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Spatial-based analysis of water erosion hazard risks in Jordan

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ABSTRACT

Soil erosion is a critical environmental issue in Jordan, particularly due to the country's fragile ecosystems, steep slopes, and varying climatic conditions. It poses significant threats to agricultural productivity, natural resource conservation, and land sustainability. This study aims to provide a detailed spatial assessment of soil erosion risk across Jordan and identify erosion-prone zones to support informed decision-making in land management. The Revised Universal Soil Loss Equation (RUSLE) model, integrated with Geographic Information System (GIS) tools, was employed to estimate soil loss and map erosion severity. The model incorporated essential factors including rainfall erosivity, soil erodibility, slope length and steepness, vegetation cover, and conservation practices. Erosion rates were categorized into three classes: low (0–10 tons ha^{-1} $year^{-1}$), moderate (10–50 tons ha^{-1} $year^{-1}$), and high (>50 tons ha^{-1} $year^{-1}$). Results revealed that 94% of Jordan's land is subject to low erosion risk, 5% to moderate risk, and approximately 1% to high risk. The areas most vulnerable to erosion are located in the northern and central highlands and parts of the Jordan Valley, primarily due to their steep topography and higher precipitation levels. This study demonstrates the effectiveness of integrating RUSLE with GIS to identify critical erosion hotspots and inform targeted soil conservation strategies, contributing to more sustainable land use planning in arid and semi-arid regions like Jordan.

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1. INTRODUCTION

Soil erosion plays a pivotal role in the widespread degradation of land in arid and semi-arid regions, such as Jordan (Alkharabsheh et al., 2023; Olika et al., 2023). Various factors, including traditional agricultural practices, declining precipitation, rising temperatures, and evolving land use, have heightened the susceptibility of soils to erosion (Aideh & Sheta, 2025; Ebabu et al., 2022; Heryani et al., 2023; Li & Fang, 2016; Rahman et al., 2017; Ziadat & Taimeh, 2013). Climatic fluctuations, such as changes in rainfall intensity and frequency (Martel et al., 2021), also influence soil and water resources, thereby affecting rainwater harvesting techniques and leading to soil loss (P. Borrelli et al., 2017; Borrelli et al., 2020). Projections indicate that an increase in the frequency of rainstorms will exacerbate SE and land degradation (Liu et al., 2022). Moreover, soil erosion can result in the contamination of freshwater bodies with agricultural chemicals, thereby depleting the oxygen supply in wetlands, canals, streams, and coral reef ecosystems (Rashmi et al., 2022). Addressing these concerns is essential for comprehending the response of soil erosion, land availability, and crop yields to global changes.

In Jordan, the severe geomorphological and climatic conditions have increased soil susceptibility to wind and water erosion. This environmental problem poses a threat to Jordan's ecosystems, leading to desertification, reduced crop yields, decreased water quality, and increased sedimentation of water reservoirs and aquatic habitats (Ziadat & Taimeh, 2013). Currently, predicting and identifying areas prone to soil erosion using modeling techniques is crucial for mitigation efforts. The Revised Universal Soil Loss Equation (RUSLE) model, a widely used approach, incorporates various factors like rainfall, soil texture, slope, erosion history, and land use types to generate erosion maps (Bonilla-Bedoya et al., 2017; Panagos et al., 2015; Renard et al., 1997). In Jordan, the severe geomorphological and climatic conditions have heightened soil susceptibility to both wind and water erosion,

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exacerbating soil degradation and leading to widespread desertification. This environmental challenge has contributed to reduced agricultural productivity, diminished water quality, and increased sedimentation in water reservoirs and aquatic habitats (Ziadat & Taimeh, 2013). Land degradation in Jordan is driven by factors such as overgrazing, deforestation, improper agricultural practices, urbanization, and climate change, with approximately 10-12% of the land being arable and over 80% classified as degraded to some degree (Makhamreh, 2019). Most of the degraded land is in the semi-arid and arid regions, particularly in the Badia region and the Jordan Valley, where wind and water erosion are major concerns. Key factors contributing to degradation include soil erosion, which reduces soil fertility and crop yields; overgrazing, particularly in the eastern Badia region, leading to loss of vegetation and soil structure; deforestation, which exacerbates soil erosion and reduces natural water retention; climate change, causing more erratic rainfall patterns and drier conditions; and urbanization, which disrupts natural water drainage and contributes to land sealing and compaction. Land use distribution in Jordan shows that around 65% of the land is used for grazing, while 15% is cultivated for crops, with the remaining land being either forested or urbanized. The Badia region, once a crucial pastoral zone, is now increasingly degraded due to unsustainable grazing practices. To deal with these problems, modeling tools like the Revised Universal Soil Loss Equation (RUSLE) are needed to find areas that are likely to erode. These tools look at things like rainfall, soil texture, slope, past erosion, and land use types. This helps make detailed erosion maps that can be used for better land management and planning how to stop erosion (Ali et al., 2023; Bonilla-Bedoya et al., 2017; Panagos et al., 2015; Renard et al., 1997; Zhang et al., 2024).

