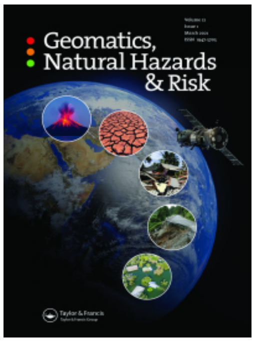

Geomatics, Natural Hazards and Risk

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tgnh20

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To cite this article: Omar Djoukbala, Salim Djerbouai, Saeed Alqadhi, Mahmoud Hasbaia, Oussama Benselama, Hazem Ghassan Abdo & Javed Mallick (2024) A geospatial approach-based assessment of soil erosion impacts on the dams silting in the semi-arid region, Geomatics, Natural Hazards and Risk, 15:1, 2375543, DOI: 10.1080/19475705.2024.2375543

To link to this article: https://doi.org/10.1080/19475705.2024.2375543

GEOMATICS, NATURAL HAZARDS AND RISK
2024, VOL. 15, NO. 1, 2375543
https://doi.org/10.1080/19475705.2024.2375543

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A geospatial approach-based assessment of soil erosion impacts on the dams silting in the semi-arid region

Omar Djoukbala[a], Salim Djerbouai[a], Saeed Alqadhi[b], Mahmoud Hasbaia[a], Oussama Benselama[a], Hazem Ghassan Abdo[c] and Javed Mallick[b]

[a]City, Environment, Hydraulics, Society and Sustainable Development laboratory, University of M'sila, M'sila, Algeria; [b]Department of Civil Engineering, College of Engineering, King Khalid University, Abha, Kingdom of Saudi Arabia; [c]Geography Department, Faculty of Arts and Humanities, Tartous University, Tartous, Syria

ABSTRACT
Soil erosion significantly impacts dam functionality by leading to reservoir siltation, reducing capacity, and heightening flood risks. This study aims to map soil erosion within a Geographic Information Systems (GIS) framework to estimate the siltation of the K'sob dam and compare these estimates with bathymetric observations. Focused on one of the Hodna basin's sub-basins, the K'sob watershed (1477 km^2), the assessment utilizes the Revised Universal Soil Loss Equation (RUSLE) integrated with GIS and remote sensing data to predict the spatial distribution of soil erosion. Remote sensing data were pivotal in updating land cover parameters critical for RUSLE, enhancing the precision of our erosion predictions. Our results indicate an average annual soil erosion rate of 7.83 t/ha, with variations ranging from 0 to 224 t/ha/year. With a typical relative error of about 13% in predictions, these figures confirm the robustness of our methodology. These insights are crucial for crafting mitigation strategies in areas facing high to extreme soil loss and will assist governmental agencies in prioritizing actions and formulating effective soil erosion management policies. Future studies should explore the integration of real-time data and advanced modeling techniques to further refine these predictions and expand their applicability in similar environmental assessments.

ARTICLE HISTORY
Received 15 January 2024
Accepted 28 June 2024

KEYWORDS
Erosive process; dams silting; GIS; RS; RUSLE; Algeria

1. Introduction

A significant factor in soil degradation is water erosion. It occurs when water washes away the topsoil, leaving behind exposed subsoil and rock (Abdo and Salloum 2017; Hao et al. 2019). This process can lead to soil compaction, loss of organic matter, and reduced fertility. It can also cause increased runoff and sedimentation in nearby waterways, leading to water pollution. Soil capital is a non-renewable or extremely slow-renewing resource. It is

CONTACT Hazem Ghassan Abdo hazemabdo@tartous-univ.edu.sy

strongly threatened by degradation and erosion (Abdo 2018; Benavidez et al. 2018; Hateffard et al. 2021; Acharki et al. 2022).

Recent research on the Mediterranean region's vulnerability to climate change show a tendency toward more frequent droughts, which speed up water erosion, one of the most common types of environmental deterioration (Berberoglu et al. 2020). Water and soil resources are limited and sensitive in Mediterranean countries with semi-arid climates. The climate in these areas is characterized by irregular, geographically and seasonally variable rainfall (Vaezi et al. 2017). Rainfall contributes to dam reservoir siltation and substantial water erosive damage in watersheds (Hao et al. 2019).

During the 20th cycle, erosion has dramatically persisted throughout the world (Wuepper et al. 2019). About 85% of land degradation is due to soil erosion, which causes a 17% reduction in land productivity (Angima et al. 2003); additionally, it poses a serious risk to all Algerian dams. It is estimated that Algerian dams lose around 20 million m^3 of capacity per year (Remini 2000).

The degradation of soils by water erosion is a well-known phenomenon in northern Algeria, but nowadays, it is becoming more and more important and is a major concern for the country.

Algeria has a large number of dams of all categories and sizes. Unfortunately, this wealth is deteriorating day by day through accelerated sedimentation. The siltation of reservoirs is caused by erosion of watersheds upstream of reservoirs in all of its forms (laminar, channel, ravine, banks, landslides, mudslides, etc.). The consequences of erosion are not limited only to the silting up of reservoirs; they also contribute to the loss of the topsoil, the most fertile of the soil, by reducing its productivity and degrading the quality of surface water, which then affects downstream infrastructures such as drinking water treatment plants and dams. The analysis of water erosion problems on a national scale shows that more than six million hectares of crops and rangelands are actually threatened by erosion, with an average annual specific loss varying between 0.65 and 42.8 (t/ha/year) (Djoukbala et al. 2022); On the one hand, it poses a threat to the sustainability of dams constructed to mobilize surface water, and on the other hand, it results in the loss of the topsoil that is the richest in organic matter and nutrients (Kumar et al. 2021), which lowers the productivity of agricultural land and creates a deficit in meeting dietary needs, as well as economic and social problems (Jiang et al. 2014).

As part of a study to update the National Water Plan, the Ministry of Water Resources in Algeria (MRE) recorded in 2010, a reduction in rainfall of 20% to 40% in the north of the country. This very important spatial and temporal irregularity of rainfall is a constant threat to the filling of reservoirs and the recharge of groundwater.

In order to reduce the extent of this phenomenon, the use of modeling appears to be an interesting tool for its prediction and evaluation.

There are several studies and models proposed to estimate soil erosion. Among many models, the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997) remains the most widely used model to estimate soil erosion in the Mediterranean region (Benselama et al. 2018; Toubal et al. 2018; Mohammed et al. 2020; Acharki et al. 2022; Kucuker and Cedano Giraldo 2022). Geographic Information Systems (GIS) and Remote Sensing can be innovative tools for identifying areas at high risk of soil erosion (M. F.

Allawi et al. 2023; Bassma Sattar and Rashid 2022; Jabar et al. 2023; Mekonnen et al. 2023; Pradhan et al. 2012; Sayl et al. 2017).

The Hodna basin, the fifth basin in Algeria, encompasses a drainage area of 26,000 km^2. The K'sob watershed, one of Hodna's sub-basins, is located northeast of the basin. It spans an area of 1,477 km^2 and is situated between longitudes 4°30′ E and 5°17′ E, and latitudes 35°45′ N and 36°9′ N. The watershed's semiarid climate is typified by high temperatures, little rain, and great spatiotemporal variability. There is roughly 363 mm of precipitation per year on average. Around 36.6 mm of rain precipitation occurs on average every day. The watershed has a single dam (K'sob), built in 1940 and with a 31.00 hm^3 capacity. The specific objectives of this study are to test the efficiency of the RUSLE model for soil erosion estimation, siltation and to evaluate and validate the performance of the model using bathymetric data.

