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Geo-environmental analysis of erosion factors in the Soummam watershed, North-East Algeria

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Abstract

Soil erosion remains insufficiently understood in terms of its spatial variability and the combined influence of environmental drivers, leaving a critical methodological gap for effective conservation planning. This study addresses this gap by integrating Geographic Information Systems, Remote Sensing, Canonical Correlation Analysis, and the Soil Water Assessment Tool to predict erosion patterns and assess key controlling factors within a large river basin. Multiple data sources, including rainfall, climate, hydrometric, land use, soil, digital elevation, and satellite records, were analyzed. The modeling process revealed considerable annual soil loss across the basin and highlighted limited zones with particularly severe erosion. Canonical Correlation Analysis showed that vegetation cover and topography were the most influential factors, with terrain effects associated with increased soil loss and vegetation cover associated with reduced soil loss. Additional modeling in a sub-basin indicated erosion consistent with documented reductions in reservoir capacity. The findings demonstrate that erosion is both significant and spatially heterogeneous, providing a basis for developing targeted soil conservation strategies. The implications of this study include improved predictive understanding of erosion risk and enhanced decision support for land and water managers seeking to mitigate environmental degradation.

Keywords: Canonical Correlation Analysis; erosion modeling; remote sensing; soil conservation; watershed management.

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1. INTRODUCTION

Algeria is one of the most erodible regions in the world (Probst & Suchet 1992) with an average annual volume of sediments ranging from 1 to 2 million m3 extracted from Mediterranean basins (Demmak 1982). Other sediment-producing regions have exceeded the critical threshold (Gomer 1994).

The Soummam Watershed in North-East Algeria features a complicated geological structure that greatly affects soil erosion processes in the area. The area's lithological composition is varied, comprising sedimentary, metamorphic, and igneous rocks, which create a heterogeneous substrate that influences soil stability (Mokhtari et al., 2024). Clay-rich materials in specific formations are linked to increased erosion rates, especially after heavy rains, due to their poorer cohesiveness and greater susceptibility to dislodgment (Khanchoul et al., 2022). The geological properties are not uniform across the watershed; instead, they display spatial heterogeneity that is essential for comprehending the localized effects of erosion.

Structural formations within the watershed, such as folds and faults, have been recognized as significant contributors to the erosion dynamics. Tectonic activity-induced fractures establish conduits for water penetration, hence augmenting sediment mobility and elevating erosion potential (EL Abıdıne Boukhrıssa et al., 2022). Furthermore, the arrangement of these geological formations might result in localized augmentations of runoff, hence expediting soil displacement. Research has emphasized the necessity of incorporating tectonic heritage into erosion models, as it identifies areas with differing susceptibility to erosion based on the varying physical qualities of rocks and soil (Kallel et al., 2017).

In addition to geological factors, land use practices in the Soummam Watershed are crucial in influencing soil erosion dynamics. Agricultural practices, primarily rain-fed farming, have caused substantial changes in land cover, therefore impacting soil retention abilities. Deforestation and overgrazing are notably widespread in the region, resulting in the deterioration of vegetative cover that safeguards soil against erosive processes. The lack of protective vegetation can result in heightened surface runoff, which has been demonstrated to intensify soil erosion during periods of high rainfall. Moreover, conventional farming practices, which often prioritize immediate output over long-term sustainability, lead to soil compaction and erosion (Brahim et al., 2024).

Climatic factors are also crucial in intensifying erosion rates in the Soummam Watershed. The region exhibits a Mediterranean climate marked by arid, sweltering summers and temperate, rainy winters. This climatic fluctuation has significant implications for soil moisture levels and plant growth. Intense rainfall events, typically marked by brief, heavy downpours, result in elevated surface runoff rates (Salah et al., 2025; Henson et al., 2024). This weather pattern correlates with heightened instances of soil erosion, since the soil does not have sufficient time to absorb moisture, resulting in surface saturation and subsequent erosion during intense rainfall episodes. The correlation between climatic variability and erosion processes underscores the necessity for integrated management strategies that account for both geological and climatic elements to effectively control erosion hazards.

