ASSESSMENT OF WATER EROSION DYNAMICS IN THE MOROCCAN'S CENTRAL PLATEAU FOR CURRENT AND FUTURE SITUATIONS USING RUSLE MODEL AND GEE PLATFORM: CASE STUDY OF KHAROUBA WATERSHED

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ABSTRACT

The Kharouba watershed, located upstream of the Ouljet Soltane dam, has a crucial importance by preserving water and soil resources in the area. Belonging to the Beht watershed, this part of the Morocco's Central Plateau is subject to a relatively high level of soil degradation. In this context, the present study was conducted to assess the spatio-temporal dynamics of Soil Loss (SL) in the Kharouba watershed during the period 2001-2023, and to predict SL rate for the future period 2041-2060 (2050s). The methodological approach integrates the RUSLE model through the dynamic nature of the erosivity (R) and the vegetation cover (C) factors, and the Google Earth Engine (GEE) platform as a tool for the computational tasks. The results indicate that 52 to 82% of the Kharouba watershed surface is subject to intense to severe erosion. Annual Soil Loss varied from 54.29 t/ha in 2011 to 27.38 t/ha in 2023. The spatial distribution of SL values is mainly controlled by the variability of the topographical factor (LS) showing a good correlation with SL (R^2=0.58). While the temporal variability of SL annual average is jointly explained by fluctuations in R and C factors, demonstrating R^2 of 0.35 and 0.23 respectively with SL. Future projections in 2050s show that the average annual Soil Loss is expected to increase by 14 and 13% in the SSP2-4.5 and SSP5-5.8 scenarios respectively compared to the current situation. In addition, this study makes it possible to calculate the quantities of lost soil that will cause silting of the Ouljet Soultane dam located at the downstream end of our watershed, and consequently to determine the lifespan of the dam.

Key-words: *Water erosion dynamics, RUSLE model, GEE platform, Morocco's Central Plateau, SSP2-4.5, SSP5-5.8.*

1. INTRODUCTION

Morocco is located in the north-western part of Africa and the south-western side of the Mediterranean basin, and has an arid to semi-arid climate over most of its territory with very low rainfall and limited surface water resources (Aahd et al., 2009; Mekki, 2017). These hydric resources are conditioned by rainfall, which is highly irregular in time and space, resulting in highly variable flood flows and a significant water erosion (Dinar, 2024). Indeed, water erosion is caused and amplified by a number of factors, both natural and anthropogenic, including climatic erosivity, intensive agriculture, deforestation, over land-exploitation, rough topography and climate change (Sadiki et al., 2004 ; Dallahi et al., 2020; Kassou et al., 2023), resulting in a deterioration of soil quality, a loss of soil fertility, a drop in agricultural productivity and a reduction in the storage capacity of dams (Dionnet et al., 2006).

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Moreover, water erosion is a major constraint for the sustainable development in watersheds (Mesrar et al., 2015). This process is very frequent and changes dynamically according to the evolution and spatial variation of the lithological nature of the rocks, the geomorphology of the landscapes, the geometry of the area and the bioclimatic situation (Zouaoui et al., 2019). This erosion is the main cause of soil degradation in Morocco. It affects almost all regions of Morocco, with different intensities. 60% of the cumulative annual SL due to water erosion is deposited in reservoirs and dams (Debbarh and Badraoui, 2003).

Several studies on water erosion have been carried out in Morocco such as El Garouani et al. (2008), Sadiki et al. (2009), Driss and Akdim (2018), Ait Yacine et al. (2019), Dallahi et al. (2020), Lakhili (2021) and Kassou et al. (2023). These studies have focused on both the quantitative and qualitative aspects of soil loss (SL) assessment, based mainly on the Revised Universal Soil Loss Equation; RUSLE (Renard et al., 1997) and the PAP-CAR (PAP/CAR., 2000; PAP/CAR., 1998) methods. However, there is a lack of research about the dynamic evolution of SL and their future projections. In this context, this study is carried out to assess the spatio-temporal dynamics of Soil Loss and to project their future evolution in the Kharouba watershed as a case study in the Moroccan's Central Plateau. This watershed plays an essential role in water and soil conservation in the area. It is characterised by primary geological formations with a relatively high specific degradation (Dallahi, 2017). Indeed, the objectives of this study are: (i) assessing the evolution of SL in the Kharouba watershed in order to analyse the current situation and identify the main factors controlling Soil Loss dynamics, and (ii) projecting the future situation based on the dynamic nature of R and C factors by using future data from global climate models (GCMs) under two scenarios of climate change (SSP2-4.5 and SSP5-8.5).

2. STUDY AREA

The Kharouba watershed is located in the province of Khémisset of Central Plateau (**Fig. 1**).

