	36.10
50	0.34	0.59	0.66	1.30	2.92	62.21	0.95	0.83	23.10
51	0.35	0.41	0.67	1.55	2.88	59.67	0.78	0.83	18.38
52	0.42	0.47	0.73	1.46	2.38	72.17	0.46	0.16	21.47
53	0.26	0.36	0.57	1.66	3.90	34.95	2.04	0.85	11.72

more rugged and varied landscape. On the other hand, a lower Relative Relief indicates a flatter terrain with less variation in elevation, slowing down water movement (Schumm 1963). We have noted that the highest relative relief is typically in SW1. This high value indicates a steep terrain, rendering the landscape perfect to experience higher runoff and erosion dynamics. SW4 and SW3 are Moderate in relative relief values, which indicate an adequate landscape that can handle water flow effectively. Moreover, sub-watersheds like SW6 and SW20 emphasize low relative relief, displaying flatter terrains characterized by less vertical variation, which contribute to reduce erosion risks.

Linear parameters

Stream length ratio (Rl) is hydrological parameter that compares the total length of streams within a watershed to the length of the mainstream or river. A higher stream length ratio indicates a greater total length of streams relative to the mainstream, while a lower stream length ratio implies a simpler drainage network (Horton 1945). In this study, sub-watersheds like SW24 and SW48 exhibit significantly elevated Rl values, suggesting a complex network of streams that may reinforce drainage system capabilities. The increased stream length often correlates with improved runoff management, but it can also indicate a higher susceptibility to flooding. In the moderate range, sub-watersheds such as SW10, SW13 and SW16 demonstrate an acceptable structure that facilitates effective water flowing. These ratios indicate a functional drainage network, allowing for reasonable runoff efficiency while mitigating the risk of excessive water retention. Conversely, SW1 and SW5 show a lower stream length ratio, making these them tend to have shorter stream networks, which may limit their ability to evacuate major runoff. The compact nature of these watersheds can lead to increased water retention, raising concerns about potential flooding during heavy rainfall events. Such conditions indicate a need for careful intervention to enhance drainage system and reduce flood risks.

Bifurcation ratio (Rb) quantifies the branching pattern of a river or stream network within a watershed. It is defined as the ratio of the number of streams of one order to the number of streams of the next higher order. A higher bifurcation ratio suggests a more complex network with many tributaries, while a lower ratio indicates a simpler network (Schumm 1956). In our study, we have noted higher bifurcation ratio in SW3, SW26, and SW45. These sub-watersheds display a highly intricate drainage network, suggesting a significant number of stream branches compared to their hierarchical levels. However, the intricacy of such systems also requires careful monitoring to prevent issues related to erosion and sedimentation. Furthermore, sub-watersheds such as SW10, SW21, and SW22 show moderate (Rb) values, demonstrating a balanced hydrological structure and a well-developed drainage network. The lower bifurcation ratio group includes sub-watersheds, such as SW4 and SW49, demonstrating simpler drainage networks, which consequently may limit their capacity to manage runoff. Rho coefficient (Rho) quantifies the relationship between the characteristics of a watershed and its hydrological response. It assesses the degree of effectiveness of a watershed in capturing and managing water. Generally, a higher Rho coefficient indicates a strong relationship between precipitation and runoff, while a lower Rho coefficient may indicate that a significant portion of precipitation is lost to infiltration or evaporation (Strahler 1952). In the current study, SW48 has the highest Rho coefficient, which suggests a vigorous hydrological system where water movement is rapid, potentially leading to increased erosion and sediment transport. The dynamics in this sub-watershed indicate a need for careful management to mitigate erosion risks. Sub-watersheds like SW10 and SW12, with moderate Rho coefficients values, highlight a more balanced relationship between stream density and watershed shape. These values suggest that these areas can manage water efficiently while minimizing erosion risks, indicating a functional hydrological system capable of handling precipitation effectively. In contrast, sub-watersheds with lower Rho coefficients, such as SW3 and SW31, demonstrate less water dynamic, which may limit erosion risks, allowing water stagnation issues.