Recent studies on soil erosion have increasingly focused on the impact of climate variability and land use changes, with significant contributions highlighting the accelerated rates of erosion and subsequent sedimentation affecting water reservoirs and agricultural productivity (Munir et al. 2021). These studies employ a range of methodologies, from traditional field surveys to advanced remote sensing techniques, to quantify erosion and its impacts (Kulimushi et al. 2021; Ghosh et al. 2022). However, despite these advancements, there remains a notable gap in localized, precise predictive modeling that integrates diverse data sources for enhanced accuracy and applicability in semi-arid regions.

In order to achieve the objectives of the study, the chosen methodological approach is based on the use of remote sensing data, which provides a spatialized knowledge of erosion factors (rainfall erosivity, land use, amount of vegetation cover, etc.); and on the use of Geographic Information Systems (GIS) to analyze and model land erosion processes in the research area.

The specific objectives of this study are to test the efficacy of the RUSLE model for estimating soil erosion and siltation rates and to evaluate and validate the model's performance using recent bathymetric observations. Through this approach, the study not only reaffirms the utility of RUSLE in semi-arid contexts but also introduces methodological enhancements that improve erosion prediction accuracy and management decisions (Table 1).

Table 1. Characteristics of the morphology of the K'sob watershed.

Characteristics	Symbol	Values
Watershed Area	A	1477 km^2
Watershed's perimeter	P	199.46 km
Maximum altitude	H_{max}	1852 m
Minimum altitude	H_{min}	606 m
Average altitude	H_{moy}	1229 m
the altitude that corresponds to 5% of the watershed's area	$H_{5\%}$	1550 m
the altitude that corresponds to 50% of the watershed's area	$H_{50\%}$	1060 m
the altitude that corresponds to 95% of the watershed's area	$H_{95\%}$	800 m
Circularity ratio	K_c	01.46
Mean slope	I_r	11.98 %
Index of Roche's Slope	I_s	31.62 %
Main wadi's length	L_m	84.90 km
Length of equivalent rectangle	L_{rec}	81.60 km
Width of equivalent rectangle	l_{rec}	18.13 km
Drainage density	D_d	Km^{-1}
Time of concentration	T_c	15.55 H
Runoff velocity	V_r	01.52 m/s

2. Methodology

2.1. The study area

The K'sob wadi watershed, a crucial sub-basin of the extensive Hodna basin, is strategically positioned in the northern sector of the basin. It is geographically bounded to the north and northwest by the Biban mountain range, providing a natural elevation that influences its climatic and hydrological patterns. To the south and southwest, it is bordered by the Hodna Mountains, which contribute to its distinctive topography and ecological diversity. The eastern limits are defined by the expansive high plains of Setif, which play a crucial role in the watershed's drainage and sediment transport dynamics (Hasbaia et al. 2017).

The watershed is located between longitudes 4°30′ and 5°17′ East, and latitudes 35°45′ and 36°9′ North. It covers a total drainage area of approximately 1,458 km^2, with a perimeter of about 200 km, culminating at the K'sob dam situated at the basin's outlet. This dam serves as a critical infrastructure for water resource management within the region, influencing both the hydrological behavior and sedimentation patterns of the watershed (Figure 1).

2.2. Data processing and analysis techniques

Primary data acquisition through satellite imagery has been integrated into the Arc GIS 10.4 software; Table 2. The realization of the ground loss factor maps and synthesis map followed the following steps:

- Extraction of the SRTM raster layer of the search area;
- The "topo to raster" tool to generate the Digital Elevation Model (DEM);
- Using the DEM to determine the slope inclination and direction.

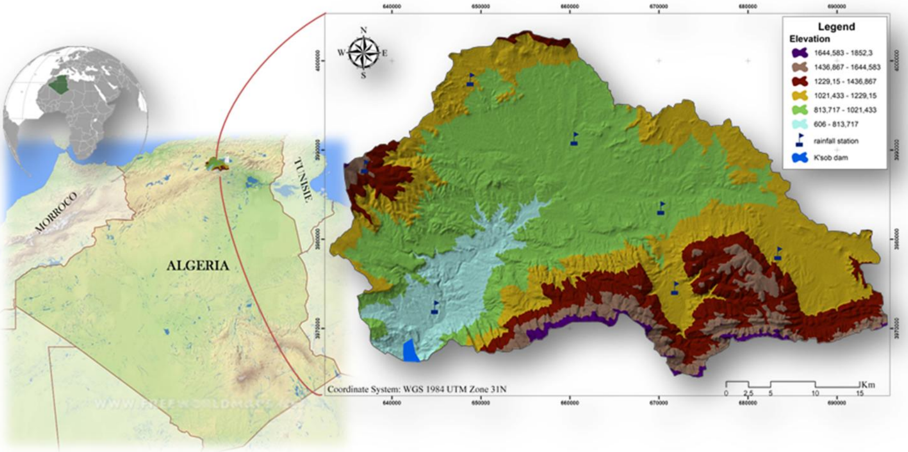

Figure 1. K'sob watershed situation.

Table 2. Database used for the study: source and types.

Dataset	Content	Resolution	Source of the data
Rainfall data	rainfall in mm	Monthly / Annual average rainfall in mm	National Agency for Hydraulic Resources (ANRH)
Soil properties	"Topsoil" organic carbon, "subsoil" clay fraction, sand fraction, and silt fraction	1 km	Harmonized world soil database (HWSD)
DEM data	ASTER GDEM	30 m of spatial resolution	United States Geological Survey "earthexplorer"
NDVI	Vegetation Indices product	30 m of spatial resolution	Landsat 8 (https://search.earthdata.nasa.gov)

- Pre-processing of the satellite image: color composition, choice of training sites, classification, verification of separability, and Kappa index; Post-classification: application of a median filter, smoothing of classes, homogenization, and vectorization;
- Soil analysis and a soil map allowed the calculation of the soil erodibility factor and the elaboration of the K-factor map;
- The potential soil loss map was generated by cross-referencing the maps of the main factors involved in soil water erosion at any point in the research area.
- Estimation of an average annual abrasion rate over the basin was based on the bathymetric surveys of the K'sob dam available and provided by "ANBT M'sila".

2.3. Soil loss equation

There are many models to estimate water erosion at different spatio-temporal scales. The USLE model (Wischmeier and Smith 1965) with its revised version, the RUSLE (Renard et al. 1997), is widely used throughout the world (Balasubramani et al. 2015; Wijesundara et al. 2018; Bagwan and Gavali 2020; Behera et al. 2020; Eniyew et al. 2021; Moisa et al. 2021). Several studies have been carried out to determine its parameters in Algeria (Benselama et al. 2018; Toubal et al. 2018).