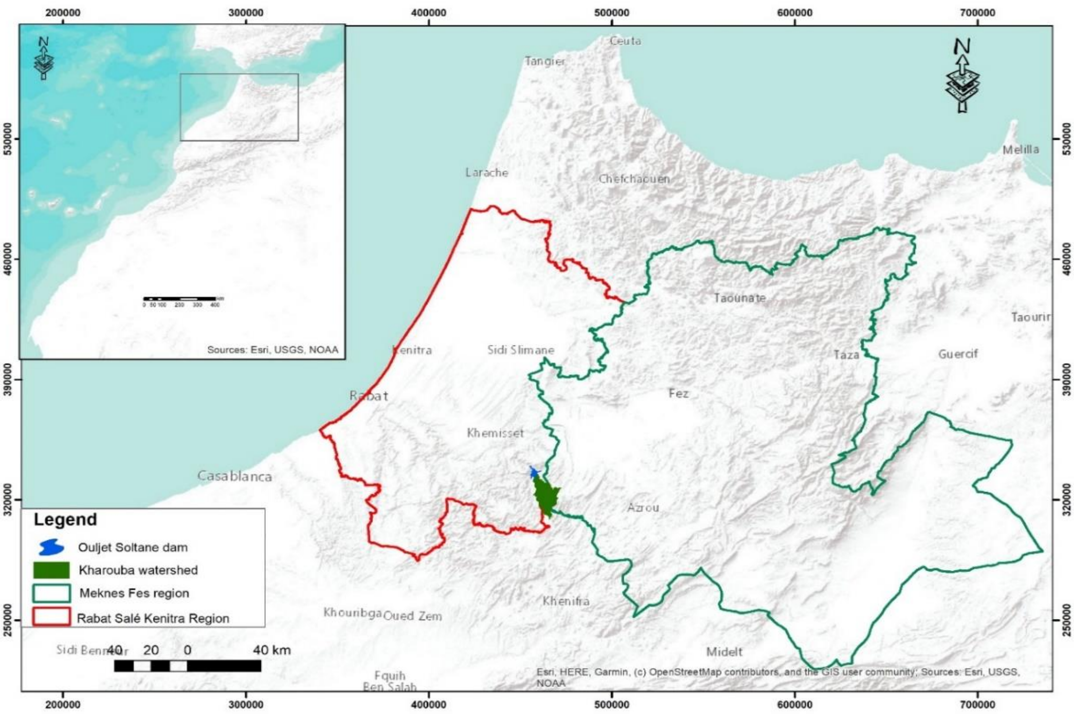

Fig. 1. Location of the Kharouba watershed.

It covers an area of 19,888.5 hectares (ha) and is located in the central part of Beht watershed. The area is dominated by Palaeozoic geological formations of shale and sandstone, which were heavily folded and tectonized during the Hercynian orogeny. In terms of vegetation, this watershed is dominated by forest formations organised by *Tetraclinis articulata* and *Quercus rotundifolia* (Dallahi et al., 2016, Dallahi et al., 2017) , which cover more than 87% of its total surface area (Fennane et al., 1987). Regarding the climate, the area is characterised by an arid to semi-arid climate with high spatial and temporal variability in rainfall.

3. METHODOLOGICAL APPROACH

3.1. Assessment of current SL dynamics

In order to assess the spatial-temporal dynamics of SL in the Kharouba watershed between 2001 and 2023, the Revised Universal Soil Loss Equation (RUSLE) (Wischmeier and Smith, 1978 ; Renard et al., 1997) was used:

$$A = R \times K \times LS \times C \times P \qquad \text{(imperial: tons/acre/yr)}$$

where:

R = is the rainfall and runoff factor depending by geographic location
K = is the soil erodibility factor
LS = is the slope length-gradient factor
C = is the vegetation cover used to represent the relative effectiveness of soil and crop management systems in controlling soil loss
P = is the support for anti-erosive practices, as the ratio of soil loss by a support practice like cross-slope cultivation, contour farming and strip cropping.

To calculate the R factor, the following formula was used (Singh et al., 1981):

$$R = 79 + 0 .363 \times P$$

where: P is the annual precipitation in mm.

To compute the LS factor, the following formula was used (McKague and Eng, 2023; Boussalim et al., 2022 ; Stone and Hilborn, 2012) :

$$LS = (0.065 + 0.0456 \times S + 0.006541 \times S^2) ((FlowAcc \times 30) \div 22.1^{0,5}))$$

where: S is the slope gradient in %;
FlowAcc is the flow accumulation having
30 as spatial resolution of the DTM;
0.5 as constant value used when the dominant slopes in the basin exceed 5%.

To compute the C factor, the following formula was used (Kouli et al., 2009) :

$$C = \exp [- \alpha \times NDVI / (\beta - NDVI)]$$

where: $\alpha = 2$ and $\beta = 1$ are constants.
NDVI (Normalized Difference Vegetation Index) was calculated by:
$NDVI = (NIR - R) / (NIR + R)$
NIR: infrared band
R: red band

We have calculated the K factor by using the correspondence table between soil texture and K, from Stone and Hilborn (2000). The values obtained were multiplied by 0.1317 (Chadli, 2016) to convert the values into the international system of units.

The P factor was estimated as a function of slope following Shin (1999) and taking into account land use types extracted from MODIS data.