Texture ratio (Rt) characterizes the arrangement and density of drainage networks within a watershed. It is defined as the ratio of the total number of streams of all orders to the total area of the watershed. A higher texture ratio indicates a denser network of streams, while a lower texture ratio suggests a less dense drainage network (Schumm 1956). In this study, we observed exceptionally high texture ratio in SW11, which suggests a complex soil structure that may support diverse vegetation and contribute to enhanced water retention capabilities. The moderate range of texture ratios, exemplified by sub-watersheds such as SW10 and SW36, indicate a well-developed soil composition that supports effective drainage systems. These sub-watersheds are likely capable of maintaining a stable hydrological environment, allowing them to handle typical precipitation patterns without significant erosion risks. On the other hand, sub-watersheds like SW32 and SW40 exhibit lower texture ratios, indicating a simpler soil composition. These areas may have limited water retention and infiltration capabilities, potentially leading to quick runoff during rainfall events.

Drainage texture (Dt) is the ratio of the total number of stream segments to the total perimeter of the watershed. It provides insight into the effectiveness of the watershed in draining excess water and its potential for surface runoff. Generally, a higher drainage texture indicates a denser network of streams, and a lower drainage texture suggests a sparser network of channels (Horton 1945). Sub-watersheds like SW6, SW8, and SW11 present interesting cases with higher drainage textures, suggesting a rich network of streams and channels. The complexity of these sub-watersheds can enhance their capacity to manage water efficiently, but it also necessitates careful monitoring to prevent potential issues related to erosion and sedimentation. Moderate values, such as those found in SW10 and SW20, indicate a functional drainage network that can effectively manage water flow. These sub-watersheds are capable of handling precipitation patterns and maintain a stable hydrological environment. In contrast, sub-watersheds like SW40 and SW2 exhibit much lower values, indicating simpler drainage networks. These lower values suggest that water may not flow as efficiently through these areas.

Stream frequency (Fs) quantifies the number of stream segments within a specific area of a watershed. It is typically expressed as the ratio of the total number of streams to the total area of the watershed. A higher stream frequency indicates a greater number of streams in a given area. Conversely, a lower stream frequency implies a less complex drainage network, which may lead to slower runoff (Horton 1932). In the current study, Sub-watershed SW49 highlights the exceptionally high stream frequency, which suggests an intricate network of streams, indicating that water flows abundantly and rapidly through this watershed. Additionally, in the moderate range, sub-watersheds such as SW5, SW6, SW14, and SW16 present an ideal example of a balanced drainage network. These sub-watersheds show a good capacity for managing water flow.

Conversely, sub-watersheds like SW40 and SW50 exhibit lower stream frequencies. These lower values suggest a less complex drainage network, which may result in slower water movement and increased water retention.

Drainage density (Dd) reflects the total length of streams per unit area. A higher drainage density indicates a more extensive network of streams and channels, while a lower drainage density implies a less developed stream network (Horton 1932). Sub-Watersheds like SW14, SW25 and SW33 show slightly elevated drainage densities, reflecting a well-developed stream network that can enhance water movement. While this can facilitate efficient water evacuation out the basin, it may also pose risks related to erosion and sediment transport during heavy rainfall events. Moderate drainage densities, such as those observed in SW1 and SW4, indicate a well-structured drainage network. These characteristics appear to manage water effectively, maintaining stability during rainfall events. In contrast, sub-watersheds like SW49 and SW47 exhibit lower drainage densities. These values suggest a less extensive drainage network, which can lead to slower water movement and increased retention in these areas.

