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Morphometric vulnerability of the Oued Rheris Watershed (Southeast Morocco): How elongated shape and sparse drainage amplify desertification risk and threaten oasis sustainability

Siham Aouzal[1*], Manare Adnani[1], Hicham El Belrhiti[2], Ilias Kacimi[1]

[1] Laboratory of Geosciences, Water and Environment, Department of Geology, Faculty of Sciences, University of Mohamed V Rabat, Morocco

[2] Department of Fundamental and Applied Sciences, Agronomic and Veterinary Institute Hassan II, Madinat Al Irfane, P.O.Box 6202. Rabat, Morocco[2]

* Corresponding author's e-mail: sihamaouzal5@gmail.com

ABSTRACT

The Oued Rheris Watershed in southeastern Morocco is highly vulnerable to water erosion and desertification, exacerbated by an arid Saharan climate with low rainfall and rising temperatures. This study aims to analyze the morphometric characteristics of the Oued Rheris Watershed to assess its hydrological response time, erosion susceptibility, and sensitivity to desertification, thereby supporting natural resource management and decision-making in at-risk areas. The analysis is based on a 30 m resolution ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) and geographic information systems (GIS) using ArcGIS 10.8 software. Morphometric parameters including drainage density, stream length, compactness index (Kc), equivalent rectangle, form index were calculated. The basin covers an area of 12,606.7 km² with a perimeter of 687.018 km. The hydrographic network, classified according to Strahler (1957), comprises six orders with a total stream length of 4,412.594 km. The first-order streams dominate (50.16% of total length). The Gravelius compactness coefficient (1.71) and form index (0.46) indicate an elongated shape, approximately seven times longer than wide (length = 300.96 km; width = 41.88 km). The drainage density is 0.35 km/km², reflecting the influence of the basin's geology and arid climate. The elongated morphology of the Oued Rheris Watershed implies a prolonged concentration time and attenuated peak flows. However, the low drainage density and arid conditions increase vulnerability to flash floods and erosion. These findings are critical for watershed management, soil conservation, and sustainable water resource planning in southeastern Morocco.

Keywords: morphometric analysis, watershed, drainage density, ASTER GDEM, GIS, desertification, Oued Rheris, Morocco.

INTRODUCTION

Environmental risks associated with climate variations represent a major global challenge, causing significant soil degradation, deterioration of water quality, and substantial sediment transport to the Earth's surface (Ghosh et al., 2023). In arid and semi-arid regions, these processes are intensified by low rainfall, high temperatures, and sparse vegetation cover, leading to accelerated desertification and water erosion (Benzougagh et al., 2017). The Oued Rheris Watershed, located in southeastern Morocco, is particularly vulnerable to these phenomena. It experiences an arid Saharan climate with warm winters, low annual precipitation, and high evapotranspiration rates. The watershed occupies a unique position between three major morpho-structural units: The High Atlas to the northwest, the Cretaceous Errachidia-Boudenib basin to the northeast, and the

Anti-Atlas to the southwest. This geological diversity, combined with climatic extremes, creates conditions favorable to both water erosion and aeolian sedimentation.

Morphometric analysis provides a quantitative framework for understanding watershed behavior and assessing hydrological responses. (Horton, 1945; Strahler, 1957). Parameters such as drainage density, stream order, compactness index, and form factor are essential tools for assessing erosion potential, flood risk, and sediment yield (Pandey et al., 2004; Sarkar et al., 2020).

Several studies worldwide have applied morphometric analysis using digital elevation models (DEM) and GIS for watershed characterization, including works by Pandey et al. (2004) in India, Subah Rais and Akram Javed (2014) in Rajasthan, Sarkar et al. (2020) in the Indo-Bangladesh Barind Tract, and Ghosh et al. (2023) in Eastern India. In Africa, Kouedjou and Anaba-Banimb (2021) analyzed the Menoua watershed in Cameroon for morpho hydrological risk management. In Morocco, Benzougagh et al. (2017) evaluated natural hazards in the Inaouene watershed using morphometric and GIS approaches, while El Boute et al. (2024) conducted a morphometric analysis and prioritization of sub-watersheds of the Inaouene River upstream of the Idris I dam.

Despite the growing use of DEM- and GIS-based morphometric analysis for watershed characterization, the Oued Rheris Watershed remains insufficiently documented. To the best of current knowledge, no previous study has provided a comprehensive morphometric characterization of this large arid watershed and interpreted its hydrological and geomorphological significance in relation to spatial patterns of water erosion susceptibility and desertification sensitivity. Unlike the Atlantic Sahara of Morocco, where the Atlantic Ocean constitutes the primary source of sand supplying the dune systems (Adnani et al., 2018; Elbelrhiti et al., 2008), the Rheris watershed has no marine sediment input. Instead, the basin itself represents the sole source of sand, with sediments generated by erosion and subsequently transported and deposited, leading to sand encroachment (Kabiri et al., 2004; Benmohammadi et al.,2000).

This knowledge gap is particularly important because the Oued Rheris Watershed forms part of the arid oasis environment of southeastern Morocco, where episodic runoff, sediment transfer, soil degradation, groundwater recharge, and sand encroachment are closely interconnected. In this context, morphometric characteristics do not only describe the geometry of the basin; they provide a physical framework for interpreting the spatial distribution of erosion-prone areas, land degradation processes, and sediment accumulation zones.

In the Oued Rheris Watershed, the downstream Tafilalet oasis system is strongly influenced by the balance between sediment production in the upstream mountainous areas, erosion through the drainage network, and sediment deposition within the oasis plain. Consequently, morphometric analysis provides more than a geometric characterization of the watershed; it offers a process-oriented framework for understanding how basin configuration may influence runoff concentration, sediment connectivity, erosion-prone areas, and zones susceptible to sediment accumulation. This process-oriented perspective distinguishes the present study from conventional DEM–GIS morphometric assessments by linking watershed morphology with erosion, sediment transfer, and oasis sustainability. Accordingly, the present study provides new insights into the geomorphological controls that may influence the long-term stability and sustainability of oasis systems in arid environments.

The originality of this study lies in linking the morphometric configuration of the Oued Rheris Watershed with previously mapped patterns of water erosion susceptibility and desertification sensitivity. The analysis therefore moves beyond a conventional descriptive morphometric assessment by examining how basin shape, drainage organization, drainage density, and stream hierarchy may control runoff concentration, sediment production and transfer, and the spatial expression of land degradation in an arid oasis landscape.