The computational operations were performed on the Google Earth Engine (GEE) platform. CHIRPS data (Funk et al., 2015) were used for the generation of the R-factor using total annual precipitation. Landsat 7 (from 2001 to 2017) and Landsat 8 (from 2018 to 2023) data were used to give rise to the vegetation cover C factor. USDA data were used to determine surface soil texture (Hengl, 2018) to spatialise the K factor. Also, a 30 m resolution digital elevation model (DEM) was used to calculate the LS factor. The P factor was estimated from MODIS land cover data (Friedl et al., 2002) and the slope steepness from DEM. SL values resulting from the spatial modelling in tonnes/hectares/year (t/ha/yr) were classified into five categories (**Table 1**).

Table 1.

Soil Loss classification applied in the study.

Categories	**Slight**	**Moderate**	**High**	**Very High**	**Severe**
SL (t/ha/yr)	<10	10<SL<20	20<SL<30	30<SL<40	SL>40

A linear regression between the annual averages of Soil Loss and the averages of the two dynamic factors (R and C) was used to explain the temporal fluctuations of SL. Similarly, the spatial variability of SL was assessed using a pixel-to-pixel linear regression between SL and the various explanatory factors (LS, R, C, K and P). The Spearman correlation test was used to evaluate the significance of the correlation. The significance level (α) was set at 0.05. Also, the strength of the correlation is assessed by the coefficient of determination (R^2).

3.2. Prediction of SL in 2041-2060 (2050s)

To predict average Soil Loss in 2050, projected data were used to estimate the future climatic erosivity (R factor). These data were downloaded from the WorldClim database with 1 km of resolution. Precipitations values was bias-corrected and downscaled with the WorldClim version 2.1 data (1970-2000) (Fick and Hijmans, 2017). The average of 3 GCMs was used (ACCESS-CM2, EC-Earth3-Veg and MIROC6), for two SSP scenarios: SSP2-4.5 (medium scenario) and SSP5-8.5 (pessimistic scenario).

To project the future C factor, we have predicted the NDVI (Normalized Difference Vegetation Index) for 2050s using MOLUSCE extension (Modules for Land Use Change Evaluation) in QGIS Desktop 2.16.3 software. Two NDVI rasters were used between two different dates (2013 and 2023) to detect spatial changes. Indeed, the prediction was made by a logistic regression model based on changes between the two cited dates. The model showed a "Pseudo R-squared: PR^2" of 0.802, therefore, it was used to anticipate the NDVI state in 2050s. The assessment of changes between the two dates, the training of the prediction model and the simulation of the future state were carried out by NDVI classes since the MOLUSCE extension take into account categorized data. Therefore, six classes were adopted:

Class 1 : NDVI<0
Class 2 : 0<NDVI<0,1
Class 3 : 0,1<NDVI<0,2
Class 4 : 0,2<NDVI<0,3
Class 5 : 0,3<NDVI<0,4
Class 6 : NDVI>0,4

The rainfall erosivity (R) and vegetation cover (C) factors calculated for 2050s were integrated with the static factors (LS, K and P) to project SL in 2050s. Then, the current and future situations were compared via SL averages and the proportion of each SL category. For the current situation, the average of Soil Loss over the period 2001-2023 was considered for the comparison.

4. RESULTS

4.1. Assessment of the current SL dynamics (2001-2023)

The RUSLE model was used to map the spatial variability of Soil Loss (**Fig. 2**). Depending on the interannual fluctuations of rainfall and vegetation dynamics, the Kharouba watershed shows severe water erosion on 23 to 45% of its surface area. Very intense erosion varies between 15 and 24% and intense erosion between 12 and 19%. Moderate water erosion varies between 7 and 15%, while low erosion between 10 and 31% **(Fig. 3**). These results indicate that 52 to 82% of the watershed surface is subject to intense to severe erosion. This spatial variability is accompanied by a large spatial-temporal variability in SL, which ranges from 27.38 t/ha in 2023 to 54.29 t/ha in 2011 (**Fig. 4**).

