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Water erosion in semi-arid Mediterranean environments: GIS-based multifactorial spatial modeling of climate, soil, lithology, topography, and land use

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Water erosion is a major land-degradation process in semi-arid Mediterranean environments, where climate, soils, lithology, topography and land cover jointly control the spatial variability of soil loss. This study assesses water-erosion susceptibility in the Oued Eddefla watershed, northwestern Tunisia, using an integrated RUSLE-GIS approach. The five model factors were combined in ArcGIS 10.8 and complemented by a morphometric analysis, a rainfall-erosivity time series, a factor-sensitivity analysis, and a Sediment Delivery Ratio (SDR)-based estimate of transfer to the downstream hill reservoir. Mean rainfall erosivity (R) reached 798.7 MJ·mm·ha^{-1}·h^{-1}·yr^{-1} under average conditions and 1563.9 MJ·mm·ha^{-1}·h^{-1}·yr^{-1} under the maximum recorded conditions, while 85% of the watershed showed soil erodibility (K) values of 0.05-0.08, mainly on marl–limestone bedrock. Mean annual soil loss was 3.22 t·ha^{-1}·yr^{-1} under average erosivity and 6.30 t·ha^{-1}·yr^{-1} under maximum erosivity, a 95.7% increase locally exceeding 234 t·ha^{-1}·yr^{-1} on the steepest slopes. Potential sediment delivery to the reservoir was 234.9–302.1 m^3·yr^{-1} under average erosivity and 459.7–591.0 m^3·yr^{-1} under maximum erosivity. Erosion susceptibility arises from the spatial interaction of erosivity, erodibility, lithology, topography and land cover, providing a quantitative basis for prioritizing soil-conservation interventions in Mediterranean watersheds.

Key words: water erosion, RUSLE-GIS, soil erodibility, rainfall erosivity, sediment delivery ratio, semi-arid Tunisia.

INTRODUCTION

Water erosion is one of the principal processes of land degradation worldwide, with significant consequences for soil fertility, water-resource quality, agricultural productivity and ecosystem sustainability. Detachment and transport of surface particles by rainfall and runoff cause losses of organic matter and nutrients, while mobilized sediments accumulate in watercourses and reservoirs. These processes represent a major challenge for soil conservation and the sustainable management of natural resources (Panagos et al., 2015, 2020; Borrelli et al., 2020; Abebe et al., 2023; Polykretis et al., 2023; Xiong and Leng, 2024). This issue is likely to intensify under climate change, particularly in regions characterized by strong rainfall variability and a potential increase in the intensity of extreme rainfall events (Nearing et al., 2017; Tramblay et al., 2018; IPCC, 2023; Polykretis et al., 2023; Xiong and Leng, 2024; Eekhout et al., 2025).

The Mediterranean basin is particularly vulnerable because of the alternation between prolonged dry periods, commonly discontinuous vegetation cover, and intense rainfall episodes. Combined changes in climate and land use can therefore produce substantial shifts in the spatial and temporal distribution of erosion (Tramblay et al., 2018; Borrelli et al., 2020). Across the wider Mediterranean region, changes in rainfall regimes and land cover have been shown to significantly alter erosion rates and the location of the most vulnerable areas. However, the erosive response of a watershed never depends on a single factor: it results from the interaction of rainfall, relief, soil properties, lithology and land use. The nature of the geological substratum controls weathering and pedogenesis, and thereby the texture, structure, depth and hydrological properties of soils. These characteristics in turn control soil resistance to detachment and constitute the main properties used to estimate soil erodibility (Karydas et al., 2013; Panagos et al., 2015; Ghosh et al., 2023).

The Revised Universal Soil Loss Equation (RUSLE) remains one of the most widely used empirical models for quantifying and mapping potential soil loss. It combines five factors: rainfall erosivity (R), soil erodibility (K), the topographic factor (LS), the cover-management factor (C), and the support-practice factor (P) (Renard et al., 1997). Coupling RUSLE with Geographic Information Systems (GIS) and remote-sensing

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data allows these factors to be mapped and areas of high erosion susceptibility to be identified, particularly where direct field observations are limited. Recent applications show, however, that results are strongly conditioned by the quality, spatial resolution and methods used to derive input data (Kumar et al., 2022; Ghosh et al., 2023). In Tunisia, a recent national-scale RUSLE-GIS application confirmed the existence of marked spatial contrasts in erosion risk and highlighted the value of this approach for planning soil-conservation measures (Serbaji et al., 2023).

Among the RUSLE factors, rainfall erosivity is a key climatic control, as it expresses the capacity of rainfall to cause particle detachment and transport. Its spatial and temporal variability is particularly pronounced in Mediterranean environments, where precipitation is strongly seasonal and can be concentrated in intense events. An appropriate representation of the *R*-factor is therefore required to characterize contrasts in erosive stress and to better capture the spatial variability of watershed response. Recent research in the Mediterranean region has highlighted the importance of brief, high-intensity rainfall events in controlling rainfall erosivity and emphasized the need for appropriate temporal resolution when estimating the *R*-factor (Woldegebrael et al., 2025).

Soil loss estimated using RUSLE does not, however, directly correspond to the amount of sediment exported at the watershed outlet. Part of the material detached may be deposited or temporarily stored on hillslopes, within channels, or in low-gradient areas. Effective sediment transfer therefore depends on hydro-sedimentary connectivity, which controls the exchange between sediment source areas and receiving areas (Borselli et al., 2008; Heckmann et al., 2018; Abebe et al., 2023). This distinction between erosive soil production and sediment export is particularly important in small watersheds draining into hill reservoirs, where sediment accumulation can progressively reduce storage capacity and compromise the long-term sustainability of hydraulic infrastructure. Coupling RUSLE with a Sediment Delivery Ratio (SDR) provides a practical approach for estimating the fraction of eroded material that is likely to reach the watershed outlet (Abebe et al., 2023; Xiong and Leng, 2024).

Despite substantial progress in erosion mapping, important knowledge gaps remain for small Mediterranean watersheds in North Africa. Approaches based primarily on spatial soil-loss estimates provide limited information on the relative contribution of individual RUSLE factors and their influence on the spatial variability of predicted erosion. Sensitivity analysis can complement conventional erosion mapping by quantifying the influence of model parameters and identifying the factors that exert the strongest control on model response. Recent studies have shown that RUSLE estimates may be particularly sensitive to topographic parameters and to the methodological approaches used to derive the *LS* factor, highlighting the value of an explicit sensitivity assessment (François et al., 2024). Moreover, the interactions between bedrock, soil properties, relief, climate, land use, erosive production and sediment transfer remain insufficiently integrated at the scale of small Tunisian watersheds, even though environmental change and conservation practices are known to substantially alter erosion and sediment-flux dynamics in this setting.

The Oued Eddefla watershed, located in the Siliana Governorate of northwestern Tunisia, provides a suitable setting in which to examine these relationships. The diversity of geological formations and soils, combined with pronounced topographic contrasts, rainfall variability and the spatial distribution of land use, favours strong heterogeneity in erosive processes. The presence of a downstream hill reservoir further allows potential source areas of erosion to be linked with the sediment inputs likely to reach the reservoir. This setting therefore makes it possible to address, within a single framework, the processes of detachment, redistribution and transfer of material across the watershed.

In this context, the present study proposes an integrated approach combining watershed morphometric analysis, lithological and pedological characterization, RUSLE-GIS modelling, a sensitivity analysis of the five model factors, and an estimate of sediment transfer using a Sediment Delivery Ratio. The main objective is to quantify and map the erosive dynamics of the Oued Eddefla watershed by evaluating the relative roles of rainfall, relief, soil properties, bedrock and land use. Specifically, the study aims to: (i) quantify and map potential soil loss using RUSLE; (ii) determine the relative contribution of the five factors through a sensitivity analysis; (iii) estimate the fraction of sediment likely to reach the reservoir using the SDR; and (iv) identify priority areas for soil-conservation measures and for reducing sediment inputs. This approach seeks to move beyond a simple erosion-susceptibility map by establishing a spatial link between rock-soil-relief-climate-land-use interactions, potential soil loss, and sediment transfer to the reservoir.

STUDY AREA

LOCATION AND PHYSICAL CHARACTERISTICS

The Oued Eddefla watershed is situated in northwestern Tunisia, near El Gabel, within the Siliana Sud delegation of Siliana Governorate (Fig. 1). Its outlet is located at X = 536053.55 m and Y = 3983340.13 m in the Carthage/UTM Zone 32N coordinate reference system (EPSG: 22332). The watershed covers an area of 2.71 km² with a perimeter of 8.91 km and has an elongated morphology oriented NE–SW. Elevation ranges from 500 m at the outlet to 805 m along the watershed divide, a relief of 305 m, reflecting the relatively pronounced topography typical of small mountainous watersheds in northwestern Tunisia. Morphometric analysis yields a Gravelius compactness coefficient (*Kc*) of 1.53, indicating an elongated shape departing markedly from a circular geometry (*Kc* = 1). This configuration tends to distribute runoff contributions over time, limiting the synchronization of flows at the outlet and thereby reducing the occurrence of very sharp flood peaks. However, the combination of pronounced relief, a substantial elevation range over a small area, and relatively steep slopes favours runoff acceleration, increases the capacity for particle detachment and transport, and enhances downstream sediment transfer. These morphometric characteristics suggest a rapid hydro-sedimentary response during intense rainfall events, making the Oued Eddefla watershed a setting particularly prone to water erosion and to siltation of the hill reservoir at its outlet.