For the purpose of quantifying soil losses in the K'sob watershed (Figure 1), the Revised Universal Soil Loss Equation (RUSLE) is used. The five factors that affect water erosion, climate aggression, soil erodibility, slope inclination and length, land use, and anti-erosion practices; are multiplicative in nature. The equation reads as follows:

$$A_{RUSLE} = R_{RUSLE} \times K_{RUSLE} \times LS_{RUSLE} \times C_{RUSLE} \times P_{RUSLE} \tag{1}$$

where A_{RUSLE} is the annual rate of soil loss in t/ha/year, R_{RUSLE} is the rainfall erosivity factor expressed in (MJ.mm/ha.h.year). The erodibility K_{RUSLE} of soils depends on the granularity, amount of organic matter, permeability and structure of the soil and is expressed in tons per hectare per hour t. ha. h/ha.MJ.mm., LS_{RUSLE} is a non-dimensional factor that represents the slope inclination (S in %) and slope length (L in m). Finally, C_{RUSLE} and P_{RUSLE} are non-dimensionalfactors which represent respectively the effect of the vegetation cover and a ratio which takes into account anti-erosion cultivation techniques such as contour ploughing.

The use of ArcGIS software has made it possible to calculate and quantify the importance of each factor in the process of water erosion (Eniyew et al. 2021). A spatialization of these different factors was carried out and made it possible to obtain the factorial maps of water erosion for the study site. The combination of all these factors resulted in the synthesis map on land loss.

2.4. Parameters of RUSLE model

2.4.1. Rainfall erosivity factor

The R_{RUSLE} factor is crucial for determining how erosion will react to the climate (Kulimushi et al. 2021). This index, according to Wischmeier and Smith (1978), is the result of an interaction between the soil surface and the kinetic energy of raindrops.

The original method for calculating the values of this index for a rainfall event requires rainfall records at 30 min time steps (Wischmeier and Smith 1978). Furthermore, obtaining such information remains difficult in many parts of the world, in addition to time-consuming and laborious data processing.

The lack of pluviograph data series has led some authors to find relationships between rainfall erosivity (R) and annual precipitation (Mohammed Falah Allawi et al. 2023; Sayl et al. 2022). Several equations have been proposed that can also estimate, with good accuracy, the monthly and annual values of this factor using rainfall data (daily, monthly, and annual average rainfall) (Cormary and Masson 1964; Van der Knijff et al. 2000; Parveen and Kumar 2012; Pal and Chakrabortty 2019; Yu et al. 2021; Halder 2023; Mohammed et al. 2023). Based on these considerations, one finds oneself in the middle of several approaches to evaluate the erosive effect of rainfall for a given region with some precision.

To calculate this factor, we used monthly and annual rainfall data from 12 rain gauge stations using the Arnoldus formula. (Cormary Y & J, 1964) which takes the form:

$$\log R_{RUSLE} = 1,74 \log \sum_{i=1}^{12} \frac{P_m^2}{P_{yr}} + 1,29 \tag{2}$$

Where:
Pm: Monthly precipitation (mm);
P_{yr} : Annual precipitation (mm).

2.4.2. Soil erodibility factor

The soil erodibility factor K characterizes the resistance of a soil to erosion (Vaezi et al. 2017). The absence of detailed pidological data is a constraint for the calculation of the K factor. The soil data in the K'sob watershed (sand, silt, clay, and organic carbon content) was extracted from the digital database of the world soil map (HWSD) prepared by FAO to characterize the soil erodibility (Fao and Isric 2012) Table 3. This approach is widely used by other studies around the world (Benselama et al. 2018; Djoukbala et al. 2018a; Wang et al. 2020; Acharki et al. 2022).

The following formulas suggested by Neitsch et al. (2011) were used in this study to determine the value of the K-factor.

$$K_{USEL} = K_w = f_{Sand} \cdot f_{clay} \cdot f_{org} \cdot f_{silt} \tag{3}$$

$$K_{factor} = f_{Sand} \cdot f_{clay} \cdot f_{org} \cdot f_{silt} \cdot 0.1317 \tag{4}$$

where: “fsand” reduces the K indicator in soils that contain a lot of coarse sand while increases it in soils that have little sand; “fclay” reduces the erodibility of soils with high clay-to-silt ratios; “forg” decreases K values in soils with a lot of organic carbon, whereas “fhisand” lowers K values in soils with a lot of sand.

$$f_{Sand} = \left(0.2 + 0.3 \cdot \exp\left[-0.256 \cdot m_s \cdot \left(1 - \frac{m_{silt}}{100}\right)\right]\right) \tag{5}$$

$$f_{clay} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right) \tag{6}$$

$$f_{orgc} = \left(1 - \frac{0.25 \cdot orgC}{orgC + \exp[3.72 - 2.95 \cdot orgC]}\right) \tag{7}$$

$$f_{hisand} = \left(1 - \frac{0.7 \cdot \left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + \exp\left[-5.51 + 22.9 \cdot \left(1 - \frac{m_s}{100}\right)\right]}\right) \tag{8}$$

Where ms represents the percentage of sand (particles with a diameter of 0.05 to 2.00 mm), msilt represents the percentage of silt (particles with a diameter of 0.002 to 0.05 mm), mc represents the percentage of clay (particles with a diameter of less than 0.002 mm), and orgC represents the percentage of organic carbon in the layer (%).

2.4.3. The LS factor for slope length and steepness

The LS factor is an important component of the RUSLE model because it reflects the influence of topography on soil erosion. The “LS” factor represents the slope length and slope steepness of the land being evaluated (Fan et al. 2021); it is one of several factors that influence soil erosion and is used to calculate the estimated rate of soil loss.

Table 3. K Factor in the K’sob watershed.

Soil sample	ms (sand) Top soil %	msilt (silt) Top soil %	mc (clay) Topsoil)%	orgC oraganic carbon %	Fcsand	Fcl-si	Forgc	Fhisand	Kusle	K
BK	81.6	6.8	11.7	0.44	0.200000	0.7406	0.9906	0.7185	0.1054	**0.01388**
XH	54.8	20.6	24.9	0.53	0.200004	0.7884	0.9856	0.9975	0.1550	**0.02042**
I	58.9	16.2	24.9	0.97	0.200001	0.7563	0.9272	0.9942	0.1394	**0.01836**
YK	63.5	17.9	18.7	0.26	0.200000	0.8069	0.9967	0.9855	0.1585	**0.02088**

The slope length (L) is the horizontal distance over which a given slope gradient (S) is measured. The slope steepness (S) is the vertical drop per unit of horizontal distance, usually expressed as a percentage.

A Digital Elevation Model (DEM) with a 30 m grid is used in a GIS system to calculate the LS factor using the mathematical formula (9) proposed by Wischmeier.

$$LS_{RUSLE} = \left(\frac{L}{22.1}\right)^{m} \times \left(0.065 + 0.045 \times \theta + 0.0065 \times \theta^{2}\right) \tag{9}$$

$$L = flow\ \ accumulation \times resolution \tag{10}$$

With

θ : is the slope (%);

f: is the flow accumulation;

R: is the resolution;

(Wischmeier and Smith 1978) have calculated a range of exponent 'm' values for various slopes depending on the steepness of the slope, with values of 0.5 for slopes greater than 5%, 0.4 for slopes between 3-5%, 0.3 for slopes under 1%, and 0.2 for slopes less than 3%.