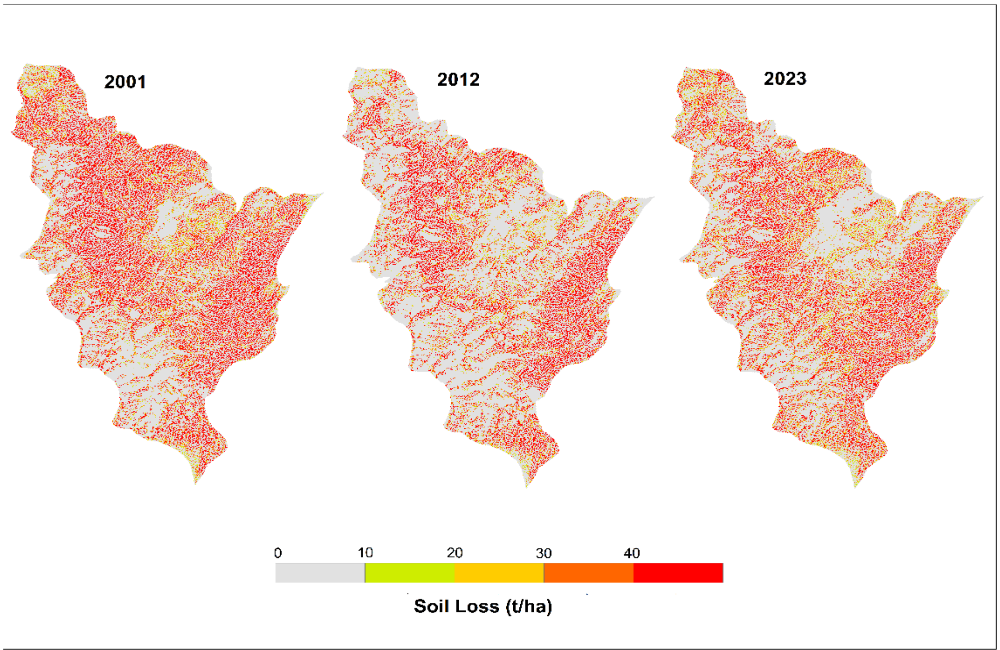

Fig. 2. Spatial distribution of SL categories in Kharouba watershed in 2001, 2012 and 2023.

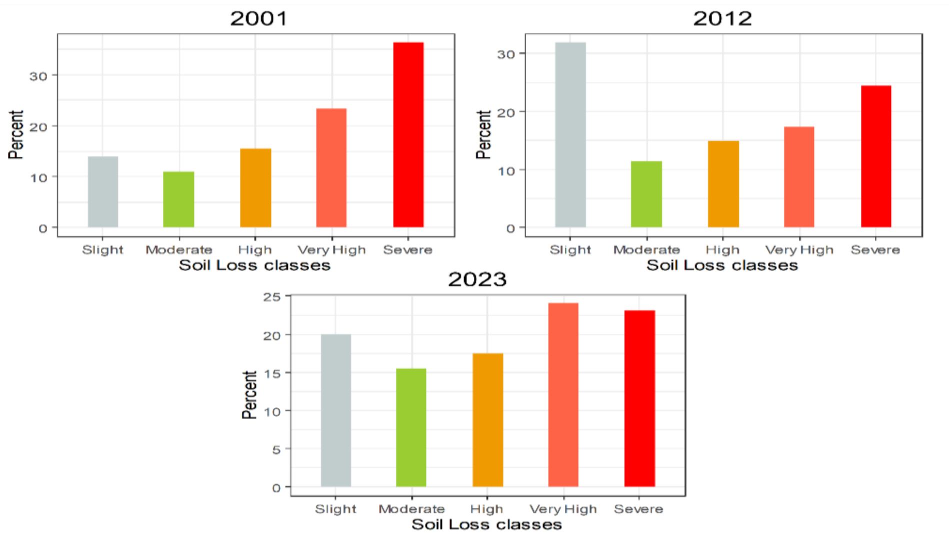

Fig. 3. Distribution of SL categories in Kharouba watershed in 2001, 2012 and 2023.

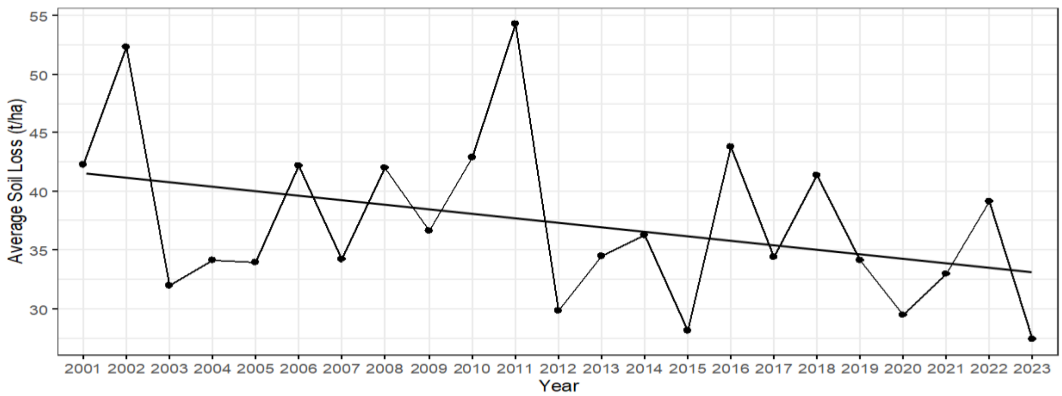

Fig. 4. Evolution of the SL averages between 2001 and 2023 in Kharouba watershed.

The pixel-by-pixel correlation between Soil Loss and the various explanatory variables shows that the LS factor is the most determinant variable influencing the spatial distribution of SL, with a coefficient of determination (R^2) of 0.58 (**Fig. 5, a**). The second and third most important variables are respectively the vegetation cover C factor, with an R^2 of 0.18 (**Fig. 5, c**) and the R factor, with an R^2 of 0.005 (**Fig. 5**, **b**). These three variables show a significant correlation with Soil Loss at α=0.05. The K and P variables, on the other hand, showed non-significant correlations to the same α level.