The spatial distribution of slope gradients shows a predominance of low-to-moderate classes. Slopes below 10% cover 44.9% of the watershed area, while slopes between 10 and 15% represent 27.4%. Sectors with slopes exceeding 15% therefore cover 27.7% of the territory and constitute the main zones favouring the development of erosive processes. Increasing slope gradient raises runoff energy, reduces infiltration time, and promotes particle detachment and transport. These sectors accordingly favour the development of linear erosion features, notably rills and gullies. These results highlight the important role of the RUSLE topographic factor (*LS*) in the spatial differentiation of water-erosion susceptibility in the Oued Eddefla watershed (Fig. 2).

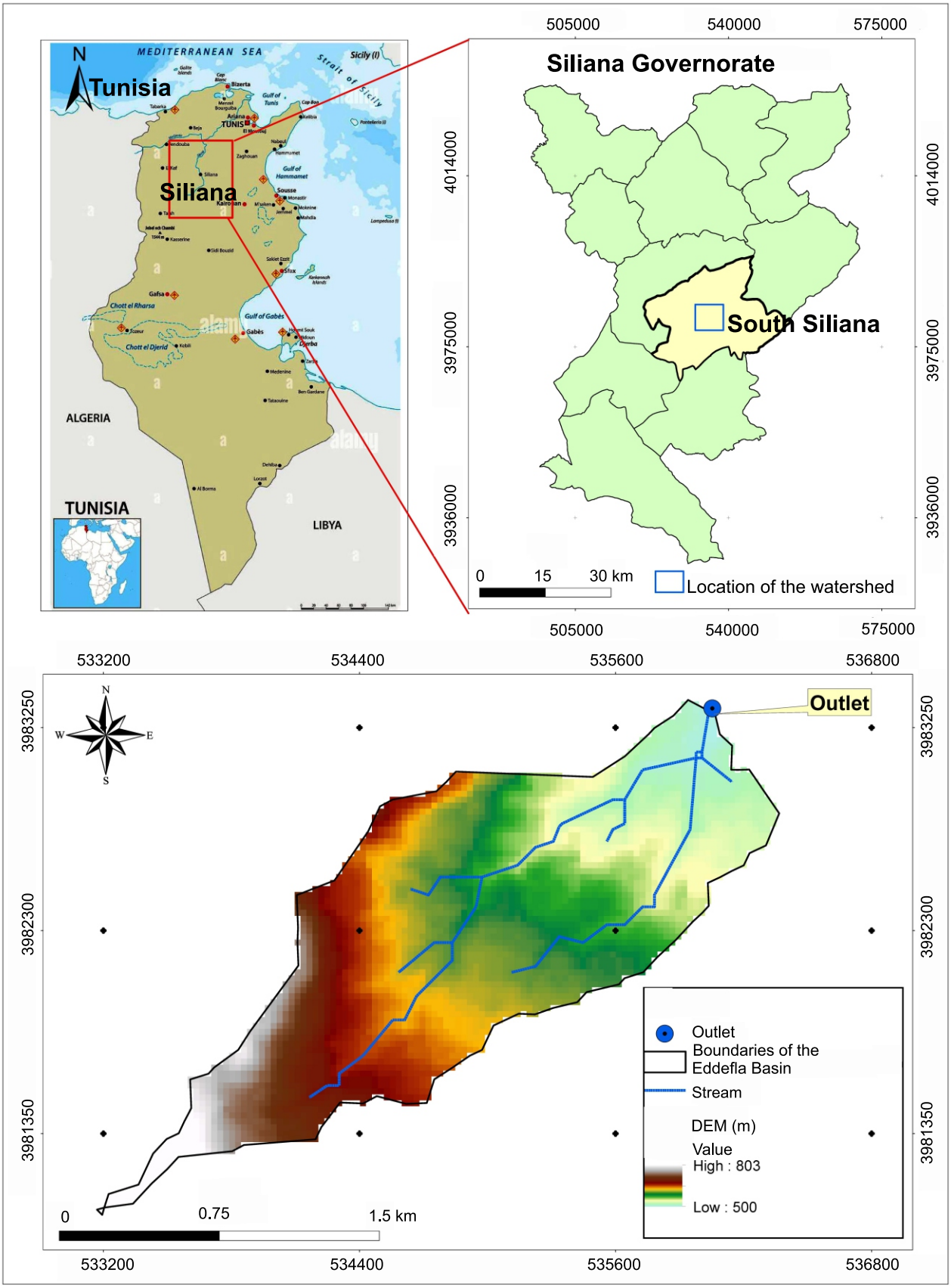

Fig. 1. Geographic location of the Oued Eddefla watershed within the Siliana Governorate and the national context of Tunisia

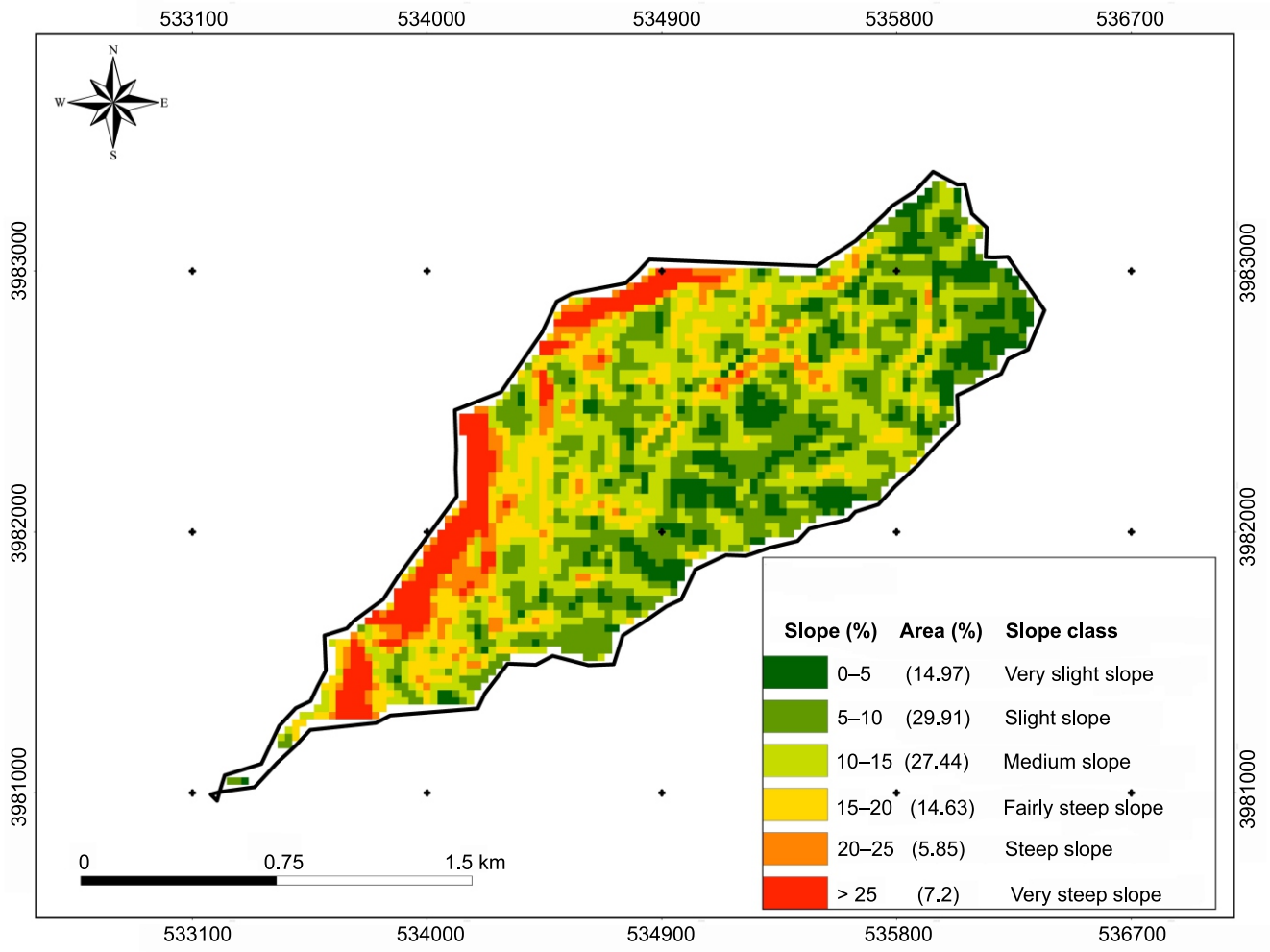

Fig. 2. Slope map of the study area

The dominant soil types in the Oued Eddefla watershed are complex soil assemblages, which cover 84.7% of the total area, followed by rendzinas (14.7%) and weakly developed alluvial soils (0.06%; see Fig. 6, Results section). Land use is largely dominated by rangeland, which accounts for 98.4% of the watershed area, while bare soil covers 1.3%, cropland 0.2% and forest 0.1% (see Fig. 8, Results section).