2.4.4. Crop management factor

The plant cover protects the soil in two ways: by improving infiltration and the physical and chemical properties of the soil and by maintaining the cohesion of materials (Tiruwa et al. 2021) on the other hand, it breaks up the kinetic energy of raindrops and intercepts part of the precipitation.

The erosion process is closely linked to the mode of land use, which largely contributes to its aggravation or attenuation. The NDVI map is necessary to compute the C factor. The normalized difference vegetation index (NDVI) is a simple graphical indicator that uses the visible and near-infrared bands of the electromagnetic spectrum to assess whether the target being observed contains live green vegetation or not (Li et al. 2021). NDVI values range from −1.0 to +1.0, with higher values indicating more live, green vegetation. The NIR and RED channels are used in the NDVI formula, as shown below:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \tag{11}$$

For Landsat 8

$$NDVI = \frac{(\text{Band}\ \ 5 - \text{Band}\ \ 4)}{(\text{Band}\ \ 5 + \text{Band}\ \ 4)} \tag{12}$$

The land cover map resulting from the processing of the Landsat 8 TM 2021 image made it possible to analyze the state of the ground's vegetation cover.

Regression between two extreme values was used to estimate the values of the factor C in the study area (Wang et al. 2002).

The regression line's equation is as follows:

$$C_{RUSLE} = 0.9167 - NDVI \times 1.1667 \tag{13}$$

2.4.5. Erosion-control practice factor

Erosion control practices are designed to reduce the amount of soil and sediment that is lost due to water erosion. These practices can include the use of vegetation, such as grasses and trees, to slow down water runoff, as well as the installation of physical barriers like terraces and check dams.

Due to the fact that no soil conservation measures have been taken in a sizable portion of the K'sob watershed area, the P-factor was determined to be 1 for the whole catchment surface.

2.5. Siltation measurement in the K'sob dam reservoir

Siltation is the process of sediment accumulation in a body of water. It can be measured by collecting samples of the sediment from the water and analyzing them for particle size, composition, and concentration. Other methods used to measure siltation include measuring turbidity, which is a measure of suspended particles in the water, or using sonar to measure the depth of sediment accumulation.

Sedimentation in dam reservoirs in Algeria frequently poses major problems that reduce the profitability of the structure (Remini 2000). In order to determine the siltation rate of reservoirs, several methods are adopted; some are direct, by measuring the total volume of deposit trapped within the reservoir, others are indirect, by calculating the rate of soil ablation, with which is associated a delivery coefficient that represents the ratio between the rate of sediments torn from the field and those deposited during transport.

Among the most used direct methods in Algeria to determine siltation is bathymetry. Bathymetry is the measurement of the depths of water in oceans, rivers, and dams. It is used to create detailed maps of the seafloor and other bodies of water. Bathymetric surveys are conducted using specialized equipment such as sonar, radar, and laser systems. The data collected from these surveys can be used to create 3D models of the seafloor or dam, which can be used for resource exploration, engineering projects, and scientific research. Bathymetry campaigns are carried out every 4-7 years. They thus make it possible to follow the rate of siltation of the dam, the monitoring of the structures, and the decision about the protective measures to be taken.

The transformation of average annual siltation into specific degradation within a catchment area is given by the following equation:

$$\boldsymbol{S_d} = \frac{\boldsymbol{V_s} \times \boldsymbol{D_d} \times 10^6}{\boldsymbol{y} \times \boldsymbol{A}} \tag{14}$$

Where:

$\boldsymbol{S_d}$ is the specific degradation in (t/ha/year), $\boldsymbol{V_s}$ is the silted volume in (Mm^3), $\boldsymbol{D_d}$ is the s dry-bulk density estimated at 1.6 according to Tadrist et al. (2016), y is the duration of the period in years and A is catchment area (ha).

Incorporating Sediment Delivery Ratio (SDR) into our analysis is crucial for understanding sediment transport dynamics and reservoir siltation in the K'sob watershed. SDR provides a quantifiable measure of the proportion of eroded soil that is actually deposited in the reservoir, rather than being transported further downstream or retained within the riverine system.

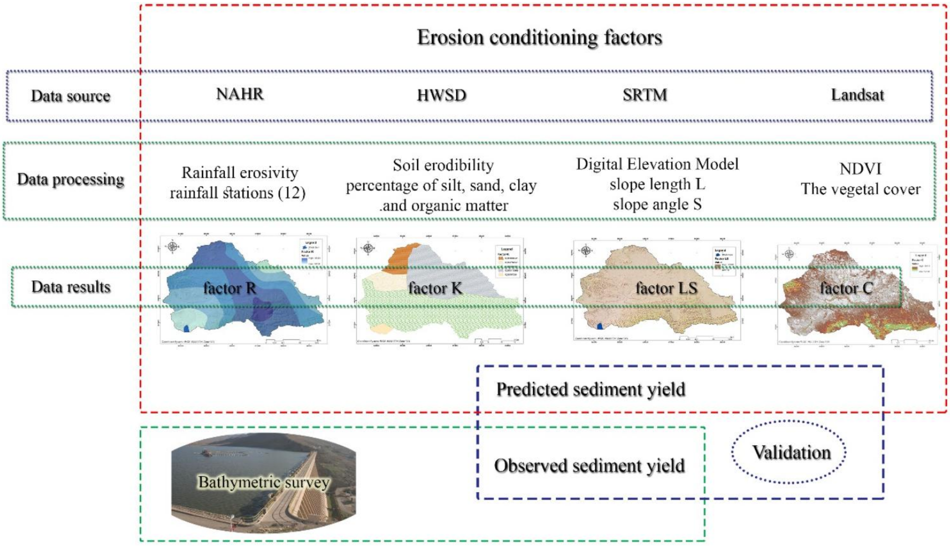

Figure 2. Methodological flowchart for soil erosion modeling.

To calculate SDR, we utilized data from extensive bathymetric surveys conducted over several decades, which provided detailed insights into sediment accumulation patterns within the K'sob dam reservoir. This long-term data set allows for a robust analysis of trends and fluctuations in sediment deposition, enhancing the accuracy of our erosion modeling efforts. Following the methodology outlined in the recent study on SDR applications in erosion studies (Othman et al. 2023), we applied a model that factors in local hydrological and topographical variables to estimate the SDR for the K'sob watershed accurately.

The flowchart of the overall methodology adopted in the present study is shown in Figure 2.

3. Results and discussion

3.1. RUSLE model

3.1.1. R fator

The National Agency for Hydraulic Resources (ANRH) provided the rainfall data used in this study, which covered the years 1980 through 2014 and were collected at twelve rainfall sites inside and surrounding the K'sob watershed.

In each station, the factor R is determined and then spatialized using Krigeage in a GIS environment (Figure 3).

Table 4 indicates that the R-factor ranges from 22 to 67 MJ mm (ha h yr)-1, with an overall average of 41.8 MJ mm (ha h yr)-1 across the entire K'sob watershed. The lower values of the R-factor can be found near the upstream and downstream boundaries of the basin, whereas the highest values are observed at the peaks of the mountain ranges that surround the basin, specifically near the cities of Medjana (North West), Guilassa (East), and in the middle of the watershed.