The geo-environmental elements influencing erosion in the Soummam Watershed are intrinsically connected to its geological attributes, land utilization methods, and climatic circumstances. This complex interaction requires a thorough comprehension of the spatial and temporal dynamics of erosion processes, guiding sustainable land management techniques in the area. Research utilizing Geographic Information System (GIS) technologies and erosion modeling methods, including the Revised Universal Soil Loss Equation (RUSLE), is essential for clarifying the intricacies of soil erosion and offering practical recommendations for erosion control and prevention strategies specific to the Soummam Watershed (Kallel et al., 2017). Land use practices are critical factors influencing erosion rates in the Soummam Watershed, where various human activities such as agricultural expansion, deforestation, and urbanization have caused significant alterations in land cover. These modifications compromise the soil structure, diminishing its stability and hence increasing vulnerability to erosion (Salem et al., 2023). In agricultural settings, the extension of croplands frequently necessitates the removal of natural vegetation, which is essential for preserving soil integrity via root systems that anchor soil particles. The resultant loss of plant cover exposes the soil surface and reduces its ability to absorb rainfall, hence increasing surface runoff and susceptibility to erosion.

Deforestation intensifies erosion hazards, especially in the sloped terrains characteristic of the Soummam Watershed, where the loss of tree cover results in increased soil degradation. Kallel et al. (2017) underscore the essential function of vegetation in soil stabilization and the regulation of hydrological cycles vital for soil health. Intense rainfall episodes, characteristic of the region's climate, combined with dry spells, result in conditions that render soil susceptible to saturation-induced erosion and subsequent fast desiccation, causing structural vulnerabilities that promote erosion processes.

The interaction between land use practices and climatic conditions has become a central theme in contemporary research, demonstrating a direct relationship between heightened runoff and substantial deterioration of vegetative cover (Mokhtari et al., 2024). Historical data demonstrate that periods of heavy rainfall substantially increase erosion rates, especially after human-induced alterations to land cover. The interplay between climate variability and modified land use practices highlights the necessity for comprehensive strategies to evaluate and manage erosion efficiently within the watershed.

Recent research, including that by Al-Falal et al. (2025), supports the adoption of efficient land management practices that correspond with the geo-environmental setting of the Soummam Watershed. These techniques, designed to reduce erosion risks, are essential for promoting environmental sustainability, given the delicate ecological balance that supports the region's agricultural output and biodiversity. The intricate elements contributing to erosion require a comprehensive understanding and focused solutions that include the various interconnected impacts in the region.

Furthermore, novel approaches like multivariate analysis and machine learning are recognized as advanced techniques to analyze and comprehend these relationships in greater detail (Salem et al., 2023). These sophisticated tools can reveal intricate linkages among geological features, land use patterns, and climatic factors, highlighting avenues for improved erosion management solutions. As study progresses in this field, it is evident that mitigating erosion in the Soummam Watershed requires a synthesis of scientific investigation, sustainable methodologies, and adaptive management to guarantee ecological resilience and sustainable land utilization.

1.1. Purpose of study

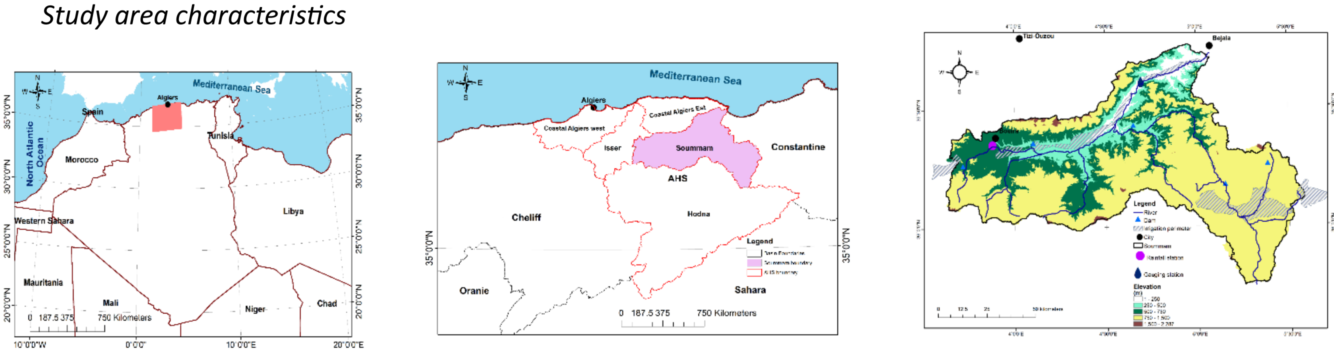
The purpose of this study is to characterize the spatial variability of soil erosion and identify its primary environmental controls using an integrated GIS–remote sensing–modeling framework. By resolving current methodological limitations, the study seeks to support more informed conservation planning and decision-making in large river basins.