Drainage intensity (Di) refers to the degree of development of the drainage network within a watershed or region. It is typically defined as the ratio of the total length of all stream channels to the area of the watershed. A higher drainage intensity indicates a more developed and denser network of streams, and a lower drainage intensity may indicate a less developed drainage system (Faniran 1968). Sub-watershed (2.06) represents the exceptionally high drainage intensity, rendering it a basin characterized by a very effective drainage network, capable of handling significant water flow. Sub-watersheds with Moderate drainage intensity values like (0.90 to 1.09) indicate an efficient drainage network that can effectively handle water flow. In contrast, many sub-watersheds exhibit lower drainage intensity values,

Table 5. Linear parameters

ID	Linear parameters									
	Rl	Rb	Rho	Rt	Dt	Fs	Dd	Di	It	Lo
1	0.46	3.88	0.12	0.79	1.05	1.28	1.72	0.74	2.19	0.29
2	0.66	4.00	0.17	0.53	0.67	1.01	1.54	0.66	1.56	0.32
3	0.96	12.81	0.07	0.69	0.91	1.09	1.18	0.93	1.29	0.42
4	0.58	2.89	0.20	0.85	1.23	1.41	1.66	0.85	2.34	0.30
5	0.57	3.11	0.18	1.10	1.49	1.47	1.58	0.93	2.32	0.32
6	0.52	3.84	0.13	3.61	4.76	1.18	1.58	0.75	1.87	0.32
7	1.23	3.67	0.34	1.05	1.31	1.47	1.36	1.09	2.00	0.37
8	0.53	4.09	0.13	4.31	5.63	1.25	1.44	0.87	1.80	0.35
9	0.49	3.50	0.14	2.14	2.89	1.37	1.46	0.94	2.01	0.34
10	1.03	4.74	0.22	1.52	1.93	1.09	1.41	0.77	1.54	0.35
11	0.54	4.24	0.13	5.58	7.33	1.25	1.44	0.87	1.79	0.35
12	0.76	3.51	0.22	2.11	2.89	1.32	1.43	0.92	1.89	0.35
13	1.10	3.60	0.31	0.93	1.18	1.34	1.38	0.97	1.84	0.36
14	0.65	3.60	0.18	1.44	2.01	1.59	1.68	0.95	2.67	0.30
15	0.58	3.74	0.16	2.16	2.89	1.29	1.43	0.90	1.85	0.35
16	1.11	5.42	0.20	0.89	1.10	1.19	1.27	0.94	1.51	0.39
17	0.74	3.50	0.21	0.83	1.10	1.54	1.41	1.09	2.18	0.35
18	0.83	3.50	0.24	0.67	0.90	1.31	1.21	1.09	1.59	0.41
19	0.70	3.63	0.19	0.74	1.02	1.38	1.33	1.04	1.83	0.38
20	0.62	3.17	0.20	1.77	2.50	1.31	1.41	0.93	1.84	0.36
21	0.61	4.22	0.15	1.10	1.43	1.51	1.45	1.04	2.19	0.34
22	0.58	4.58	0.13	0.72	0.99	1.08	1.75	0.62	1.89	0.29
23	0.75	4.20	0.18	0.54	0.73	0.99	1.33	0.74	1.32	0.37
24	2.05	3.93	0.52	1.12	1.62	1.44	1.42	1.01	2.05	0.35
25	0.49	4.35	0.11	1.32	1.72	1.14	1.82	0.63	2.06	0.28
26	0.60	5.18	0.12	1.83	2.41	1.24	1.64	0.76	2.03	0.30
27	0.55	3.87	0.14	2.19	2.93	1.34	1.46	0.92	1.96	0.34
28	0.50	3.62	0.14	1.91	2.56	1.22	1.54	0.80	1.87	0.33
29	0.94	6.85	0.14	0.94	1.23	1.37	1.40	0.97	1.92	0.36
30	0.52	3.56	0.15	1.22	1.79	1.57	1.77	0.89	2.79	0.28
31	0.43	4.05	0.11	1.17	1.49	1.09	1.55	0.70	1.70	0.32
32	1.03	2.63	0.39	0.46	0.68	1.22	1.63	0.75	1.98	0.31
33	0.64	2.83	0.23	0.72	1.11	1.50	1.89	0.79	2.82	0.26
34	0.97	4.70	0.21	0.87	1.11	1.40	1.58	0.88	2.20	0.32
35	0.79	3.56	0.22	2.05	2.70	1.44	1.48	0.97	2.14	0.34
36	0.97	3.56	0.27	1.10	1.52	1.25	1.50	0.83	1.89	0.33
37	0.59	3.68	0.16	3.01	4.08	1.29	1.53	0.84	1.96	0.33
38	0.51	4.24	0.12	1.22	1.58	1.30	1.41	0.92	1.83	0.35
39	0.61	3.50	0.17	0.77	1.01	1.22	1.38	0.88	1.67	0.36
40	0.57	3.38	0.17	0.45	0.66	0.95	1.39	0.68	1.32	0.36
41	0.59	4.30	0.14	0.83	1.10	1.30	1.26	1.03	1.64	0.40
42	0.63	3.75	0.17	0.65	0.83	1.20	1.30	0.92	1.57	0.38
43	0.45	3.63	0.12	0.79	1.01	1.01	1.48	0.68	1.50	0.34
44	0.54	3.96	0.14	1.19	1.46	1.14	1.23	0.93	1.40	0.41
45	0.99	5.00	0.20	0.43	0.51	1.02	1.35	0.76	1.38	0.37
46	0.55	2.50	0.22	0.41	0.61	1.03	1.22	0.85	1.25	0.41
47	0.56	3.50	0.16	0.46	0.60	1.00	1.13	0.88	1.13	0.44
48	2.58	3.50	0.74	0.61	0.81	1.17	1.35	0.86	1.59	0.37
49	0.63	2.00	0.31	0.46	0.81	2.24	1.09	2.06	2.43	0.46
50	0.58	6.61	0.09	1.18	1.49	0.99	1.27	0.77	1.26	0.39
51	0.50	3.76	0.13	1.18	1.51	1.26	1.17	1.08	1.48	0.43
52	0.92	3.33	0.28	0.64	0.88	1.37	1.26	1.09	1.74	0.40
53	0.52	3.35	0.16	3.03	4.05	1.18	1.45	0.81	1.71	0.34