GEOLOGICAL SETTING

The Oued Eddefla watershed is mainly underlain by Upper Cretaceous formations, locally covered by recent Quaternary deposits (Fig. 3). The geological setting is characterized by NW–SE and NE–SW faults that locally influence drainage and hillslope dynamics. The oldest unit is the Coniacian, consisting of alternating marls and *Inoceramus*-bearing limestones, locally affected by synsedimentary slump structures. It is overlain by lower–middle Santonian marls of the Aleg Formation and Upper Santonian formations. Quaternary deposits include low terraces, composed mainly of silty clays with gravelly to pebbly components, and recent alluvium (a) occupying the wadi beds.

The geological cross-section A–A′ (Fig. 4) highlights the relationship between the Cretaceous substratum and the Quaternary surface deposits. The latter are mainly concentrated along the valley floor and lower surfaces, while the Cretaceous formations constitute the surrounding hillslopes. This configuration, combined with marly lithologies, unconsolidated deposits, topography and discontinuous vegetation cover, favours runoff concentration, soil detachment and sediment transport.

Field observations reveal surface incisions, rills, gullies, and coarse-particle concentrations in unconsolidated materials (Fig. 5). These features are mainly concentrated along the wadi bed near the watershed outlet and on both watershed margins. Their distribution is influenced by topography, slope morphology, and drainage-network organization, which promote runoff concentration and sediment transfer toward the hill reservoir.

MATERIALS AND METHODS

RUSLE MODEL

The Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith from extensive plot-scale experimental observations, is one of the most widely used empirical models for estimating soil loss caused by water erosion (Wischmeier and Smith, 1965, 1978). Subsequent developments led to the Revised Universal Soil Loss Equation (RUSLE), which improves the representation of the main controlling factors and extends its application to larger areas, including at the watershed scale (Renard et al., 1997).

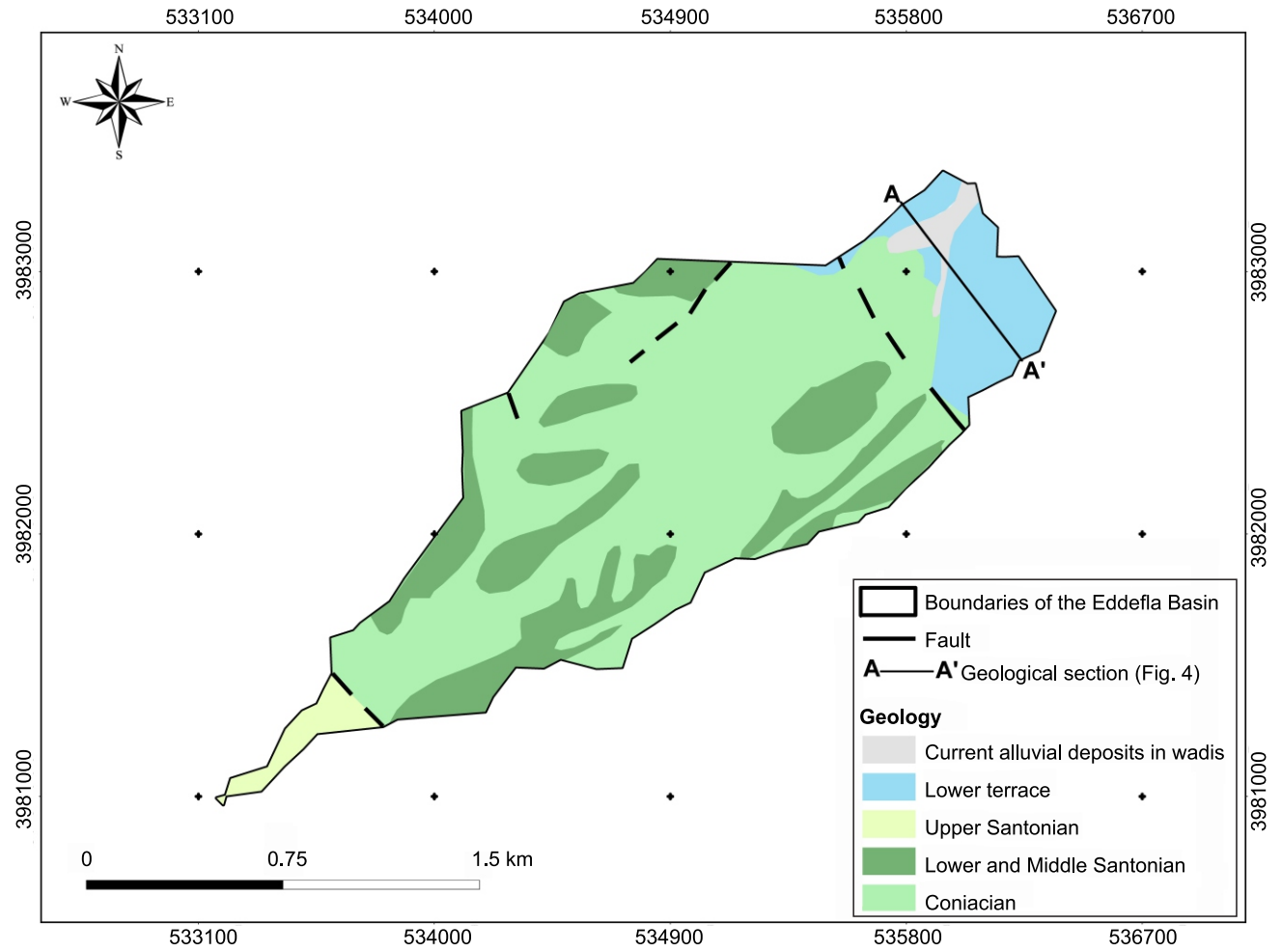

Fig. 3. Geological map of the Oued Eddefla watershed, compiled from the Siliana geological map (Sheet 46; scale 1:50.000)

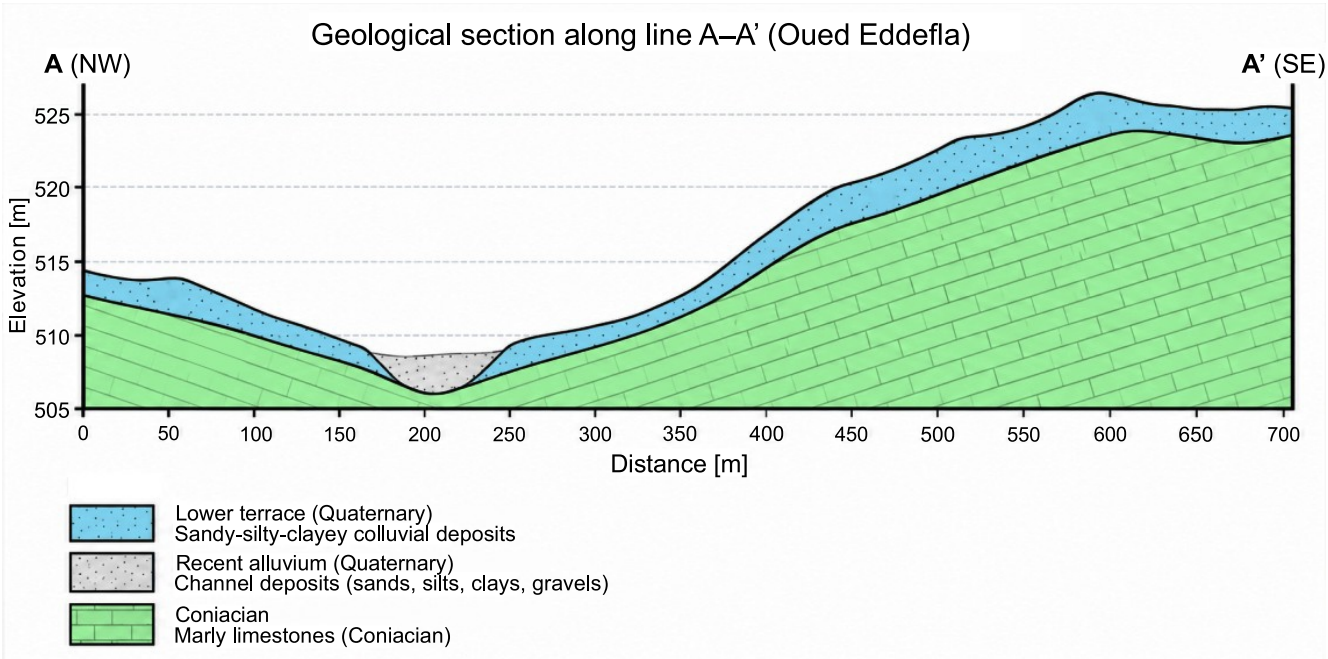

Fig. 4. Geological cross-section along the A–A′ transect of the Oued Eddefla watershed, showing the spatial relationships between the Cretaceous formations and Quaternary deposits