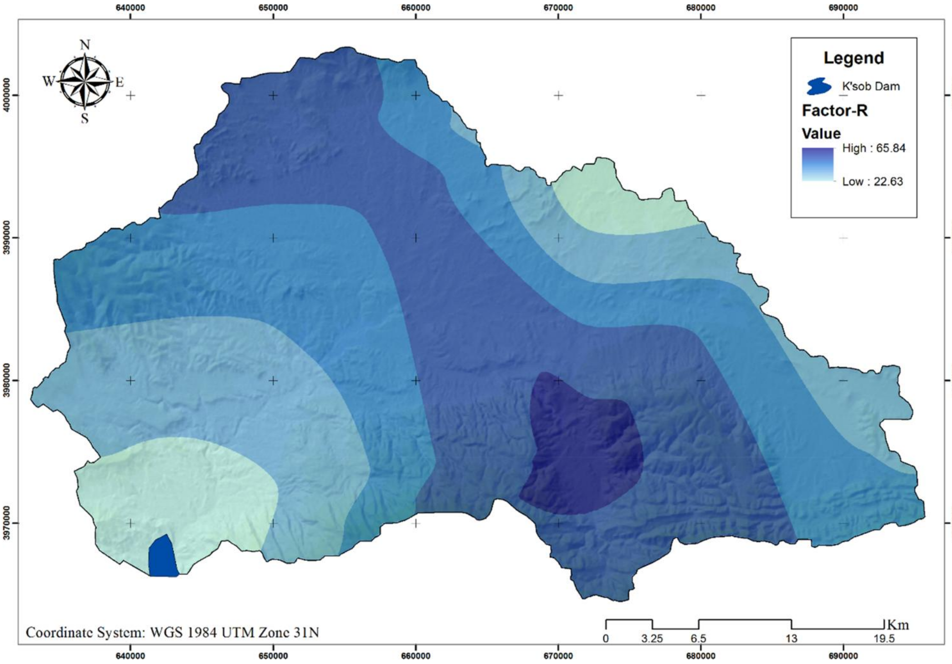

Figure 3. Averaged rainfall erosivity factor.

Table 4. Classification of rainfall erosivity.

ID	R factor	The area in km^2	The area in %
1	22.63-35.53	131.32	9%
2	35.53-45.33	312.87	21%
3	45.33-55.00	463.38	31%
4	55.00-60.00	506.9	34%
5	60.00-65.84	61.80	4%

3.1.2. K factor

The K factor varies by soil type. The soil erodibility factor (K) for the K'sob Basin is shown in Figure 4. In order to indicate the degree of erodibility variability, five classes of K-factor were created and ranged from 0.014 to 0.0208.

Over the entire research area, the average value of the erodibility factor K is 0.01766 (t.h.ha./MJ.ha. mm). The areas with very low erodibility K 0.015 (t.h.ha./MJ. ha. mm) cover 12% of the total area. The zone with average erodibility of 0.018 to 0.020 (t/h/ha/MJ-1 ha-1 mm-1) is represented by Calcic Xerosols and Chromic Luvisols, this class is the most representative of the area and occupies an area of 1273.19 hectares, or 86% of the total area (Table 5).

In general, soils with faster water infiltration, higher levels of organic matter, and better structural qualities demonstrate greater resistance to erosion.

3.1.3. LS factor

The topographic factor (LS) was calculated by overlaying maps of slope lengths and slope gradients from GIS processing of the DEM of the study area (Figure 5).

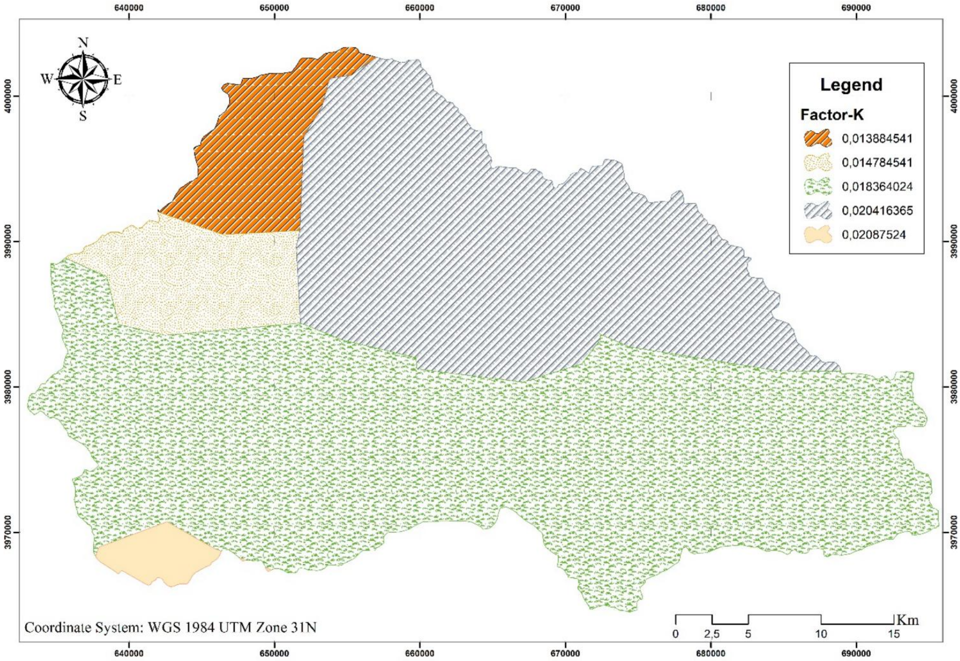

Figure 4. Map of soil erodibility.

Table 5. K classes distribution in the K'sob watershed.

ID	*K factor*	*The area in km^2*	*The area in %*
1	0.013885	86.7768	6%
2	0.014785	94.2705	6%
3	0.018364	808.325	55%
4	0.020416	464.879	31%
5	0.020875	22.9107	2%

In the K'sob Basin, the LS factor varies from 0 to 48. The southern and northeastern basin limits, which correspond to the mountainous bulk of marly limestones and marl-limestone formations, are where the highest values are primarily concentrated. Within the basin, two other regions with greater LS factor values have been identified: one near K'Sour in the west and another near Medjana in the basin's extreme north. Large plains make up the majority of the basin's remaining terrain.