The correlation between annual Soil Loss average and the rainfall erosivity (R) and vegetation cover (C) factors shows that the temporal variation in SL is jointly controlled by the interannual variations of R and C, which demonstrated respective R^2 values of 0.35 and 0.23 (**Fig. 6**).

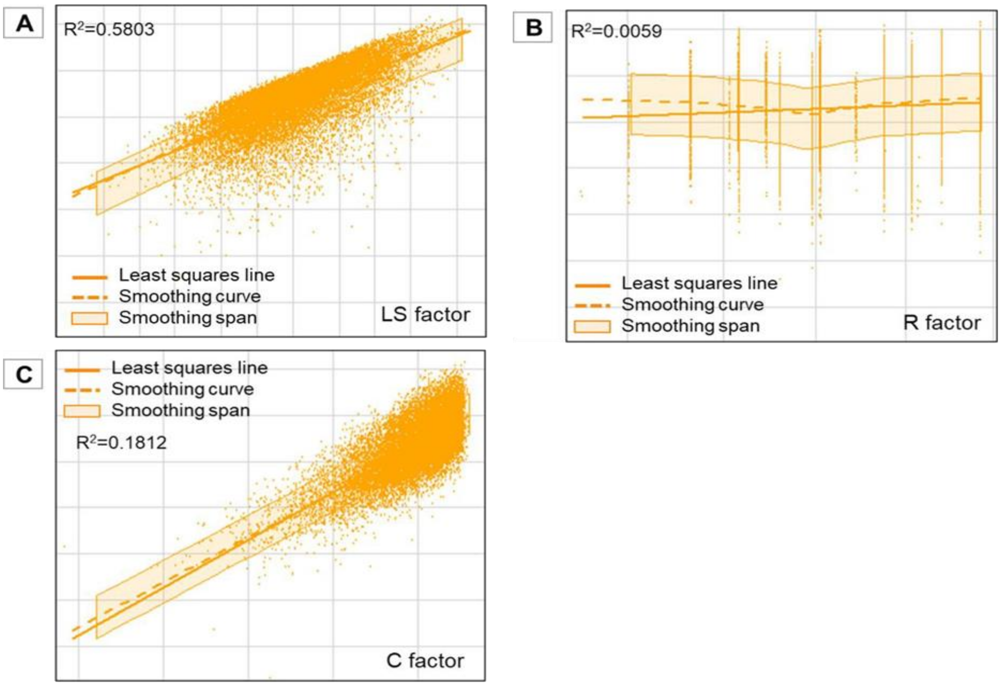

Fig. 5. Variables with significant correlation at α=0.05; pixel-to-pixel linear regression between SL and RUSLE factors.

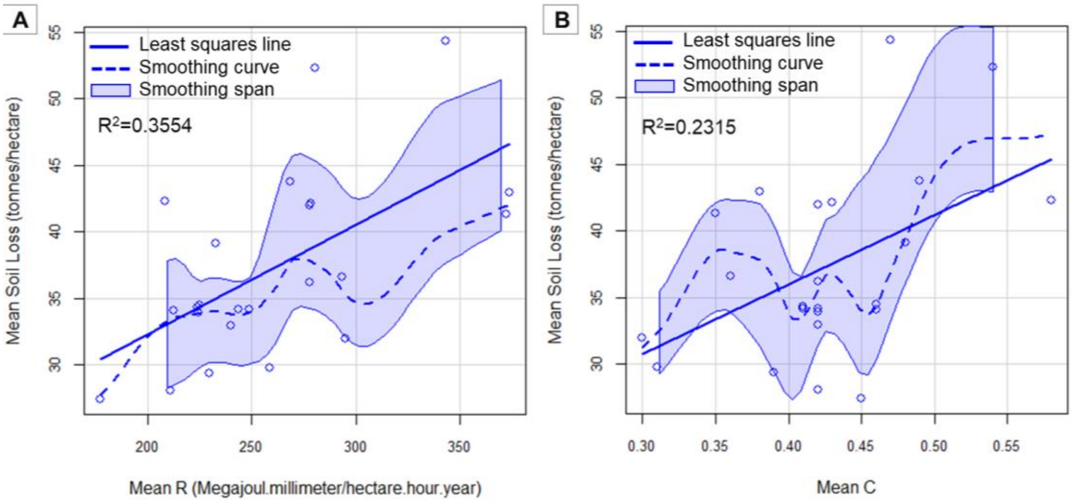

Fig. 6. Linear regression between the annual SL averages and dynamic factors of RUSLE: R (a) and C (b).

4.2. SL projections in 2050s

The NDVI compared between 2013, 2023 and projected for 2050s shows a regressive vegetation dynamic over time, with a decrease in areas with high NDVI values and an increase in those with low NDVI values (**Fig. 7**). Comparison of NDVI classes between 2013 and 2023 showed that 33% of areas with NDVI>0.3 were converted to areas with NDVI<0.3. Furthermore, the future NDVI projection in 2050s shows that 15% of areas with NDVI>0.2 should be converted to areas with NDVI<0.2 compared to 2023 (**Table 2**).