2. METHOD AND MATERIALS

The Soummam Basin, situated in the northeast of Algeria, experiences both continental and Mediterranean climates. Its rainfall is torrential and irregular, both in space and in time, with cloudbursts being particularly frequent in autumn when the vegetation cover is absent. The present study aims to estimate and map soil loss using the SWAT model, which has been indicated as one of the most useful models in recent years (Borrelli et al. 2021). The application of this model in the prediction of water erosion using GIS and remote sensing consists of the elaboration of the thematic map. The combination of these thematic layers will help to identify the areas at risk of water erosion in order of importance, the impact of each factor on soil losses, and the estimation of sediment transport, especially in dam basins. The Soummam basin is part of the watersheds of the large hydrographic basin of Algérois Hodhna Soummam, located in the central part of northern Algeria

Figure 1

Study area characteristics



It is bordered to the north by the Coastal Algiers basin (Figure 1), to the east by the Constantinois basin, to the west by the Isser basin, and to the south by the Hodhna basin, with a total area of 9,125 km². The relief of the Soummam basin has a rather irregular shape, and the orography is very pronounced. To the north, the basin is bordered by the Djurdjura mountain range, where the highest peak (Lalla Khedidja) reaches an altitude of 2,308 m. Climatic conditions in the Soummam watershed are not homogeneous. The climate in the lower Soummam valley is Mediterranean, humid, with slight temperature variations. In contrast, on the plateaus of Sétif and Bouira, it is continental, with wet winters and hot, dry summers.

3. RESULTS

After applying the SWAT model to the study basin, the results illustrated in Figure 2 show that the risk of erosion differs between areas. According to the classification adopted in the United States and applied in different African countries (Siddik et al. 2017): values between 0 and 7.41 t/ha/year are attributed to low erosion risk, between 7.41 and 12 t/ha/year are classified as moderate erosion risk, between 12 and 19.77 t/ha/year are classified as high erosion risk, while values exceeding 19.77 t/ha/year are considered very high erosion risk. The results of the model calibration and validation based on the liquid flow measurements at the Latraille station (Figure 2) are satisfactory. The average annual erosion is 2.4 t/yr/yr, and 93 % of the total basin areas fall within the low risk of erosion. The specific erosion simulated in the Ain Zada dam basin, located in the south of the study area, is estimated at 2.9 t/ha/year. The results of the variation between simulated and observed flows presented in Figure 3 show that the model's statistical performance parameters are acceptable.