3.1.4. C Factor

The soil cover factor C map varies widely, from 0.19 to 0.91, ranging from bare soil to soil with dense vegetation cover (Figure 6). An area of 418 km^2 corresponding to 28.7% of the total area of the research area, is covered by vegetation cover values between 0.65 and 0.91, These areas have a very dense vegetation cover and are less vulnerable to water erosion. However, the class with a vegetation cover value between 0.1 and 0.65, which covers an area of 561 km^2 or 38.59% of the total area of the zone,

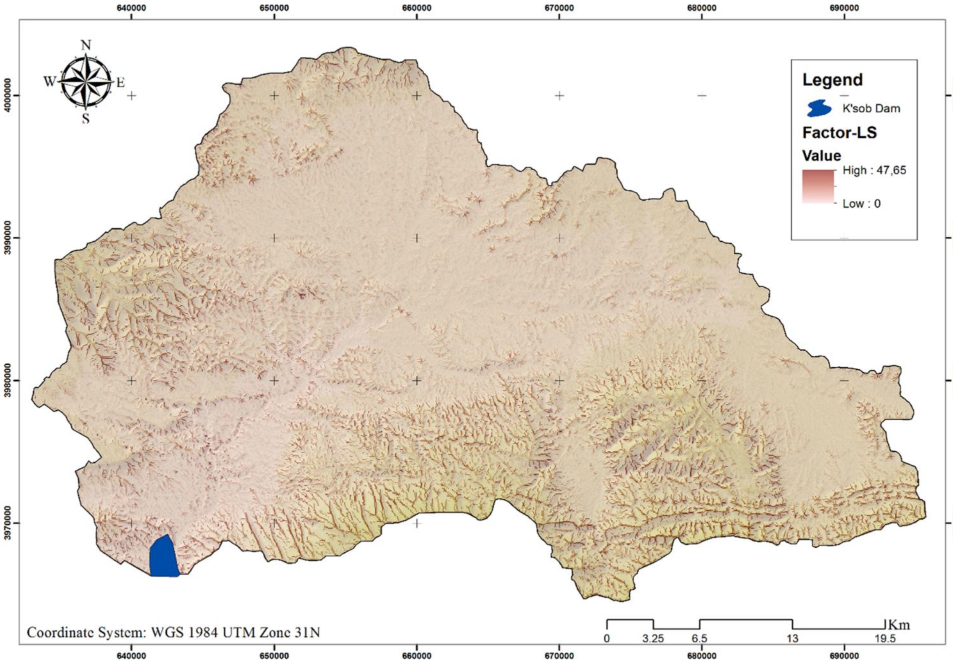

Figure 5. Topographic factor LS map of K’sob watershed.

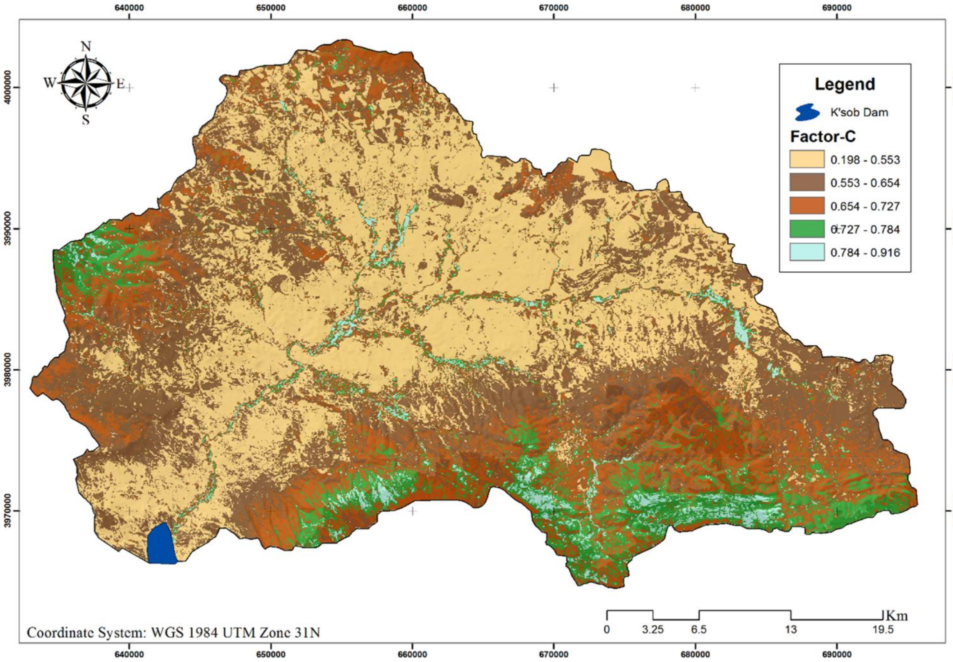

Figure 6. Crop management factor C map of K’sob watershed.

has a very low vegetation cover and is more exposed to erosion. The research area is predominantly covered by moderately dense vegetation.

3.1.5. Soil erosion

The mapping of the specific soil loss throughout the whole surface of the basin is now possible because of the superposition of the four factor maps (Figure 7). The statistics show that the K'sob watershed loses 114,614 (t) annually, with an average soil loss of 783 (t/km^2/year).

According to the erosion map that was generated, the particular soil loss in the K'sob watershed ranges from 0 to 224 (t/ha/year). A first class, which comprises areas with a low potential for erosion of less than 4 (t/ha/year), accounts for 52% of the basin under study and primarily consists of its borders and a small portion near its outlet. The second class, which makes up 20% of the K'sob area and is primarily concerned with the plain in the middle and north of the watershed, includes areas with a moderate potential for erosion of between 4 and 8 (t/ha/year); the third class, which makes up 16% of the K'sob region, has a high potential for erosion of 8 to 16 (t/ha/year). With a significant potential erosion rate of more than 16 (t/ha/year), the fourth class makes up 12% of the K'sob surface. They are situated close to Bordj Ghdir and Ghilassa in the southeast of the basin, as well as Medjana in the north-west of the basin in the mountainous regions (Figure 8).

3.2. Bathymetry survey

In our study area, the method for assessing solid transport at the outlet of the reservoirs was developed from regular measurements of the bathymetry of the K'sob Dam.

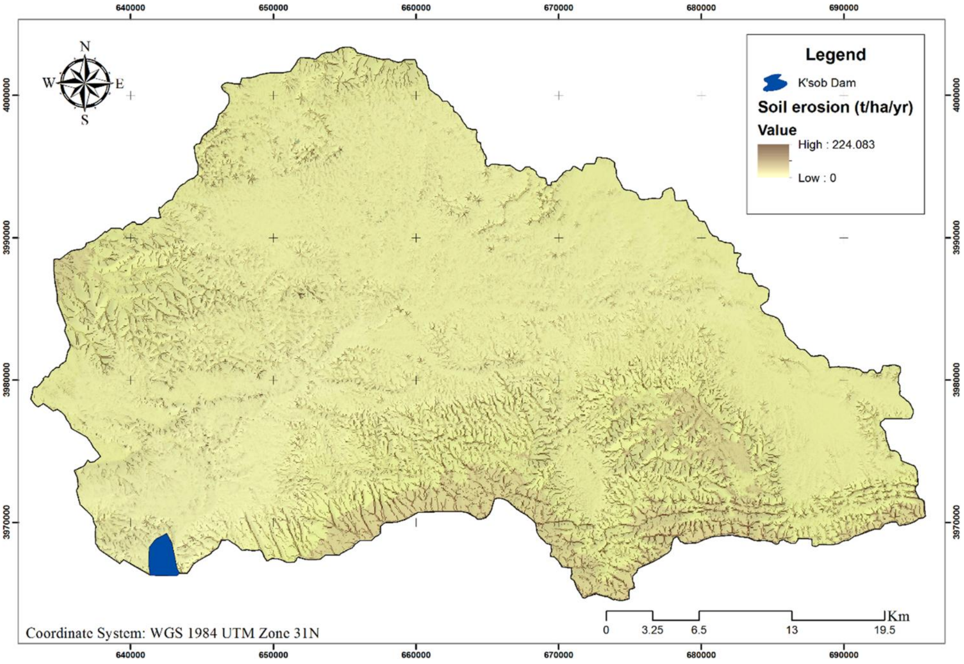

Figure 7. The soil loss in K'sob watershed.