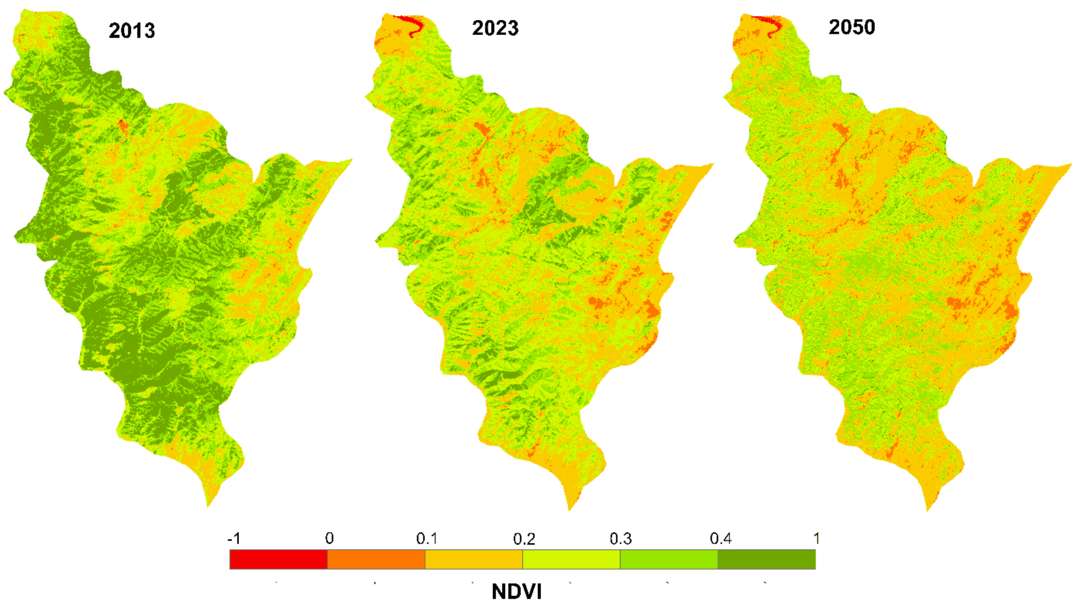

Fig. 7. Spatial changes in NDVI between 2013 and 2023, and prediction result for 2050s.

Table 2.
Comparison between classes of NDVI between 2013, 2023 and the predicted situation 2050s.

Area and change	2013 (ha)	2023 (ha)	From 2013 to 2023 (%)	2050 (ha)	From 2023 to 2050 (%)
NDVI<0	1,53	38,25	+0,16	50,04	+0,05
0<NDVI<0,1	65,79	553,41	+2,20	892,71	+1,53
0,1<NDVI<0,2	2954,16	7005,96	+ 18,31	10084,14	+ 13,91
0,2<NDVI<0,3	5760,63	8586,81	+ 12,77	6540,57	-9,24
0,3<NDVI<0,4	6449,58	4699,53	-7,90	4363,47	-1,51
0,4<NDVI<1	6893,55	1241,28	-25,54	194,31	-4,73

Future rainfall and NDVI projections were used to map the rainfall erosivity R and vegetation cover C factors for 2050s in order to anticipate Soil Loss status (**Fig. 8**). Comparison of the average SL obtained for the period 2001-2023 with the average projected for 2050s shows an increase in SL rate by 14% for SSP2-4.5 and 13% for SSP5-5.8 (**Table 3**).

Rainfall erosivity is expected to be less important in 2050s with an average decrease of 1.5% in the SSP2-4.5 scenario. This reduction is around 2.2% in the SSP5-8.5 scenario. Thus, the C Factor is intended to increase by +16% by 2050s (**Table 3**). The assumed increase in the rate of water erosion in 2050s is the result of an increase in areas with severe erosion to the detriment of areas with low erosion (**Fig. 9**). The distribution of the other categories of Soil Loss is projected to be relatively constant in space.