This model estimates the annual rate of soil loss by incorporating key variables such as soil erodibility, rainfall-runoff erosivity, topographic characteristics, and land management practices. It is highly regarded for its capability to evaluate both sheet and rill erosion and has gained wide acceptance for assessing soil degradation (Renard et al., 1997). Numerous studies have expanded our understanding of erosion dynamics in Jordan's varied terrains. For instance, Al-Sheriadeh et al. (2000) applied the RUSLE model in northern Jordan, reporting annual soil loss ranging from 0 to 75 tons ha^{1} yr^{1}, with the most severe losses occurring in steep, cultivated regions. Their findings emphasized the role of slope and land use as critical determinants of erosion severity. Further investigations by Farhan et al. (2013) integrated RUSLE with GIS tools in the Zarqa River watershed, revealing that approximately 33% of the area faced moderate to severe erosion risks (exceeding 10 tons ha^{1} yr^{1}). The study demonstrated a strong association between erosion intensity and the LS factor, especially in agricultural zones situated on steep slopes. Advancements in geospatial analysis, as highlighted by Panagos et al. (2015) and Bonilla-Bedoya et al. (2017), have significantly enhanced the capacity to detect and evaluate erosion-vulnerable regions. RUSLE's user-friendly framework supports the incorporation of high-resolution inputs, including satellite-derived land cover and digital elevation models (Panagos et al., 2015). The innovative aspect of this study lies in its integration of RUSLE with GIS to generate a detailed soil erosion risk map for Jordan—a country marked by arid to semi-arid conditions. Unlike broader assessments, this study emphasizes spatial precision by identifying erosion hotspots, particularly in critical areas like the Jordan Valley and Northern Highlands. This targeted approach offers valuable guidance for sustainable land management and soil conservation in regions previously underrepresented in erosion studies. Thus, this research aims to model water-induced soil erosion using RUSLE within a GIS framework, culminating in the development of a national erosion risk map for Jordan.

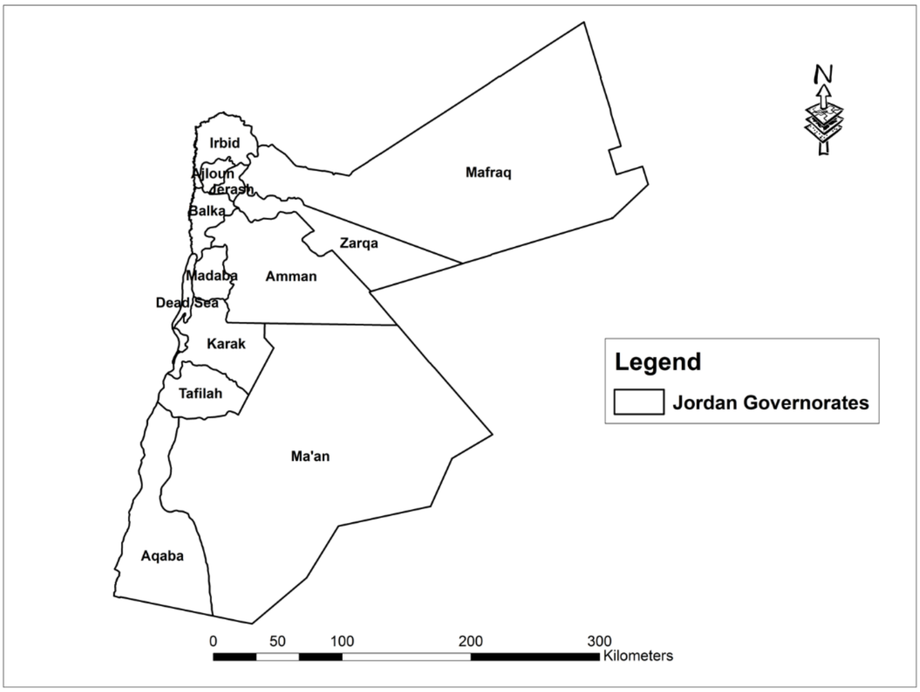

Figure 1. Map of Jordan

2. MATERIAL AND METHODS

2.1. The study area

Jordan is situated at 31°00 N, 36°00 E as seen in Figure 1. The desert covers 90% of the country's land area. However, the northern area is regarded as part of the Fertile Crescent. Jordan has warm, dry summers and moderate, rainy winters. The average yearly temperature ranges between 12 and 25°C, with desert sections seeing temperatures as high as 40 °C. Rainfall ranging from 50 to 600 mm in the desert northern highlands respectively (source: Jordan Meteorological Department 1990-2019) (Jordan Meteorological Department, 2025).