such as 0.62 and 0.63. These low-value sub-basins suggest less efficient drainage systems.

Infiltration number (It) quantifies the capacity of a watershed to absorb water. This metric provides insight into how efficient water can permeate the soil and contribute to groundwater recharge. A higher infiltration number indicates a greater capacity for water to be absorbed by the soil, while a lower infiltration number may signify limited ability for water absorption (Faniran 1968). SW30 represents the highest infiltration number across the entire study area. This suggests a highly permeable soil structure, capable of absorbing significant amounts of water and maintaining stable water levels. With this high infiltration capacity is beneficial for reducing runoff and minimizing erosion, supporting healthy vegetation and groundwater recharge. Other sub-watersheds with Moderate infiltration numbers, such as SW4 and SW14, indicate a modest capacity for water absorption. These sub-watersheds can manage rainfall effectively, promoting stable hydrological conditions. In contrast, sub-watersheds like SW47 and SW46 exhibit lower infiltration numbers. These lower values indicate that these sub-watersheds may have compacted or less permeable soils, which can lead to increased surface runoff. The limited infiltration capacity can hinder plant growth and reduce overall watershed health.

Length overland flow (Lo) measures the distance water travels over the ground before reaching a channel. A shorter length of overland flow indicates that water quickly reaches a stream, and vice versa; a longer length of overland flow suggests that water takes more time to reach the stream (Horton 1945). Our results indicate that the highest length of overland flow is observed in SW49, measuring 0.46. This suggests that water takes a longer route before entering a stream. These longer hydrological paths increase water erosion upstream and sedimentation issues downstream. Such conditions may affect water quality and the overall sub-watersheds' ecosystem. Furthermore, most watersheds, such as SW1 and SW6, exhibit moderate lengths of overland flow. These values reflect a well-structured hydrological system where water can move efficiently while maintaining stability in sediment transport. In contrast, sub-watersheds like SW25 and SW30 present shorter overland flow lengths. These shorter distances indicate more efficient drainage, potentially reducing the risk of erosion and enhancing water quality.