Accordingly, this study aims to: (i) delineate the Oued Rheris Watershed and quantify its principal linear, areal, shape, and relief morphometric parameters using ASTER GDEM and GIS; (ii) analyze the hierarchical organization and spatial structure of its hydrographic network; (iii) examine the relationship between morphometric characteristics and the spatial patterns of water erosion susceptibility and desertification sensitivity previously mapped in the watershed; and (iv) identify implications for sediment management, soil conservation, and sustainable water-resource planning in the Rheris oasis.

STUDY AREA

Geographic location

The Rheris watershed, situated in southeastern Morocco, is part of the Guir–Ziz–Rheris Hydraulic Basin Agency (ABHGZR). It is bordered by the Ziz watershed to the north and east, the Draa watershed to the west, the Oum Er-Rbia watershed to the northwest, and the Maider watershed to the south (Aouzal et al., 2025) (Figure 1). The watershed covers a total area of 12,606.7 km², making it one of the significant drainage basins in southeastern Morocco. The main channel, Oued Rheris, originates in the High Atlas and flows southeastward across the Tafilalet plain before joining Oued Ziz near the Algerian border.

The Rheris watershed is considered an area of significant interest due to its physical characteristics, including morphology, geology, hydrography, and vegetation cover, as well as its unique position between three morpho-structural units: The High Atlas, the Cretaceous Errachidia-Boudenib basin, and the Anti-Atlas. Additionally, there is a lack of studies on this area.

The morpho-structural unit of the upper basin, which corresponds to the High Atlas, is distinguished by a large basin area into which four main oueds flow: Oued Todgha, Oued Tanguerfa-Ferkla, Oued Rheris. The downstream portion of the basin crosses an arid plain before entering the Tafilalet plain, where it flows parallel to Oued Ziz, eventually joining it further downstream.

Climate

The Oued Rheris Watershed is characterized by an arid to Saharan climate, with warm winters, scarce and highly irregular rainfall, and high evaporative demand (Aouzal et al., 2025). Precipitation is mainly concentrated in short duration, high-intensity events that can generate Hortonian overland flow and localized flash floods (Figure 2), particularly where soils are bare, crusted, or characterized by low infiltration capacity. These climatic conditions, combined with sparse vegetation cover (Figure 3) and the presence of erodible sedimentary formations, contribute to the susceptibility of the watershed to water erosion, land degradation, desertification, and sand-encroachment processes.

Geology and morphology

The morpho-structural unit of the upper basin is distinguished by a large catchment area into which four main oueds flow: Oued Todgha, Oued Tanguerfa-Ferkla, Oued Rheris, and Oued Tarda. The downstream portion crosses an arid plain before entering the Tafilalet plain, where it flows parallel to Oued Ziz.

The geology of the Oued Rheris Watershed is characterized by a wide range of lithological formations spanning from the Paleozoic to the Quaternary. The dominant lithologies include Paleozoic sandstone, quartzite, and