2.2. Data Sets for RUSLE

The Revised Universal Soil Loss Equation (RUSLE) is a well-established and extensively applied model designed to estimate soil erosion caused by water, with particular emphasis on predicting the long-term average annual soil loss. The model utilizes several input parameters that are derived from various sources, including Digital Elevation Models (DEM), field survey data, land use classifications, rainfall records, and Normalized Difference Vegetation Index (NDVI) values. As outlined in Equation 1, these parameters collectively represent the key physical and environmental factors influencing soil erosion processes. The model is formulated according to Equation 1 (Li et al., 2021; Thapa, 2020).

$$\boldsymbol{A} = \boldsymbol{R} \times \boldsymbol{K} \times (\boldsymbol{L} \times \boldsymbol{S}) \times \boldsymbol{C} \times \boldsymbol{P} \qquad [1]$$

Where A = Soil loss (ton/ha/year), R = Rainfall erosivity factor, K = Soil erodibility factor, L = Slope length factor, S = Slope steepness factor, C = Cover management factor, P = Support practice factor.

2.2.1. Rainfall Erosivity (R factor)

The rainfall erosivity factor (R) (Andriyani et al., 2024) It is an indicator of potential water erosion risk and is defined as the capacity of rainfall to generate soil loss via water. R is often determined by taking a long-term average of a storm's annual total of kinetic energy (E) and maximum 30-minute intensity (I30), also known as EI30. The standard international unit (SI) for R is (MJ. mm / ha.h.yr). The main factors affecting the R are the total annual amount, average monthly intensities during months with a high frequency of erosive rain, and the energy of rainfall during erosive storms (Ssewankambo et al., 2023). R refers to soil properties that influence the rate of rainwater infiltration and susceptibility to detachment. The properties that affect susceptibility to detachment and soil matter transport include organic matter content, texture, profile structure, permeability, stone content, moisture content, and temperature. In the present study, the R is computed using a precipitation map created from precipitation data (1990-2019), source of data: Jordan metrological department, as mentioned in Equation 2, and the equation to estimate R as Equation 2.

$$R = 23.61 \times e0.0048p \qquad [2]$$

Where P is the annual long-term rainfall (mm). Figure 2 shows the values of the R factor (MJ.mm / ha^{-1} h^{-1} $year^{-1}$).

2.2.2. Soil Erodibility Factor (K)

The soil erodibility factor (K) quantifies the susceptibility of soil particles to detachment and transport by water runoff during rainfall events (Ke & Zhang, 2022; Luvai et al., 2022). This factor is primarily influenced by characteristics such as soil texture, organic matter content, structure, and permeability (Thapa, 2020). The K value is typically estimated using the nomograph developed by Wischmeier and Smith (1978), as shown in Equation 3. In this study, data from soil laboratory analyses conducted on field samples were employed as inputs for the K factor calculation (Eq. 3)