Ranking and prioritization of sub-watersheds

On the basis of the compound parameter, twelve of the 53 sub-watersheds (≈23%) rank as very high priority (Cp 19.63–23.33) (Figure 9) (Table 6). These form a contiguous core along the upper Sebou channel in the centre of the basin — SW-34 to SW-37 — extending south to SW-12, SW-13, and SW-14, with a detached eastern pocket at SW-7, SW-9, and SW-10 (alongside SW-4 and SW-5). Seventeen sub-watersheds are high priority (Cp 23.33–27.03), including the large peripheral catchments SW-6 in the west and SW-8 and SW-11 in the east, together with the units fringing the very-high core (SW-1, SW-3, SW-32, SW-33). The moderate class (sixteen sub-watersheds; Cp 27.03–30.73) occupies the northern rim and the south-western margin, while the low (five; Cp 30.73–34.43) and very-low (three; Cp 34.43–38) classes are few and spatially clustered, SW-40, SW-43, and SW-47 forming a north-central very-low pocket. SW-43 is the principal anomaly, centrally placed among the very-high units yet carrying the highest Cp. This pattern is consistent with prioritization, since the very-high-priority units coincide with the densest and most incised part of the network along the central trunk. Because the drainage network also underlies several morphometric parameters, this agreement reflects internal consistency rather than independent validation.

DISCUSSION

The spatial concentration of the highest-priority sub-watersheds along the central Sebou corridor and the eastern flank can be explained by the physical characteristics that the morphometric parameters capture. The very high and high units combine steep relief with a high drainage density and stream frequency and with compact basin shapes, and this combination shortens the time that water needs to reach the channels, concentrates runoff, and raises its erosive power. The dense, sixth-order dendritic network of the watershed reflects an efficient drainage system in which the channels are actively incised. Because the drainage network also underlies several of the morphometric parameters, the coincidence of the highest-priority units with the densest, most incised reaches is best read as internal consistency rather than independent validation. Independent corroboration comes instead from the more erodible lithologies and the low-NDVI sectors, which coincide with the same units but are not inputs to the compound parameter (Horton, 1945; Strahler, 1964; Aher et al., 2014; Layan et al., 2026).

The terrain context is consistent with this pattern. The central and southern uplands of the basin are formed of erodible Middle Atlas formations and carry steep slopes under a semi-arid climate with intense, short seasonal rains, a combination that strongly favours water erosion and gully development. The morphometric method does not include lithology or land cover directly, yet the priority map agrees with the known sensitivity of this terrain, which suggests that the morphometric signal is, in this basin, a reasonable surrogate for erosion susceptibility (Layan et al., 2025; Nairi et al., 2026).

These results have practical value for conservation planning. Because the high and very high classes together cover about 84% of the watershed and include its largest catchments, conservation