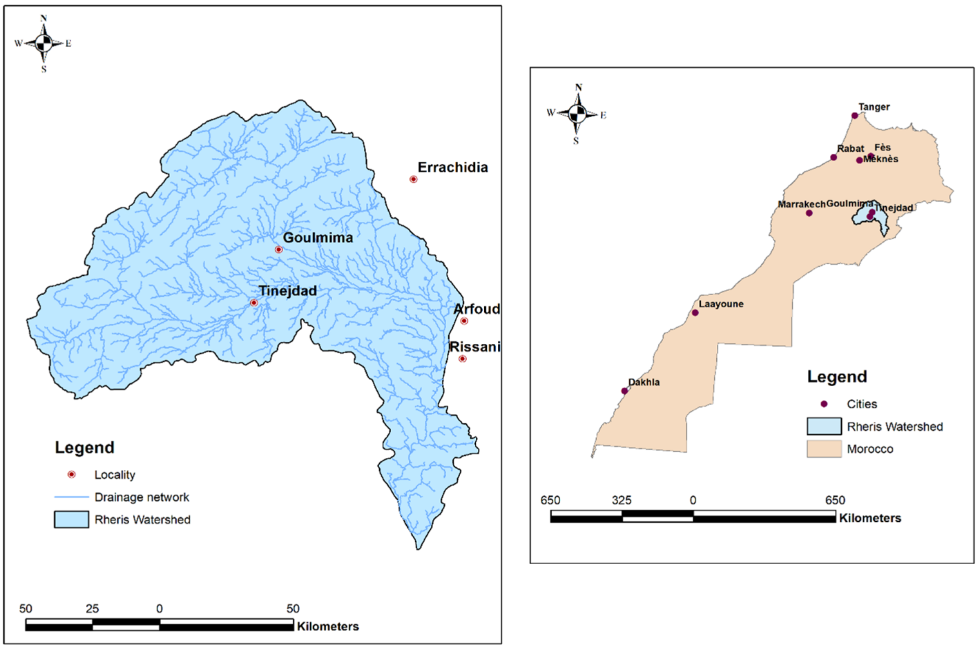

Figure 1. Geographical location of the study area

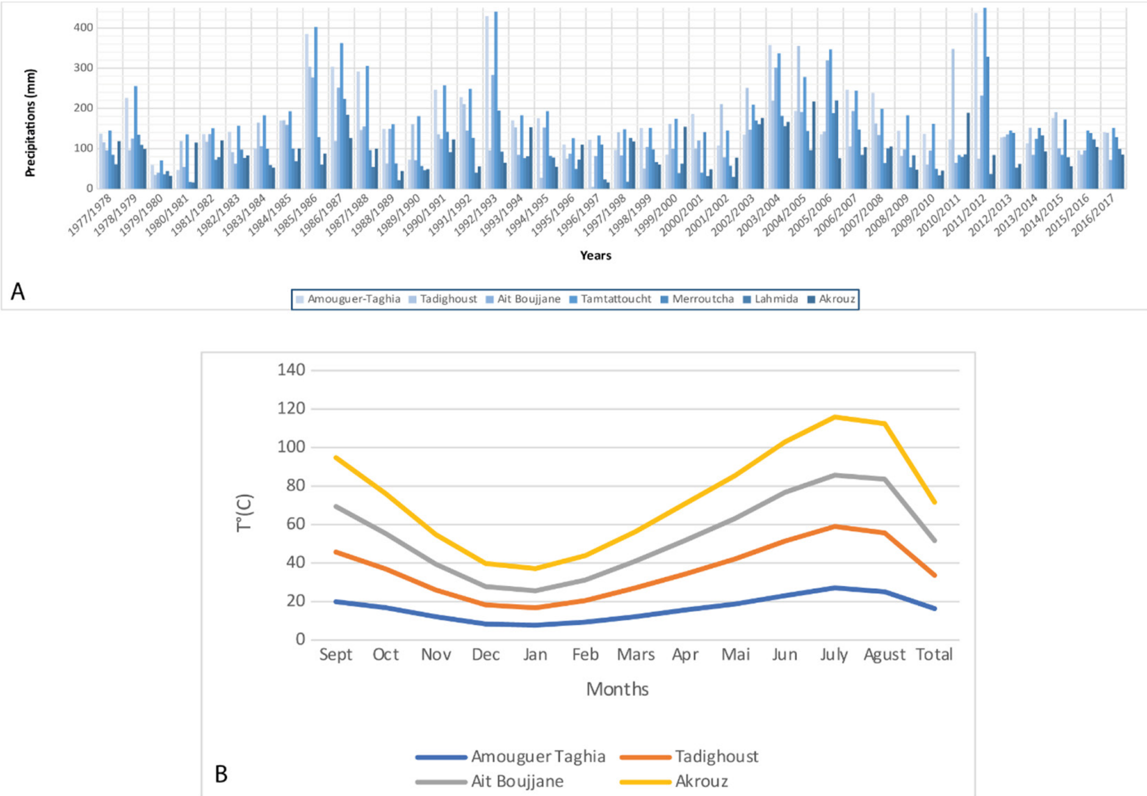

Figure 2. Climate parameters of Rheris Basin: (A, B): (A) Annual average precipitation trends, (B) Evolution of the average annual temperature

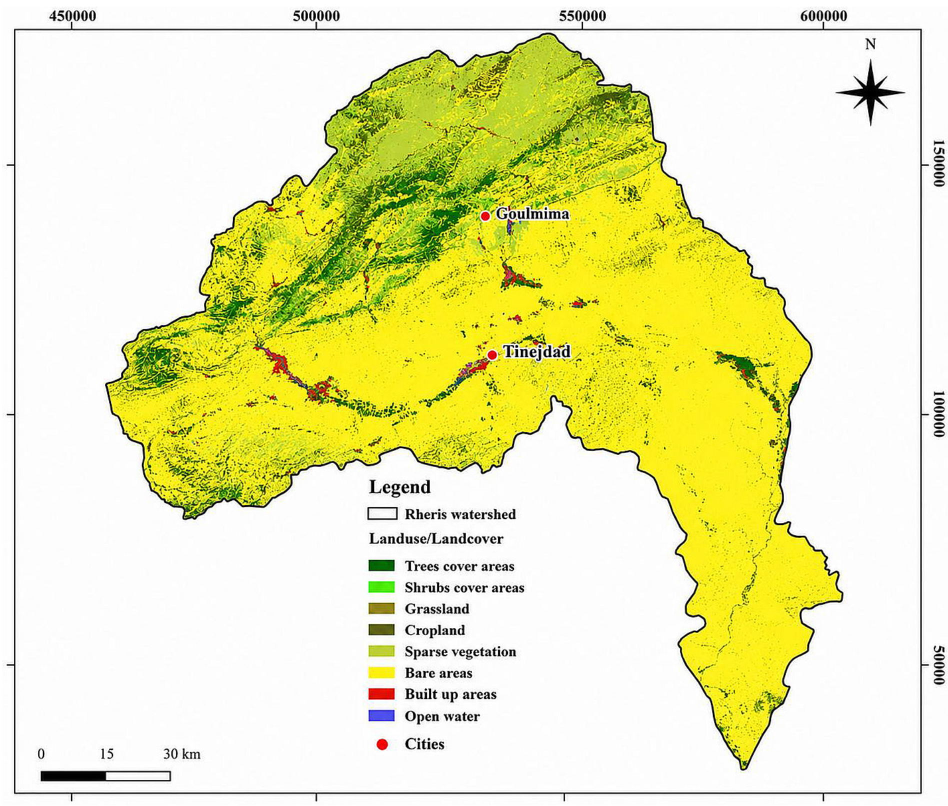

Figure 3. Land cover map of the Oued Rheris Watershed

shale; Jurassic limestone and dolomite; Cretaceous limestone and sandstone; and Plio-Quaternary alluvial deposits, silts, and aeolian sands (Margat, 1962).

From north to south, the watershed can be divided into three main morphostructural units. The northern sector corresponds to the southern flank of the High Atlas, which is mainly composed of Aalenian and Dogger limestones and dolomites separated by Toarcian marl formations. The central sector consists of the Cretaceous basin, expressed as an asymmetrical synclinorium and composed of Turonian carbonate deposits, Infra-Cenomanian sandstones interbedded with gypsum, and Senonian clayey sands containing evaporitic and gypsiferous formations (Jossen et al., 1989). The southern sector is represented by the Quaternary plain, where alluvial deposits predominate and locally overlie Paleozoic and, in some areas, Precambrian bedrock. Travertine deposits and sandstone-schist formations are locally exposed. In the northern part of the plain (Goulmima–Tadighoust and north of Ferkla), the Quaternary deposits rest directly on the Infra-Cenomanian formations, whereas in the southern part (Toudgha Ferkla), they overlie Paleozoic formations (Jossen et al., 1989).

The Rheris basin hosts the Khettara(foggara) irrigation networks the largest traditional hydraulic system in southeastern Morocco. These inherited systems were developed over centuries under arid conditions characterized by scarce and irregular rainfall, violent storms, and negligible vegetation cover. The khettara function as underground channels that tap shallow aquifers recharged by High Atlas runoff, delivering water by gravity to oasis palm groves through a collective management system. However, these traditional systems now face competition from intensive modern agriculture. Large scale date palm plantations and industrial crops, supported by deep boreholes and modern pumping infrastructure, extract groundwater at unsustainable rates. This agricultural intensification upstream directly threatens the resilience of oasis communities downstream, which depend on the inherited Khettara networks and the surface water flows regulated by transformation dams (Figure 4).