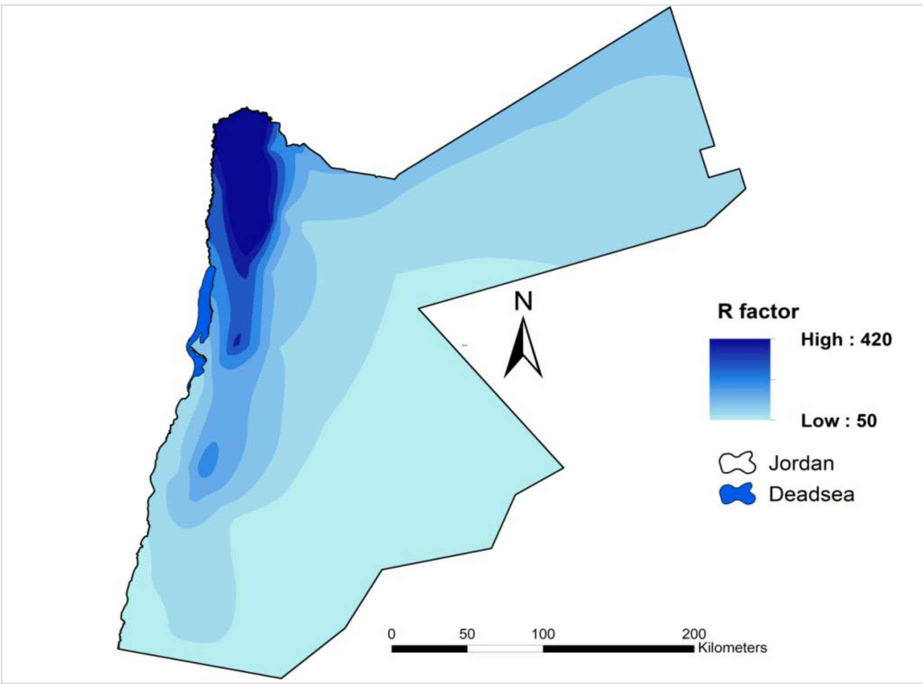

Figure 2. R factor

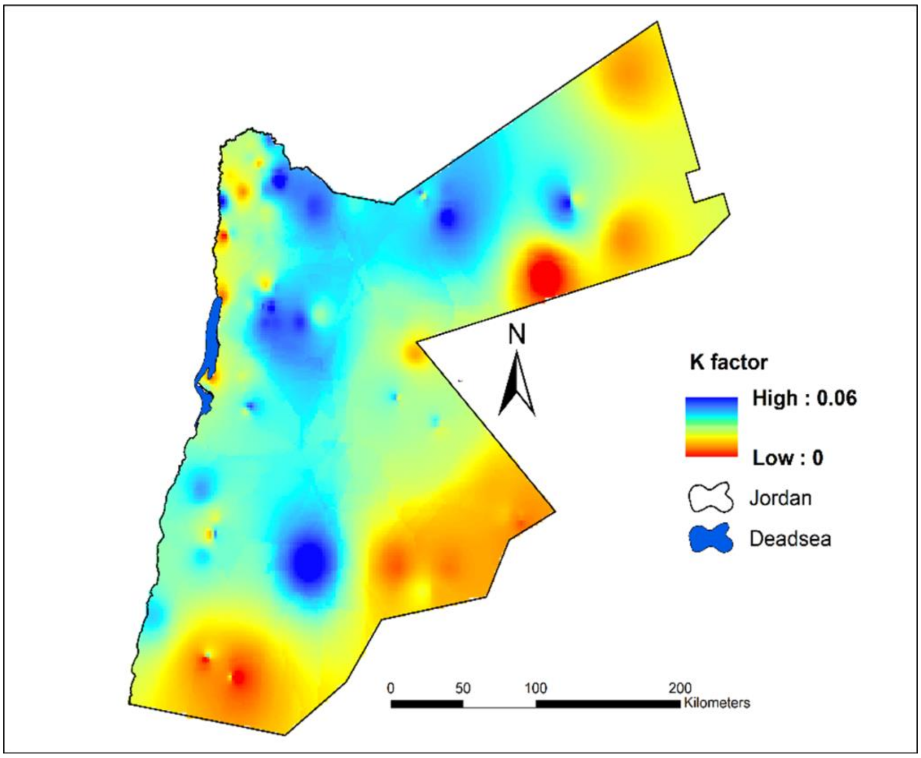

Figure 3. K factor

$$K = 27.66m1.14 \times 10 - 8 \times (12 - a) + 0.0043 \times (b - 2) + 0.0033 \times (c - 3) \quad [3]$$

Where K is the soil erodibility factor (ton ha h ha-1 -MJ-1 mm-1), m: is particle size parameter (% silt + %very fine sand) * (100 - % clay), a: is the organic matter content (%), b: is soil structure code used in soil classification, c: is the soil permeability class. The unit for the K factor is t ha h ha^{-1} MJ^{-1} mm^{-1}. The result K is shown in Figure 3.

The soil erodibility factor was calculated using the nomograph developed by Wischmeier and Smith (1978) based on soil texture. According map units available in the National Soil Map and Land Use Project (1994) (Jordan Ministry of Agriculture, 1994), we obtained the soil texture, % silt + very fine sand, % sand.

2.2.3. Slope Length and Steepness Factor (LS)

The Slope Length and Steepness (LS) factor reflects the combined topographic parameters (Thapa, 2020) The parameters L and S are used to quantify the effects of slope angle and slope length on erosion (Thapa, 2020). The L factor is the distance between the runoff source and the point when deposition begins, or when runoff is channelled into a particular channel. The LS factor was calculated using the DEM, which included slope in degrees, flow direction, and flow accumulation, as shown in Equation 4, and Figure 4 shows the LS value.

$$\boldsymbol{LS} = \boldsymbol{Pow}([\boldsymbol{FlowAcc}]) \times \boldsymbol{resolution}/\mathbf{22.1}, \mathbf{0.6}) \times \boldsymbol{Pow}(\mathbf{sin}([\boldsymbol{Slope\ Degree}]) \times \mathbf{0.01745})/\mathbf{0.09}, \mathbf{1.3}) \quad [4]$$

2.2.4. The Support Practice (P Factor)

The support practice factor (P) indicates the ratio of soil loss caused by a particular support practice to soil loss caused by traditional up-and-down cultivation methods. This contouring method is used with P values of 1 because there is no geographic representation indicating the actual locations of these practices. To integrate this information into a GIS, a database of georeferenced support practices would need to be established along with the corresponding P-factor values.