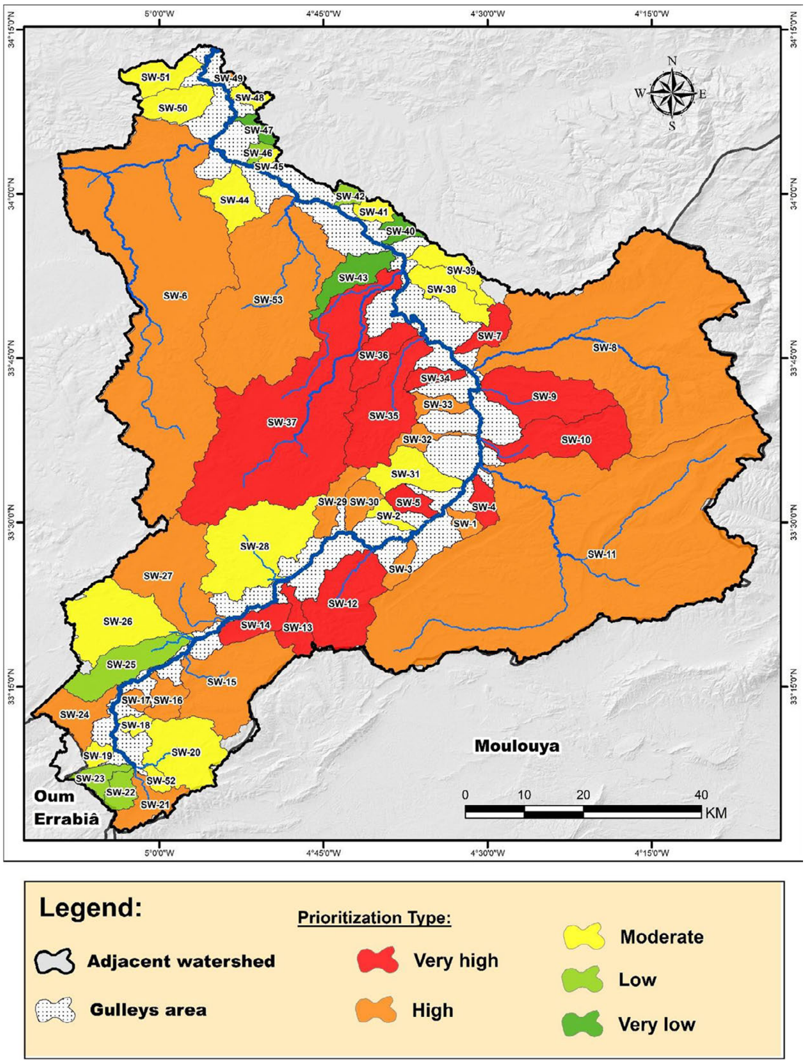

Figure 9. Prioritization map of the Upper Sebou sub-watersheds

Table 6. Prioritization classes of the Upper Sebou sub-watersheds

Priority	Values	Sub watershed
Very low priority	34.43–38	40-43-47
Low priority	30.73–34.43	22-23-25-42-46
Moderate priority	27.03–30.73	2-18-19-20-26-28-31-38-39-41-44-45-48-50-51-52
High priority	23.33–27.03	1-3-6-8-11-15-16-17-21-24-27-29-30-32-33-49-53
Very high priority	19.63–23.33	4-5-7-9-10-12-13-14-34-35-36-37

measures cannot be applied everywhere at once, and the prioritization allows them to be staged. The small very-high units in the central headwaters, such as Aichoun, Skoura, Abouha, and Taghit, are well suited to localized, low-cost works (check dams, gully plugs, and vegetative barriers), while the large high-priority catchments, particularly Maasser, Marz, and Zeloul, deliver most of the sediment simply because of their size and require basin-scale measures such as reforestation, rangeland management, and contour works. Targeting these areas is important for protecting downstream infrastructure, above all the Allal Al Fassi reservoir on the Sebou, whose storage capacity and service life are threatened by siltation from the upstream slopes (Eddoum et al., 2025; Mofidi et al., 2025; Maamare et al., 2026).

Several limitations qualify these results. The compound-parameter method assumes that each morphometric index is monotonically related to erosion susceptibility and that all indices contribute equally, which is a deliberate simplification suited to rapid, low-data screening rather than a process-based prediction. Because the method uses terrain geometry alone, it does not represent the lithological and land-cover heterogeneity of the basin, and the assumed index–susceptibility relationships need not hold uniformly across these contrasts. A high drainage density, for instance, raises runoff potential, but its erosional expression also depends on substrate erodibility and vegetation cover, which the ranking does not calibrate. Prioritization is corroborated by the coincidence of the highest-priority units with the more erodible lithologies and the low-NDVI sectors, which are not used in the compound parameter. It has not, however, been validated against measured or modelled soil loss or sediment yield, and no formal uncertainty analysis was undertaken. The compound parameter should therefore be read as a relative screening index that orders sub-watersheds for attention, not as an absolute measure of erosion rate. Validation against independent erosion or sediment-yield data, and integration of lithology and land cover through weighted or process-based methods, are the priorities for subsequent work.