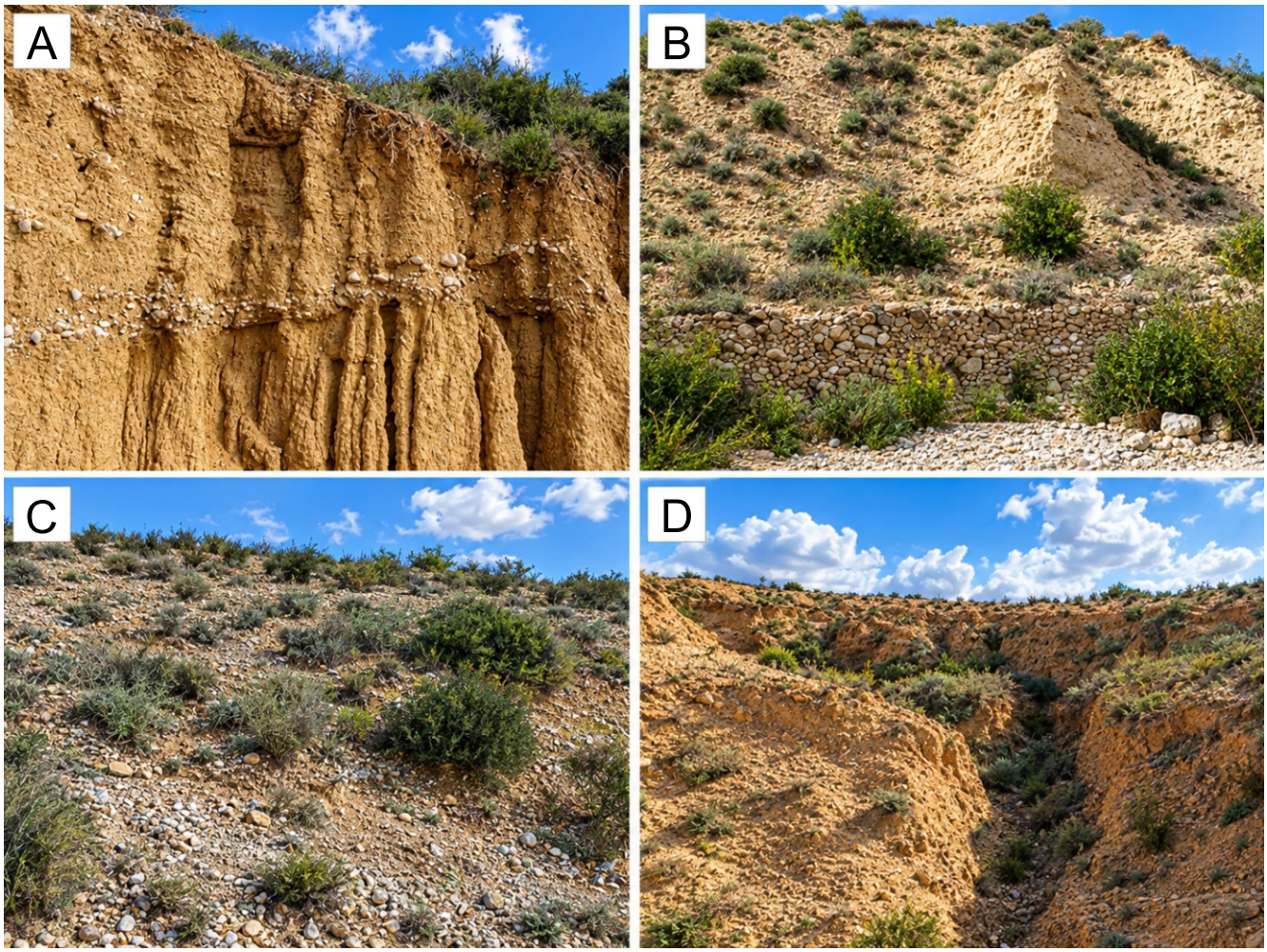

Fig. 5. Morphological expressions of water erosion in the Oued Eddefla watershed

A – incision and gullying of fine-grained materials; **B** – eroded surface with a high concentration of coarse clasts; **C** – superficial gullying associated with discontinuous vegetation cover; **D** – development of a deep gully in unconsolidated materials under concentrated runoff

In this study, RUSLE was implemented within a GIS environment to estimate mean annual soil loss and to analyse its spatial distribution across the Oued Eddefla watershed. The model combines five factors multiplicatively: rainfall erosivity (*R*), soil erodibility (*K*), the topographic factor (*LS*), the cover-management factor (*C*), and the support-practice factor (*P*). The general equation is:

$$A = R \times K \times LS \times C \times P$$

where: *A* is the mean annual soil loss ($t \cdot ha^{-1} \cdot yr^{-1}$); *R* is rainfall erosivity ($MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$); *K* is the intrinsic soil erodibility ($t \cdot h \cdot MJ^{-1} \cdot mm^{-1}$); *LS* is the topographic factor combining the effects of slope length and steepness; *C* expresses the effect of land cover and management; and *P* represents the effect of soil-conservation practices. *C* and *P* are dimensionless.

DATABASE

The database used in this study comprises the following elements:

- Rainfall erosivity factor (*R*): The rainfall data used to determine the rainfall erosivity factor (*R*) were collected from the nearest rainfall station to the Eddefla River watershed, namely Siliana Agricultural Station, due to the absence of a rainfall gauge within the watershed.
- Soil erodibility factor (*K*): The soil erodibility factor (*K*) was determined using two thematic maps, namely the agricultural vocation map and the soil map of the Siliana Governorate, produced by the Hydraulic and Rural Development Company (HRDC) in 2003 at a working scale of 1:100,000. These maps were digitized using ArcGIS, and subsequently updated and verified using recent satellite imagery available through Google Earth (2024). The *K*-factor values were also assigned based on a review of the available literature, particularly the studies conducted by Zante and Collinet (2001) at the El Hnach site (Maktar, Tunisia) and by Collinet et al. (2001) at the Zanfour site (Kef, Tunisia).
- Topographic factor (*LS*): The topographic factor (*LS*) was calculated from a Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) with a spatial resolution of up to 30 m, obtained from the OpenTopography platform. The SRTM dataset consists of topographic raster and vector data acquired through a joint effort involving the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA). The interferometric radar data were acquired by the Space Shuttle Endeavour in February 2000 at an altitude of ~233 km.

– Land use/land cover (*LULC*): Land use/land cover information was derived from the agricultural map of Siliana, particularly the land-use map produced by the Hydraulic and Rural Development Company (HRDC) in 2003 at a working scale of 1:100,000. These data were complemented by recent land-use information digitized from satellite imagery available through Google Earth (2024). Values of C attributed to each land use class are determined from the work done in Tunisia by Cormary and Masson (1964), Masson (1971), and Zante and Collinet (2001) relating to the El Hnach site (Maktar, Tunisia), Zante et al. (2003) on the Abdessadok site (Maktar, Tunisia), and Collinet et al. (2001) in Zanfour (Kef, Tunisia).
– Support practice factor (*P*): The support practice factor (*P*) was assigned based on values reported in studies conducted by the Food and Agriculture Organization (FAO, 1977) for Tunisia.

All thematic layers were generated, reprojected to a common coordinate system, and combined through multiplicative raster overlay in ArcGIS 10.8. The resulting continuous erosion-risk raster was subsequently reclassified to support spatial interpretation and zonation of erosion-prone areas.

ESTIMATION OF SEDIMENT DELIVERY TO THE HILL RESERVOIR

The quantity of sediment likely to reach the hill reservoir was estimated from RUSLE-derived soil loss and a Sediment Delivery Ratio (*SDR*), determined empirically as a function of watershed area following relationships proposed for small Mediterranean and North African watersheds (Vanmaercke et al., 2011, 2014). Annual sediment yield (*SY*, $t \cdot yr^{-1}$) was calculated as $SY = SDR \times A$, where: *A* is total annual soil loss ($t \cdot yr^{-1}$). The annual volume of sediment potentially reaching the reservoir was then estimated assuming a mean bulk density of 1.3 $t \cdot m^{-3}$, following $Vs = SY/\rho s$. This approach provides an indicative estimate of the potential for sediment transfer and siltation of the hill reservoir.

RESULTS

RAINFALL EROSIVITY FACTOR (*R*)

Wind and water are the main agents of erosion. Intense rainfall promotes runoff and soil-particle detachment, with its erosive potential represented by the *R* factor (Wischmeier and Smith, 1978). The *R* factor was calculated using the empirical relationship proposed by Renard and Freimund (1993). Based on 30 years of observations (1989–2019) at the Siliana Agricultural Station, mean rainfall erosivity was 798.7 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$, corresponding to a mean annual rainfall of 417 mm. The 2002/2003 hydrological year recorded the highest erosivity (1563.9 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$), while 1993/1994 recorded the lowest (216.2 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$), with corresponding rainfall amounts of 633 and 185.2 mm, respectively.

SOIL ERODIBILITY FACTOR (*K*)

Soil erodibility refers to the intrinsic susceptibility of soils to water erosion. It mainly depends on their physical and chemical properties and is represented in the RUSLE model by the *K* factor. Higher *K* values indicate greater soil susceptibility to erosion (Renard et al., 1997). In the Oued Eddefla watershed, *K*-factor values range from 0.013 to 0.08 $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$, reflecting spatial variability in soil erodibility (Fig. 6). Complex soils dominate the watershed (84.7%; $K = 0.05$), followed by rendzinas (14.7%; $K = 0.013$). Weakly developed soils, covering only 0.06% of the watershed, exhibit the highest erodibility ($K = 0.08$). This distribution highlights spatial heterogeneity that may influence water-erosion risk across the watershed.

TOPOGRAPHIC FACTOR (*LS*)

The *LS* factor represents the combined effect of slope length and steepness, two major parameters controlling water erosion (Roose, 1994). It was calculated from the Digital Elevation Model (DEM) using the formulation proposed by Wischmeier and Smith (1978). *LS*-factor values range from 0 to 29.3, showing a highly heterogeneous spatial distribution. Low values dominate the central and eastern sectors of the watershed, whereas high values are mainly associated with the steepest slopes, particularly in the western and southern parts. These areas therefore constitute zones where topographic conditions enhance runoff and particle transport (Fig. 7).