2.2.5. The Cover Management C Factor

In the RUSLE, vegetation cover is quantified using the cover management factor (C-factor), which reflects the impact of plant cover on soil erosion potential (Wischmeier & Smith, 1978). The C-factor ranges from 0, representing full vegetation cover with minimal erosion risk, to 1, indicating bare soil with maximum susceptibility to erosion. This factor is influenced by both the extent of vegetation and its developmental stage. To derive the C-factor for this study, high-resolution Sentinel-2 satellite imagery (10-meter spatial resolution) was utilized to generate Normalized Difference Vegetation Index (NDVI) maps. These NDVI maps were processed using remote sensing techniques to estimate vegetation density across the study area. According to Essa (2004), a C-factor value of 0.35 is appropriate for Jordanian rangelands. Land cover data were reclassified in ArcGIS based on assigned C values using the “Look Up” tool, thereby enabling the generation of a spatially explicit C-factor layer. This process required first creating a land cover map and then assigning appropriate C values to each category, which were then used to reclassify the data accordingly. The RUSLE model calculates the C-factor through multiple subcomponents, including the effects of surface residue, plant canopy, soil roughness, and soil moisture (Felix et al., 2023; Renard et al., 1997). Figure 5 presents the final C-factor distribution across Jordan.

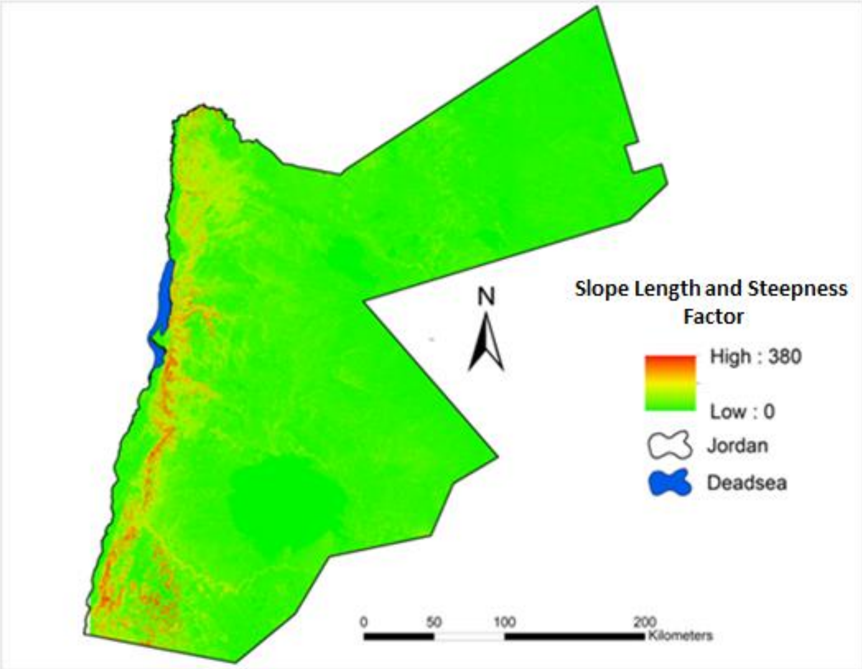

Figure 4. Slope Length and Steepness Factor

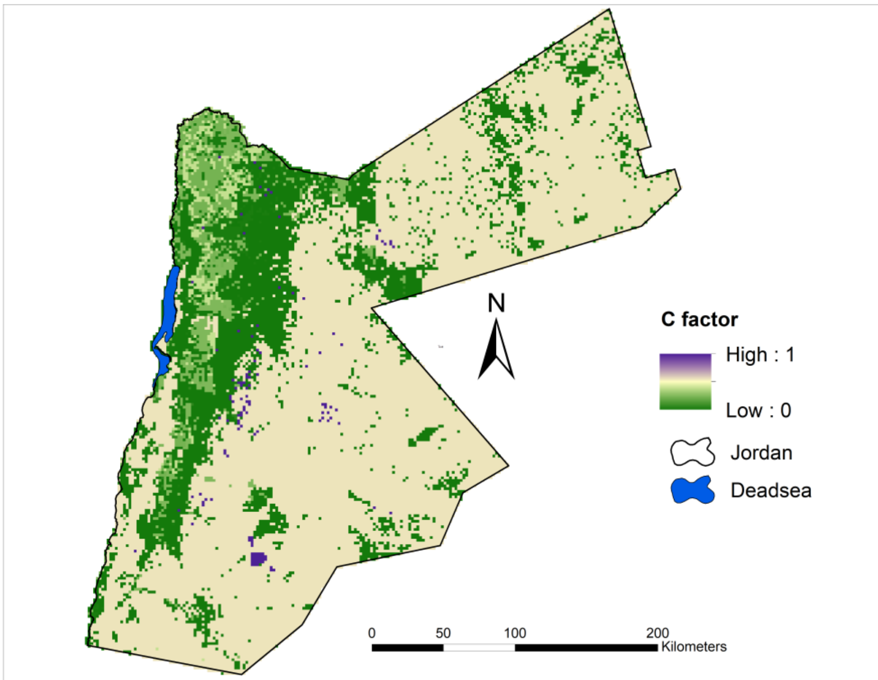

Figure 5. Cover Management (C) Factor Map of Jordan

3. RESULTS

3.1. Overview of Soil Erosion Classes

The RUSLE model integrated with GIS tools was utilized to generate a soil erosion map for Jordan. The land was classified into three erosion risk categories: low (0–10), moderate (10–50), and high (>50) tons ha^{-1} yr^{-1}. Based on the findings, approximately 94% of Jordan's land area falls within the low erosion category, with 5% falling under the moderate erosion category, and around 1% classified as high erosion (Table 1). This classification demonstrates that while the majority of the country experiences relatively low erosion rates, specific regions, particularly those with higher precipitation levels and steeper slopes, are significantly more susceptible to severe erosion.

3.2. Spatial Distribution of Soil Erosion

Figure 6 presents the spatial distribution of soil erosion rates across Jordan, highlighting the most at-risk areas. The low erosion rates (0–10 tons ha^{-1} yr^{-1}) are predominant in the desert regions and areas with low slopes and minimal annual rainfall. Conversely, the moderate erosion rates (10–50 tons ha^{-1} yr^{-1}) are found primarily in parts of the highlands in the north and central regions, as well as in parts of the Jordan Valley.

Table 1. Area Percentage of Erosion Hazard Classes

Erosion hazard	Area percentage (%)	Soil loss rate (tons ha^{-1} yr^{-1})
Low	94	10-0
Medium	5	10-50
High	1	>50