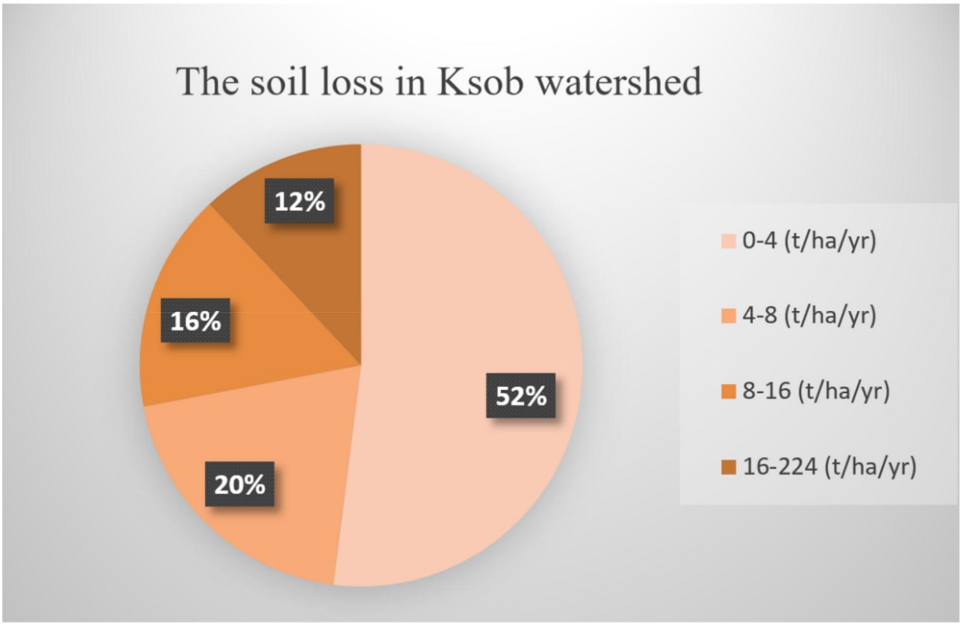

Figure 8. The K'sob watershed's soil loss's distribution.

The bathymetry of the dam is determined by punctual soundings of the bottom of the dam, following transversals between the two banks of the dam.

Knowing that 1 m3 of mud with an apparent density of Ad = 1.6 and a real density of Rd = 2.5, contains 1.2 tons of dry solid matter, this gradual sedimentation of the reservoir leads to an increasing reduction in the water storage capacity of the dam.

Campaigns for measuring or quantifying sedimentation were carried out continuously at the beginning and then spaced out thereafter. The equipment used is the ultrasonic echosounder, whose principle is to identify the topography of the bottom of the basin along transverse profiles. The results of the various campaigns for measuring show that:

- The total volume of siltation (period 1986-2008) amounts to (14.5 million m^3), which is 44.1% of the total capacity of the dam.
- The siltation rate of the reservoir is 2% per year, which gives the structure a life expectancy of 50 years.

The average annual siltation for the period 1986-2000 is evaluated at 0.77 Hm^3, and for the period 2000-2008 at 0.47 Hm^3; it varies according to the study periods (short or long). There are four periods (Figure 9):

- From 1986 to 1993, after raising the dam by 15 m, periodic siltation reached 3.8% of the volume of sediment throughout the study period. During this period, the bottom emptying operation is carried out regularly.
- From 1993 to 2000, the siltation reached its maximum at 70.4%, and all the volume of the solid contribution from this period accumulated in the reservoir of the dam.

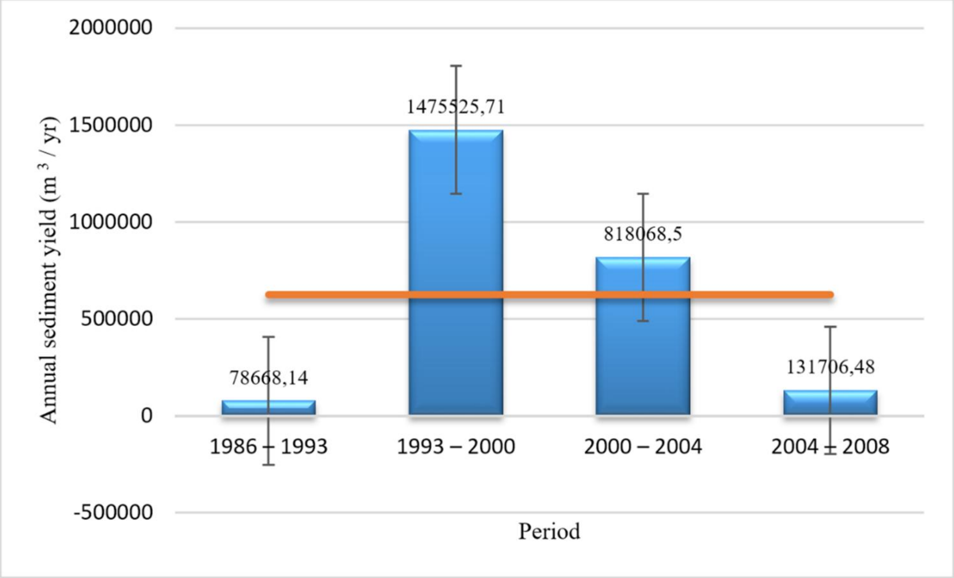

Figure 9. Histogram of annual sediment production.

- From 2000 to 2004, the annual siltation dropped to 0.206 Hm^3, same as the previous period.
- From 2004 to 2008, siltation increased, reaching 0.33 Hm^3 annually.

Our calculations revealed that the Sediment Delivery Ratio for the K'sob watershed is significantly higher than the regional average, indicating a high level of efficiency in sediment transport to the reservoir. Specifically, the SDR was calculated to be 7.3 (t/ha/year), which suggests that a substantial proportion of eroded material from the watershed is captured by the K'sob dam. This high SDR is consistent with the findings from bathymetric surveys, which show notable sediment accumulation within the dam reservoir.

The implications of these findings are critical for future erosion management and reservoir maintenance strategies in the watershed. A high SDR indicates that current land management practices may need to be revised to reduce sediment load and enhance water quality and storage capacity in the dam.

4. Validation

Sediment yield data from sediment volume estimates as a consequence of bathymetric measurements of the K'sob reservoir are used to validate the RUSLE model. For the K'sob reservoir, bathymetric studies were conducted between 1986 and 1993, 1993 and 2000, 2000 to 2004, and 2004 to 2008 (Table 6). Using an experimental mean bulk density (1.6 t/m3) that was derived from the reservoir's sediments, the sediment volumes were converted to mass volumes. The K'sob watershed's calculated mean annual sediment yield (6.86 t/ha/year) and the RUSLE model's predicted yearly soil loss were compared (7.83 t/ha/year).