COVER-MANAGEMENT FACTOR (*C*)

The *C* factor represents the influence of vegetation cover and land use on water erosion. Dense vegetation reduces soil particle detachment and runoff, whereas bare soils are more exposed to erosion (Kinnell, 2010). In the Oued Eddefla watershed, *C*-factor values range from 0.01 for forests to 1 for rangelands. The watershed comprises four land-use classes (Fig. 8).

SUPPORT-PRACTICE FACTOR (*P*)

The *P* factor represents the influence of soil conservation practices on reducing water erosion. It depends mainly on land management practices and slope, with $P = 1$ representing the absence of conservation measures (Panagos et al., 2015). In the Eddefla river watershed, *P*-factor values range from 0.55 to 1, depending primarily on slope and soil conservation practices (Fig. 9).

SOIL-LOSS AND EROSION-RISK MAPPING

The multiplicative combination of the five RUSLE factors ($R \times K \times LS \times C \times P$) produced the spatial map of soil loss across the Oued Eddefla watershed (Fig. 10). Under the mean-erosivity scenario, soil loss shows strong spatial variability, ranging from 0 to more than 234 $t \cdot ha^{-1} \cdot yr^{-1}$, with a mean of 3.22 $t \cdot ha^{-1} \cdot yr^{-1}$ (Table 1). This distribution reflects marked heterogeneity in the erosive functioning of the watershed, controlled mainly by the combination of slope, erodibility of the surface deposits, vegetation-cover density and climatic aggressiveness.

Under mean-erosivity conditions, the tolerable class ($<5\ t \cdot ha^{-1} \cdot yr^{-1}$) dominates the watershed, covering 87.4% of the total area. However, approaching 1.6% of the territory already falls within the high and very-high classes, located mainly on steep slopes characterized by reduced vegetation cover and marly lithological formations that are highly susceptible to erosion. These sectors constitute erosion hotspots where detachment and transport processes are particularly active.

The maximum-erosivity scenario ($R = 1563.9\ MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$) reveals a marked sensitivity of the watershed to climatic variability. Mean soil loss then reaches 6.30 $t \cdot ha^{-1} \cdot yr^{-1}$, an increase of 95.7% relative to the reference scenario (Fig. 11).

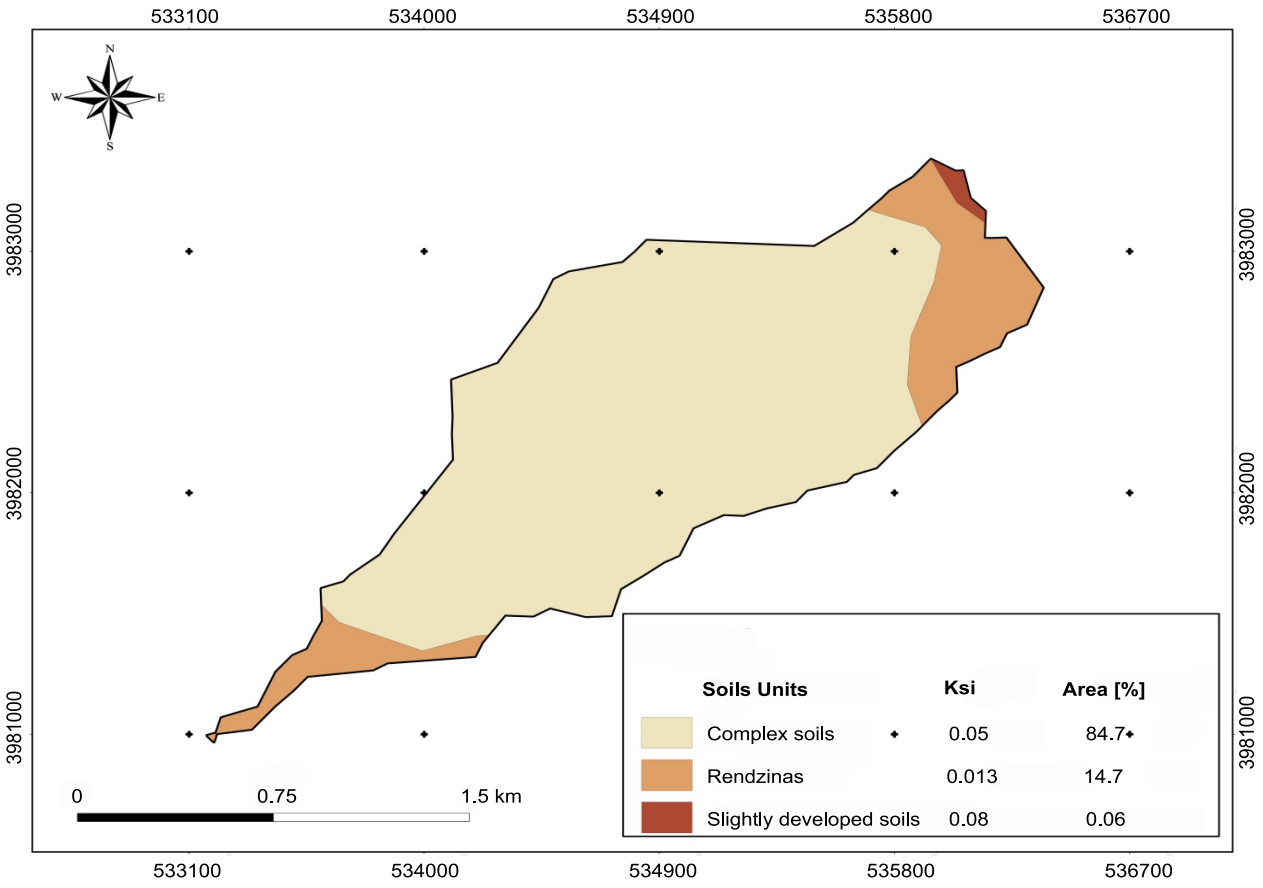

Fig. 6. Spatial distribution of pedological units and erodibility coefficients (*Ksi*) in the study area