The highest erosion rates (>50 tons ha^{-1} yr^{-1}) are localized in areas characterized by steep slopes and high rainfall, particularly in the northern highlands and the Jordan Valley, as depicted in Figure 6. Figure 6 illustrates the soil erosion hazard across Jordan, showing the critical areas where soil erosion exceeds 50 tons ha^{-1} yr^{-1}. These hotspots, primarily located in the northern highlands and the Jordan Valley, indicate regions where soil conservation measures are urgently needed. The severity of erosion in these areas is likely due to the combination of steep slopes, high rainfall intensity, and vulnerable soil types, which collectively contribute to accelerated soil loss (Wischmeier & Smith, 1978).

3.3. Identification of Erosion Hotspots

Identifying erosion hotspots is essential for implementing effective soil conservation strategies. As shown in Figure 7, these hotspots are areas with moderate to high erosion risk, where annual soil loss surpasses 50 tons ha^{-1} yr^{-1}. Such zones are predominantly found in the Jordan Valley and the highland regions, where a combination of high rainfall erosivity (R factor), steep terrain (LS factor), and limited vegetation cover (C factor) contributes to intense erosion. Figure 7 highlights the need for prioritizing these zones in conservation planning to curb ongoing land degradation. In these vulnerable areas, applying interventions such as afforestation, terracing, and contour farming could play a significant role in reducing erosion rates and maintaining land productivity. Moreover, these areas should be prioritized for future research and monitoring to ensure that conservation strategies are effectively reducing erosion rates (Pasquale Borrelli et al., 2017).

3.4. Implications for Land Management

The spatial analysis of soil erosion across Jordan highlights the need for targeted soil conservation practices, particularly in identified hotspots. Implementing reforestation, terracing, and contour plowing measures in these areas could significantly reduce soil loss and enhance land productivity. Moreover, integrating detailed data on support practices (P factor) into future models would improve the accuracy of erosion risk assessments and help formulate more effective land management strategies.

4. DISCUSSION

Integration of the RUSLE model with GIS tools enabled the development of a comprehensive soil erosion map for Jordan, dividing the country into three erosion risk categories: low, moderate, and high. This approach highlights the utility of advanced modeling techniques in addressing soil conservation challenges and is consistent with recent advances in spatial erosion assessment methods (Khan & Rahman, 2024).

Spatial analysis of soil erosion patterns across Jordan provides important insights into environmental sustainability and agricultural productivity. The integration of RUSLE with GIS, as demonstrated by Farhan and Nawaiseh (2015), provides a robust methodological framework for spatially assessing erosion risks. This approach is instrumental in identifying high-risk areas, particularly those influenced by steep slopes and land-use changes, facilitating targeted conservation measures. As shown in Figure 6, desert regions experience low erosion rates due to minimal rainfall and gentle slopes.