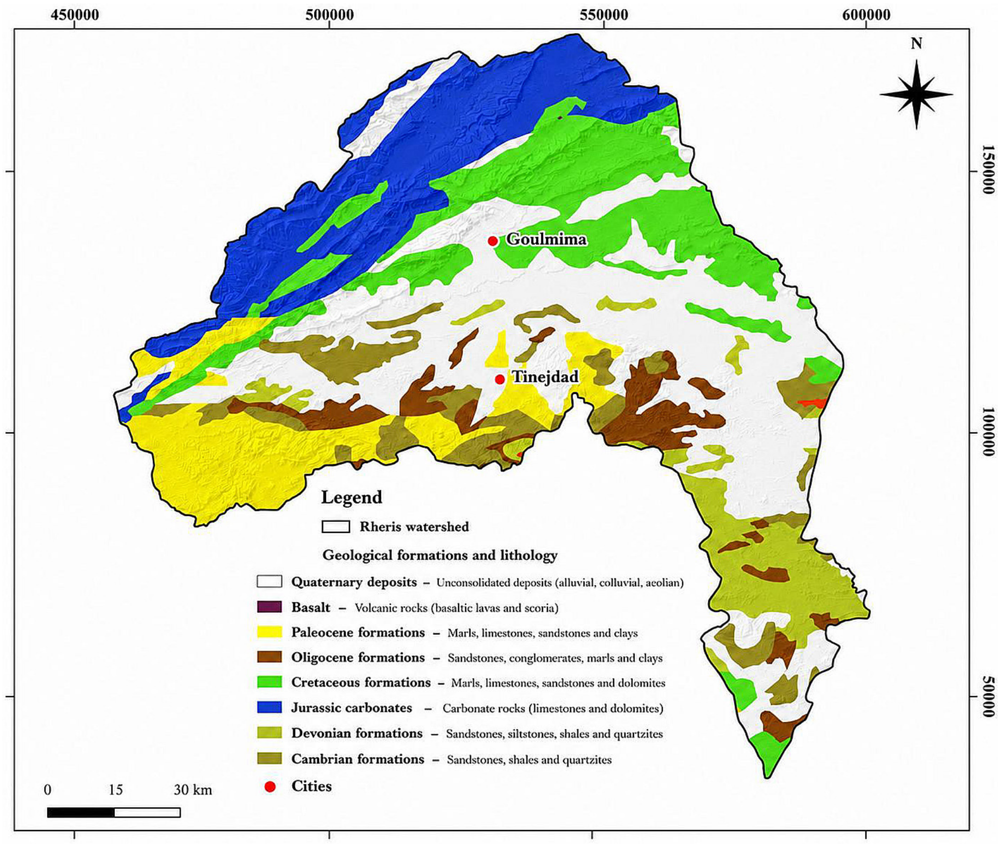

Figure 4. Geological map of the study area

MATERIALS AND METHODS

Data sources

The primary dataset used in this study is the ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) version 3, with a spatial resolution of 30 meters. This DEM was downloaded from the NASA Earth data portal. The ASTER GDEM has been widely used for morphometric analysis in similar studies (Sarkar et al., 2020; El Boute et al., 2024) and provides sufficient resolution for regional-scale watershed characterization.

Additional data include geological maps of Tafilalet at a scale of (1:200,000 scale) (Choubert et al., 1956) the most comprehensive and widely used geological map covering the entire Tafilalet region territory. Climatic data obtained from the Guir-Ziz-Rheris Basin Watershed Agency (ABHGZR).

GIS processing

All GIS processing was performed using ArcGIS 10.8 (ESRI, Redlands, California, USA) with the Spatial Analyst and Hydrology extensions. The workflow comprised the following steps (Figure 5).