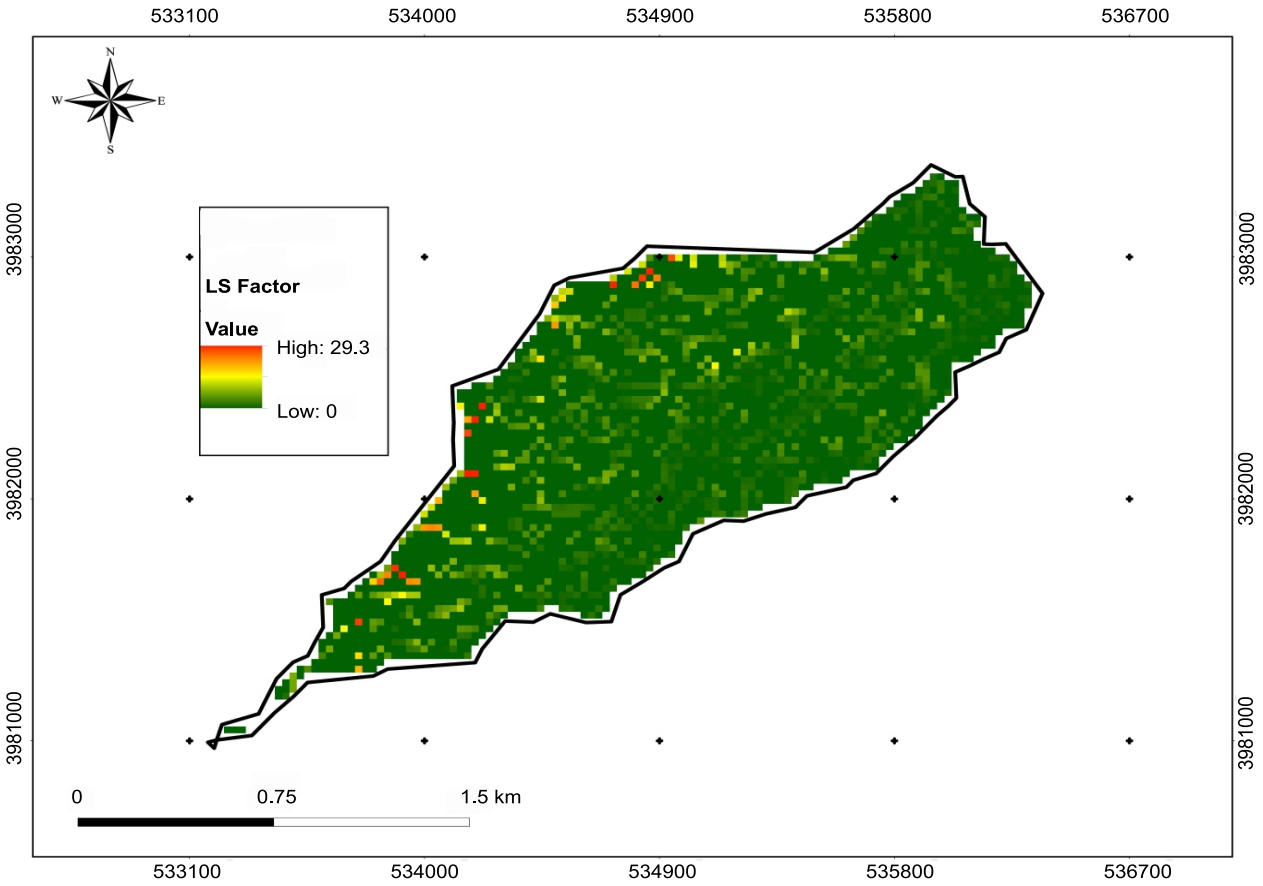

Fig. 7. *LS* factor map of the Eddefla River watershed

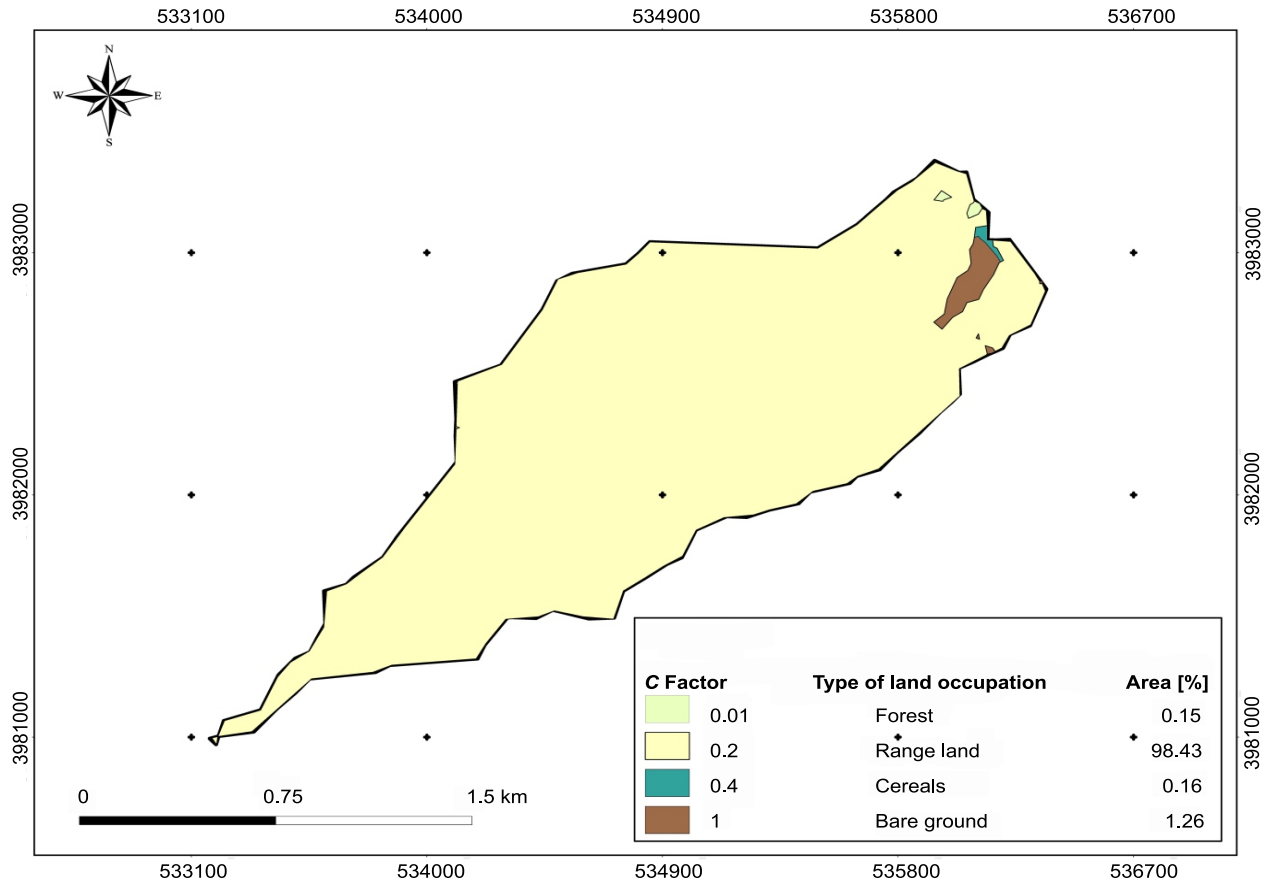

Fig. 8. *C* factor map of the Eddefla River watershed

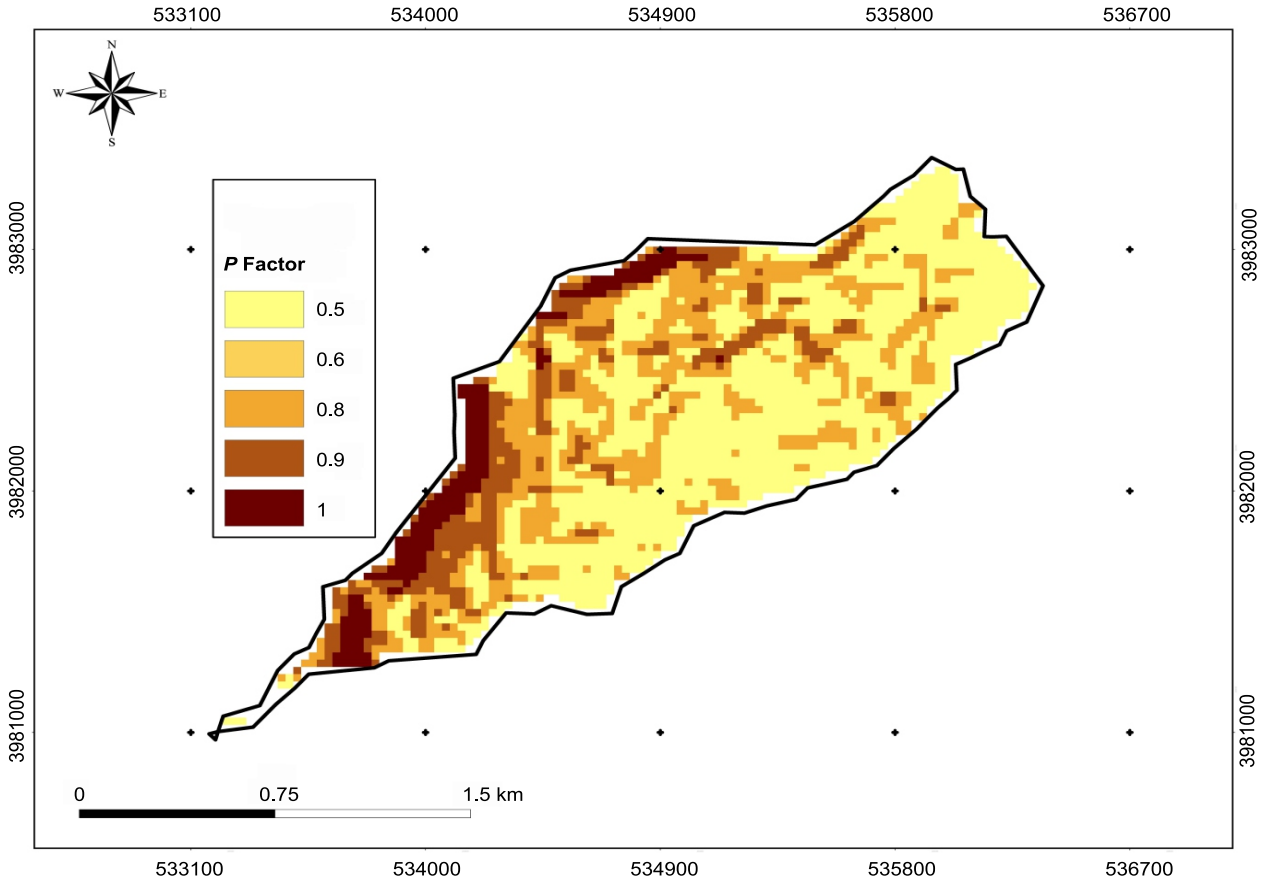

Fig. 9. *P* factor map of the Eddefla River watershed

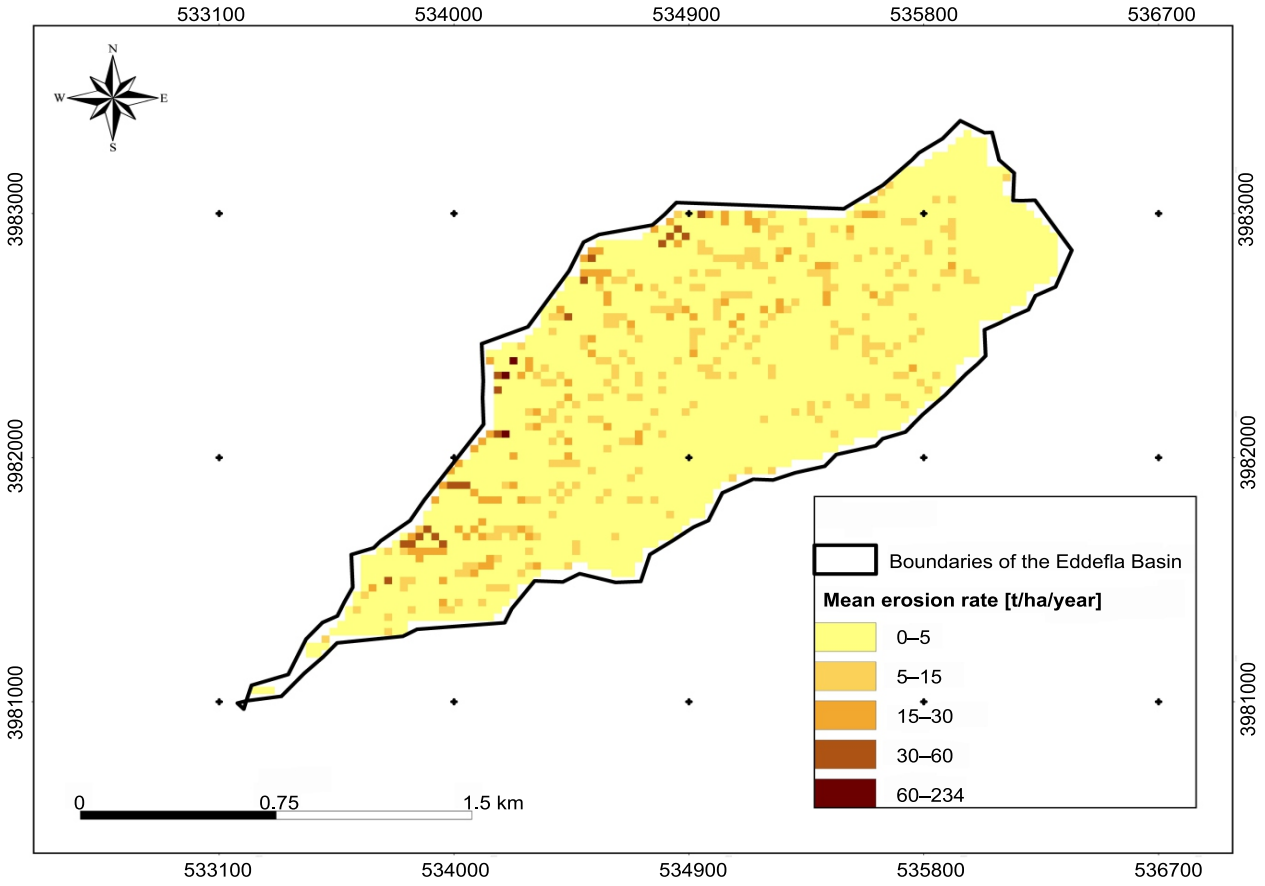

Fig. 10. Spatial distribution of mean annual soil loss in the Oueed Eddefla watershed under the average-erosivity scenario

This intensification is accompanied by a spatial expansion of the high-risk classes, with the combined area of the high and very-high categories increasing from 1.6 to 4.97% of the watershed. This evolution corroborates the major role of rainfall erosivity in amplifying erosion risk and underlines the potential vulnerability of small Mediterranean watersheds to a future increase in intense rainfall events.

SEDIMENT DELIVERY TO THE HILL RESERVOIR

Potential sediment transfer to the hill reservoir was estimated from the RUSLE-derived soil loss, using an SDR range of 0.35–0.45 adopted as an empirical bracket for the potential transfer efficiency in this small, steep watershed. For an area of 2.71 km² (271 ha), the mean-erosivity scenario, corresponding to a soil loss of 3.22 t·ha^{-1}·yr^{-1}, yields a total mass of potentially eroded material of 872.62 t·yr^{-1}. The fraction potentially delivered to the outlet is thus estimated at 305.42–392.68 t·yr^{-1}, i.e. 1.13-1.45 t·ha^{-1}·yr^{-1}. Assuming a sediment bulk density of 1.3 t·m^{-3}, these values correspond to a potential volume of 234.9–302.1 m³·yr^{-1}.

Under the maximum-erosivity scenario, corresponding to a mean soil loss of 6.30 t·ha^{-1}·yr^{-1}, the total mass of potentially eroded material reaches 1707.30 t·yr^{-1}. The quantity potentially delivered to the outlet then ranges between 597.56 and 768.29 t·yr^{-1}, i.e. 2.21–2.84 t·ha^{-1}·yr^{-1}, corresponding to a potential volume of 459.7–591.0 m³·yr^{-1}.