Figure 2

Soil erosion map with the SWAT model

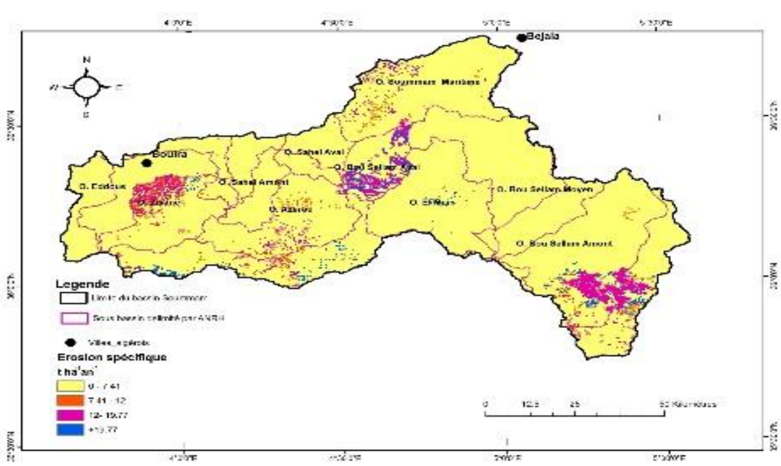
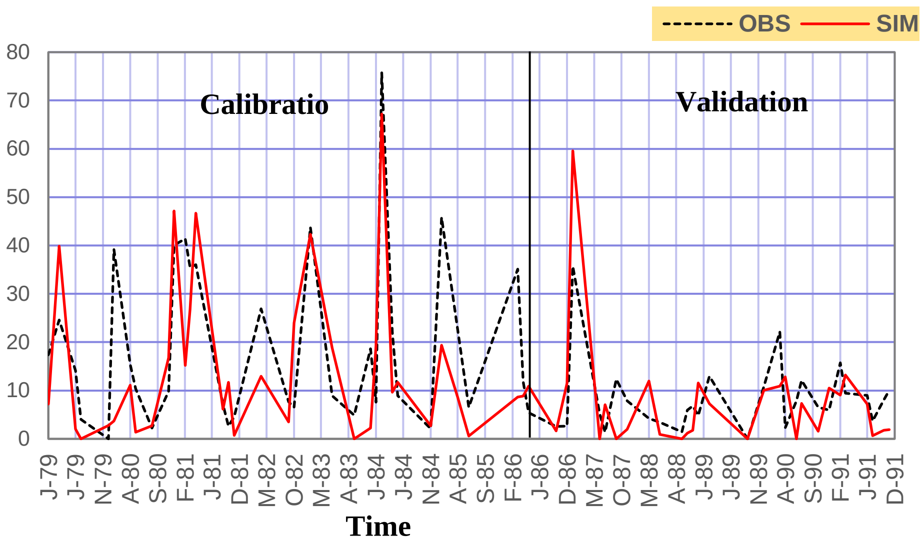


Figure 3

Comparison of measured and calculated annual sediment volumes



The factors influencing specific erosion are diverse, such as plant cover, topography, cultivation practices, and rainfall intensity. In order to evaluate the impact of each, Canonical Analysis has been applied to 2 groups of variables. The first group consists of 2 variables: the first is specific erosion established by the SWAT model, and the second is specific erosion established by the revised universal soil loss method (RUSLE). The second group consists of 4 variables: the cultivation practices factor P, the slope factor, the rainfall factor, and the Normalized Digital Vegetation Index (NDVI) for the month of March. The results of the application of Canonical Analysis are in Table 2.

Table 2

Correlation coefficients between soil loss factors (V, W) and canonical factors.

N°	Variables	V1	V2	W1	W2
1	NDVI	-0.131	-0.977		
2	P factor	0.789	0.043		
3	Slope	0.847	0.054		
4	Rainfall	-0.426	-0.310		
5	Erosion RUSLE			0.953	-0.302
6	Erosion SWAT			0.419	0.908

Canonical correlation analysis was employed to investigate the associations between simulated soil loss derived from the RUSLE method and the SWAT model and the set of predictors that influence soil loss, namely the normalized difference vegetation index, the P factor, slope, and rainfall. The canonical vectors V1 and V2 were generated from the group of dependent variables that represent the four erosion conditioning factors, and the canonical vectors W1 and W2 were computed from the independent variables consisting of soil loss estimated by the RUSLE and SWAT models. The findings reported in Table 2 indicate that both the P factor and slope display a statistically significant positive correlation with the V1 vector, while the normalized difference vegetation index exhibits a statistically significant negative correlation with the V2 vector. Since V1 is associated with W1 and V2 is associated with W2, the factor that reflects slope characteristics and land management practices shows a positive association with soil loss simulated by the RUSLE method. In contrast, the vegetation cover factor has a negative association with soil loss simulated by the SWAT model.

4. DISCUSSION

Erosion poses a considerable environmental problem to the Soummam Watershed in Algeria, stemming from a confluence of geomorphological elements such as geological structure, land utilization, and climate effects. Comprehending these aspects is essential for executing efficient soil and water conservation measures in the region. The Soummam Watershed features a complicated geological structure with diverse lithological units that dramatically affect erosion processes. The geological composition comprises sedimentary rocks, clays, and sandstone formations that display differing levels of erodibility (Benaiche et al., 2024). The resistance of these materials to erosional forces determines the patterns of soil loss observed across the watershed. Additionally, the pronounced gradients characteristic of the area's topography intensify vulnerability to erosion, especially in areas dominated by softer rock types (Mokhtari et al., 2024).