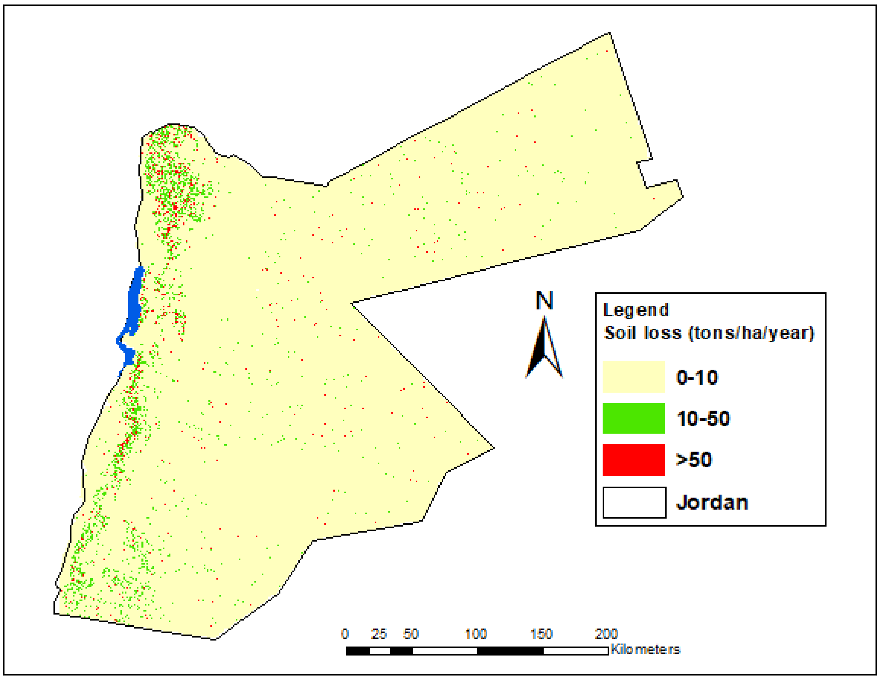

Figure 6. Soil Erosion Map

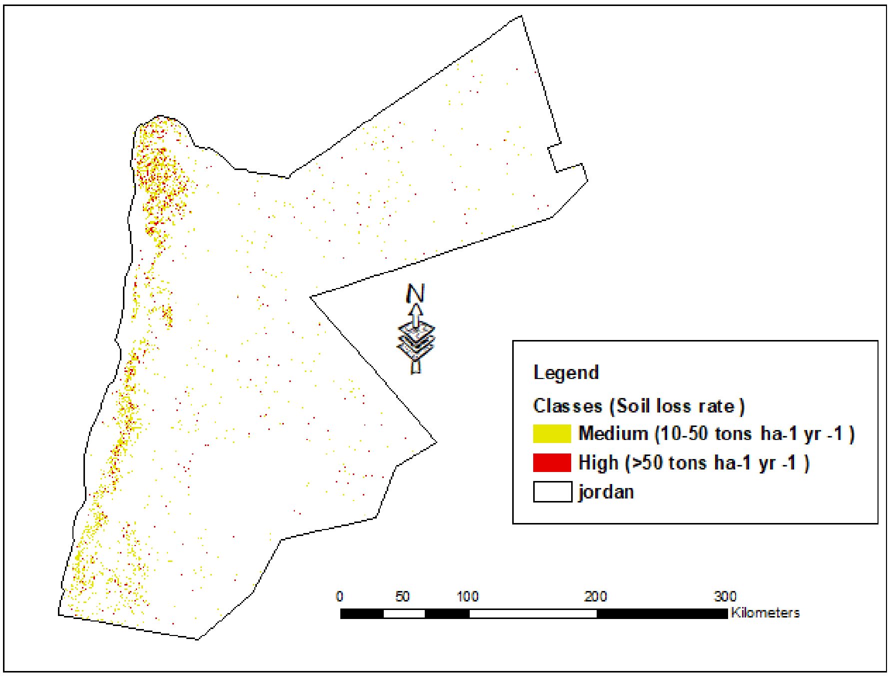

Figure 7. The Hotspot Areas Susceptible to High SE (medium & high)

However, hotspots have been identified in highland areas and the Jordan Valley, where soil erosion poses significant risks. These results confirm previous studies by Alkharabsheh et al. (2013) and Al-Wadaey and Ziadat (2014), which highlight the vulnerability of semiarid landscapes to soil degradation.

The analysis shows that 94% of Jordan's land area is affected by low-level erosion, especially in arid and semi-arid regions characterized by flat terrain and sparse vegetation. Moderate erosion affects 5% of the area, while severe erosion is concentrated in 1% of the land, typically in regions with steep slopes and higher rainfall (Table 1). Farhan and Alnawaiseh (2018) highlighted the significant influence of rainfall erosivity on erosion patterns, with seasonal and annual variability playing a critical role. Their findings align with the hotspots identified in the northern highlands and Jordan Valley, where intense rainfall events exacerbate soil loss. This distribution is consistent with global evidence linking topographic and climatic factors to the intensity of soil erosion (Mousavi et al., 2023). Moderate erosion rates found in the northern and central highlands and parts of the Jordan Valley highlight the interplay between precipitation, slope gradient, and soil displacement.