These results provide an order-of-magnitude estimate of the potential sediment transfer to the reservoir and a first quantitative basis for assessing its exposure to siltation risk (Table 2). They should, however, be interpreted with caution, as the SDR adopted represents an empirical estimate of the fraction of eroded material actually transferred to the outlet.

Table 1

Distribution of erosion-risk classes in the Oued Eddefla watershed

Risk class	Soil loss (t·ha^{-1}·yr^{-1})	% area (mean *R*)	% area (max *R*)
Tolerable	<5	87.39	80.99
Low	5–15	7.47	9.09
Moderate	15–30	3.54	4.95
High	30–60	0.98	3.42
Very high	>60	0.63	1.55

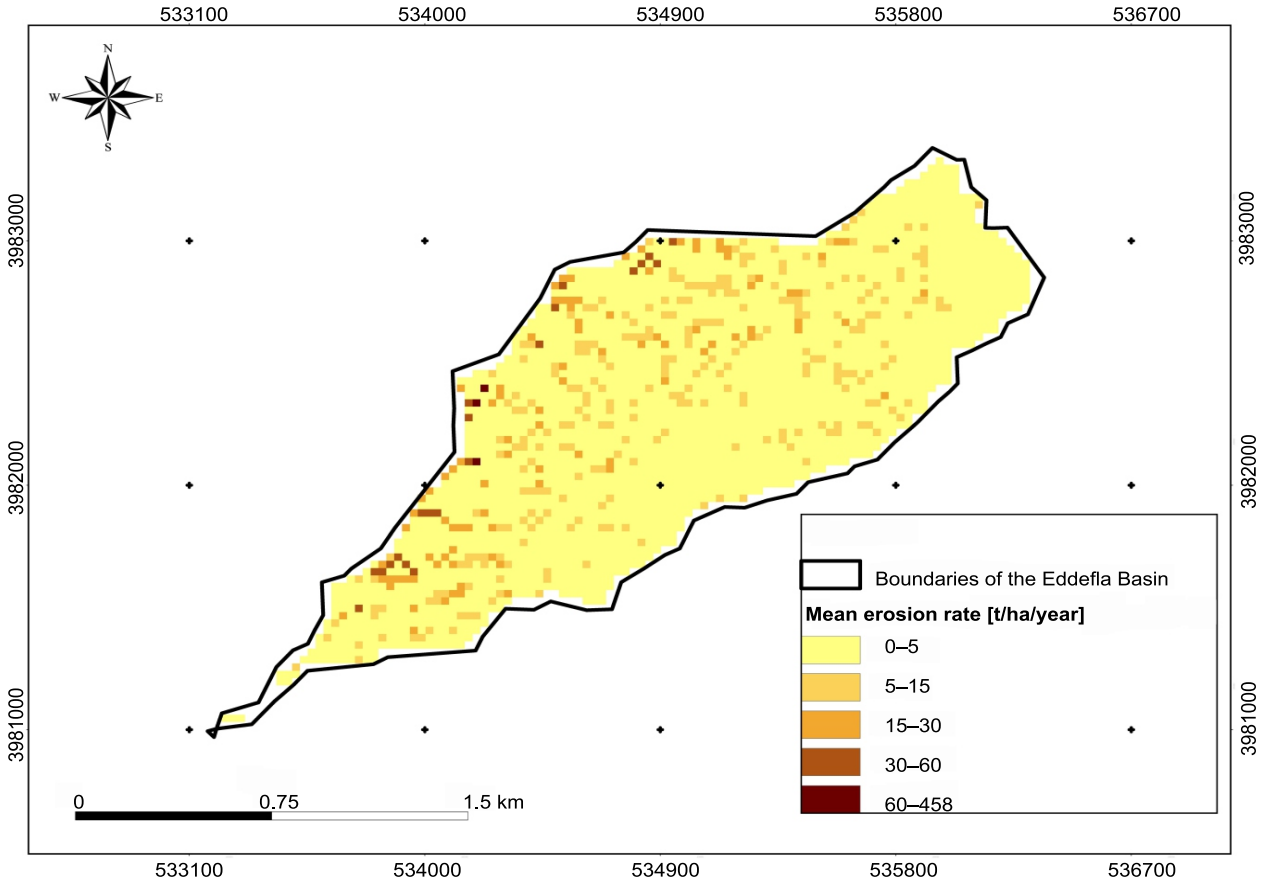

Fig. 11. Spatial distribution of mean annual soil loss in the Oued Eddefla watershed under the maximum-erosivity scenario

Validation will require direct measurements of sediment load, together with bathymetric monitoring of the reservoir to quantify the volumes actually accumulated.

DISCUSSION

DOMINANT CONTROLS ON EROSION

The results show that water erosion in the Oued Eddefla watershed results from the interaction between climatic conditions, lithological characteristics, topography and land cover. The rainfall erosivity factor (*R*) also contributes to the spatial and temporal variability of soil loss. Its variability reflects differences in the erosive potential of rainfall and can intensify runoff, soil-particle detachment, and sediment transport, particularly during years characterized by intense or abundant rainfall. Thus, higher *R*-values may increase soil-loss rates, especially when combined with erodible soils, steep slopes, and limited vegetation cover.