The prioritization is conditioned by the flow-accumulation threshold used to define the channel network, set here at 300 cells (about 0.27 km²), which allows the extraction of the smaller drainage channels. A higher threshold extracts a sparser network, removes part of the first-order streams, and lowers the stream frequency, drainage density, drainage texture, and texture ratio, which in turn alters the compound value. The effect is not uniform across the basin. The large, densely incised central-core units (SW-34 to SW-37 and SW-12 to SW-14) keep a dense network under reasonable threshold changes and remain very-high priority, so the core of the ranking is stable. The small headwater and rim units near the class limits, such as Khouabi (SW-49, 3.1 km²) and El Ahrar (SW-45, 5.9 km²), are more sensitive, because a small change in the number of extracted streams shifts their density-based parameters.

The 30 m SRTM resolution acts in the same direction: narrow first-order channels and small gullies are under-represented at this scale, so drainage density is underestimated in the smallest sub-watersheds and their priority may be understated. Finer terrain models (10 m, or 1–5 m LiDAR or photogrammetric DTM) capture more channel detail and have been reported to improve drainage-density accuracy by roughly 15–25% in dissected terrain (Farhan et al., 2017). The ranking reported here should therefore be read as threshold- and resolution-dependent: robust for the densely incised very-high core, but less certain for the smallest marginal units, whose quantitative re-evaluation across several thresholds and resolutions is a priority for future work. Finally, the proportion of the Upper Sebou that falls in the high and very high classes is broadly comparable to that reported for other semi-arid Moroccan basins studied with the same approach, which supports the transferability of the method in data-poor regions (Layan et al., 2026; Eddoum et al., 2025; Mofidi et al., 2025). At the same time, the results should be read as a first, low-cost screening rather than a final assessment. Future work could validate the ranking against measured or modelled soil loss, test how sensitive the drainage density and stream frequency are to the resolution and the flow-accumulation threshold of the digital elevation model, and integrate land use and the ongoing pressure of warming and recurrent drought, all of which would refine the priorities identified here (Aher et al., 2014; Nairi et al., 2026).

CONCLUSIONS

This study successfully achieved its aim of identifying and ranking the most erosion-prone sub-watersheds of the Upper Sebou, showing how a small set of terrain-derived parameters can translate the physical structure of a semi-arid mountain catchment into a clear, actionable map of where land degradation is most likely to advance. By revealing that the highest-priority units cluster along the central corridor and the eastern flank, and that they coincide with the gullying already visible on the ground, the analysis turns a broad, poorly monitored territory into a manageable set of intervention targets. Its contribution is therefore practical and anticipatory, giving land and water managers a defensible basis for directing limited conservation resources before soil loss becomes irreversible, particularly upstream of the Allal Al Fassi reservoir. Beyond this basin, the approach confirms the value of morphometric prioritization as a first line of assessment in data-poor regions, where it can guide more detailed studies rather than replace them. The priorities established here are best seen not as a final verdict but as an opening framework, one that invites validation against measured erosion, refinement through weighted and process-based methods, and extension to how these fragile highlands will respond to intensifying drought and warming.

The datasets and GIS artifacts supporting this study are openly available in the Zenodo repository at (DOI) The deposit includes the SRTM 1 Arc-Second DEM used, the ArcGIS project (.mxd), the intermediate raster products (filled DEM, flow-direction and flow-accumulation rasters), the basin delineation layers (the 53 sub-watershed boundaries, the extracted drainage network, and the outlet points), and the morphometric parameter tables. The analysis did not use custom scripts or automated models: the morphometric parameters were computed in Microsoft Excel from values extracted in ArcGIS, and all spatial processing and mapping were performed interactively in ArcGIS 10.8.2. The workflow is fully specified by the methodology, the DEM-parameters table (Table 2), and the flowchart (Figure 6).

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