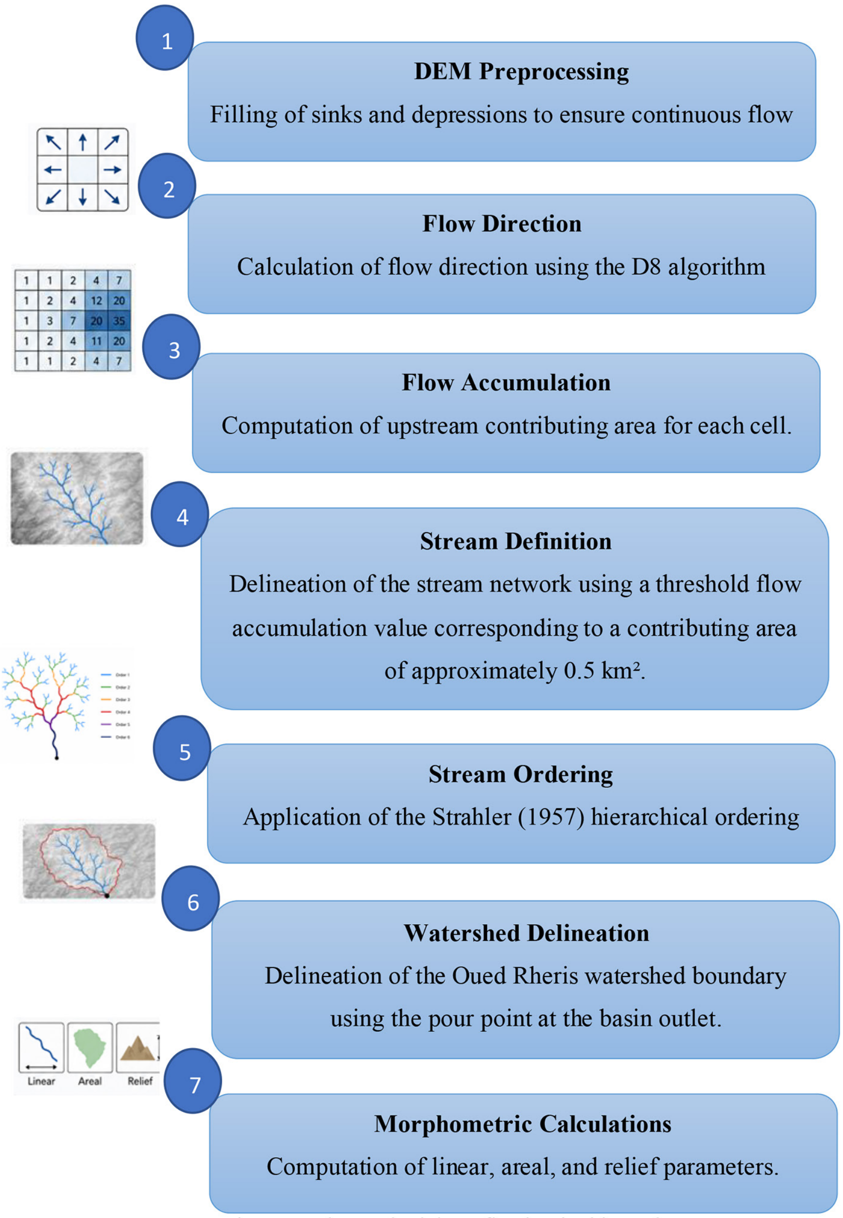

Figure 5. The methodology flowing in this study

Figure 5 summarizes the GIS workflow adopted for watershed delineation and morphometric analysis. Prior to the analysis, the ASTER GDEM was projected into the Nord Maroc coordinate system to ensure spatial consistency throughout the GIS processing. DEM preprocessing began with the Fill tool to remove spurious depressions and ensure continuous surface drainage. Flow direction was computed using the deterministic eight-direction (D8) algorithm, followed by Flow Accumulation to estimate the upstream contributing area for each raster cell. The drainage network was extracted from the flow-accumulation raster using an empirically selected accumulation threshold that provided the most realistic representation of the natural drainage pattern. The extracted streams were subsequently classified according to the Strahler (1957) stream-ordering system. Watershed delineation was then performed from the selected outlet (pour point) using the Watershed tool. Finally, the delineated basin and extracted drainage network were used to compute the linear, areal, shape, and relief morphometric parameters.

To ensure the reliability of the GIS-derived watershed boundary and drainage network, the delineation results were validated using independent reference datasets. The extracted hydrographic features were visually compared with high-resolution satellite imagery and available topographic information. The close spatial agreement between the extracted drainage channels, the visible valley morphology, and the regional drainage divide confirmed the accuracy of the watershed delineation.

Morphometric parameters

The following morphometric parameters were calculated (Table 1).

RESULTS

Topographic characteristics of the Oued Rheris Watershed

The topographic characteristics derived from the ASTER GDEM are presented in Figures 6.

The slope map (Figure 6A) shows that the steepest slopes are concentrated in the northern and northwestern mountainous sectors corresponding to the High Atlas, whereas low-gradient areas dominate the central and downstream parts of the watershed. The elevation map (Figure 6B) illustrates the topographic variation across the basin, with high elevations occurring in the upstream mountainous areas and progressively decreasing toward the downstream alluvial plain. Together, these topographic characteristics provide additional information for interpreting the spatial organization of the drainage network, runoff concentration, and the potential distribution of erosion-prone areas within the watershed.

Table 1. Formulas and definitions of morphometric parameters used in this study

Parameter	Symbol	Definition
Basin area	A	Planimetric area (km²)
Basin perimeter	P	Length of watershed boundary (km)
Stream length	Lu	Total length of streams of order u (km) Horton, 1945
Basin length	L	Distance from outlet to farthest point on watershed divide (km) Schumm, 1956
Basin width	l	A / L (km)
Drainage density	Dd	Lt / A (km/km²) Horton, 1945
Compactness index	Kc	$P / (2\sqrt{(\pi A)})$ Gravelius, 1914
Form index	Rapport l/L	l / L
Circularity ratio	(Rc)	$Rc=4\pi A/ P^2$
Form factor	(Ff)	$Ff = Lb^2 / A$
Elongation ratio	(Re)	$Re=Lb^2 \times A / \pi$
Stream frequency	(Fs)	Fs=N/A
Bifurcation ratio	(Rb)	Rb=Nu/Nu+1

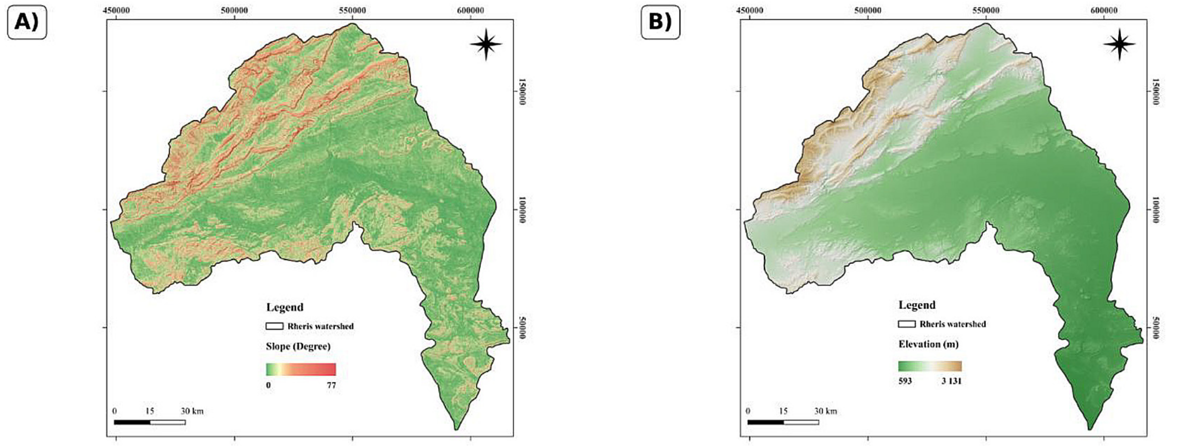

Figure 6. A) Slope map; B) elevation map

Hydrographic network analysis

The hydrographic network of the Oued Rheris Watershed was extracted from the ASTER GDEM and classified according to the Strahler (1957) stream ordering system. The network comprises six orders, from first-order ephemeral rills to the sixth-order main channel of Oued Rheris (Figure 7).

The total length of the hydrographic network is 4,412.594 km, distributed across the six orders as follows (Table 2).

First order streams constitute the dominant component of the network, representing 50.16% of the total stream length. This high proportion of low order streams is characteristic of arid watersheds where ephemeral drainage dominates. The progressive decrease in both stream number and length with increasing order reflects the hierarchical structure of the drainage system.

Table 2. Stream order, number, length, and percentage of total length in the Oued Rheris Watershed

Order of the oueds	Length (km)	Percentage %
1	2213.44	50.16
2	1169.59	26.50
3	419.458	9.50
4	243.619	5.52
5	201.471	4.56
6	165.016	3.73
Total	4 412,594	100

Areal parameters

The morphometric characteristics of the Oued Rheris Watershed are summarized in Table 3. The basin area of 12,606.7 km² represents the catchment's capacity to receive precipitation and generate runoff. The perimeter of 687.018 km reflects the irregularity of the watershed boundary, influenced by the complex topography of the High Atlas and Anti-Atlas margins.