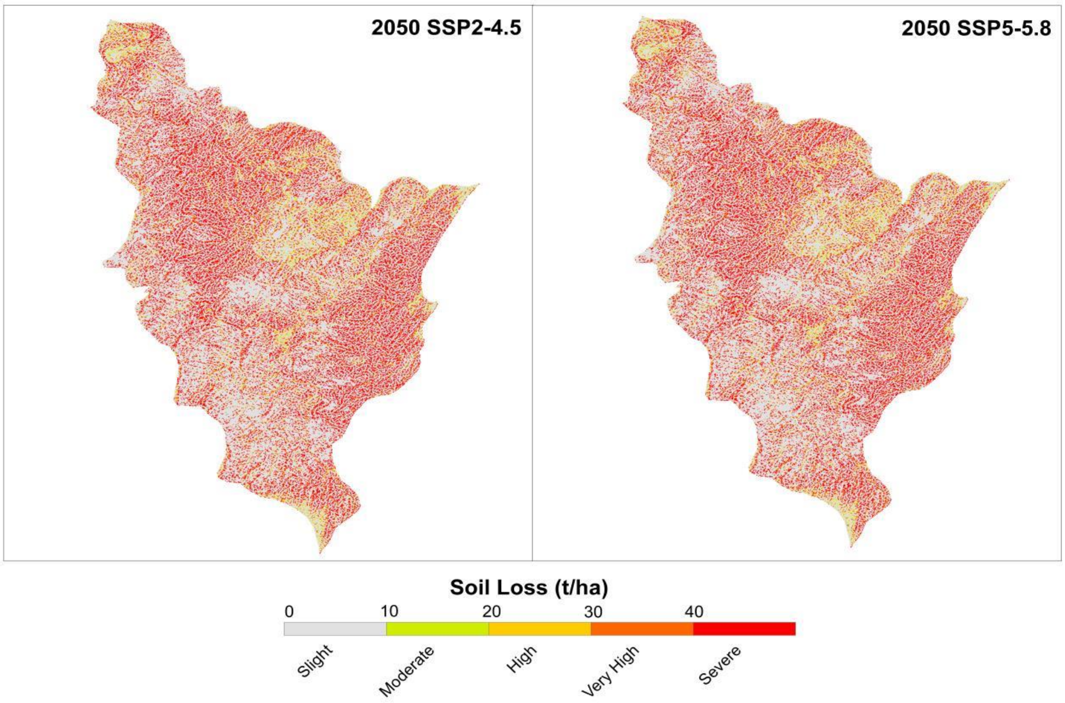

Fig. 8. Projected SL for 2050s: SSP2-4.5 and SSP5-8.5 Scenarios**.**

Table 3.
Means of R, C and soil loss calculated for the reference period 2001-2023 compared to projected means for 2050.

Period	2001-2023	2050s under SSP2-4.5	2050s under SSP5-8.5
R value (Mgj.mm/ha.h.yr)	260,79	256,65	255
C value	0,42	0,49	0,49
Mean of Soil Loss (t/ha)	37,29	42,54	42,27

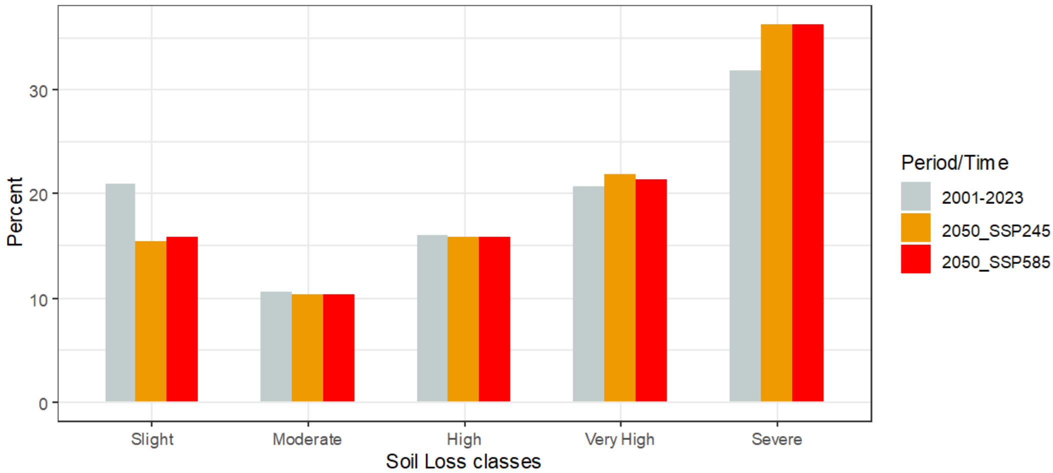

Fig. 9. Comparison of the averages soil loss by categories between 2001-2023 and the predicted situation in 2050.

5. DISCUSSION

The significance of the spatial-temporal dynamics of Soil Loss in the Kharouba watershed was evaluated by this study. The variability of the topographical factor, which demonstrated a determination coefficient of 0.58 with Soil Loss, primarily controls the spatial dynamics of SL. The slope influences water erosion mainly through its inclination and length; both parameters considered in the RUSLE model. The slope affects erosion in two ways: by transferring the ejected particles downstream, after the raindrops have hit the ground; and by imparting energy to runoff water along the slope, when large quantities of water are on the ground, run-off occurs more quickly, preventing the water from infiltrating the soil. Thus contributing to the uprooting and transport of soil particles (Sadiki, 2005).

In the western Meseta, including the area of the central plateau where the studied watershed is located, the topographical factor is the most determinant variable influencing water erosion, with a relatively greater effect than the other factors in the RUSLE model (Lamane et al., 2022). In the same geographical area, the correlation between SL and the various explanatory factors in the Oued Cherrat watershed also shows the dominance of the topographical factor over the other RUSLE variables, demonstrating a correlation coefficient of 0.67 (R^2=0.45) with Soil Loss (Boussalim et al., 2022).