Erosion hotspots, located mainly in the highlands and Jordan Valley, are caused by high rainfall erosivity (R factor), steep slopes (LS factor), and sparse vegetation (C factor). These conditions exacerbate land degradation and threaten agricultural productivity. Figure 7 illustrates these vulnerable areas and highlights the need for targeted interventions. Recent studies, such as Al-Shabeeb et al. (2018) point out that extreme weather events further exacerbate these risks and require proactive soil management strategies.

Implementing soil conservation measures such as reforestation, terracing and contour plowing is critical to reducing the risk of erosion. Research demonstrates the effectiveness of these measures in improving soil retention and ecosystem services. For example, Angulo-Martínez and Barros (2015) reported a reduction in soil loss of up to 80% through integrated conservation strategies. Similarly, Panagos et al. (2015) highlighted the benefits of combining multiple conservation techniques to increase land productivity and stability.

The spatial variability of soil erosion in Jordan requires regionally specific protective measures. In high-risk areas in the northern highlands and Jordan Valley, interventions such as reforestation and terracing can minimize runoff, while contour plowing improves soil retention. Incorporating the support practice factor (P factor) into future assessments will refine erosion models and support more effective management strategies (Panagos et al., 2022).

Comparative studies in the Mediterranean and Ethiopian regions with analogous climatic and topographical conditions confirm the results in Jordan. In these regions, high erosion rates often occur in steep slope areas with intense rainfall and sparse vegetation (Panagos et al., 2015; Wolka et al., 2015). This cross-regional consistency highlights the universality of soil erosion drivers and highlights the importance of tailored conservation approaches. Climate variability significantly impacts soil erosion, especially in Jordan's semi-arid environment. Projections for the Mediterranean region suggest increased rainfall intensity and reduced frequency, exacerbating erosion risks in vulnerable areas (Rodrigo-Comino et al., 2018). These changes necessitate adaptive soil conservation strategies to mitigate potential impacts.

Addressing areas at high risk of erosion requires targeted conservation measures, including reforestation, terracing, and contour plowing. These interventions have shown significant effectiveness in reducing soil loss (Angulo-Martínez & Barros, 2015; Montgomery, 2007). Furthermore, integrating advanced technologies such as remote sensing and machine learning can improve the accuracy of erosion prediction and identify subtle risk patterns (Arabameri et al., 2019). Incorporating socioeconomic factors into erosion models will provide a comprehensive understanding of impacts on local communities, supporting sustainable land management (Keesstra et al., 2018).

5. CONCLUSION

This study highlights the critical role of spatial analysis in understanding and managing soil erosion risks in Jordan. By integrating the Revised Universal Soil Loss Equation (RUSLE) with Geographic Information Systems (GIS), a comprehensive soil erosion map was generated, revealing the spatial distribution of erosion risks across the country. The results show that approximately 94% of Jordan's land area falls under low erosion risk (0-10 tons ha^{-1} yr^{-1}), while 5% and 1% are categorized as moderate (10-50 tons ha^{-1} yr^{-1}) and high erosion risk areas (greater than 50 tons ha^{-1} yr^{-1}), respectively. This indicates that, while the majority of the country experiences relatively low erosion rates, specific regions, particularly in the northern highlands and the Jordan Valley, are highly susceptible to severe erosion.

The spatial distribution analysis revealed that low erosion rates are predominantly found in desert areas and regions with low slopes and minimal rainfall. In contrast, the moderate and high erosion rates are associated with areas of steeper terrain, higher rainfall, and more intensive land use, especially in the northern highlands and Jordan Valley. These areas, identified as erosion hotspots, face significant soil loss, with rates exceeding 50 tons ha^{-1} yr^{-1}, underscoring the urgent need for targeted soil conservation efforts.

To mitigate the risks of soil degradation, it is crucial to focus on conservation measures in these high-risk regions. Recommended interventions include reforestation, terracing, contour farming, and the establishment of vegetative cover to stabilize soil and reduce erosion. In moderate-risk areas, sustainable agricultural practices such as controlled grazing and soil cover restoration should be promoted to prevent further erosion. Additionally, the use of advanced technologies such as GIS and remote sensing can enhance real-time monitoring of soil erosion and improve decision-making for land management.

The findings of this study emphasize the importance of integrated soil erosion management, combining technological tools with on-the-ground conservation efforts. Collaborative efforts between government agencies, local communities, and environmental organizations are essential to ensure the effective implementation of soil conservation practices. The adoption of policies that encourage sustainable land-use practices and the restoration of degraded areas will be critical to reducing soil erosion and maintaining Jordan's agricultural and natural landscapes for future generations.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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