The equivalent rectangle has a length (L) of 300.96 km and a width (l) of 41.88 km, indicating that the basin is approximately 7.2 times longer than it is wide. This pronounced elongation has significant hydrological implications, as discussed below (Figure 8).

Shape parameters

The Gravelius compactness coefficient ($Kc = 1.71$) indicates that the watershed deviates substantially from a circular shape ($Kc = 1.0$). Values > 1.5 are characteristic of elongated basins (Gravelius, 1914).

Form index (rapport $l/L = 0.46$) confirms that the basin width is less than half its length, reinforcing the conclusion of pronounced elongation.

Form factor ($Ff = 0.14$) – the calculated form factor (0.14) indicates that the Oued Rheris Watershed has a markedly elongated shape. Such basins generally exhibit longer runoff travel times and a more gradual concentration of streamflow than circular watersheds. This configuration may reduce the likelihood of rapid peak discharge at the basin outlet, although local flooding may still occur depending on rainfall intensity and catchment conditions.

Elongation ratio ($Re = 0.42$) – the elongation ratio (0.42) further confirms the elongated morphology of the watershed. According to morphometric classifications, values below 0.50 are

Table 3. Areal morphometric characteristics of the Oued Rheris watershed

Morphometric characteristics of the Rheris Watershed			
Perimeter P(km)	Area A (km²)	Compactness index (Kc)	Drainage density (km/km²)
687.018	12606.7	1.71	0.35

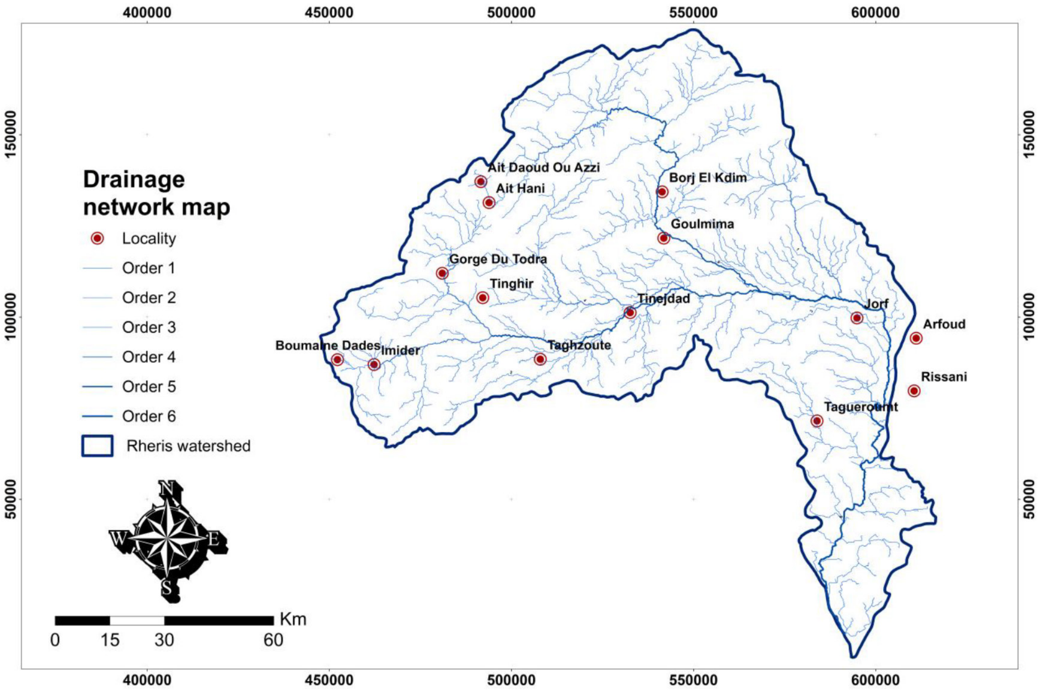

Figure 7. Hydrographic network of the Oued Rheris Watershed according to Strahler's classification (1957)

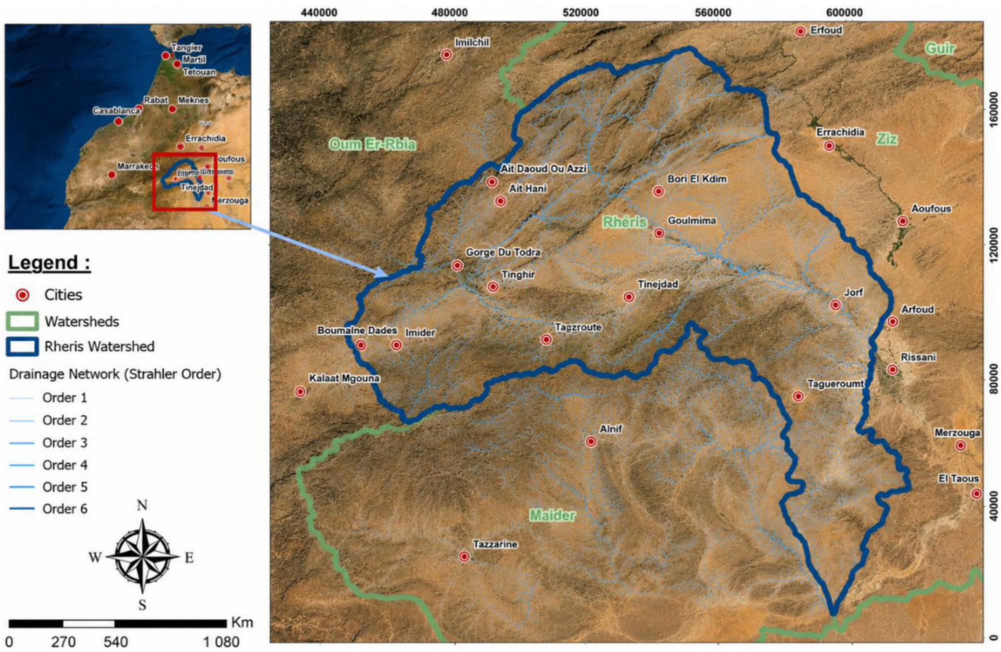

Figure 8. Validation of the GIS-derived watershed boundary and drainage network through comparison with satellite imagery

characteristic of highly elongated basins. This elongated geometry influences the hydrological response by distributing runoff over a longer period, thereby reducing flow concentration compared with more compact watersheds.