The high soil erodibility, with 85% of the watershed showing *K* values between 0.05 and 0.08, can largely be attributed to the predominance of Upper Cretaceous marl–limestone formations. These formations, characterized by relatively low cohesion, high weatherability and a strong susceptibility to runoff, constitute substrates that are particularly conducive to erosion in Mediterranean environments (Descroix and Mathys, 2003). The values obtained are comparable to those reported for watersheds dominated by marl and marl–limestone formations elsewhere in North Africa, notably in Tunisia (Ben Cheikha et al., 2023; Serbaji et al., 2023), reinforcing the regional consistency of the results.

Sensitivity analysis also highlights the predominant role of the cover-management factor (*C*), whose variation exerts a stronger influence on soil loss than that of the other RUSLE

Table 2

Estimated sediment production and potential sediment delivery to the hill reservoir under the two erosivity scenarios

Parameter	Mean erosivity	Maximum erosivity
Mean soil loss (A)	3.22 t·ha^{-1}·yr^{-1}	6.30 t·ha^{-1}·yr^{-1}
Total eroded soil mass	872.62 t·yr^{-1}	1707.30 t·yr^{-1}
Adopted SDR	0.35–0.45	0.35–0.45
Sediment delivered to outlet	305.42–392.68 t·yr^{-1}	597.56–768.29 t·yr^{-1}
Specific sediment yield	1.13–1.45 t·ha^{-1}·yr^{-1}	2.21–2.84 t·ha^{-1}·yr^{-1}
Bulk density	1.3 t·m^{-3}	1.3 t·m^{-3}
Potential sediment volume	234.9–302.1 m^3·yr^{-1}	459.7–591.0 m^3·yr^{-1}

Table 3

Regional comparison of estimated soil-loss rates

Study area	Mean soil loss (t·ha^{-1}·yr^{-1})	Dominant driver	Reference
Oued Eddefla, Siliana	3.22 (mean) – 6.30 (maximum erosivity)	Slope gradient and degraded vegetation cover	This study
Merguellil catchment, central Tunisia	16–18	Land-use change, cultivation on steep slopes and vegetation degradation	Hermassi et al. (2023)
Rmel watershed, Tunisia	>5 over ~60% of the basin; up to 65 in the most critical sub-watershed	Slope and agricultural land use	Bouguerra et al. (2017)
Oued Boussouab, Eastern Rif, Morocco	55.35	Slope, soil erodibility and vegetation cover	Sadiki et al. (2004)
EU-28 water erosion-prone lands	2.46	Rainfall, topography, soil properties and land cover	Panagos et al. (2015)

factors. This sensitivity underlines the importance of vegetation cover in controlling water erosion, particularly in Mediterranean and semi-arid environments, where seasonal and inter-annual variations in vegetation can substantially alter the degree of soil protection against rainfall impact and runoff (Vrieling, 2006; Panagos et al., 2021). Conservation and restoration of vegetation cover therefore represent essential levers for reducing soil vulnerability to erosion.

The topographic factor also plays a major role in the spatial distribution of soil loss. Nearly 27% of the watershed area has slopes exceeding 15%, which generally increases runoff velocity, the erosive power of flows, and particle-transport capacity. In the RUSLE framework, the *LS* factor explicitly represents the effects of slope length and slope steepness on soil loss, with steeper slopes generally associated with greater erosion potential (Renard et al., 1997; Panditharathne et al., 2019). This relationship between relief and erosion intensification is also consistent with the findings of Gayen et al. (2019), who identified slope and other topographic variables among the important conditioning factors controlling the spatial distribution of erosion susceptibility. Similarly, studies applying RUSLE in watershed environments have highlighted the significant contribution of slope length and steepness to the spatial variability of soil erosion (Fayas et al., 2019; Lu et al., 2020). In the Eddefla River watershed, however, the effect of topography is closely conditioned by interactions between slope, soil erodibility, and vegetation cover. This combination helps to explain why high soil-loss values are concentrated in certain sectors rather than uniformly distributed across all hillslopes.

Furthermore, the morphometric analysis indicates a Gravelius compactness coefficient of *Kc* = 1.53, reflecting a relatively elongated watershed morphology. This configuration may contribute to a less synchronized hydrological response than that of a more compact watershed, owing to the spatial variability of the times of concentration among the different sub-basins. However, watershed morphometry is not a factor directly incorporated into the RUSLE formulation; its role should therefore be regarded as complementary to the analysis of potential erosion and sediment transfer. An elongated morphology can modify flow-concentration and transfer conditions, but it does not, on its own, imply a regular sediment supply to the hill reservoir. Effective transfer of eroded material also depends on hydro-sedimentary connectivity, the configuration of the drainage network, riparian vegetation, and deposition and remobilization processes.

The interest of this study therefore lies in relating the RUSLE factors to the morphometric and environmental characteristics of the watershed, allowing a more integrated interpretation of the spatial distribution of erosion. This approach shows that identifying sectors with high soil loss should not rely solely on the watershed-scale mean value, but also on the joint analysis of rainfall erosivity, lithology, soil erodibility, relief, vegetation cover and sediment-transfer conditions. It thus provides a relevant basis for identifying priority sectors for soil conservation and for reducing sediment inputs to the hill reservoir.

REGIONAL COMPARISON

The mean soil-loss rate estimated at 3.22 t·ha^{-1}·yr^{-1} in the Oued Eddefla watershed is relatively moderate compared with values reported for Mediterranean and North African catchments. This may be related to the small watershed size (2.71 km²), the predominance of partially vegetated areas, and the limited extent of steep slopes. Soil erosion is strongly influenced by watershed scale, topography, land use, vegetation cover, and environmental conditions (Vanmaercke et al., 2011, 2014).

Despite this moderate mean, soil loss is highly heterogeneous. The steepest sectors, characterized by sparse vegetation and highly erodible marly formations, locally exceed 234 t·ha^{-1}·yr^{-1}, identifying clear erosion hotspots. Under the maximum-erosivity scenario, the mean soil-loss rate increases to 6.30 t·ha^{-1}·yr^{-1}, highlighting the influence of rainfall erosivity.

Regional studies show similarly strong variability. Hermassi et al. (2023) reported mean soil-loss rates of 16–18 t·ha^{-1}·yr^{-1} in the Merguellil catchment, while Bouguerra et al. (2017) found values exceeding 5 t·ha^{-1}·yr^{-1} over ~60% of the Rmel watershed. Sadiki et al. (2004) reported a mean of 55.35 t·ha^{-1}·yr^{-1} for the Oued Boussouab watershed in the Eastern Rif. These differences reflect variations in topography, lithology, land cover, rainfall, watershed size, and modelling approaches.

The contrast between the moderate mean and the locally high values emphasizes the need for targeted soil-conservation measures. Vegetation restoration, hillslope stabilization, and runoff control should therefore focus on erosion hotspots to reduce soil loss and potential sediment delivery to the hill reservoir. Regional comparisons should nevertheless be in-

terpreted cautiously because of differences in spatial scale, data, and modelling methodology (Nadal-Romero et al., 2011; Panagos et al., 2015).

CONCLUSIONS

This study provides a quantitative assessment of water-erosion dynamics in the Oued Eddefla watershed by integrating the RUSLE model, Geographic Information Systems (GIS), morphometric analysis, the temporal variability of rainfall erosivity, a sensitivity analysis of the model factors, and an estimate of sediment transfer using a Sediment Delivery Ratio (SDR). The results indicate a mean soil loss of 3.22 $t \cdot ha^{-1} \cdot yr^{-1}$ under average erosivity conditions, while local soil-loss values exceed 234 $t \cdot ha^{-1} \cdot yr^{-1}$ in the most sensitive sectors. This contrast highlights strong spatial heterogeneity and underlines the importance of identifying erosion hotspots beyond the sole watershed-scale mean value.

The spatial distribution of soil loss reflects the interaction between marl-limestone lithology, topography and vegetation cover. The high erodibility of the marl-limestone formations, combined with steep-slope sectors and sparser vegetation cover, favours the concentration of soil loss in specific zones. The sensitivity analysis identifies the *C* factor as the parameter exerting the strongest influence on soil-loss estimates, underlining the importance of maintaining and restoring vegetation cover together with sustainable land-management practices.

Analysis of rainfall erosivity over the 1989–2019 period reveals substantial inter-annual variability, an essential indicator of the watershed's vulnerability to hydro-climatic variation. The estimate of potential sediment transfer to the hill reservoir indicates volumes of 234.9–302.1 $m^3 \cdot yr^{-1}$ under the mean-erosivity scenario, and 459.7–591.0 $m^3 \cdot yr^{-1}$ under the maximum-erosivity scenario. These values represent a first order-of-magnitude estimate of potential sediment transfer to the reservoir and remain indicative, owing to the use of an empirical SDR ranging between 0.35 and 0.45 and to the absence of direct measurements of sediment transport and deposition within the reservoir.

From an operational standpoint, the results provide a scientific basis for prioritizing soil-conservation interventions, targeting the high-and very-high-risk sectors. Vegetation-cover restoration, conservation tillage practices, hillslope stabilization and runoff-attenuation structures could help to reduce soil loss and sediment inputs to the reservoir. Future work should prioritize field validation through erosion plots, sediment-load measurements and bathymetric surveys, as well as the integration of extreme rainfall events and process-based hydro-sedimentary models. These developments would improve the robustness of the estimates and strengthen conservation and adaptation strategies for small Mediterranean watersheds facing ongoing hydro-climatic change.

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