Table 6. The silt capacity of the dam during the observed period (1986–2008).

Period	Duration (year)	Dam's siltation In (m^3)	Dam's siltation In (%)	Annual sediment yield (m^3/ year)	Annual sediment yield (t/ year)	Annual sediment yield (t /km/ year)
1986 – 1993	7	550677	3.8	78668.14	125869.024	86.33
1993 – 2000	7	10328680	70.4	1475525.71	2360841.136	1619.23
2000 – 2004	4	3272274	22.3	818068.50	1308909.600	897.74
2004 – 2008	4	526825.9	3.6	131706.48	210730.368	144.53
			Mean	**625992.2075**	**1001587.53**	**686.96**

The current results are also compatible with other works on the assessment of water erosion carried out at the level of watersheds in Algeria with similar climatic and environmental characteristics, according to Djoukbala et al. (2018b) the watershed of Oued El ham records an average annual loss of 5,3 (t/ha/year); in the North-West of Algeria, the average sediment production measured in the Wadi El Maleh watershed was around 4 (t/ha/year) (Benselama et al., 2019). And in the whole hodna basin there is an average loss of 4,3 (t/ha/year) (Djoukbala et al. 2022).

To enhance the credibility and precision of our findings, we incorporated a series of statistical analyses. These analyses not only assess the accuracy of our results but also address potential uncertainties inherent in environmental modeling. Inspired by recent advancements in our field (Bashir et al. 2021; Al-Attar et al. 2022), we tailored our approach to fit the specific challenges associated with predicting soil erosion.

First, we calculated basic descriptive statistics, including mean, median, mode, standard deviation, and variance for our soil loss estimates across different subregions of the K'sob watershed. These measures provide a summary of the central tendency and dispersion of our data, helping to identify patterns or anomalies in soil erosion rates.

Our statistical analyses revealed that the average soil erosion rate within the K'sob watershed is significantly higher than previously reported, with a mean value of 6.8 t/ha/year. The regression analysis indicated a strong positive correlation between soil erosion rates and factors such as slope steepness and poor vegetation cover ($R^2 = 0.78$, $p < 0.05$).

The uncertainty analysis further supported these findings, showing that the most critical variable affecting the prediction accuracy was the rainfall erosivity factor, which varied significantly across different years. Results obtained by Wang et al. (2020) indicate that increased rainfall and temperature may increase the risk of soil erosion, highlighting the sensitivity of watersheds to climate change.

The higher rates of soil erosion and sediment transport in the watershed are responsible for the higher sediment productivity values in our study (Boukhrissa et al. 2013; Hasbaia, Paquier, et al. 2017). Several reasons contribute to this: (1) the high intensity of erosive agents (impacts of raindrops, surface runoffs, concentrated flows), which are associated with soil erosive factors such as steepness of slopes, sparse vegetation cover, and a higher soil erodibility factor. (ii) Small catchment sizes, which reduce the possibility of sediment being deposited before it reaches the network of streams.

Our study's application of the RUSLE model integrated with GIS and remote sensing data provides an advanced approach to estimating soil erosion within the K'sob watershed, an area prone to significant erosion and siltation issues. This methodological integration offers a more precise and dynamic assessment compared to traditional methods, which typically rely on less frequent or static data inputs. Our findings indicate an average annual soil erosion rate significantly higher than previously reported in the region by Hasbaia et al. (2017), likely due to our incorporation of real-time land use changes and more detailed topographical data.

Comparatively, (Vaezi et al. 2017) reported lower erosion rates in a similar semi-arid watershed, which can be attributed to differences in vegetation cover and soil management practices, highlighting the critical role of localized conditions in erosion dynamics. These comparisons underscore the importance of context-specific models and the necessity of updated data in soil erosion assessments.

The relevance of our work extends beyond academic contributions, offering substantial benefits for regional planning and conservation efforts. By providing more accurate predictions of erosion and siltation, our study supports more effective reservoir management strategies, aiding in the prolongation of dam lifespans and ensuring more sustainable water resource management. Furthermore, our methodology can be adapted for similar semi-arid regions worldwide, where water scarcity and soil conservation are of paramount concern.

Given the variability in erosion processes observed across different studies, further research should focus on integrating newer remote sensing technologies and exploring the impact of climate change on erosion rates. Such studies could enhance the predictive accuracy of models like RUSLE and refine conservation strategies in response to evolving environmental conditions.

5. Conclusion

The methodology employed in this study utilized advanced mapping and remote sensing techniques to evaluate soil erosion and its consequent impact on dam silting within the semi-arid K'sob watershed. By integrating the Revised Universal Soil Loss Equation (RUSLE) with contemporary geospatial technologies, we provided a nuanced quantitative and qualitative assessment of soil erosion, which markedly surpasses the precision of traditional field surveys and sediment sampling methods previously dominant in the region.

Our findings reveal that the soil loss rate in the K'sob watershed is approximately 7.83 t/ha/year, significantly exceeding the permissible limit of 3 t/ha/year. This elevated rate underscores the critical need for enhanced soil conservation strategies in the watershed. Moreover, bathymetric studies conducted by the Algerian Agency for Dams from 1986 to 2008 have allowed us to estimate that approximately one million tons of sediment have accumulated in the K'sob dam, equating to a specific soil loss rate of 6.86 t/ha/year. The precision of our erosion estimates, with a mean relative error of about 13.4%, demonstrates the robustness and high quality of our analytical approach.

This study not only confirms the utility of the RUSLE model within the Algerian context, which has been widely adopted since the 1960s but also highlights its ongoing relevance and effectiveness in generating data critical for operational prediction models. Our research contributes significantly to the existing body of knowledge by offering a refined methodology that enhances the accuracy of soil loss identification and localization.

Moreover, the accumulated efforts over more than five decades in the region have culminated in the ability to formulate a comprehensive, integrated watershed management strategy. Such a strategy is pivotal for reducing soil erosion risks, mitigating dam siltation, enhancing soil fertility, boosting land productivity, and restoring and protecting land-related ecosystems in the K'sob watershed and similar settings.

In conclusion, our study demonstrates that sophisticated modeling techniques can assess the vulnerability of agricultural landscapes more efficiently and cost-effectively than traditional methods. This enables the formulation of targeted, effective solutions for conserving water and soil resources, thus supporting sustainable agricultural practices and environmental conservation in semi-arid regions.

Acknowledgements

The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through Large Groups Project under grant number RGP 2/442/44.

Authors' contributions

Conceptualization, O.D and S.D. ; methodology, O.D. S.D. H.G.A. and M.H. writing—original draft preparation, O.D. S.D. H.G.A. O.B. S.A. J.M. and M.H.; writing—review and editing, M.T.R.I. M.T.R. A.R. A.A.B. J.M. H.G.A. All authors have read and agreed to the published version of the manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through Large Groups Project under grant number RGP 2/442/44.

ORCID

Omar Djoukbala http://orcid.org/0000-0002-2595-8384

Availability of data

The data that support the findings of this study are available on request from the corresponding author.

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