Circularity ratio (Rc = 0.34) – the circularity ratio (0.34) indicates that the watershed departs considerably from a circular shape. Such low values are generally associated with structurally controlled drainage basins and suggest a lower degree of runoff concentration. The result is consistent with the elongated geometry of the watershed and reflects the influence of regional geological and topographic controls on basin development.

The extracted drainage network consists of six Strahler stream orders. The calculated stream frequency (Fs) is 0.68 streams km^{-2}, indicating a relatively low channel frequency across the watershed. The mean bifurcation ratio (Rbm) is 2.07, suggesting a moderately branched drainage network with a drainage pattern primarily controlled by topography rather than strong structural disturbances.

Drainage density and texture

The drainage density (Dd = 0.35 km/km²) is equally well developed and as dense as those of the neighboring and other comparable watersheds. According to the classification of Strahler (1957), this value indicates a coarse drainage texture, characteristic of arid regions with permeable or resistant lithologies, low rainfall, and high infiltration rates.

DISCUSSION

Comparison with other watersheds

The morphometric characteristics of the Oued Rheris Watershed were compared with those of drainage basins from contrasting climatic settings to assess the influence of climate on watershed geometry and drainage network development (Table 2). The Oued Rheris Watershed (12,606.7 km², Kc = 1.71, Dd = 0.35 km/km², Form index = 0.46) was compared with the semi-arid Inaouene watersheds in Morocco (Dd = 0.78 and 0.82 km/km²; Benzougagh et al., 2017; El Boute et al., 2024), the humid tropical Menoua basin in Cameroon (Dd = 1.24 km/km²; Kouedjou and AnabaBanimb, 2021), and the tropical Kopai watershed in India (Dd = 1.92 km/km²; Ghosh et al., 2023). However, direct comparison of drainage density values should be interpreted with caution because different stream-order thresholds were used to delineate the drainage networks. In the present study, the drainage network was extracted up to the sixth Strahler order, whereas El Boute et al. (2024) considered streams up to the eighth order and Adnani et al. (2016) up to the seventh order for the neighboring Ziz watershed. Despite these methodological differences, Adnani et al. also described the Ziz watershed as having a well-developed drainage network. Considering the geographical proximity and the similar geological and climatic context of the Ziz and Rheris watersheds, these findings support the interpretation that the Oued Rheris Watershed also possesses a well-developed drainage network.

The observed drainage network pattern is likely influenced by the geological framework of the basin. The resistant lithological formations that dominate the upstream part of the watershed may have contributed to the preservation and hierarchical organization of the drainage system, whereas the less resistant formations in the downstream sector may have favored channel adjustment and sediment redistribution. The hypsometric integral of the Oued Rheris Watershed (Form index = 0.46) is lower than the values reported for the Inaouene (0.62 and 0.58) and Kopai (0.65) watersheds, suggesting a more advanced stage of

Table 4. Linear morphometric characteristics of the Oued Rheris Watershed

Stream order	Number of streams (Nu)	Total stream length (Lu, km)	Mean stream length (Lsm, km)
1	4305	2213.44	0.514
2	2079	1169.59	0.563
3	1090	419.46	0.385
4	529	243.62	0.461
5	317	201.47	0.636
6	119	165.02	1.387

geomorphic evolution. Similarly, the compactness coefficient (Kc = 1.71) is close to that of the Menoua basin (1.68), indicating that basin geometry may be influenced primarily by lithological and structural factors rather than by climate alone. Overall, the morphometric characteristics suggest that the Oued Rheris drainage network may represent an inherited fluvial system that developed under wetter paleoclimatic conditions and was subsequently modified by successive climatic fluctuations. Therefore, the present-day drainage configuration is consistent with the combined influence of lithological resistance, long-term geomorphic evolution, and paleoclimatic inheritance.

These comparative findings suggest that, although drainage density and landscape maturity are strongly influenced by climatic conditions, basin geometry appears to retain a degree of climatic independence, possibly reflecting the dominant influence of tectonic setting and bedrock lithology on watershed configuration. Consequently, the morphometric signature of the Oued Rheris Watershed is consistent with the expected geomorphic response to prolonged aridity, characterized by low drainage efficiency and subdued relief rejuvenation.

The inherited Khettara irrigation systems of the Rheris watershed and the Tafilalet plain represent an adaptation to the arid environmental conditions of southeastern Morocco, characterized by low rainfall, intense convective storms, and sparse vegetation cover. These systems were originally designed to operate under a hydrological regime in which episodic surface flows may contribute to the recharge of shallow aquifers supplying the underground channels. In this context, the relatively low drainage density (0.35 km/km²) may favor a slow and spatially distributed recharge pattern that could have contributed to sustaining these systems during extended dry periods. However, the dominance of first-order ephemeral channels (50.16% of the total stream length) suggests a landscape where limited vegetation cover may reduce soil protection during high-intensity rainfall events. Under such conditions, concentrated runoff may promote gully incision and sediment transport, potentially contributing to the siltation of hill dams and transformation dams that support Khettara recharge. Likewise, modern agricultural development in the upper and middle parts of the watershed, including intensive groundwater abstraction and the construction of new hydraulic infrastructures, may alter the natural hydrological functioning of the basin and could increase pressure on traditional oasis irrigation systems. Consequently, the combined effects of sedimentation, reduced recharge, and groundwater abstraction may affect the long-term resilience of oasis agriculture under increasing climatic variability. Overall, the Oued Rheris Watershed exhibits the lowest drainage density (0.35 km/km²) among the compared basins, suggesting the combined influence of climate, geology, and tectonic setting on its morphometric configuration. The upstream part of the basin is largely underlain by resistant Jurassic limestones and dolomites together with Paleozoic quartzites and sandstones, lithologies that generally resist fluvial incision and limit the development of closely spaced drainage channels. In addition, carbonate formations may locally enhance infiltration through fractures and secondary porosity, thereby reducing surface runoff available for channel initiation. Downstream, extensive Plio-Quaternary alluvial deposits also favor infiltration and transmission losses along ephemeral channels. Although less resistant Cretaceous marls and gypsiferous formations locally facilitate channel development, the overall drainage pattern reflects the dominant influence of resistant and relatively permeable lithologies inherited from the regional geological framework. Consequently, the low drainage density observed in the Oued Rheris Watershed is likely the result of the interaction between lithological resistance, infiltration capacity, long-term tectonic evolution, and the prevailing arid climate.