On the other hand, our results show that Soil Loss at basin level are characterised by significant inter-annual temporal variability over the study period, with a minimum in 2023 and a maximum in 2011. This spatial variability is controlled by the dynamic factors in the equation.

The erosivity of rainfall has a greater impact on this variability than fluctuations in vegetation cover (R^2=0.35). This is essentially explained by the high inter-annual and intra-annual rainfall variability characterizing Morocco (Sebbar, 2013). These fluctuations in rainfall input are the main cause of the temporal variability of SL in Kharouba watershed. Indeed, fluctuations in NDVI, reflecting vegetation dynamics, contribute also significantly to the interannual variability of SL (R^2=0.23). The quality of the vegetation cover can considerably reduce or accentuate the effects of climatic erosivity. A dense vegetation can slow run-off, facilitate infiltration and decrease the intensity of erosion.

Our results show also that rainfall erosivity (R) and vegetation cover (C) factors have a weak but significant impact on the spatial variability of SL. This is explained by the fact that these two factors do not show great variability in their spatial distribution. Rainfall distribution is homogeneous throughout the watershed with low spatial fluctuations. Similarly for land use, which 87% of the watershed's area is occupied by *Tetraclinis articulata* and holm oak forests (Dallahi, 2017). The results also indicate that the two factors, soil erodibility (K) and anti-erosion practices (P) have no significant effect on the spatial distribution of Soil Loss. For the K factor, this result can be explained by the homogeneity of the edaphic substratum : more than 90% of crude mineral soils on schist substratum (Dallahi, 2017). Thus, P factor was mainly estimated on the basis of land use, which is more or less homogeneous as already explained (see above).

In the same watershed and using the PAP/CAR method, (Dallahi et al., 2020) showed that water erosion was intensified between 1986 and 2008 and that surfaces that are vulnerable to water erosion were increased by 6% between these two reference dates. The main cause was the regression of vegetation (Dallahi et al., 2023). According to HCEFLCD (2007), analysis of erosion maps demonstrated that erosion is active and apparent over more than 75% of the total surface area of the watershed. This result is similar to our findings, which showed that 52% to 82% of the watershed is subject to intense to severe erosion. Our results are therefore close to those obtained for the large Oued Beht watershed, which Kharouba is part of. The authors of the study concluded that potential erosion has been greatly accelerated in the Oued Beht watershed due to the low vegetation cover observed over 70% of its territory (HCEFLCD, 2007). Also, the study carried out by Lakhili (2021) in the Beht watershed showed that 76% of the area is exposed to moderate to severe erosion.

The results obtained show that the C factor will increase in 2050s because of the decrease in NDVI according to the projections made. Thus, climatic erosivity will decrease in 2050s, which directly translates into a reduction in annual precipitation in this period, since the equation for calculating the R factor only takes into account total annual rainfall in an equation where the two factors (climatic erosivity and annual precipitation) are positively correlated (see methodology section). As a result, the projected decrease in NDVI in 2050s can be attributed to this reduction in rainfall; the only future variable element in the soil loss quantification model used. However, the NDVI modelling process was not carried out in a multifactorial manner. As a result, other factors were not taken into account, such as temperature and stochastic forces (fires, etc.). Few of the existing models for the future projection of factor C take these into account, due to the nature and complexity of modelling these phenomena.

Our results show also that water erosion rate will rise in the watershed in 2050s with an increase in average Soil Loss by 14% and 13% in the SSP2-4.5 and SSP5-5.8 scenarios respectively. In Morocco, few studies have focused on SL future projections. Our study appears to be the first for the central Moroccan plateau. The finding of other studies are consistent with our result regarding the Moroccan context. A study conducted by (Jazouli et al., 2019) in the upper basin of the Oum Er Rbia river demonstrated that the average annual SL will go up in 2030 compared to year 2003. In the Haouz plain, for instance, (Bammou, et al., 2024) was projected SL in the future situations using SSP scenarios. The findings also show that water erosion will grow in this region in 2040s compared to the current situation.

6. CONCLUSIONS

The RUSLE dynamic approach was used to quantify Soil Loss in the Kharouba watershed and to make projections in the future situation. Our results highlight that the erosion is intense to severe in the Kharouba watershed and the regression of vegetation will be responsible in the future in an increase of Soil Loss rates in the Moroccan's Central Plateau. This will certainly lead to the silting up of the Ouljet Soultane dam located downstream of the watershed affecting also the limited water resources of the area. Anti-erosion practices are needed, particularly in the context of a rapid global warming to ensure soil protection and conservation and to preserve the ecosystems, avoiding therefore the Ouljat Soltane dam siltation.

Soil erosion and the effects of global warming are a vast and multidisciplinary area of research. To develop and improve soil management practices, we can develop a more advanced climate model to predict the effects of climate change on soil erosion rates in different regions, and develop sensors and networks to continuously monitor soil parameters. These research orientations can help to better understand the underlying mechanisms of soil erosion and to develop innovative and effective solutions to preserve soils and ecosystems in the face of the challenges posed by climate change.

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