The land usage in the Soummam Watershed exacerbates the erosion dynamics. Agricultural methods, particularly those that subject soil to environmental exposure, are common in this area. Unsustainable agricultural methods, including overgrazing and monoculture, reduce vegetation cover, resulting in heightened soil erosion rates (Zeghmar et al., 2024). Khanchoul et al. (2022) emphasize that the transformation of forested regions into agricultural land greatly affects erosional susceptibility. Moreover, urban expansion and the corresponding infrastructure development led to soil destabilization, frequently exacerbating runoff and erosion (Bechroune et al., 2024).

Climatic factors significantly impact the erosional processes occurring in the Soummam Watershed. The region exhibits a Mediterranean climate marked by pronounced rainy and dry seasons. Precipitation patterns, especially severe rainfall occurrences during the wet season, displace soil particles and may result in flash flooding, hence intensifying erosion (Basin, 2024; Renggono et al., 2025). Mokhtari et al. (2024) highlight the relationship between intense precipitation and elevated erosion rates, suggesting that extreme weather occurrences are becoming more prevalent due to climate change. These climatic variations require adaptive land management practices to effectively mitigate erosion.

The combined utilization of Geographic Information Systems (GIS) and the Revised Universal Soil Loss Equation (RUSLE) is advantageous for identifying erosion-prone regions in the Soummam Watershed (El Abıdıne Boukhrıssa et al., 2022). These approaches allow for the observation of regional patterns of soil erosion and support targeted intervention tactics. The utilization of machine learning methodologies to improve these models, as demonstrated by Achour et al. (2021) and Prasad et al. (2026), has augmented the precision of erosion forecasts, facilitating more efficient planning of erosion mitigation strategies.

Moreover, research concentrating on particular sub-watersheds within the Soummam basin has underscored the efficacy of multi-criteria decision-making (MCDM) techniques in sustainable land use planning (Benaiche et al., 2024). By examining parameters such as soil properties, vegetation density, and hydrological reactions, planners can prioritize regions for conservation initiatives and execute techniques that improve soil stability.

The impact of groundwater quality on erosion processes is significant. Salem et al. (2023) demonstrate that water quality challenges, possibly intensified by erosion, necessitate comprehensive management strategies that combine both land and water resources. It highlights the relationship between erosional processes and the overarching hydrological systems of the Soummam Watershed.

As research advances, it is crucial to further investigate the interaction between geological formations, land utilization patterns, and climatic fluctuations, particularly in light of the anticipated effects of climate change on these elements (Kallel et al., 2017). Comprehending these relationships is essential for formulating an adaptive framework for land management and erosion control in the Soummam Watershed.

In conclusion, the erosion dynamics of the Soummam Watershed result from intricate geomorphological elements, encompassing geological structure, deforestation, land use alterations, and climatic disturbances. Collaborative research that combines modern modeling approaches with field studies will be crucial in tackling erosion issues, guiding policy frameworks, and fostering sustainable land use practices in the region. Subsequent research should focus on integrating extensive datasets and refined models to clarify these interactions, enabling the formulation of targeted interventions to effectively address soil erosion throughout the watershed (Kallel et al., 2017; Pinthong et al., 2025).

5. CONCLUSION

The application of the SWAT model to the Isser basin yielded an average annual soil loss of approximately 2.4 t/ha/year. 2% of the areas belong to the medium-risk class, scattered in the form of very small patches in the north and south of the basin. Through Canonical Correlation Analysis, it was determined that vegetation cover and topography exerted the most substantial influence on erosion.

Consequently, the study identified spatially heterogeneous erosion throughout the study area. The impact of land topography and cultural practice factors on soil loss was found to be directly proportional, while vegetation cover exhibited an inverse proportional relationship. Modeling specific erosion for the Ain Zada dam sub-basin estimated a rate of around 2.9 T/ha/year, thus accounting for the recorded capacity loss of 17.80% compared to the bathymetric survey conducted in 2019.

The findings of this research provide valuable decision-support tools for soil conservation managers, empowering them to make informed decisions regarding soil conservation measures.

Conflict of Interest: The authors declare no conflict of interest.

Ethical Approval: The study adheres to the ethical guidelines for conducting research.

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