Hydrological implications

The form index of the Oued Rheris Watershed = 0.46 suggests a longer concentration time and potentially attenuated peak flows compared with more compact basins of equivalent area. As water requires more time to travel from the farthest points to the outlet, this geometry may contribute to lower flood peaks and longer flood durations are extended, while greater transmission losses occur due to prolonged channel flow in permeable alluvial reaches. This process may enhance groundwater recharge along the channel system, a mechanism that may contribute to sustaining the traditional Khettara irrigation systems of the Rehris area and Tafilalet region. Nevertheless, the low drainage density (0.35 km/km²) indicates that surface connectivity remains limited. In arid environments, this may create a hydrological paradox: although the elongated shape attenuates floods, the sparse network means that when high intensity rainfall occurs on saturated or impermeable surfaces, flash floods may still develop rapidly in localized areas, particularly in the steep upper basin.

Erosion and desertification risk

The morphometric characteristics of the Oued Rheris Watershed provide useful insights into the potential spatial distribution of soil erosion and desertification processes. The high proportion of first-order streams (50.16%) suggests that these ephemeral channels may act as preferential zones for erosion during infrequent but high-intensity rainfall events, potentially transporting sediment from hillslopes to higher-order channels. Concurrently, the low drainage density indicates limited surface drainage efficiency, which may favor the concentration of overland flow and could contribute to sheet erosion and gully development in susceptible areas.

The potential effects of sediment deposition on hill dams, transformation dams, and traditional khettara systems remain hypothetical and require dedicated field investigations.

Furthermore, the arid climatic conditions, characterized by sparse vegetation cover, highly erodible Cretaceous and Cenozoic formations, and episodic high-intensity rainfall, are likely to increase the susceptibility of the watershed to both water and Aelian erosion. Nevertheless, the relative contribution of these factors to land degradation in the downstream part of the basin should be evaluated using complementary geomorphological and remote-sensing investigations.

Management implications

The morphometric analysis provides useful information for watershed management in the Oued Rheris basin. Regarding flood risk management, the elongated basin geometry suggests that flood-warning strategies may benefit from considering relatively long runoff concentration times while remaining attentive to the possibility of localized flash floods in steep tributaries during high-intensity rainfall events. For soil conservation, first-order stream channels and adjacent hillslopes may represent priority areas for erosion-control measures because they are likely to constitute important sediment source zones.

The morphometric characteristics suggest that the upper basin may present conditions potentially favorable for groundwater recharge owing to its relatively low drainage density. However, groundwater recharge depends on several additional factors, including lithology, soil permeability, infiltration capacity, and climatic conditions. Therefore, this interpretation should be considered as a preliminary inference requiring hydrogeological investigations.

The preservation of traditional hydraulic infrastructure could benefit from appropriate sediment-management practices if future hydrological and geomorphological investigations confirm progressive sediment accumulation within hill dams and transformation dams. The morphometric characteristics suggest that Managed aquifer recharge using ephemeral channel flows may represent a complementary management strategy; however, its technical feasibility and long-term effectiveness should be evaluated through dedicated hydrogeological studies.

Overall, the morphometric analysis provides a valuable framework for supporting watershed planning and identifying areas that may require priority management interventions. However, the relationships between morphometric characteristics and hydrological or geomorphological processes should be regarded as potential implications rather than direct evidence. Future studies integrating hydrological monitoring, sediment-yield measurements, hydrogeological investigations, field observations, and remote-sensing analyses would further improve the understanding of watershed processes and strengthen management recommendations for the Oued Rheris basin.

Limitations and future perspectives

Despite the contribution of morphometric analysis to understanding the geomorphological characteristics of the Oued Rheris Watershed, several limitations should be acknowledged. First, the absence of continuous field measurements of river discharge, sediment load, rates prevents the direct quantification and validation of the relationships inferred between basin morphology, runoff response, sediment transfer, and erosion processes. Therefore, the hydrological and sedimentological interpretations presented in this study should be considered as potential mechanisms supported by morphometric evidence rather than directly measured processes.

Second, groundwater recharge and the functioning of traditional Khettara irrigation systems could not be quantitatively evaluated due to the lack of long term hydrogeological observations, groundwater level monitoring, and water use data. Future studies integrating piezometric measurements, isotopic tracing, and hydrological modelling would provide a better understanding of the links between watershed morphology, recharge processes, and oasis water sustainability.

Third, the extraction of the drainage network and watershed characteristics was based on ASTER GDEM at 30 m spatial resolution. Although this dataset is suitable for regional scale morphometric analysis, finer resolution elevation data and high resolution remote sensing products could improve the representation of small ephemeral channels and local geomorphological features. Finally, future investigations combining field surveys, sediment monitoring, hydrological modelling, and multi-temporal remote sensing analysis would strengthen the validation of the proposed relationships between morphometric configuration, erosion susceptibility, sediment dynamics, and desertification processes in the Rheris watershed.

CONCLUSIONS

This study provides the first comprehensive morphometric characterization of the Oued Rheris Watershed in southeastern Morocco using ASTER GDEM and GIS. The Oued Rheris Watershed (12,606.7 km²) exhibits a pronounced elongated shape (Kc = 1.71), being approximately 7.2 times longer than wide, with a hydrographic network comprising six stream orders and a total length of 4,412.594 km dominated by first-order ephemeral streams (50.16%). The drainage density (0.35 km/km²) is among the lowest reported for Moroccan watersheds, reflecting the combined influence of arid climate, permeable geology, and high infiltration capacity. This elongated morphology implies prolonged concentration times and attenuated peak flows, yet the low drainage density and arid conditions maintain flash flood risk and sediment transport during extreme rainfall events. Consequently, these characteristics contribute to the siltation of hydraulic infrastructure in the Rheris region, threatening the sustainability of traditional irrigation systems and oasis agriculture. The inherited Khettara irrigation systems of the oasis of Rheris and Tafilalet plain, developed under arid conditions with sparse vegetation and storm-driven hydrology, face existential threats from dam siltation, groundwater overexploitation by intensive agriculture, and progressive climate aridification. The morphometric characteristics of the Oued Rheris Watershed particularly its form index and low drainage density define the natural limits within which these systems must operate. Sustainable management therefore requires integrating the protection of inherited hydraulic heritage with regulated agricultural development, ensuring that oasis resilience is not sacrificed to short term intensive production. This morphometric analysis provides a quantitative foundation for hydrological modeling, soil conservation planning, and integrated water resource management in this vulnerable arid region. Future research should integrate rainfall-runoff modeling, and climate change scenarios to predict the evolution of hydrological regimes under changing climatic conditions.

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